

# Experimental comparison of the buckling behavior of axially compressed thin-walled closed-section profiles manufactured by fused deposition modeling and carbon fiber-reinforced polymer

Kuba Rosłaniec<sup>1\*</sup> 

<sup>1</sup> Department of Machine Design and Mechatronics, Faculty of Mechanical Engineering,  
Lublin University of Technology, Nadbystrzycka 36, 20-618 Lublin, Poland  
E-mail: k.rosłaniec@pollub.pl

## ABSTRACT

The aim of this study was to conduct an experimental comparative analysis of the stability of axially compressed thin-walled closed-section profiles with identical geometries, manufactured from PLA, PETG, PETG-CF, and ABS thermoplastic materials using fused deposition modeling (FDM), and from a carbon fiber-reinforced polymer (CFRP) composite with a quasi-isotropic stacking sequence. The profiles had square cross-sections with internal dimensions of  $40 \times 40$  mm, a height of 200 mm, and a wall thickness of 1.24 mm. Three specimens were manufactured from each FDM material, resulting in a total of 12 profiles. Axial compression tests were conducted using a universal testing machine, an ARAMIS 2D digital image correlation system, and an acoustic emission system. The critical loads were determined from the experimental load–displacement curves using the intersection method based on fitted straight-line segments. Among the thermoplastic materials, the highest mean critical load was obtained for PLA; it was approximately 1.29 times higher than that obtained for PETG, 1.70 times higher than that obtained for PETG-CF, and 1.36 times higher than that obtained for ABS. The mean critical load of the CFRP profile was approximately 13.9 times higher than that of the PLA profiles. Five complete buckling half-waves were observed in the PLA, PETG, and ABS structures, seven in the PETG-CF structures, and four in the CFRP profile. Despite substantial differences in the critical load values, the experimental load–displacement responses and the overall buckling behavior of the investigated structures were similar. The acoustic emission signals recorded near the critical state did not indicate the initiation of permanent material damage, as confirmed by the absence of stiffness degradation and the recovery of the specimens' original shapes after unloading. The novelty of the present study lies in the comparison of the behavior of thin-walled structures manufactured using FDM additive technology with that of thin-walled composite structures. The obtained results may provide a basis for assessing the applicability of additive manufacturing technologies in the design of thin-walled load-bearing structures.

**Keywords:** buckling, thin-walled closed-section profiles, fused deposition modeling, axial compression, critical load, thermoplastic materials, carbon fiber-reinforced polymer.

## INTRODUCTION

In recent years, there has been a rapid increase in interest in components manufactured using additive manufacturing technologies, particularly fused deposition modeling (FDM), which is one of the most widely used 3D-printing techniques. This technology is applied across numerous

industrial sectors, including rapid and cost-effective prototyping, as well as the production of wall panels, air ducts, tools, decorative components, electronic parts, assembly fixtures, load-bearing structures, and components with complex geometries [1–6]. The dynamic development of FDM technology and the continuous expansion of its application areas justify the need for further

research into the properties and behavior of structures manufactured using this method. This need is particularly important for load-bearing components, as the transition from prototyping to structural applications requires an understanding not only of the material properties of printed parts, but also of their behavior under complex structural phenomena, such as buckling.

Composite materials have gained considerable popularity, replacing conventional materials such as metal alloys and wood in many applications [7], owing to the increasing demands placed on modern structural materials. One of their key characteristics is the ability to tailor their properties through deliberate design, which enables their optimization for specific applications. The complex mechanical behavior of fiber-reinforced composites, such as carbon fiber-reinforced polymers (CFRPs), results from their anisotropy, whereby their mechanical properties strongly depend on the orientation of the fibers relative to the direction of the applied load. Components made of fiber-reinforced composites exhibit high strength and stiffness while maintaining a relatively low self-weight [8–10]. Current research on composite materials frequently focuses on the axial compression of thin-walled composite structures, defined as structures in which the characteristic dimension of the internal hollow cross-section is at least 20 times greater than the wall thickness [11–14].

Previous studies on axially compressed thin-walled CFRP structures have addressed, among other aspects, the effects of cross-sectional geometry, laminate configuration and ply orientation, and boundary conditions on the critical load, buckling mode, post-buckling response, and load-carrying capacity failure mechanisms [11–14]. These studies have provided extensive knowledge of the stability of composite structures; however, they have generally focused on comparisons between different laminate configurations or geometries within the same material group. By contrast, considerably less attention has been devoted to comparing the behavior of such structures with that of additively manufactured thin-walled polymer structures.

Components manufactured using FDM technology should not be treated as homogeneous isotropic materials. The layer-by-layer deposition process leads to the formation of a clearly defined mesostructure, whose principal directions are determined by the orientation of the

deposited material paths within individual layers and by the build direction. Consequently, the mechanical properties of the manufactured components, including their stiffness and strength, depend on the direction of loading relative to the printing paths and interlayer bonding planes. For this reason, the behavior of FDM materials is often described using orthotropic material models or approaches derived from laminate mechanics. The mechanical properties of the final structure are also influenced by layer thickness, path geometry and arrangement, the quality of bonding between adjacent paths and layers, and the presence of voids. Interlayer interfaces are particularly important, as they may constitute the weakest direction of the structure and promote crack initiation and damage propagation. As a result, the properties of the manufactured component may differ significantly from those of the isotropic bulk material. The influence of anisotropy is especially important in thin-walled components subjected to compression. During buckling, the walls are simultaneously exposed to compressive stresses and local bending, while the directions of these stresses may vary relative to the deposited paths and interlayer boundaries. Anisotropy and local mesostructural heterogeneities may therefore affect the effective structural stiffness, critical load, location of buckling initiation, number of developed half-waves, and subsequent evolution of post-buckling deformation. The structural similarity between FDM-printed components and layered composite materials therefore justifies comparative studies of thin-walled FDM and composite structures, particularly with respect to their pre-buckling response, buckling behavior, and post-buckling performance [15–23]

A distinct group of materials used in FDM technology comprises thermoplastics modified with short fibers, including carbon-fiber-reinforced PETG (PETG-CF). The incorporation of short carbon fibers into the PETG matrix is primarily intended to increase material stiffness. In components printed using filaments reinforced with short discontinuous fibers, fiber orientation is largely determined by the flow of the material through the nozzle and its deposition along the printing paths. Consequently, the properties of PETG-CF components depend simultaneously on the characteristics of the matrix, fiber content and orientation, fiber–matrix interfacial bonding, porosity, and manufacturing process parameters.

Available studies indicate that the addition of short carbon fibers generally increases the elastic modulus of printed components, although it does not necessarily lead to a proportional improvement in strength. The properties of PETG-CF are also strongly influenced by parameters such as infill pattern and density, layer thickness, extrusion temperature, porosity, and heat treatment [24–26]. The use of PETG-CF in studies of thin-walled profiles makes it possible to assess whether increasing material stiffness through the addition of short carbon fibers results in a higher critical load and changes in the buckling mode compared with unreinforced PETG.

A substantial proportion of previous research on the mechanical behavior of FDM-manufactured components has focused on material specimens and on the influence of process parameters, such as build orientation, printing path direction, layer thickness, and interlayer bonding conditions, on their elastic and strength properties [15, 27, 28]. These studies have confirmed that the build direction and path configuration may result in pronounced orthotropy of the mechanical properties, thereby justifying the use of models analogous to those applied in laminate mechanics. However, they do not provide a complete understanding of the behavior of finished thin-walled structural components under buckling conditions.

Components manufactured using FDM additive technology are characterized by geometric and structural imperfections arising from technological limitations and the specific nature of the manufacturing process. These imperfections, particularly in load-bearing components and structures subjected to mechanical loading, may reduce their load-carrying capacity. Components produced using this technology exhibit relatively high strength, compatibility with a wide range of materials, including fiber-modified polymers reinforced, for example, with carbon or glass fibers, and comparatively low production costs [6, 29–31]. Economic considerations are currently among the most important factors taken into account in industrial manufacturing. In the case of composite components, manufacturing costs are relatively high owing to the high cost of raw materials, the complexity of the production process, the need for dedicated tooling, such as molds, and the use of expensive equipment, including ovens and autoclaves. Another important factor contributing to the high production cost of composite components, particularly

in one-off or low-volume manufacturing, is the long production time. This includes the design and manufacture of production tooling, multi-stage component preparation, such as ply lay-up, as well as time-consuming curing processes and post-processing operations [32, 33]. An additional advantage of additive manufacturing technologies is their greater design flexibility. These technologies enable the production of components with complex geometries without the need for drilling holes or performing other machining operations, thereby reducing the risk of introducing additional stresses during processing [34–37]. From the perspective of structural applications, it is therefore important to determine not only the absolute load-carrying capacity of FDM profiles, but also the extent to which their pre-buckling response and buckling behavior resemble those of more expensive CFRP structures.

The literature review indicates that previous studies have primarily focused on the separate analysis of thin-walled CFRP structures or structures manufactured using FDM technology. The cited studies did not provide a systematic comparison of geometrically equivalent profiles made of a conventional carbon–epoxy composite and several unreinforced FDM thermoplastics tested under identical loading and boundary conditions. In particular, the differences between these structures in terms of pre-buckling stiffness, critical load, spatial distribution of buckling half-waves, and the relationship between buckling and damage initiation remain insufficiently understood [38–41]. Such a comparison requires the use of profiles with equivalent geometries and a consistent experimental procedure, thereby limiting the influence of geometric factors and allowing the effects of material type and manufacturing technology to be identified more clearly.

The studies on composite structures were conducted at an earlier stage of the research, and the results obtained serve as a reference for comparison with the results obtained for structures of identical geometry manufactured using FDM additive technology. The novelty of the present study lies in the analysis and comparison of the buckling behavior of thin-walled profiles manufactured from thermoplastic materials using FDM additive technology with that of thin-walled composite structures [13, 42]. Unlike previous studies, the comparison was performed for profiles with identical geometric parameters and under the same experimental conditions, encompassing

both a conventional CFRP composite and four commonly used thermoplastic materials.

This study compares the behavior of thin-walled structures in the pre-buckling and critical regimes, manufactured from polylactic acid (PLA), glycol-modified polyethylene terephthalate (PETG), and acrylonitrile-butadiene-styrene (ABS) using FDM additive manufacturing technology, with that of structures made of a carbon-epoxy composite. All specimens had identical geometric parameters, including cross-sectional area, height, and wall thickness. The experimental tests were conducted using a universal testing machine, the ARAMIS 2D digital image correlation system to record buckling modes, and the acoustic emission method to determine whether any indications of damage initiation occurred as the profiles approached buckling. The novelty of this study lies in the comparison of geometrically identical anisotropic specimens manufactured using different production technologies and made of different material types, namely a CFRP, PLA, glycol-modified PETG, and ABS. The contribution of the study extends beyond a quantitative comparison of critical loads and includes a comparison of pre-buckling response characteristics, the identification and assessment of buckling modes, and verification of whether the attainment of the critical state is accompanied by indications of damage initiation detected using acoustic emission. This approach makes it possible to assess whether the structural similarity between composite structures and FDM-manufactured components results in comparable buckling mechanisms despite fundamental differences in their materials and manufacturing technologies.

## MATERIALS

The objects of the study were thin-walled columns made of PLA, PETG, ABS, and glycol-modified polyethylene terephthalate reinforced with carbon fibers (PETG-CF), all having identical geometries. In the case of PETG-CF, glycol-modified polyethylene terephthalate formed the matrix, whereas short carbon fibers constituted the reinforcing phase. To assess the influence of material type on structural behavior, the additively manufactured profiles were compared with profiles made of a CFRP with the symmetric stacking sequence  $[0/45/-45/90/90/-45/45/0]$ . The analysis compared the buckling modes and

critical loads of profiles with a wall thickness of 1.24 mm, a height of 200 mm, and a cross-section with external dimensions of  $40 \times 40$  mm (Figure 1). The profiles manufactured using FDM additive technology are shown in Figure 2. Three profiles were produced from each material used in the FDM manufacturing process, resulting in a total of 12 test specimens. The CFRP composite profiles were used solely as a reference for comparison with the primary objects of the study, namely the profiles manufactured using FDM additive technology. The composite specimens were produced using CYCOM 985-42%-HS-135-305 prepreg tape with a width of 305 mm. The tape consisted of 985 resin, accounting for 42% of its volume, and carbon-fiber reinforcement with a fiber areal weight of  $135 \text{ g/m}^2$ . The columns were manufactured by wrapping the prepreg tape around a mold at angles corresponding to the prescribed stacking sequence. The profiles were cured in an autoclave at a temperature of  $177^\circ\text{C}$  and a pressure of 0.6 MPa. The mechanical properties of the composite were determined in [42], which also provides a detailed description of the corresponding characterization methodology. The composite profiles used for comparison were also analyzed in several previous publications, including [13, 38, 43–49].

The profiles were manufactured using FDM additive technology with a Bambu Lab X1 Carbon (X1C) 3D printer compatible with all the aforementioned materials. The CoreXY kinematic system used in the printer provides high printing accuracy owing to its greater structural rigidity compared with conventional Cartesian printers, while maintaining a high printing speed. The 3D printer was equipped with a Micro Lidar system comprising a miniature laser sensor that scans the printed surface. This system was used to calibrate the filament flow before printing each specimen. The thin-walled profiles were printed along the machine Z-axis, i.e., in the vertical orientation, which reduced the manufacturing time while maintaining a high quality of both the internal and external surfaces of the specimens. Each layer of the model consisted of three equally wide wall lines, forming a wall with a total thickness of 1.24 mm and a layer height of 0.2 mm. Owing to the relatively small contact area between the specimens and the magnetic build plate mounted on the heated bed, a brim was used to improve bed adhesion.

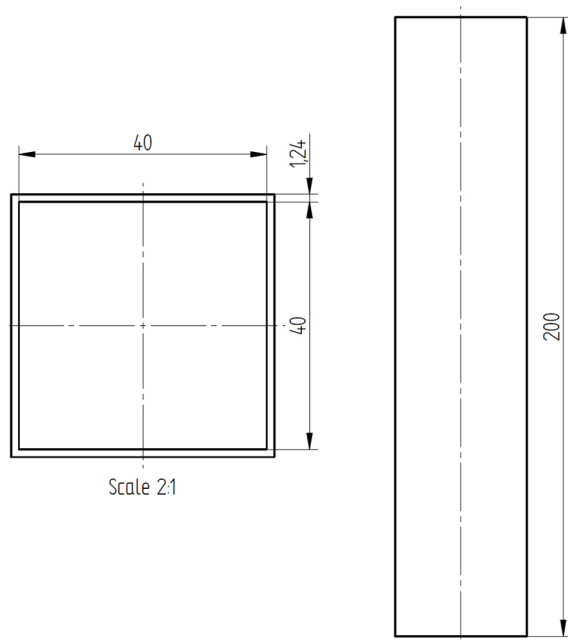


**Figure 1.** The dimensions of the samples analyzed in [mm]

The brim is a single-layer auxiliary structure generated around the base of the profile and connected to its edges. Its purpose was to increase the contact area with the magnetic build plate and stabilize the printing process by reducing the risk of the model corners detaching from the build surface. The FDM profiles were manufactured using Bambu Lab filaments with a diameter of 1.75 mm, whose material properties, as specified by the manufacturer, are presented in Table 1 [50]. The deposition of successive material layers involved feeding the thermoplastic filament through the extruder into a heated nozzle, where it was melted and subsequently extruded as a thin material path. The moving print head deposited successive layers, which bonded together upon cooling to form a structure corresponding to the instructions contained in the G-code generated from the three-dimensional model using Bambu Studio slicing software. To

reduce the risk of the nozzle rubbing against the printed component during travel movements, i.e., movements performed without material extrusion, the Z-hop function was applied. This function temporarily raises the nozzle, creating a clearance between the nozzle and the printed component and thereby preventing collisions during non-printing movements. A Z-hop height of 0.4 mm was used in the present study, with a spiral movement pattern in which the nozzle followed a helical trajectory while being raised to the specified height. This solution additionally reduced the formation of stringing. The use of Z-hop also decreased the risk of model damage and layer shifting. After completing the travel movement, the nozzle returned to the printing height and resumed material extrusion.

The individual filament types used in the study required different printing process parameters. The manufacturing process was carried out using the printing parameters recommended by the filament manufacturer, adjusted to the printer nozzle diameter of 0.4 mm, a layer height of 0.2 mm, and the type of magnetic build plate used for printing. Owing to the use of materials with increased abrasiveness, particularly PETG-CF, a hardened nozzle was employed for the manufacture of all profiles. Its enhanced wear resistance limited erosion of the nozzle orifice, thereby maintaining a constant extrusion diameter and contributing to high dimensional accuracy and repeatability of the manufactured components. All specimens were printed on a heated bed equipped with a smooth BIQU Panda BuildPlate CryoGrip Pro Glacier magnetic build plate. This plate is intended for technical and precision printing applications and is characterized by high temperature resistance and compatibility with the filaments used in the study. Selected printing process parameters are presented in Table 2, whereas the profiles manufactured using FDM 3D printing are shown in Figure 3. Before the printing process was initiated, the printer was thoroughly cleaned,

**Table 1.** Strength and stiffness properties of the selected filaments [50]

| Filament properties                                     | Filament type |         |      |         |
|---------------------------------------------------------|---------------|---------|------|---------|
|                                                         | PLA           | PETG HF | ABS  | PETG CF |
| Toughness – Impact strength XY (kJ/m <sup>2</sup> )     | 26.6          | 31.5    | 39.3 | 41.2    |
| Strength – Bending strength XY (MPa)                    | 76            | 64      | 62   | 70      |
| Stiffness – Bending modulus XY (MPa)                    | 2750          | 2050    | 1880 | 2910    |
| Layer adhesion – Impact strength Z (kJ/m <sup>2</sup> ) | 13.8          | 10.6    | 7.4  | 10.7    |

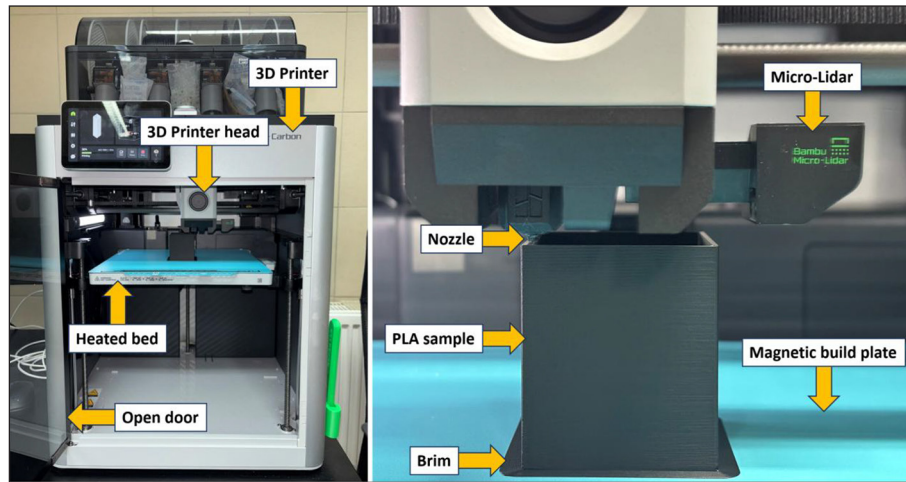


Figure 2. 3D printing station during PLA test printing

lubricated, and calibrated on the stable surface on which the test specimens were subsequently manufactured. In addition, before each print, the magnetic build plate was cleaned with isopropyl alcohol to remove contaminants and improve first-layer adhesion.

To prevent premature softening of the material during printing due to excessive temperature inside the build chamber, which could lead to filament deformation within the extruder, improper extrusion, or nozzle clogging, the front door of

the printer chamber was removed when processing PLA. This measure was intended to limit the temperature rise inside the chamber and was consistent with the recommendations of the printer and filament manufacturers [51]. At the same time, stable ambient conditions were maintained by eliminating air movement within the room, which could otherwise cause non-uniform cooling of the manufactured structures. According to the manufacturer's recommendations, for materials with a softening temperature below 60 °C,

Table 2. Selected printing process parameters

|               |         |                                  |     |
|---------------|---------|----------------------------------|-----|
| Filament type | PLA     | Nozzle temperature [°C]          | 220 |
|               |         | Bed temperature [°C]             | 45  |
|               |         | Outer wall printing speed [mm/s] | 200 |
|               |         | Inner wall printing speed [mm/s] | 300 |
|               |         | Layer height [mm]                | 0,2 |
|               | PETG    | Nozzle temperature [°C]          | 245 |
|               |         | Bed temperature [°C]             | 75  |
|               |         | Outer wall printing speed [mm/s] | 200 |
|               |         | Inner wall printing speed [mm/s] | 300 |
|               |         | Layer height [mm]                | 0,2 |
|               | PETG CF | Nozzle temperature [°C]          | 255 |
|               |         | Bed temperature [°C]             | 70  |
|               |         | Outer wall printing speed [mm/s] | 200 |
|               |         | Inner wall printing speed [mm/s] | 300 |
|               |         | Layer height [mm]                | 0,2 |
|               | ABS     | Nozzle temperature [°C]          | 270 |
|               |         | Bed temperature [°C]             | 90  |
|               |         | Outer wall printing speed [mm/s] | 200 |
|               |         | Inner wall printing speed [mm/s] | 300 |
|               |         | Layer height [mm]                | 0.2 |

such as PLA, the printer chamber should remain open when the heated-bed temperature exceeds 45 °C. Profiles made of PETG, PETG-CF, and ABS were printed with the build chamber closed, which enabled stable thermal conditions to be maintained throughout the manufacturing process. To improve the quality of the manufactured structures, all filaments used in the study were dried before printing, as thermoplastic materials employed in FDM technology are capable of absorbing moisture from the surrounding air. The extent of moisture absorption depends on the type of material. Excessive moisture content in the filament may cause the absorbed water to evaporate when the material is heated in the nozzle, resulting in the formation of water-vapor bubbles and local expansion of the molten material, thereby producing unstable extrusion. This phenomenon may deteriorate the surface quality of printed components, reduce their mechanical properties, and decrease the repeatability of the printing process. A Creality Space Pi 360 filament dryer was used to remove excess moisture from the filaments. The drying parameters were selected in accordance with the material manufacturer's recommendations [52]. All filaments used in the study were dried for 8 h at 50 °C for PLA, 65 °C for PETG and PETG-CF, and 80 °C for ABS.

## METHODS

Axial compression tests were conducted using a Comotech QC505M2F universal testing machine controlled by AMIS Plus software and capable of applying loads of up to 50 kN. The experiments were performed at a constant room temperature and a constant machine crosshead displacement rate of 1 mm/min. The tests were intended to determine the critical state, including analysis of the buckling phenomenon and determination of the corresponding critical loads. The critical loads of the thin-walled structures manufactured using FDM technology were determined using an approximate straight-line intersection method. This method is based on experimentally obtained load-shortening curves and involves approximating two appropriately selected segments of the experimental curve, one located before the onset of buckling, prior to the change in structural stiffness, and the other immediately after buckling, following the change in stiffness. The selected curve segments should exhibit a linear character, i.e., they should follow a straight-line trend as closely as possible. The intersection point of the two fitted straight lines corresponds to the approximate displacement and load values at which buckling occurred [53, 54].

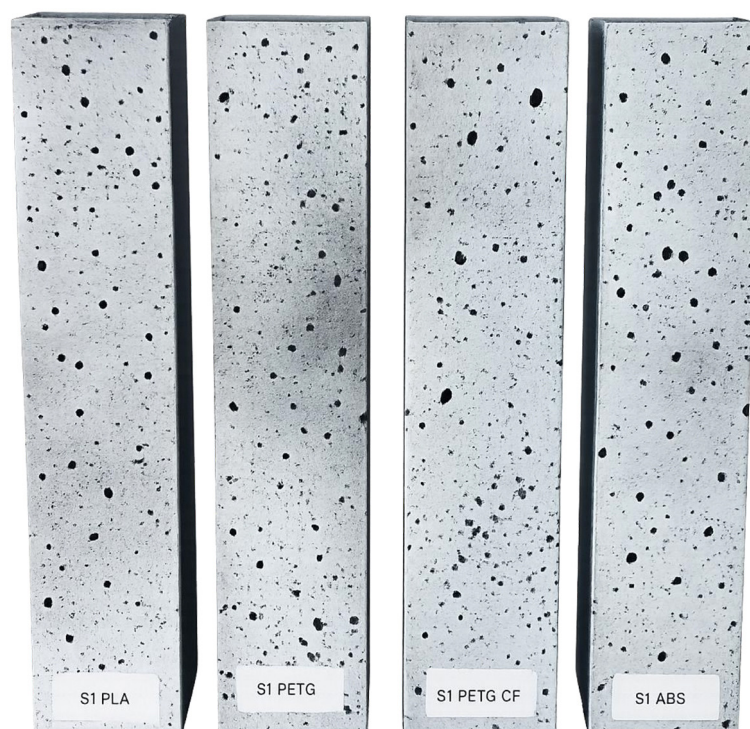


**Figure 3.** Test specimens manufactured using FDM 3D printing technology prepared for measurements with the Digital Image Correlation (DIC) system

For the approximation, segments of the curve corresponding to stable compression behavior were selected. The initial loading range, during which the contact conditions between the test specimen and the components of the testing machine were stabilizing, was excluded from the analysis. This range could exhibit variations associated with the seating of the specimen end surfaces, the elimination of small clearances, and the attainment of proper axial alignment of the specimen within the test setup. The immediate transition region associated with the onset of buckling, in which a pronounced change in the slope of the response curve occurred, was also omitted. No uniform, predetermined length of the curve segments used for approximation was adopted because the response curves of the individual specimens were not identical. The ranges were selected individually, with the aim of including the longest possible segments exhibiting stable and approximately linear behavior. This approach was intended to minimize the influence of local measurement disturbances and to obtain the highest possible quality of fit for the approximating straight lines.

The results obtained using the straight-line intersection method were verified by determining the coefficient of determination  $R^2$ . The results obtained using the straight-line intersection method were verified by determining the coefficient of determination,  $R^2$ , which was used to assess the quality of the approximation employed to identify the buckling load. This coefficient was determined for the selected segments of the experimental curve located before and immediately after the onset of buckling and describes the agreement between the fitted trend lines and the corresponding experimental data. The determined critical load was considered acceptable when the  $R^2$  value for each approximated segment was at least 0,95. The maximum possible value of the coefficient of determination is 1, indicating perfect agreement between the approximation and the experimental data; however, such a result is rarely achieved in practice. The closer the  $R^2$  value is to unity, the higher the accuracy of the approximation used to determine the critical load [53, 54]. For all analyzed structures, the coefficient of determination satisfied the adopted minimum criterion and remained close to unity, confirming the high quality of the applied approximation. For the composite structures, the approximate buckling load and the corresponding displacement were determined using the same procedure.

The critical loads of the individual test specimens were determined using a matrix-based method, which reduces to solving the following equation: [53, 54].

$$\begin{cases} A_1x + B_1y + C_1 = 0 \\ A_2x + B_2y + C_2 = 0 \end{cases} \quad (1)$$

where:  $A_1$  and  $A_2$  – coordinates of the points defining the direction of line  $x$ ,  $B_1$  and  $B_2$  – coordinates of the points defining the direction of line  $y$ ,  $C_1$  and  $C_2$  – numerical values specifying free expression of the function.

The intersection point corresponding to the critical value is obtained by rearranging Equation 1 into the form given in Equation 2:

$$\begin{cases} A_1x + B_1y = -C_1 \\ A_2x + B_2y = -C_2 \end{cases} \quad (2)$$

Using Cramer's rule, the above system of equations can be expressed and solved as follows:

$$W = \begin{vmatrix} A_1 & B_1 \\ A_2 & B_2 \end{vmatrix} = A_1 \times B_2 - A_2 \times B_1 \quad (3)$$

$$W_X = \begin{vmatrix} -C_1 & B_1 \\ -C_2 & B_2 \end{vmatrix} = (-C_1) \times B_2 - (-C_2) \times B_1 \quad (4)$$

$$W_Y = \begin{vmatrix} A_1 & -C_1 \\ A_2 & -C_2 \end{vmatrix} = (-C_2) \times A_1 - A_2 \times (-C_1) \quad (5)$$

When the determinant is ( $W \neq 0$ ) the above system has a unique solution, given by the following equations:

$$\begin{cases} x = \frac{W_X}{W} \\ y = \frac{W_Y}{W} \end{cases} \quad (6)$$

where:  $x$  and  $y$  correspond to the coordinates of the intersection point of the two selected line segments, that is, the displacement and the load corresponding to the buckling force.

An ARAMIS 2D optical deformation measurement system was used to record the buckling modes, enabling precise, non-contact observation and measurement of specimen deformation using a single camera. The system operates on the basis of a sequence of images acquired

in real time during the experiment, which are subsequently correlated and analyzed using specialized algorithms that track the coordinates of selected reference points. An important advantage of this system is the elimination of potential disturbances and measurement errors resulting from direct contact between the measuring device and the specimen. The ARAMIS 2D optical deformation measurement system records in-plane deformation and subsequently identifies and tracks individual points using grayscale analysis. This enables the positions of selected points to be determined on each recorded image with subpixel accuracy [45, 55–57]. In addition, the test setup was equipped with an LED light source to provide adequate and uniform illumination of the specimens. To ensure the correct recording of deformation by the ARAMIS 2D system and to reduce undesirable light reflections, the specimens were spray-painted with matte white and black paints to obtain an appropriate stochastic speckle pattern on their surfaces. Acoustic emission was used to verify the occurrence of damage in the specimens during loading. This method enabled the recording of potential acoustic signals generated by the release of accumulated elastic strain energy within the material, a sudden increase in which may indicate damage initiation and, in many cases, its subsequent propagation. The tests were conducted using a single-channel Vallen SpotWave 201 acoustic emission system equipped with a dedicated VS150-L piezoelectric sensor. Acoustic emission signals were recorded using the dedicated SpotWave Acquisition software [58–60]. The specimens intended for experimental testing were placed between the flat and parallel working surfaces of specially designed fixtures, which ensured axial loading and maintained parallelism throughout the compression process. The fixture design provided stable and rigid restraint of the specimen ends, limiting their displacement and rotation. The adopted boundary conditions corresponded to both ends being clamped. Before each test, the specimen was carefully centered relative to the loading axis to minimize eccentric loading and the development of additional bending moments. The method of mounting and positioning the specimens was identical in all tests. The load and displacement of the testing machine fixtures were recorded in real time. On the basis of these data, the critical load was determined using the approximate straight-line intersection method.

Before testing, no quantitative measurements of the initial geometric imperfections of the specimens were performed, such as deviations of the longitudinal axis from straightness, wall irregularities, or local dimensional deviations. The specimens were subjected only to visual inspection, and only components without visible damage or significant deformation were selected for testing. It should be emphasized, however, that minor imperfections introduced during the manufacturing process may have affected both the critical load and the buckling mode. The main limitation of the present study was the lack of experimentally determined mechanical properties of the thermoplastic materials used. The properties of FDM-manufactured components depend not only on the material type, but also on process parameters, printing path orientation, and the quality of interlayer bonding. The absence of an independent material characterization prevented the reliable development and validation of finite element models. The present experiments should therefore be regarded as a preliminary stage of further research, which will include the determination of the mechanical properties of the printed materials, measurements of geometric imperfections, and the development of numerical models for analyzing the behavior of the investigated structures in the buckling and post-buckling regimes (Figure 4).

## RESULTS

The use of complementary experimental techniques, including a universal testing machine, a digital image correlation (DIC) system, and an acoustic emission system, enabled assessment of the influence of material type on the buckling behavior of thin-walled structures manufactured using FDM technology, followed by comparison of the obtained results with those determined for geometrically equivalent composite structures. The tests conducted using the universal testing machine made it possible to determine experimental equilibrium paths, on the basis of which approximate critical (buckling) loads were identified using the straight-line intersection approximation method. The experimentally determined equilibrium paths were compiled and presented in Figure 5, providing a graphical representation of the differences between the individual results. Figure 6 presents the experimental equilibrium

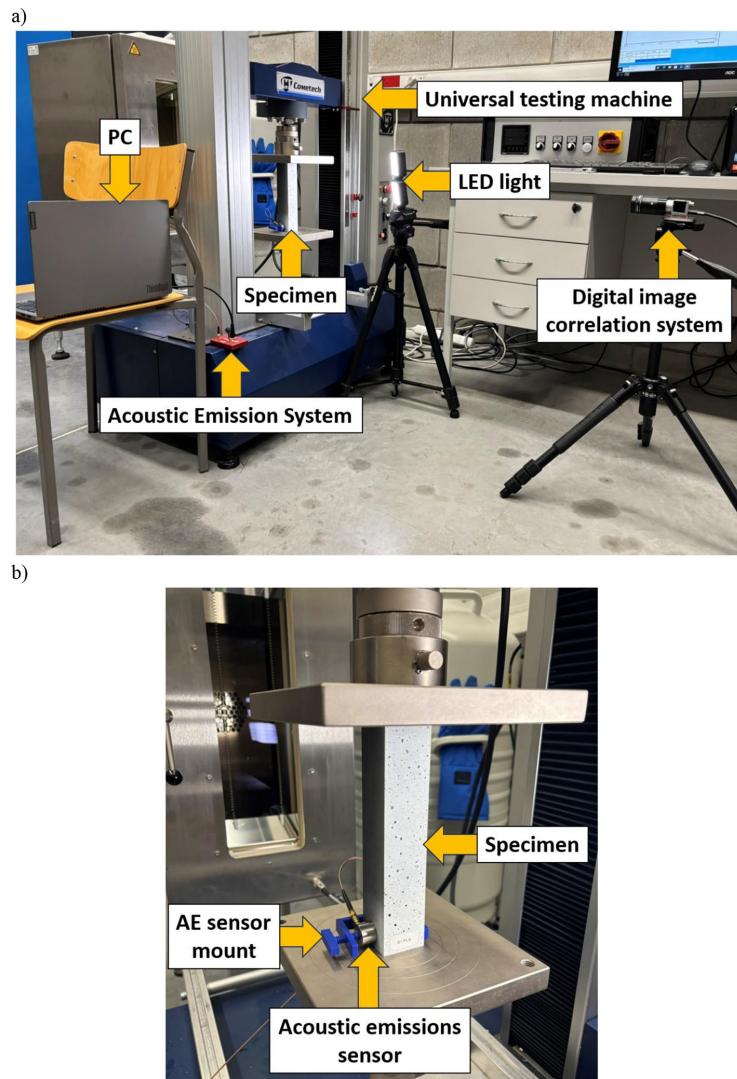


**Figure 4.** Experimental setup for axial compression tests: a) overall view of the test stand; b) detailed view of the specimen mounting and acoustic emission sensor

paths of the composite structures obtained in previous studies, which were used for comparison with the results determined for the FDM-manufactured structures.

Based on the presented figures, it can be observed that, during the initial stage of the experiment, the relationship between the applied load and displacement is nonlinear. This behavior results from the stabilization of the boundary conditions and the mutual seating of the components of the test setup during the initial loading stage. Once the boundary conditions have stabilized, the structural response in the pre-buckling range becomes nearly linear. This is evidenced by the very close agreement between the experimental response and the fitted linear relationship, as confirmed by a coefficient of determination close to unity. Minor deviations from ideal

linearity arise from imperfections in the measurement system and the tested structures and do not affect the overall character of their behavior in the pre-buckling regime. The nearly linear structural response observed in the pre-buckling range is consistent with Hooke's law, according to which stress is proportional to strain within the elastic range of the material. Based on the recorded experimental results, it can be concluded that the load–displacement curves obtained for PETG and ABS exhibit very similar characteristics, as clearly illustrated in Figure 5.

Analysis of the experimental equilibrium paths showed that, despite substantial differences in the load values and the corresponding displacements, all investigated FDM and composite structures exhibited very similar response characteristics. After eliminating the influence of

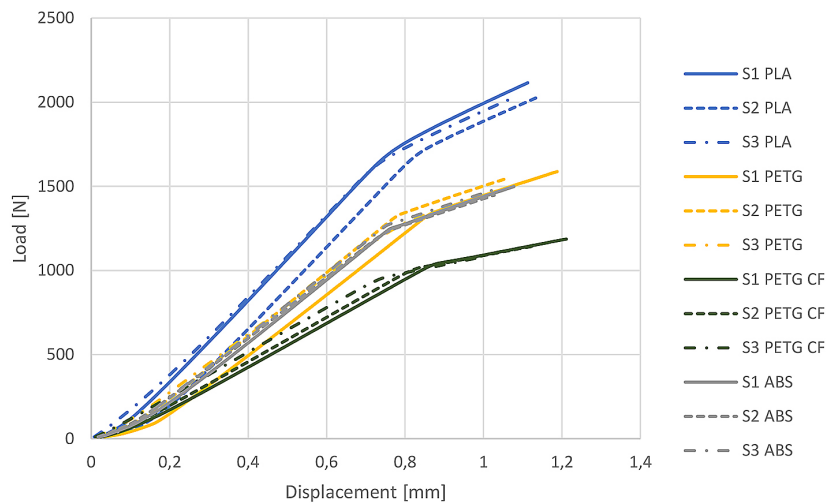


**Figure 5.** Experimentally determined equilibrium paths for FDM specimens

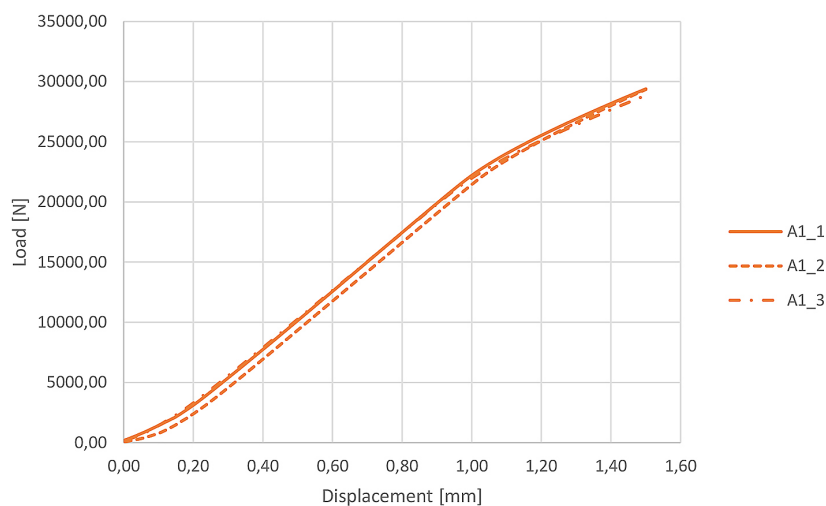


**Figure 6.** Experimentally determined equilibrium paths for CFRP specimens

the absolute values of the analyzed parameters, the experimental curves displayed comparable shapes, indicating a similar buckling mechanism and a similar structural response throughout the loading process.

The critical loads were determined using an approximation method based on identifying the intersection point of two straight lines, using the experimental data recorded during the tests and presented in Figure 5. The following figures graphically illustrate the procedure used to determine the critical load for the twelve specimens manufactured by FDM additive technology. In addition, each figure presents the acoustic emission signals recorded during the experiment using the Vallen SpotWave system, shown as a green curve. In the following Figures 7–11, the line colors denote the following:

the black dashed line indicates the critical load value, the red solid line represents the effective approximation range, and the red dashed line corresponds to the fitted approximation function. Table 3 and 4 summarizes the critical load values obtained for all profiles manufactured using FDM technology.

The experimental results showed that, among the geometrically identical structures manufactured from thermoplastic materials using FDM additive technology, the PLA specimens exhibited the highest mean critical load. The mean buckling load obtained for PLA was approximately 1.29 times higher than that obtained for PETG, 1.70 times higher than that obtained for PETG-CF, and 1.36 times higher than that obtained for ABS. It was also demonstrated that the addition of short carbon fibers

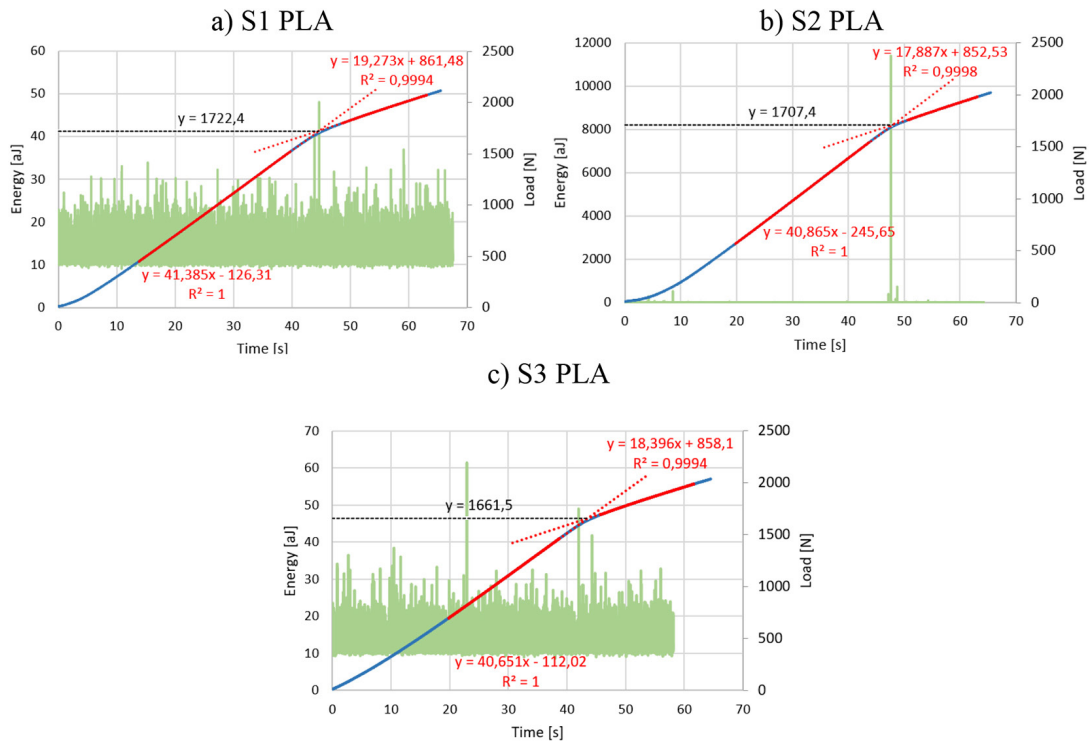


**Figure 7.** Experimental equilibrium path together with the corresponding acoustic emission signals for PLA specimens

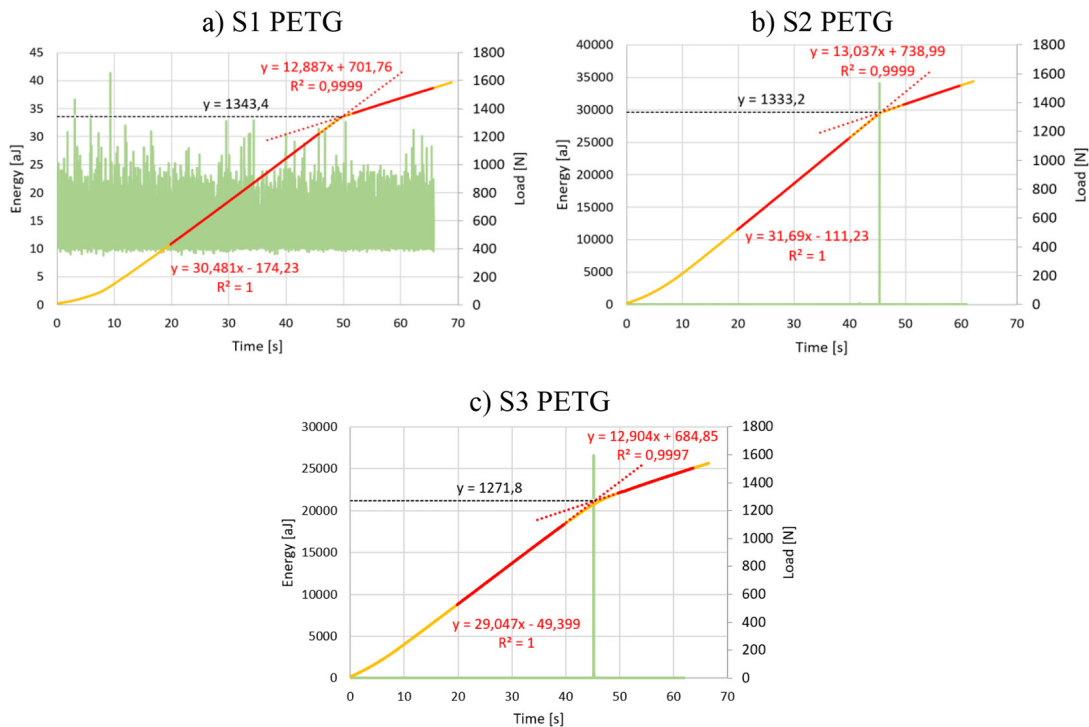


**Figure 8.** Experimental equilibrium path together with the corresponding acoustic emission signals for PETG specimens

to PETG reduced the buckling load compared with unmodified PETG. The mean critical load of the PETG specimens was approximately

1.32 times higher than that of the PETG-CF specimens. For comparison, the mean critical load obtained for the carbon–epoxy composite

with the quasi-isotropic stacking sequence  $[0/45/-45/90/90/-45/45/0]$  was approximately 13.9 times higher than the highest mean critical load determined for the FDM-manufactured

structures. The tests also confirmed the high repeatability of the results obtained for the additively manufactured FDM structures. The greatest scatter was observed for PETG-CF, for which

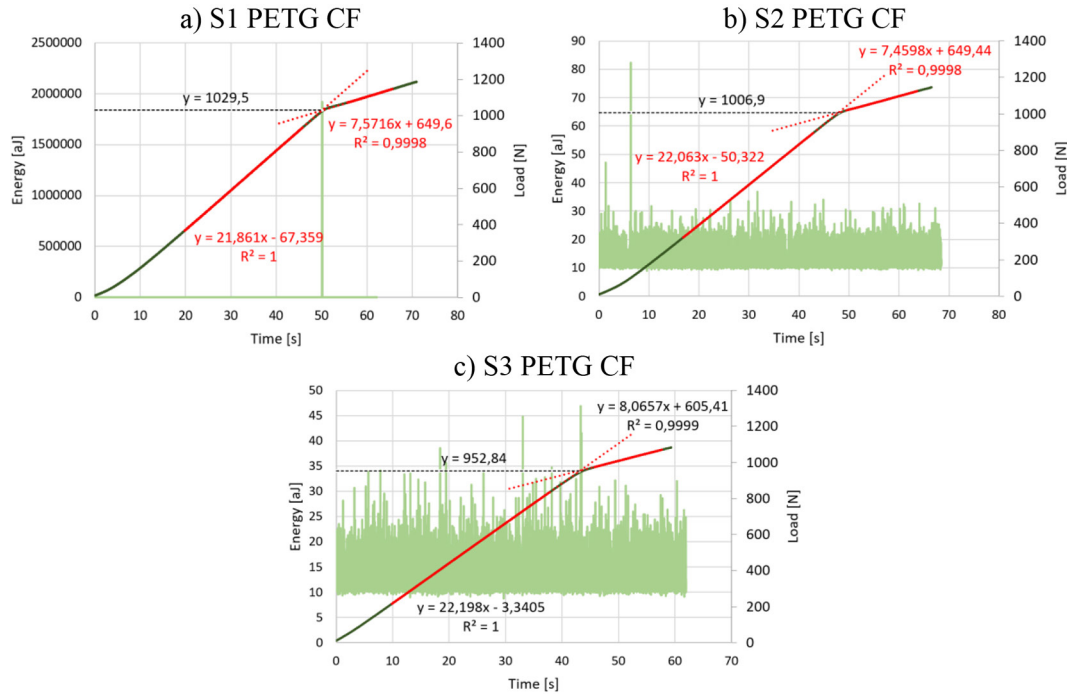


**Figure 9.** Experimental equilibrium path together with the corresponding acoustic emission signals for PETG CF specimens

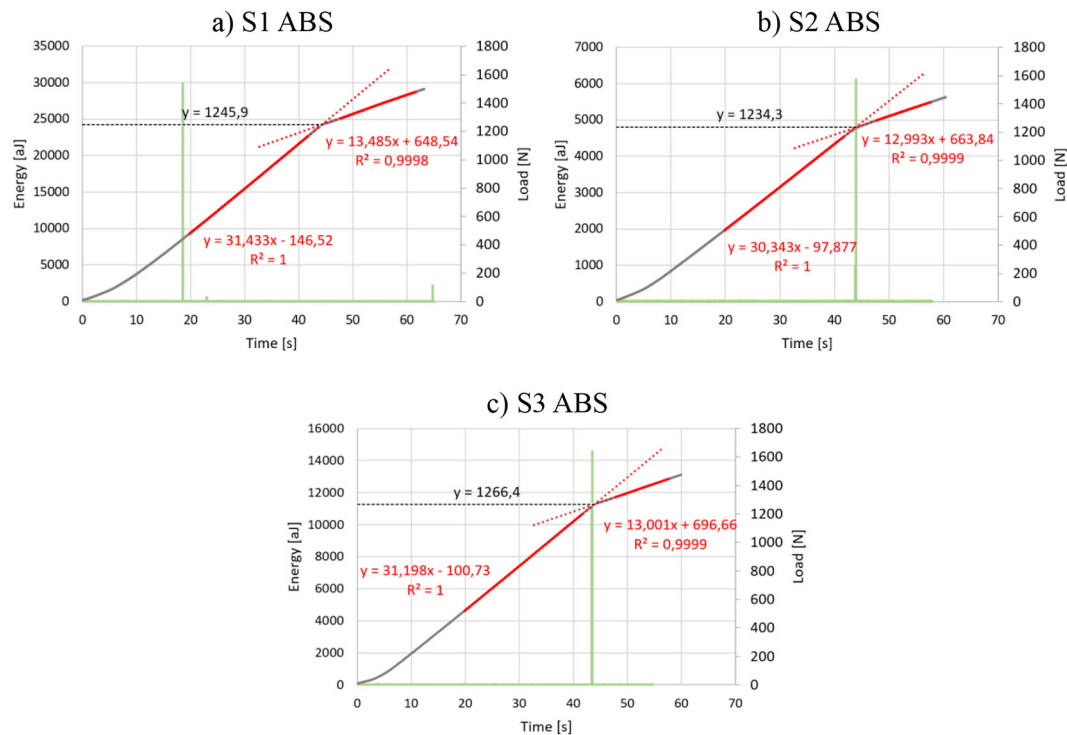


**Figure 10.** Experimental equilibrium path together with the corresponding acoustic emission signals for ABS specimens

**Table 3.** Comparison of critical load values for FDM profiles

| Material | Specimen   | Critical load [N] | Average critical load [N] | Percentage deviation from the mean [%] |
|----------|------------|-------------------|---------------------------|----------------------------------------|
| PLA      | S1 PLA     | 1722.45           | 1697.12                   | 1.47                                   |
|          | S2 PLA     | 1707.40           |                           | 0.60                                   |
|          | S3 PLA     | 1661.51           |                           | 2.14                                   |
| PETG     | S1 PETG    | 1343.39           | 1316.13                   | 2.03                                   |
|          | S2 PETG    | 1333.23           |                           | 1.28                                   |
|          | S3 PETG    | 1271.78           |                           | 3.49                                   |
| PETG CF  | S1 PETG CF | 1029.50           | 996.41                    | 3.21                                   |
|          | S2 PETG CF | 1006.90           |                           | 1.04                                   |
|          | S3 PETG CF | 952.84            |                           | 4.57                                   |
| ABS      | S1 ABS     | 1245.90           | 1248.84                   | 0.24                                   |
|          | S2 ABS     | 1234.27           |                           | 1.18                                   |
|          | S3 ABS     | 1266.36           |                           | 1.38                                   |

**Table 4.** Comparison of critical load values for composites profiles [38]

| Material | Specimen | Critical load [N] | Average critical load [N] | Percentage deviation from the mean [%] |
|----------|----------|-------------------|---------------------------|----------------------------------------|
| CFRP     | A1_1     | 23807,68          | 23574,69                  | 0.98                                   |
|          | A1_2     | 23605,78          |                           | 0.13                                   |
|          | A1_3     | 23310,60          |                           | 1.13                                   |

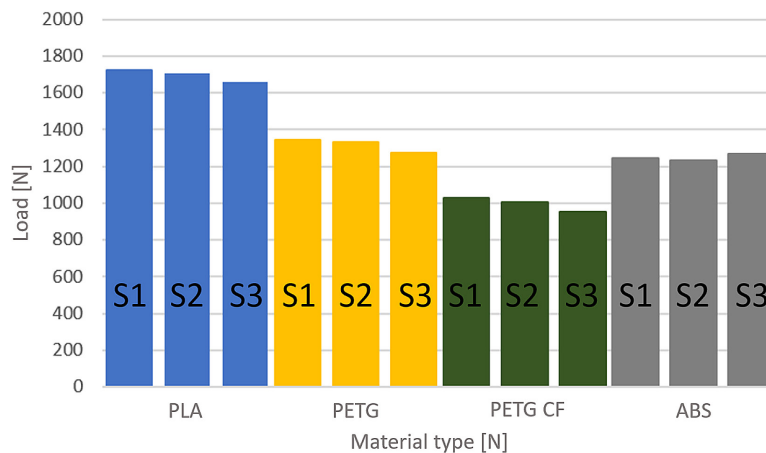


**Figure 11.** Comparison of the buckling load values obtained from the experimental tests

the maximum deviation of the critical load from the mean value was 4.57%, whereas the mean deviation was 2.94%. The greater scatter in the PETG-CF results may be attributed to the presence of short carbon fibers with varying orientations within the polymer matrix, as well as to the greater technological difficulties associated with both the manufacture of components from this material and the production of the filament itself compared with unmodified PETG. The small differences in both the critical load values

and the experimental equilibrium paths indicate high manufacturing quality and good repeatability of the FDM specimens. The observed deviations may be associated with minor geometric and structural imperfections that are unavoidable in real structures. Nevertheless, the differences between the individual values were small and did not affect the quality of the experimental results. During the experiments, the acoustic emission system recorded isolated events characterized by a sudden increase in acoustic signal

activity for selected profiles. In most of the analyzed cases, local increases, or spikes, in acoustic emission signal energy were observed at the moment corresponding to structural buckling. The signals were recorded using the attojoule (aJ) as the unit of energy because of the very low signal energy measured before the onset of buckling. The recorded signals were most likely associated with phenomena accompanying structural buckling rather than with the initiation of material damage at this stage of loading. The fact that the signals appeared close to the onset of buckling in most cases may indicate local changes in contact conditions and stress redistribution occurring during the buckling process. These phenomena may have been accompanied by microslip between adjacent material paths, local separation between layers or deposited filaments, temporary changes in the contact area, and frictional processes characteristic of FDM-manufactured components. The absence of any observed loss of structural stiffness and the complete recovery of the specimens' original shape after unloading indicate that the recorded events were not associated with the initiation of permanent damage. Furthermore, signals characteristic of material cracking generally exhibit higher amplitudes and energies and occur as sequences of events associated with damage propagation, none of which were observed in the present tests. A detailed analysis of the acoustic emission signal parameters, particularly under conditions

involving material damage and more representative signals, will be presented in a subsequent publication devoted to the loss of load-carrying capacity of thin-walled structures manufactured using FDM technology.

The buckling modes were analyzed using the ARAMIS 2D digital image correlation system. The acquired data were processed and analyzed using ZEISS INSPECT 2026 software. To graphically present the strain distribution over the surfaces of the tested specimens, the von Mises equivalent strain visualization function was applied. In addition, median filters were used to enhance the visibility of the strain distribution in the investigated FDM-manufactured structures. The experimentally recorded buckling modes are presented in the following Figures 12–15.

The experimental results showed that the type of thermoplastic material used to manufacture the structures by FDM additive technology affected both the buckling load and the corresponding displacement. For the unreinforced materials, namely PLA, PETG, and ABS, the buckling mode was characterized by the formation of five complete half-waves in all specimens. By contrast, the buckling mode of the carbon-fiber-modified material (PETG-CF) consisted of seven complete half-waves. These results indicate that the incorporation of reinforcing additives into the polymer matrix may significantly affect the buckling behavior

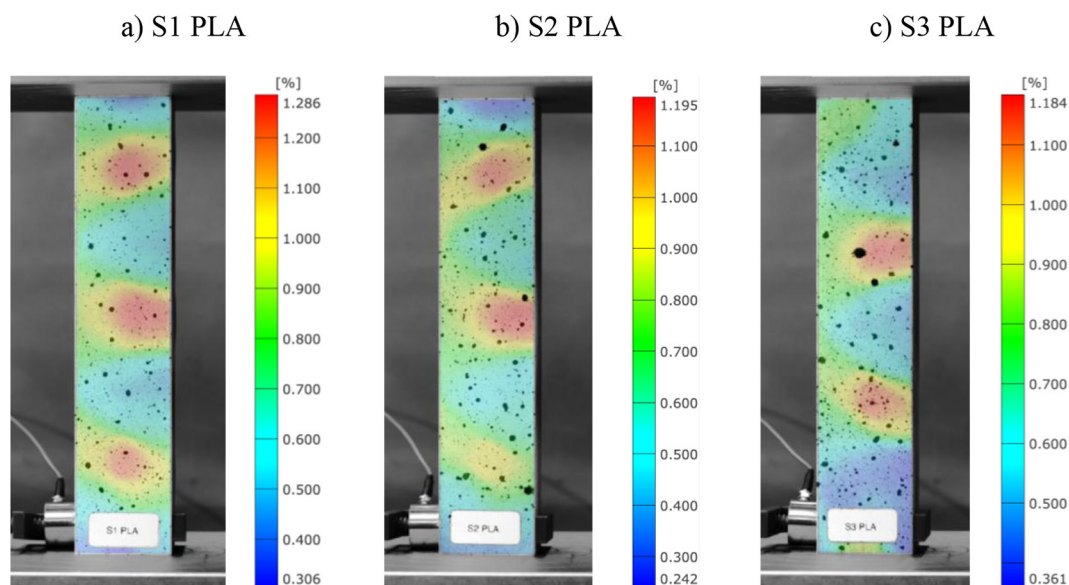


**Figure 12.** Buckling modes and corresponding von Mises equivalent strain fields recorded using Digital Image Correlation (DIC) for PLA specimens

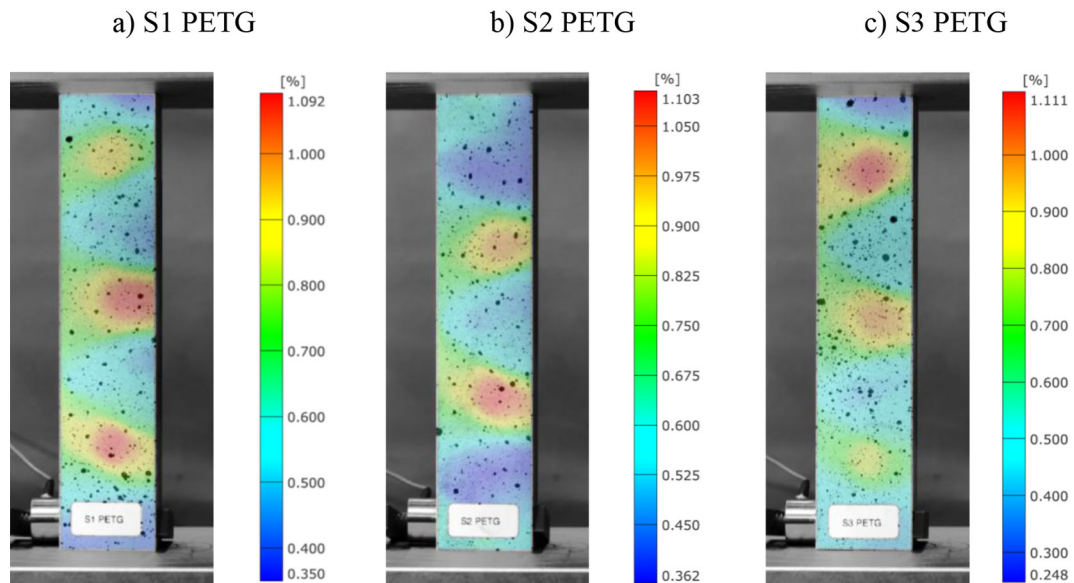


**Figure 13.** Buckling modes and corresponding von Mises equivalent strain fields recorded using Digital Image Correlation (DIC) for PETG specimens

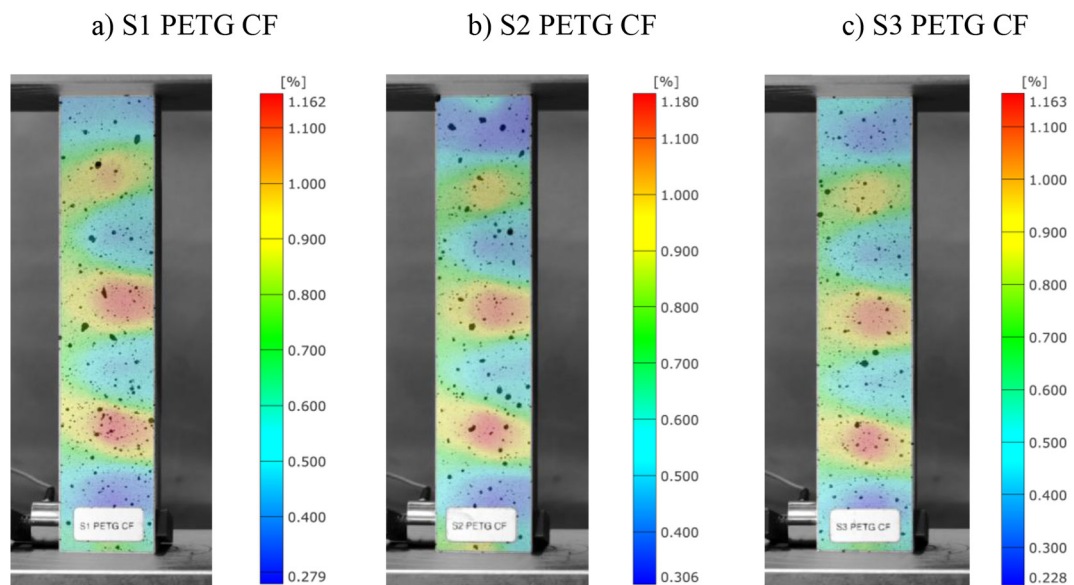


**Figure 14.** Buckling modes and corresponding von Mises equivalent strain fields recorded using Digital Image Correlation (DIC) for PETG CF specimens

of the structure. Incomplete half-waves were also observed near the ends of the specimens. An additional noteworthy observation was that some of the half-waves, particularly those located near the mid-height of the structure, were shifted to one side relative to the vertical axis of the specimen. This phenomenon may be associated with the characteristics of the printing process and the presence of a seam along one corner of the structure, visible as a narrow vertical line or protrusion on the printed surface at the location where the printer starts and terminates each

layer. The presence of the seam at one corner may additionally increase the local stiffness of the structure. Distinct buckling modes were also observed in previous studies of carbon–epoxy composite structures, in which four complete half-waves were identified, as shown in Figure 16. The similar behavior of the FDM-manufactured and carbon–epoxy composite structures at the onset of buckling and immediately thereafter may indicate comparable buckling mechanisms despite the use of different manufacturing technologies and structural materials.

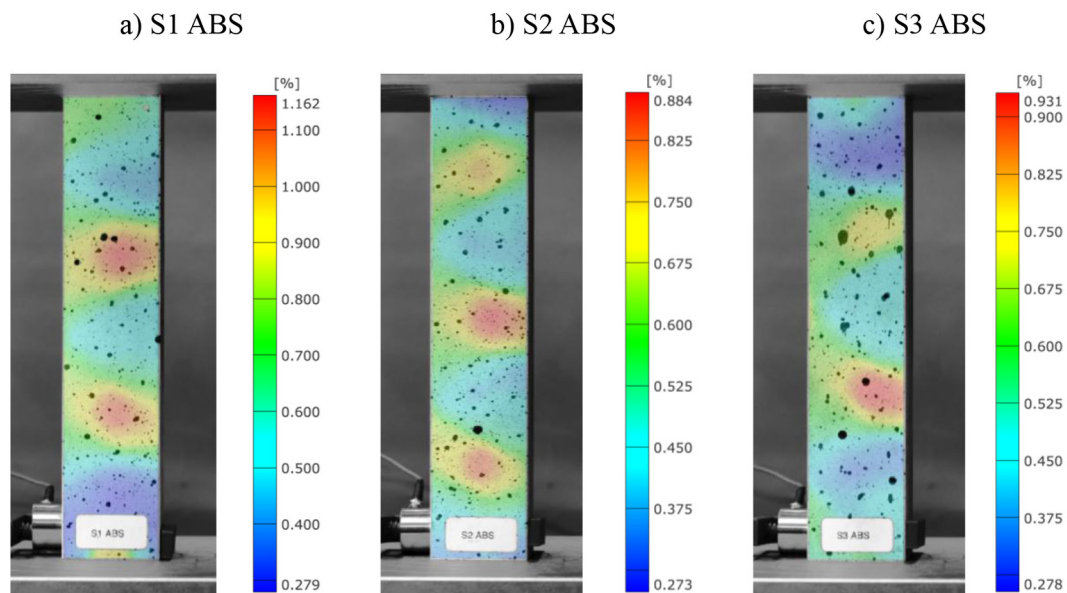
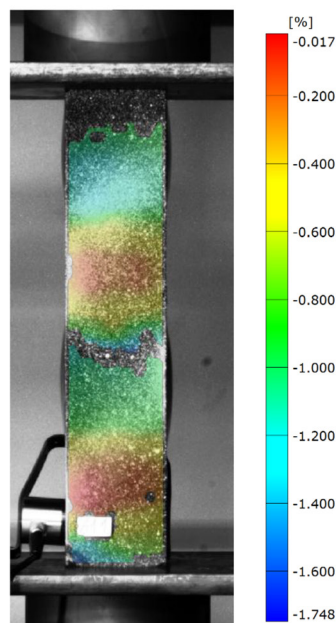


**Figure 15.** Buckling modes and corresponding von Mises equivalent strain fields recorded using Digital Image Correlation (DIC) for ABS specimens

a) A1\_1 experimental studies



b) A1\_1 numerical analysis

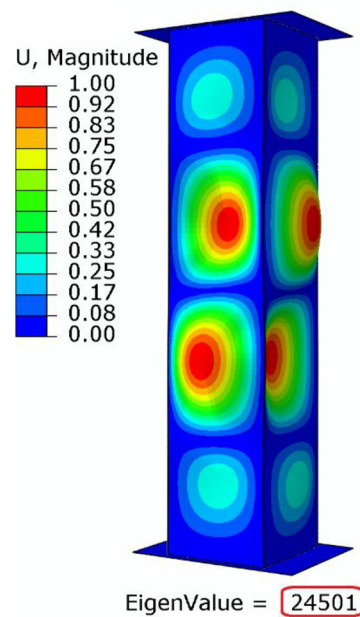


**Figure 16.** Buckling mode of the CFRP composite structure with the stacking sequence [0/45/-45/90/90/-45/45/0]

## DISCUSSION

The results showed that the FDM-manufactured PLA structures exhibited the highest critical load among all the thermoplastic materials analyzed. The mean critical load of the PLA structures was approximately 1.29 times higher than that of PETG, 1.70 times higher than that of PETG-CF, and 1.36 times higher than that of

ABS. It was also observed that the addition of carbon fibers to PETG reduced the critical load. The mean load at which the composite structure buckled was approximately 13.9 times higher than the mean value obtained for the PLA structures. The substantially higher critical loads obtained for the CFRP components result primarily from their high elastic modulus and the presence of continuous carbon-fiber reinforcement. In contrast

to FDM-manufactured structures, CFRP composites do not contain the characteristic boundaries between individual extrusion paths, which may act as sites for the initiation of local damage, such as inter-path debonding, and adversely affect the buckling load [61]. The results clearly demonstrate that the type of material used has a significant influence on the critical load. Analysis of the recorded experimental curves showed that the responses obtained for PETG and ABS were very similar in terms of both curve shape and the resulting values. No differences were observed in the buckling modes of the structures manufactured from PLA, PETG, and ABS, with five complete half-waves occurring in all cases. By contrast, the buckling mode of the PETG-CF structures consisted of seven complete half-waves. Owing to the limited number of specimens made from unmodified thermoplastics, it cannot be conclusively determined whether the material type alone affects the resulting buckling mode. Nevertheless, the results indicate that the addition of carbon fibers to PETG significantly alters the buckling mode. It was also observed that the presence of a manufacturing seam along one corner of the structure locally increased its stiffness, resulting in a shift of the half-waves, particularly those located near the mid-height of the specimen, relative to its vertical axis.

All specimens were manufactured using identical FDM printing paths and process parameters, except for the build-plate and nozzle temperatures, which were adjusted to the requirements of each material. This approach limited the influence of printing parameters other than temperature on the behavior of the investigated structures. All specimens were also printed in the same orientation, thereby eliminating build orientation as a variable. This is particularly important because FDM-manufactured structures exhibit anisotropic behavior; consequently, the results obtained in this study are applicable only to the specific build orientation investigated. Despite the use of otherwise identical manufacturing conditions, the critical load values varied depending on the material from which the specimens were produced. These differences may be attributed to the different mechanical properties of the materials and to variations in the quality of bonding between adjacent deposited paths, which depend on the characteristics of the individual polymers. Because the specimens were manufactured using the same printing strategy and comparable process conditions, the

influence of process-induced imperfections was expected to be broadly comparable across the investigated materials. Nevertheless, the interaction of these imperfections with the material-specific mechanical properties of each polymer may have contributed to the observed differences in buckling behavior [62, 63]. According to the manufacturer's data, the presence of short carbon fibers in PETG-CF increases the stiffness of the base material relative to unreinforced PETG. However, in the present study, the PETG-CF profiles exhibited a lower mean buckling load of 996.41 N than the PETG profiles, for which the mean buckling load was 1316.16 N. Thus, the buckling load obtained for PETG was approximately 1.32 times higher than that obtained for carbon-fiber-modified PETG-CF. This difference may result from the influence of the FDM process on the actual mechanical properties of the printed components. The addition of short carbon fibers may reduce interlayer bonding quality, increase structural porosity, and result in a non-uniform fiber distribution, potentially decreasing the effective stiffness of an FDM-manufactured profile [64, 65]. The results therefore indicate that the stability of thin-walled components is governed not only by the properties of the base material, but also by the quality of the structure formed during the manufacturing process. Consequently, the properties of an FDM-manufactured component may differ from those of the bulk material, and its actual structural stiffness may be lower than would be expected from the properties of the base material alone, resulting in reduced resistance to buckling [66].

In the present study, no analytical calculations of the critical load based on classical buckling theory were performed, because the primary objective was to experimentally compare the behavior of thin-walled profiles manufactured from different materials. Nevertheless, the results obtained for PLA, PETG, ABS, and CFRP are consistent with the general principles of stability theory, according to which an increase in structural stiffness leads to an increase in the critical load [67]. In the case of FDM-manufactured components, the critical load is additionally influenced by material anisotropy and printing-process imperfections, which are not accounted for in classical theoretical models. For PETG-CF reinforced with short carbon fibers, however, the relationship expected on the basis of classical stability theory was not observed. Although this

material exhibits higher stiffness than unreinforced PETG, the structures manufactured from PETG-CF showed lower mean critical loads. This indicates that, in the analyzed case, resistance to buckling was governed not only by the intrinsic material properties, but also by factors associated with the FDM manufacturing process. The possible causes of this behavior, related to the characteristics of the printing process and the effect of carbon-fiber addition on the internal structure of the printed material, were discussed in the preceding paragraph [64, 65].

The buckling behavior of the FDM-manufactured structures and the composite structure was similar despite the different numbers of half-waves. Four complete half-waves were observed for the analyzed composite structure. It was also demonstrated that the experimental load–displacement characteristics of the composite and FDM-manufactured structures followed very similar trends, despite substantial differences in the critical load values and the corresponding displacements. This may indicate a similar buckling mechanism and a comparable structural response to loading.

## CONCLUSIONS

Based on the results, FDM technology can be considered to have potential for the manufacture of thin-walled components subjected to compressive loading. The investigated structures retained their load-carrying capacity after the onset of buckling, and the shapes of their load–displacement curves were similar to those obtained for the composite structures. Thin-walled FDM-manufactured structures may therefore be suitable primarily for lightly loaded components, functional prototypes, and applications in which low weight, rapid manufacturing, and ease of geometric customization are important. This technology also enables the production of components with complex geometries without the need for additional tooling. At the same time, the results obtained for PETG-CF demonstrate that a higher stiffness of the base material does not necessarily translate directly into greater buckling resistance of the printed structure. The behavior of the component is also governed by the quality of bonding between adjacent layers and material paths, anisotropy, and imperfections introduced during the manufacturing process.

The investigated FDM structures cannot be unequivocally qualified for use in safety-critical load-bearing applications. Such an assessment would require independent characterization of the mechanical properties of the printed materials, quantitative evaluation of geometric imperfections, determination of the effects of printing parameters and build orientation, and the development of validated numerical models. Nevertheless, the present study provides a basis for further assessment of the potential application of FDM technology in the design of thin-walled load-bearing structures.

## REFERENCES

1. Bikas, H., Stavropoulos, P., Chrysosolouris, G., Additive manufacturing methods and modelling approaches: a critical review, *The International Journal of Advanced manufacturing Technology*, 2016, 83, 389–405. <https://doi.org/10.1007/s00170-015-7576-2>
2. Aldhafeeri, T., Alotaibi, M., Barry, C.F., Impact of melt processing conditions on the degradation of polylactic acid, *Polymers*, 2022, 14(14), 2790. <https://doi.org/10.3390/polym14142790>
3. Benamira, M., Benhassine, N., Ayad, A., Dekhane, A., Investigation of printing parameters effects on mechanical and failure properties of 3D printed PLA, *Engineering Failure Analysis* 2023, 148, 107218. <https://doi.org/10.1016/j.engfailanal.2023.107218>
4. Chmielowiec, A., Woś, W., Czyżewski, J. Numerical analysis of inertia forces in the connecting rod and their impact on stress formation, *Materials*, 2025, 18(6), 1385. <https://doi.org/10.3390/ma18061385>
5. Bouzouita, A., Notta-Cuvier, D., Raquez, J.M., Lauro, F., Dubois, P., Poly(lactic acid)-based materials for automotive applications, *Industrial Applications of Poly(lactic acid)*, 2017, 282, 177–219. [https://doi.org/10.1007/12\\_2017\\_10](https://doi.org/10.1007/12_2017_10)
6. Chmielowiec A., Sikorska-Czupryna S., Klich, L., Woś W., Kuraś, P., Optimization of quality control processes using the NPGA genetic algorithm, *Advances in Science and Technology Research Journal*, 2024, 18(7), 264–276. <https://doi.org/10.12913/22998624/193195>
7. Chung D., *Carbon Fiber Composites*, Newton: Butterworth-Heinemann, MA 1994.
8. Weiland K., Jones M. P., Zinsser F., Kontturi E., Mautner A., Bismarck A., Grow it yourself composites: delignification and hybridisation of lignocellulosic material using animals and fungi, *Green Chemistry*, 2021, 23(19), 7506–7514. <https://doi.org/10.1039/d1gc01835c>

9. Upton R. L., Fedosyuk A., Edel J. B., Carbon nanofiber/SiO<sub>2</sub> nanoparticle/HDPE composites as physically resilient and submersible water-repellent coatings on HDPE substrates, *ACS Applied Nano Materials*, 2021, 4(10), 10090–10102. <https://doi.org/10.1021/acsanm.1c01498>
10. G. Sherif G., Chukov D., Tcherdyntsev V., Torokhov V., Effect of formation route on the mechanical properties of the polyethersulfone composites reinforced with glass fibers, *Polymers*, 2019, 11(8), 1364. <https://doi.org/10.3390/polym11081364>
11. Berardi V. P., Perrella M., Deo L., Cricri G., Creep behavior of GFRP laminates and their phases: Experimental investigation and analytical modeling, *Composites Part B: Engineering*, 2017, 122, 136–144. <https://doi.org/10.1016/j.compositesb.2017.04.015>
12. Fascetti A., Feo L., Nisticò N., Penna R., Web-flange behavior of pultruded GFRP I-beams: A lattice model for the interpretation of experimental results, *Composites Part B: Engineering*, 2016, 100, 257–269. <https://doi.org/10.1016/j.compositesb.2016.06.058>
13. Rosłaniec K., Różyło P., Influence of composite lay-up on the load-carrying capacity of structures with closed rectangular cross-section, *Acta Mechanica et Automatica*, 2025, 19(2), 189–196. <https://doi.org/10.2478/ama-2025-0022>
14. Rocha Pereira T., Patterson A. E., Lee Y. H., Messimer S. L., Critical buckling load of thin-walled plastic cylinders in axial and radial loading: Overview and FEA case study, *EngrXiv*, 2019. <https://doi.org/10.31224/osf.io/2mtfu>
15. Ahn, S.H., Montero, M., Odell, D., Roundy, S., Wright, P.K., Anisotropic material properties of fused deposition modeling ABS, *Rapid Prototyping Journal*, 2002, 8(4), 248–257. <https://doi.org/10.1108/13552540210441166>
16. Popovich, V., Borisov, E., Popovich, A., Sufiarov, V., Masaylo, D., Alzina, L., Functionally graded Inconel 718 processed by additive manufacturing: Crystallographic texture, anisotropy of microstructure and mechanical properties, *Materials & Design*, 2017, 114, 441–449. <https://doi.org/10.1016/j.matdes.2016.10.075>
17. Alaimo, G., Marconi, S., Costato, L., Auricchio, F., Influence of meso-structure and chemical composition on FDM 3D-printed parts, *Composites Part B: Engineering*, 2017, 113, 371–380. <https://doi.org/10.1016/j.compositesb.2017.01.019>
18. Allum, J., Gleadall, A., Silberschmidt V.V., Fracture of 3D-printed polymers: Crucial role of filament-scale geometric features, *Engineering Fracture Mechanics*, 2020, 224, 106818. <https://doi.org/10.1016/j.engfractmech.2019.106818>
19. Tronvoll, S.A., Vedvik, N.P., Elverum, C.W., Welo, T. A new method for assessing anisotropy in fused deposition modeled parts using computed tomography data, *The International Journal Advanced Manufacturing Technology*, 2019, 105, 47–65. <https://doi.org/10.1007/s00170-019-04081-7>
20. Sun Q., Rizvi G.M., Bellehumeur C.T., Gu P., Effect of processing conditions on the bonding quality of FDM polymer filaments, *Rapid Prototyping Journal*, 2008, 14(2), 72–80. <https://doi.org/10.1108/13552540810862028>
21. Somireddy M., Czekanski A., Mechanical characterization of additively manufactured parts by FE modeling of mesostructure, *Journal of Manufacturing and Materials Processing*, 2017, 1(2). <https://doi.org/10.3390/jmmp1020018>
22. Li M., Xu Y., Fang J., Orthotropic mechanical properties of PLA materials fabricated by fused deposition modeling, *Thin-Walled Structures*, 2024, 199, 111800. <https://doi.org/10.1016/j.tws.2024.111800>
23. Casavola, C., Cazzato, A., Moramarco, V., Pappalettere, C., Orthotropic mechanical properties of fused deposition modelling parts described by classical laminate theory, *Materials & Design*, 2016, 90, 453–458. <https://doi.org/10.1016/j.matdes.2015.11.009>
24. Jiang, D., Smith, D.E., Anisotropic mechanical properties of oriented carbon fiber filled polymer composites produced with fused filament fabrication, *Additive Manufacturing*, 2017, 18, 84–94. <https://doi.org/10.1016/j.addma.2017.08.006>
25. Batista, M., Lagomazzini, J.M., Ramirez-Peña, M., Vazquez-Martinez, J.M., Mechanical and tribological performance of carbon fiber-reinforced PETG for FFF applications, *Applied Sciences*, 2023, 13(23), 12701. <https://doi.org/10.3390/app132312701>
26. Economides, A.L., Islam, M.N., Baxevanakis, K.P., Additively manufactured carbon fibre PETG composites: Effect of print parameters on mechanical properties, *Polymers*, 2024, 16(23), 3336. <https://doi.org/10.3390/polym16233336>
27. Chacón, J.M., Caminero, M.A., García-Plaza, E., Núñez, P.J., Additive manufacturing of PLA structures using fused deposition modelling: Effect of process parameters on mechanical properties and their optimal selection, *Materials & Design*, 2017, 124, 143–157. <https://doi.org/10.1016/j.matdes.2017.03.065>
28. Casavola, C., Cazzato, A., Moramarco, V., Pappalettere, C., Orthotropic mechanical properties of fused deposition modelling parts described by classical laminate theory, *Materials & Design*, 2016, 90, 453–458. <https://doi.org/10.1016/j.matdes.2015.11.009>
29. Wach, R.A., Wolszczak, P., Adamus-Włodarczyk A., Enhancement of mechanical properties of FDM-PLA parts via thermal annealing, *Macromolecular Materials and Engineering*, 2018, 303(9), 1800169. <https://doi.org/10.1002/mame.201800169>

30. Fafenrot, S., Grimmelsmann N., Wortmann M., Ehrman A., Three-dimensional (3D) printing of polymer-metal hybrid materials by fused deposition modeling, *Materials*, 2017, 10(10), 1199. <https://doi.org/10.3390/ma10101199>
31. Richter, C., Schmülling, S., Ehrmann, A., Finsterbusch K., FDM printing of 3D forms with embedded fibrous materials. In *Design, Manufacturing and Mechatronics, Proceedings of the 2015 International Conference on Design, Manufacturing and Mechatronics (ICDMM2015)*, Wuhan, China, 17–18 April 2015, Shahhosseini, A.M., Ed., World Scientific: Singapore, 2015, 961–969.
32. Rajak D. K., Wagh P. H., Menezes P. L., et. al., Critical overview of coatings technology for metal matrix composites, *Journal of Bio- and Tribo-Corrosion*, 2020, 6(12). <https://doi.org/10.1007/s40735-019-0305-x>
33. Rajak D. K., Pagar D. D., Kumar R., Pruncu C. I., Recent progress of reinforcement materials: a comprehensive overview of composite materials, *Journal of Materials Research and Technology*, 2019, 8(6), 6354–6374. <https://doi.org/10.1016/j.jmrt.2019.09.068>
34. Bochnia J., Blasiak M., Kozior T. A., Comparative study of the mechanical properties of FDM 3D prints made of PLA and carbon fiber-reinforced PLA for thin-walled applications, *Materials*. 2021, 14(22), 7062. <https://doi.org/10.3390/ma14227062>
35. Zmarzły, P., Kozior, T., Gogolewski, D., Dimensional and shape accuracy of foundry patterns fabricated through photo-curing, *Tehnički vjesnik – Technical Gazette*, 2019, 26(6), 1576–1584. <https://doi.org/10.17559/TV-20181109115954>
36. Nowakowski, L., Miko, E., Skrzyniarz, M. Designation of the minimum thickness of machined layer for the milling process of duralumin PA6. In *Proceedings of the 23rd International Conference of Engineering Mechanics*, Svratka, Czech Republic, 15–18 May 2017, 722–725.
37. Gogolewski, D., Bartkowiak, T., Kozior, T., Zmarzły, P. Multiscale analysis of surface texture quality of models manufactured by laser powderbed fusion technology and machining from 316L steel, *Materials*, 2021, 14(11), 2794. <https://doi.org/10.3390/ma14112794>
38. Różyło P., Dębski H., Stability and load carrying capacity of thin-walled composite columns with square cross-section under axial compression, *Composite Structures*, 2024, 329, 117795. <https://doi.org/10.1016/j.compstruct.2023.117795>
39. Torre, R., Brischetto, S., Dipietro, I.R., Buckling developed in 3D printed PLA cuboidal samples under compression: Analytical, numerical and experimental investigations, *Additive Manufacturing*, 2021, 38, 101790. <https://doi.org/10.1016/j.addma.2020.101790>
40. McCann, F., Rossi, F., Sultan, S.D., Experimental analysis and design of 3D-printed polymer elliptical tubes in compression, *Applied Sciences*, 2024, 14(17), 7673. <https://doi.org/10.3390/app14177673>
41. Kalova, M., Rusnakova, S., Krzikalla, D., Mesicek, J., Tomasek, R., Podeprelova, A., Rosicky, J., Pagac, M., 3D printed hollow off-axis profiles based on carbon fiber-reinforced polymers: mechanical testing and finite element method analysis, *Polymers*, 2021, 13(17), 2949. <https://doi.org/10.3390/polym13172949>
42. Różyło P., Smagowski W., Paśnik J., Experimental research in the aspect of determining the mechanical and strength properties of the composite material made of carbon-epoxy composite, *Advances in Science of Technology Research Journal*, 2023, 17(2), 232–246. <https://doi.org/10.12913/22998624/161598>
43. Różyło P., Rosłaniec K., An influence of cross-sectional features on the stability and load-carrying capacity of carbon-epoxy composite structures, *Acta Mechanica et Automatica*, 2025, 19(3), 426–433. <https://doi.org/10.2478/ama-2025-0049>
44. Rosłaniec K., Różyło P., Stability of thin-walled composite structures with closed sections under compression, *Advances in Science of Technology Research Journal*, 2024, 18(3), 188–199. <https://doi.org/10.12913/22998624/186473>
45. Różyło P., Rosłaniec K., Kuciej M., Buckling of compressed thin-walled composite structures with closed sections, *Advances in Science of Technology Research Journal*, 2023, 17(6), 63–72. <https://doi.org/10.12913/22998624/174193>
46. Różyło, P., Study on the loss of load-carrying capacity of thin-walled composite columns with closed cross-sections, *Scientific Reports*, 2025, 15, 42137. <https://doi.org/10.1038/s41598-025-26003-2>
47. Różyło P., Limit states of thin-walled composite structures with closed sections under axial compression, *Composites Part B: Engineering*, 2024, 287, 111813. <https://doi.org/10.1016/j.compositesb.2024.111813>
48. Różyło P., Rogala M., Paśnik J., Load-carrying capacity of thin-walled composite columns with rectangular cross-section under axial compression, *Materials*, 2024, 17(7), 1615. <https://doi.org/10.3390/ma17071615>
49. Różyło P., Rogala M., Paśnik J., Buckling analysis of thin-walled composite structures with rectangular cross-sections under compressive load, *Materials*, 2023, 16(21), 6835. <https://doi.org/10.3390/ma16216835>
50. Bambu Lab. 3D Printer Filament Comparison Guide [Internet]. [cited 2026 Jul 21]. Available from:

- <https://bambulab.com/en-eu/filament/guide>
51. Bambu Lab. Filament guide – Printer, nozzle, AMS, build plate, glue compatibility and required parameters [Internet]. [cited 2026 Jul 21]. Available from: <https://wiki.bambulab.com/pl/general/filament-guide-material-table>
  52. Bambu Lab. Filament Drying Recommendations [Internet]. [cited 2026 Jul 21]. Available from: <https://wiki.bambulab.com/pl/filament-acc/filament/dry-filament>
  53. Paszkiewicz M., T. Kubiak T., Selected problems concerning determination of the buckling load of channel section beams and columns, *Thin-Walled Structures*, 2015, 93, 112–121. <https://doi.org/10.1016/j.tws.2015.03.009>
  54. Kamarudin M. N. B., Aabid J. S. M., Ibrahim Y. E., Buckling analysis of a thin-walled structure using finite element and design of experiments methods, *Aerospace*, 2022, 9(10), 541. <https://doi.org/10.3390/aerospace9100541>
  55. Walotek K., Bzówka J., Ciołczyk A., Examples of the use of the ARAMIS 3D measurement system for the susceptibility to deformation tests for the selected mixtures of coal mining wastes, *Sensors*, 2021, 21(13), 4600. <https://doi.org/10.3390/s21134600>
  56. Pan, B., Qian, K., Xie, H., Asundi, A. Two-dimensional digital image correlation for in-plane displacement and strain measurement: A review, *Measurement Science and Technology*, 2009, 20(6), 062001. <https://doi.org/10.1088/0957-0233/20/6/062001>
  57. Bermudo Gamboa C., Martín-Béjar S., Trujillo Vilches F.J., Castillo López G., Sevilla Hurtado L., 2D–3D digital image correlation comparative analysis for indentation process, *Materials*, 2019, 12(24), 4156. <https://doi.org/10.3390/ma12244156>
  58. Kubiak T., Samborski S., Teter A., Experimental investigation of failure process in compressed channel-section GFRP laminate columns assisted with the acoustic emission method, *Composite Structures*, 2015, 133, 921–929. <https://doi.org/10.1016/j.compstruct.2015.08.023>
  59. Samborski S., Rzeczkowski J., Korzec-Strzałka I., Experimental study of delamination process in elastically coupled laminates with the acoustic emission technique, *Engineering Structures*, 2024, 300, 117196. <https://doi.org/10.1016/j.engstruct.2023.117196>
  60. El Mohtadi R., J. Rzeczkowski J., Korzec-Strzałka I., Samborski S., Aymerich F. Czajka A., Experimental tensile testing of the lap joint composite laminates supported with the acoustic emission and machine learning techniques, *Composite Structures*, 2024, 345, 118394. <https://doi.org/10.1016/j.compstruct.2024.118394>
  61. Gao, X., Qi, S., Kuang, X., Su, Y., Li, J., Wang, D., Fused filament fabrication of polymer materials: A review of interlayer bond, *Additive Manufacturing*, 2021, 37, 101658. <https://doi.org/10.1016/j.addma.2020.101658>
  62. Omer M. A. E., Shaban I. A., Mourad A. H. and Hegab H., Advances in interlayer bonding in fused deposition modelling: a comprehensive review, *Virtual and Physical Prototyping*, 2025, 20(1), e2522951. <https://doi.org/10.1080/17452759.2025.2522951>
  63. Wickramasinghe S., Do T., Tran P., FDM-based 3D printing of polymer and associated composite: A review on mechanical properties, defects and treatments, *Polymers*, 2020, 12(7), 1529. <https://doi.org/10.3390/polym12071529>
  64. Tóth C., Molnár K., Virág Á.D., Short fiber reinforcement in material extrusion 3D printing: A meta-analysis review with insights into sustainable alternatives, *Polymer Composites*, 2025, 46(2), 9–47. <https://doi.org/10.1002/pc.29850>
  65. Abualbandora T. A., Alshneeqat M. G., Mourad A-H. I., Impact of 3D printing parameters of short carbon fiber reinforced polymer CFRP on the mechanical and failure performance: Review and future perspective, *Next Materials*, 2025, 8, 100645. <https://doi.org/10.1016/j.nxmte.2025.100645>
  66. Țisari V., Mihalache MA., Nagîț G., Ermolai V., Irimia AI., Grădinaru CG., Spiridon AA., Crăciun E., Hobjâlă RG., Slătineanu L., The influence of certain operating conditions of the FDM process on the mechanical properties of polymeric materials-a review, *Polymers*, 2026, 18(10), 1183. <https://doi.org/10.3390/polym18101183>
  67. Bažant, Z.P., Cedolin, L. *Stability of Structures*. Oxford University Press, New York, 1991.