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THREE-POINT BENDING OF ELEMENTS PRODUCED BY ADDITIVE TECHNOLOGY WITH A THIN-WALLED SPATIAL STRUCTURE

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Abstract

Additive technologies, also known as 3D printing technologies, are becoming more and more widely used in industrial conditions for the production of finished elements, especially for the production of parts that would be very difficult or even impossible to produce using existing technologies. Technologically difficult elements include parts with a thin-walled spatial structure. This work presents the research results and describes the problems of producing specimens of thin-walled profiles filled with an appropriate spatial structure, also thin-walled, using 3D printing technology. The results of a three-point bending test of specimens of various lengths and specimens filled with chemically cured resin are presented. Print simulations were discussed, paying attention to problems related to applying lines and layers in FDM/FFF technology and the impact of print technological parameters on the properties of the manufactured specimens.

Keywords:

additive technologies, thin-walled specimens, bending test, technological parameters

1 INTRODUCTION

Due to the development of industry, especially Industry 4.0, additive technologies are enjoying great interest due to their unique capabilities. They are perfect for producing complex, unusual shapes that cannot be produced using previously known methods or are possible but very difficult [Nguyen 2023a; Nguyen 2023b]. Thin-walled structures, which are increasingly used in the construction of various elements, are difficult to produce. They can be made using 3D printing technology. The inspiration for building thin-walled structures comes from nature itself, e.g. the structure of plants or bones. Typically, these types of elements consist of an outer shell filled with thin walls inside. Sometimes the space between these walls is filled with another substance. Regular and irregular structures can be found.

All 3D printing technologies are suitable for making thin-walled structures, but due to low production costs, the FDM/FFF technology (Fused Deposition Modeling/Fused Filament Fabrication) is often used, provided that the strength of the manufactured element meets the construction requirements. These technologies use thermoplastic materials produced in the form of filaments. The manufactured products are characterized by high quality and precision of workmanship, great design freedom and the availability of materials that have been used in industry [Banic 2024; Ngeow 2024]. One of the most popular filaments used in 3D printing, due to its good mechanical properties, hardness, and biodegradability, is (Polylactic Acid) PLA. PLA is a thermo-plastic semi-crystalline polyester, a bio-polymer that can be made from natural materials such as starch and sugar and can also be broken down by composting in industrial settings [Ngeow 2024. PLA filaments are relatively durable, but elements made of this material are characterized by different mechanical properties in different directions (anisotropy of the material), which has a significant impact on their quality [Banic 2024; Bochnia 2021]. This is due to the specificity of 3D printing technology.

A lot of publications have been published on thin-walled elements and structures. This article cites only some of them from the area of additive technologies. Generally, these publications can be divided into two groups:

- regarding the properties of single thin walls [Bochnia 2021; 2020; 2023a; 2023b; 2023c] [5–9],
- regarding the properties of elements made of thin-walled structures [Bhat 2021; He 2024; Kannan 2023; Kozior 2021; Kumar 2017; Nagesha 2022; Platek 2020; Rudnik 2022; Sindinger 2021; Spignoli 2024; Wang 2023; Zhang 2023].

The results of testing single thin walls (samples) enable the assessment of the strength of materials, the impact of components, e.g. carbon fibers, aramid fibers, and additions of metal and ceramic powders, on the mechanical properties and the analysis of technological production parameters.

Examples of works on thin-walled structures include articles [Platek 2020; Sindinger 2021]. At work [Platek 2020] the application of the finite element method in the design of appropriate thin-walled structures is described. The anisotropy of mechanical properties resulting from the orientation of the elements on the printer's build platform was taken into account, which improved the quality of the manufactured elements. Strength tests were carried out, Young's moduli and Poisson's ratios were estimated for individual orientations, and three-point bending tests were performed on elements filled with a thin-walled structure. Work [Sindinger 2021] presents the results of feasibility studies, strength tests of the base material, and experimental and numerical compression tests of the developed regular thin-walled cellular structures. The elements are made of flexible thermoplastic polyurethane TPU-Polyflex using the 3D printing technique (FFF). The hyperelastic properties of the TPU-Polyflex material were described using a simplified rubber material (SRM) constitutive model.

This work describes the construction of a thin-walled beam, the model of which was developed based on the structure of a typical wood structure. Test results are presented based on a three-point bending test of specimens of various lengths and samples filled with chemically cured resin. Problems related to manufacturing thin-walled elements using 3D printing technology were discussed.

2 MATERIALS AND METHODS

The following procedure was used:

- making specimens in the shape of round thin-walled beams using FDM technology;
- filling the empty spaces between the walls of the structure with chemically cured resin;
- performing static bending tests;
- analysis of test results.

The specimens were made of a material with the trade name MakerBot PLA. This is a filament whose selected properties are presented in Table 1.

Table 1. Mechanical properties PLA [https://ultimate3dprintingstore.com/products/makerbot-pla].

Properties	Value	Standard
Heat Deflection	52-49°C	ASTM 648, 66 psi
Flexural Modulus	2600 MPa	ASTM D790, 15 mm/min
Tensile Strength at yield	62 MPa	ASTM D638, 50 mm/min
Tensile Modulus	3600 MPa	ASTM D638, 50 mm/min
Strain at Yield	>4.4%	Elongation (%)
Notched Impact Strength	32 J/m	ASTM D256

The inspiration to design the shape of the specimens was the cross-section of pine wood, which is displayed in Figure 1 along with the printed specimen.

The dimensions of thin-walled beam samples designed using a 3D CAD program are shown in Figure 2. Specimens were designed with two lengths: 120 mm and 180 mm.

a)

b)

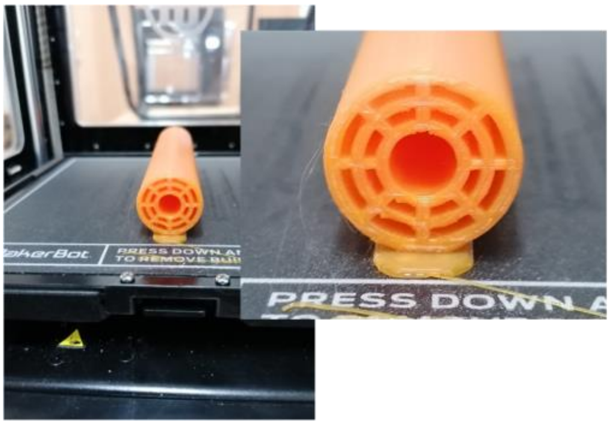
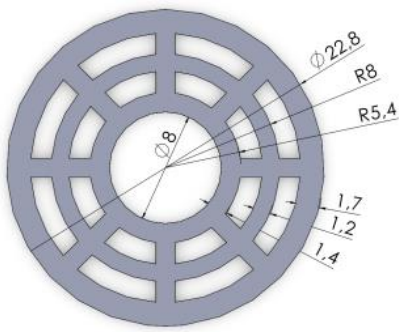


Fig. 1: a) a cross-section of the pine wood, b) the specimen made with the MakerBot Sketch printer.

a)



b)

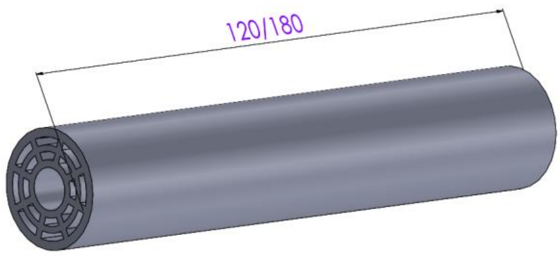


Fig. 2: a) the cross-section dimensions, b) the length dimensions.

Files with solid models of specimens were saved in a digital file with the .stl extension using triangulation parameters in the export options: resolution - adjusted, linear deviation - tolerance 0.016 mm, angle - tolerance 1°. Then the .stl files were exported to the Makerbot program to enter the printing technological parameters. A cross-section and simulation of specimen placement on the build tray of MakerBot Sketch and Replicator 5th Gen printers is presented in Figure 3.

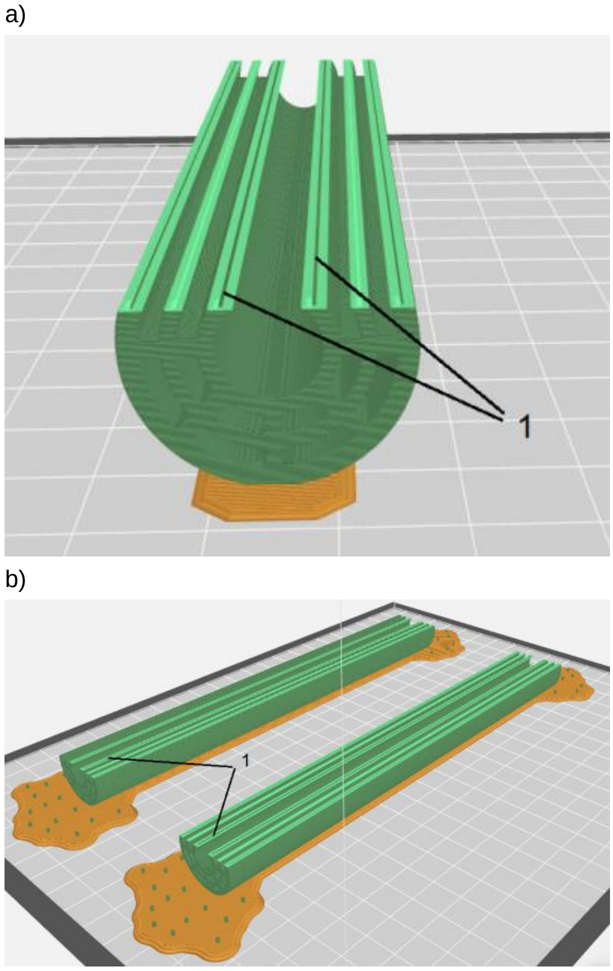


Fig. 3: Print simulations made using the MakerBot program, a) for the Sketch printer, b) for the Replicator 5th Gen. printer, 1 - places not filled with material.

The printing time of the specimen shown in Fig. 3a was 7h 21m, while the printing time of the specimens shown in Fig. 3a was 14h 6m.

The following print parameters were used:

- o layer height – 0.1 mm,
- o infill density – 95%,
- o extruder temperature – 220ºC,
- o about support – none,
- o nozzle diameter – 0.4 mm.

Five specimens with a length of 120 mm and 14 samples with a length of 180 mm were made. The free spaces between the walls were filled with chemically cured resin in seven specimens. The manufactured specimens were intended for a three-point bending test, which was performed using the Inspect mini machine. The punch speed used was 5 mm/min.

3 RESULTS AND DISCUSION

Various bending phases of an exemplary short specimen are shown in Figure 4, while the results of the bending test of all 120 mm long specimens are presented in Figure 5 in the form of graphs in Load – Deflection coordinates.

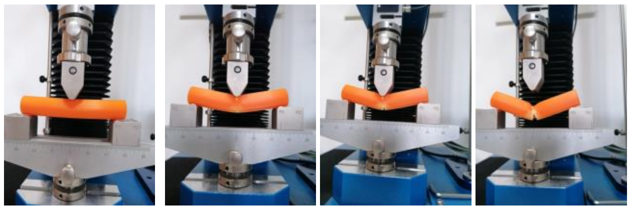


Fig. 4: Different phases of bending of a short sample.

The bending characteristics are shown in Figure 5, and the results are presented in Table 2.

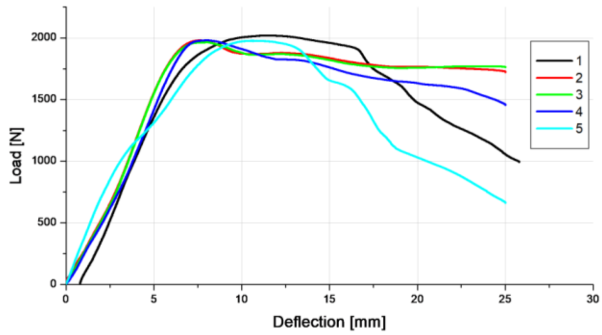


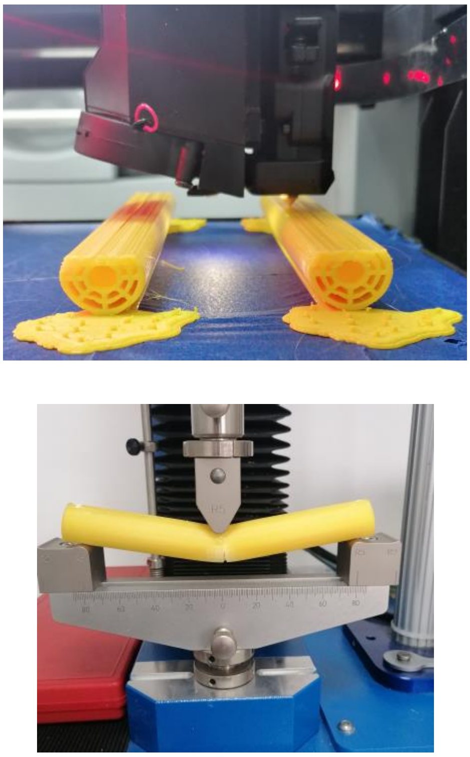
Fig. 5: Bending diagrams of short specimens 120 mm.

Tab. 2: Results of a three-point bending test of the short specimens 120 mm

Specimen number	Maximum bending force Fm [N]	Modulus of stiffness in bending Es [N/mm]
1	2019	254
2	1979	271
3	1965	326
4	1979	268
5	1976	250
$\bar{X}$	1983	273.8
SD	18.4	31.7

The above bending test results show that the cellular structure made of thin walls does not fail immediately, but gradually deteriorates. However, these results are slightly distorted because the total deflection consists of the beam deflection and the punch indentation in the beam structure. Longer samples were made and some of them were filled with chemically hardened resin. Figure 6 shows selected samples during printing and in the final phase of the bending test.

a)



b)

Fig. 6: *The specimens 180 mm long, a) during printing, b) in the final phase of the bending test*

Two specimens were damaged when removing from the work platform and removing the raft and floor, and five specimens were used for further testing. The bending characteristics of samples with a length of 180 mm are shown in Figure 7, and the results are presented in Table 3.

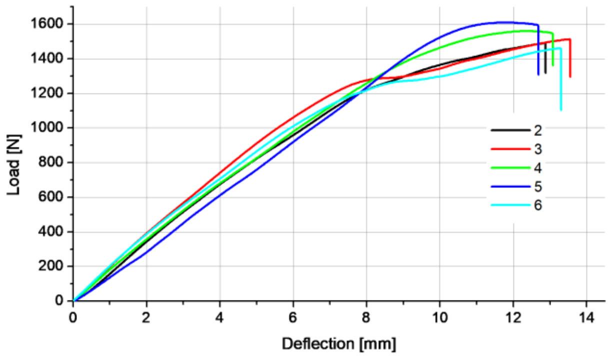


Fig. 7: Bending diagrams of 180 mm long specimens.

Tab. 3: Results of the three-point bending test of 180 mm long specimens

Specimen number	Maximum bending force Fm [N]	Modulus of stiffness in bending Es [N/mm]
2	1489	159
3	1511	175
4	1559	162
5	1608	154
6	1459	166
$\bar{X}$	1526	163
SD	58.7	7.9

The bending characteristics of 180 mm long specimens filled with chemical curing resin are shown in Figure 8 and the results are presented in Table 4.

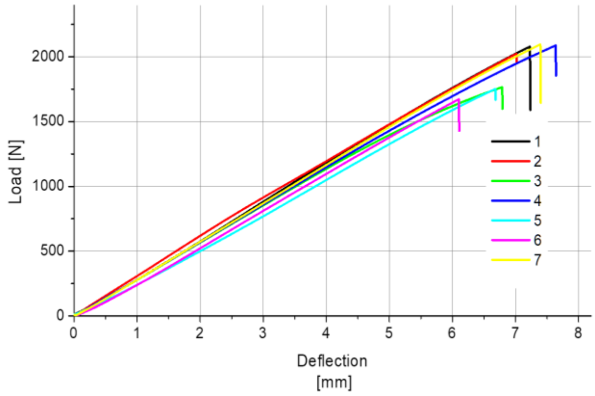


Fig. 8: Bending charts of 180 mm long specimens filled with chemically cured resin.

Tab. 4: Results of a three-point bending test of 180 mm long specimens filled with resin

Specimen number	Maximum bending force Fm [N]	Modulus of stiffness in bending Es [N/mm]
1	2078	295
2	2023	293
3	1766	270
4	2088	283
5	1752	265
6	1673	275
7	2096	290
$\bar{X}$	1925	282
SD	186	11.8

Filling the empty spaces between the thin walls with chemically cured resin improved the mechanical properties of the developed samples. The maximum bending force increased by 26%, while the stiffness modulus increased by 73%. Only specimens of the same length can be compared. At this stage of the analysis, the bending strength was not calculated due to the rather complicated method of calculating the moment of inertia of the cross-section of thin-walled samples with a cellular structure. This will be the subject of further work.

4 CONCLUSIONS

The bending test of samples having a thin-walled structure is distorted due to the penetration of three-point bending devices. However, the results obtained indicate the usefulness of this type of tests for comparative purposes. The repeatability of the results in a given series (especially in terms of proportionality of force and deflection) allows us to assess the correctness of individual samples.

Three-point bending tests of the described specimens with a thin-walled spatial structure indicate an improvement in the mechanical properties achieved by this type of structure. Empty spaces can be filled with various substances that can modify strength parameters. In the described case, filling the voids between the thin walls with a chemically cured resin increased the stiffness of the specimens and the ability to withstand higher bending loads.

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