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ANALYSIS OF THE POSSIBILITIES OF MANUFACTURING FUNCTIONAL ELEMENTS USING THE FFF METHOD

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Abstract
The article presents the course and results of research aimed at assessing the strength and practical usability of a furniture hinge additively manufactured from thermoplastic material. The research activities included: development of design assumptions, adoption of target geometry, creation of a 3D-CAD model, preliminary strength analysis in the FEM environment, prototype manufacturing using FFF method with thermoplastic material (pet-g), and conducting tests under conditions similar to real ones. The hinge geometry was based on typical market-available design solutions, while considering the specifics of the adopted manufacturing method. Strength analysis via FEM was conducted on the 3D-CAD model, allowing estimation of stress values and determination of the suitability of the developed geometry for testing on a real model. Subsequently, research models were produced using FFF technology with various infill patterns: linear 30%, hexagonal 30%, linear 60%, hexagonal 60%, and solid 100%. Bench tests were conducted to determine the maximum load-bearing capacity of the hinge under perpendicular loading to the axis and to assess hinge wear under conditions simulating real-life door usage. The results revealed that the hinge with solid infill safely carried a load of 160 kg without damage, while the hinge with hexagonal 30% infill exhibited the lowest load-bearing capacity, failing at 85 kg. To determine the hinge's durability, the clearance at two reference points on the doors was measured.

Keywords:
3D printing, FFF, hinge, PET-G

1 INTORDUCTION

The primary advantage of additive manufacturing technologies is the ability to produce a finished product in a short time by eliminating or simplifying the multi-stage manufacturing process compared to traditional manufacturing technologies [Gibson 2021]. Furthermore, additive technologies offer broader capabilities for creating parts with complex geometries that are challenging or impossible to achieve with traditional technologies. However, additive manufacturing also has its drawbacks, primarily including the anisotropy of the printed part's material and the accuracy of part fabrication.

Fused Filament Fabrication (FFF) technology belongs to the group of additive manufacturing processes known as Material Extrusion (MEX), which involves extruding thermoplastic material into filament form, deposited layer by layer according to a numerically defined path. FFF technology is a variant of the well-known FDM (Fused Deposition Modeling) technology developed by Stratasys. The expiration of Stratasys patents has enabled manufacturers of printers using FDM variants to reduce the purchase costs of these devices to the level of individual consumer budgets. Additionally, there is a fairly wide selection of materials available at relatively low prices for use in FFF technology, including PLA, PC, ABS, PET-G, Nylon, and composite materials such as those with carbon fiber additives. These materials exhibit various physical and mechanical properties, which are the subject of numerous studies [Yadav 2023]. These studies focus on the impact on material properties and fabrication accuracy: material additives [Mirasadi 2024], [Kalova 2021], part orientation on the platform [Erdaş 2024], and process parameter selection. [Güdür2023], [Algarni 2021], [Juračka 2021], [Rismilia 2019], [Pisula 2019].

The article examines the feasibility of utilizing Fused Filament Fabrication (FFF) technology for producing a functional component [Dziubek 2023]. Due to the low cost of purchasing equipment and consumable materials, FFF technology is widely popular among enthusiasts of new technologies, including 3D printing. However, due to its limitations, this technology is primarily used for hobbyist purposes or for creating prototypes and demonstration models. For this reason, an analysis was conducted to assess the possibility of manufacturing a fully functional product using this technology. The choice of technology imposes certain constraints on the design process, particularly concerning the feasible geometry. For this reason, the manufactured component needed to have a simple construction, and therefore a uniaxial furniture hinge was chosen as the research model [Budzik 2023]. The research methodology was designed to allow virtually any 3D printer user (including hobbyists and amateurs) to carry out the study. For this reason, the experimental setup was constructed from widely available materials, and the research process was conducted in such a way that any interested individual could replicate it in a home environment. This constitutes a significant contribution to the development of additive manufacturing technologies among hobbyist users. It was demonstrated that for simple models, the use of advanced research tools is not necessary to verify the functionality of the developed design solution.

The scope of the research work included:

- Developing the geometry of the research model considering the specifics of the FFF method.
- Conducting static Finite Element Method (FEM) analyses of the model to preliminarily verify the correctness of the designed element and to estimate its load-bearing capacity.
- Manufacturing models intended for bench tests from thermoplastic PET-G using the FFF additive manufacturing technology.
- Conducting bench tests to determine the maximum static load capacity under a load acting perpendicular to the axis and to determine the hinge's durability depending on the load in conditions simulating real-world operation.

2 RESEARCH MODEL

Based on the conducted analysis of available structural solutions in the market, a 3D-CAD model of a hinge was developed. To highlight the advantages of additive manufacturing, the design incorporated features not feasible with other methods. The hinge was modeled as a single component consisting of two parts (two wings of the hinge, one of which contains a pin). The overall dimensions of the hinge are 55 mm x 50 mm x 20 mm, with a pin element of 10 mm diameter. Since the hinge was to be produced in one process, appropriate clearances between interfacing elements were necessary. These clearances were determined experimentally through a series of test prints. A clearance of 0.3 mm was established between the interfacing surfaces, and 0,6 mm between other surfaces. The modeling process was carried out using Autodesk Fusion software.

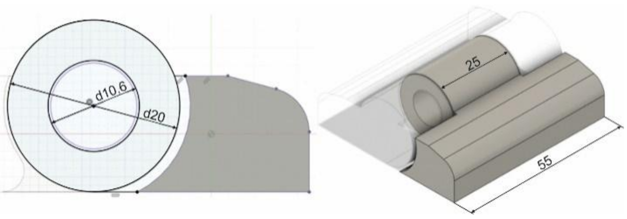

Fig. 1: Stages of the modeling process.

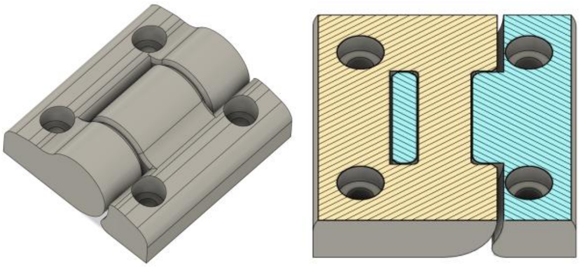

Fig. 2: Research model of the hinge.

3 FINITE ELEMENT METHOD (FEM) STRENGTH ANALYSIS

3.1 Analysis Assumptions

The FEM strength analysis was performed using Autodesk Nastran software. The analysis considered two loading scenarios. In the first case, the hinge was loaded with a force acting radially to the pin, while in the second case, the analysis simulated the load on a pair of hinges supporting a cabinet door. Due to the inability to determine the actual material parameters accounting for internal structure and anisotropy resulting from the printing process, PET material from the program's library was used for the analysis, which constitutes a simplification affecting the obtained results.

3.2 Radial Load Analysis

The purpose of the radial load analysis was a preliminary verification of the developed design under a static load of 250 N. This verification involved analyzing the distribution and maximum values of stress and displacement. The initial conditions of the analysis are shown in the figures (Fig. 3) one wing of the hinge was fixed on the plane adjacent to the beam (door frame), and the load was applied to the extreme right plane of the second hinge wing. The boundary conditions were defined to exclude the influence of mounting holes, as the primary objective was to verify the hinge itself rather than its mounting method.

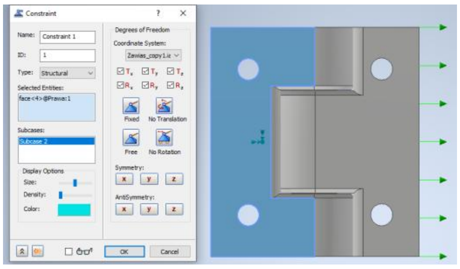

Fig. 3: Constraints and load.

To perform the analysis, it was also necessary to define contacts (Fig. 4) between the cooperating front and cylindrical surfaces of the hinge.

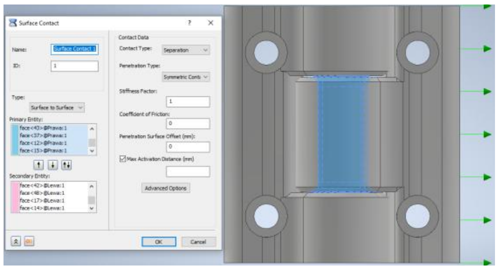

Fig. 4: Contacts defining.

After generating and optimizing the FEM mesh, the analysis was conducted, resulting in stress distribution (Fig. 5) and displacement (Fig. 6) data.

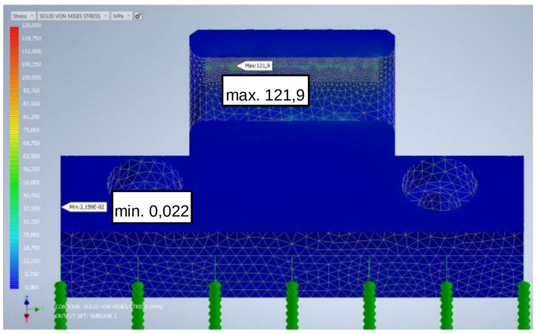

Fig. 5: The resulting stress distribution.

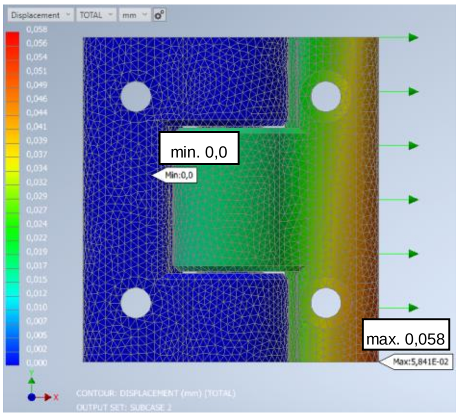

Fig. 6: The resulting displacement distribution.

The analysis showed that the hinge deformed minimally under a radial load of 250 N. The deformation of 0.06 mm is insignificant and does not adversely affect the hinge's functionality.

3.3 Analysis for Hinges Supporting Cabinet Doors

The second analysis aimed to verify the designed hinge's performance under loads similar to those experienced in real-world conditions. For this purpose, a model consisting of a pair of hinges and a door made of pine plywood with dimensions of 600 mm x 1000 mm x 18 mm was created (Fig. 8). The assumptions of the analysis included conducting it for different door opening angles. The door was additionally loaded with a force applied near the upper outer corner over a length of 100 mm.

The preparation for this analysis followed a similar procedure to the previous case, including defining boundary conditions (Fig. 7), generating contacts (Fig. 8), and creating and optimizing the mesh (Fig. 9).

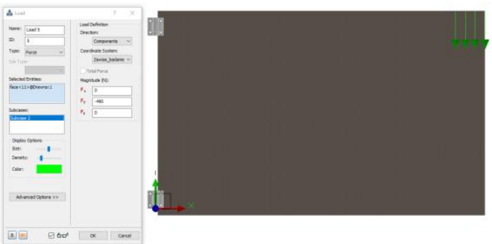
Fig. 7: Assumed additional load of 490 N.

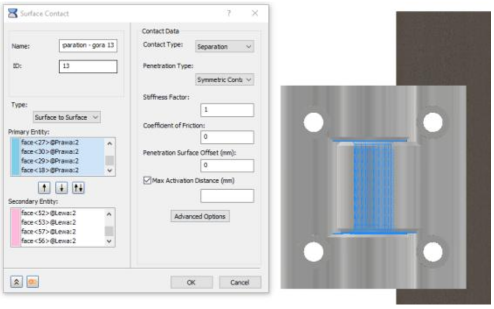
Fig. 8: Contacts defining.

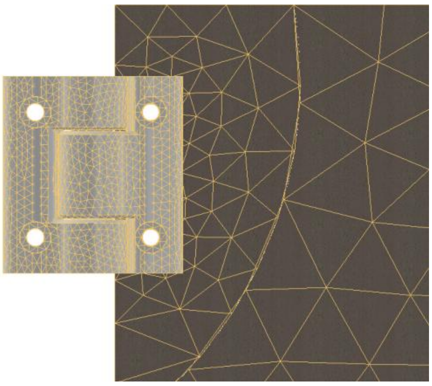
Fig. 9: FEA mesh after compaction.

The analysis was conducted for door opening angles ranging from 0-90˚ in 15˚ increments. Results for a 30˚ opening angle are shown in the stress distribution (Fig. 10) and displacement (Fig. 11) figures.

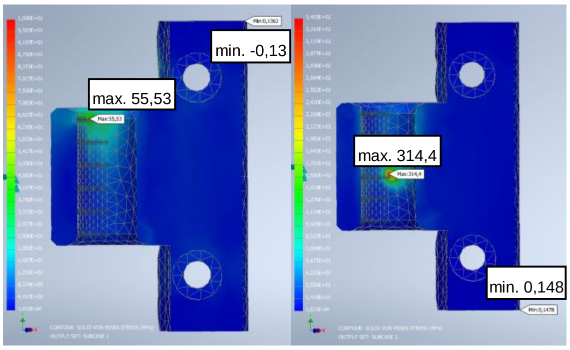

Fig. 10: Stress distribution for an opening angle of 30º. On the left - the upper hinge, on the right - the lower hinge.

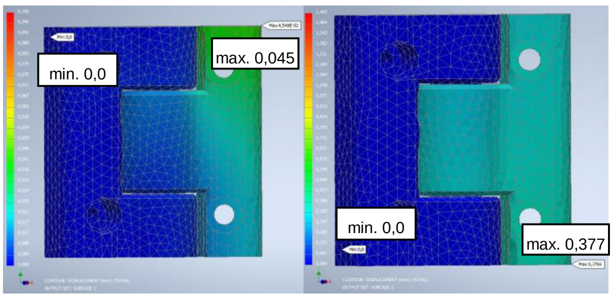

Fig. 11: Distribution of displacements for an opening angle of 30º. On the left - the upper hinge, on the right - the lower hinge.

Results for other opening angles are presented in a table (Tab. 1).

Tab. 1: Results of strength analyses.

	Upper hinge	Lower hinge

Angle [º]	Maximum stresses Von Misess [MPa]	Maximum displacement [mm]	Maximum stresses Von Misess [MPa]	Maximum displacement [mm]
0	87,82	0,074	104,3	0,574
15	82,52	0,065	128,7	0,537
30	55,53	0,045	314,4	0,377
45	73,73	0,039	131,2	0,162
60	34,36	0,041	30,48	0,035
75	55,41	0,114	111,3	0,546
90	40,42	0,051	15,65	0,075

Upon analyzing the collected results, it was found that the maximum stresses ranged from 30.48 MPa to 128.7 MPa. In one case, a value of 314.4 MPa was obtained, nearly a threefold difference in stress values at a 30° angle, which may result from improper mesh density in the given area and the associated numerical error. Maximum displacements in most cases did not exceed 0.12 mm, which is negligible considering the high flexibility of PET-G. This suggests that a system composed of two hinges and a door of dimensions similar to those in the analysis will not fail under a load applied to the upper plane of the door up to 50 kg.

4 PROTOTYPE FABRICATION USING FFF WITH PET-G MATERIAL

Following the virtual strength analyses and achieving satisfactory results, prototypes were produced using thermoplastic PET-G with FFF technology. For the bench tests, the prints were made with the following infill patterns: linear 30%, hexagonal 30%, linear 60%, hexagonal 60%, and solid 100%.

Print parameters:

- Nozzle diameter: 0.4 mm
- Layer height: 0.2 mm
- Number of perimeters: 2
- Solid layers: 3 for the top and bottom
- Support material: None
- Nozzle temperature: 220°C
- Bed temperature: 70°C

PrusaSlicer 2.4.1 software was used to prepare the printing process (Fig. 12), and the print was carried out on a Voron V0.1 printer.

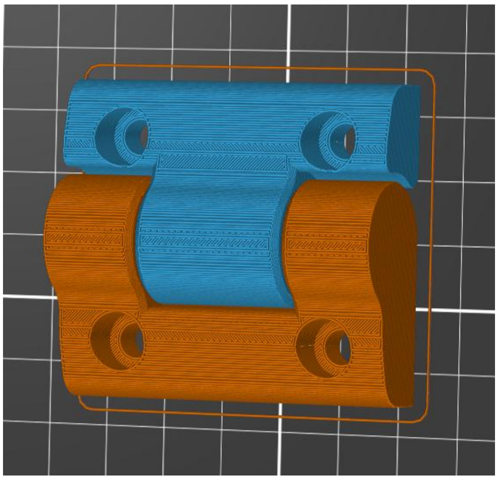

Fig. 12: The hinge model after importing into the PrusaSlicer 2.4.1 software.

5 TESTING ON A REAL MODEL

5.1 Bench Testing for Radial Load

Bench tests for radial load were conducted on prototypes with the infills mentioned in section 4. A test rig was designed and built to suspend a load of approximately 160 kg from the hinge. The hinge was directly attached to a wooden beam, and a 160-liter water container was attached to the other side of the hinge via a wooden plate and rope (Fig. 13). The load was increased by filling the container with water until the hinge failed. For safety reasons, tests were conducted with a maximum load of 160 kg.

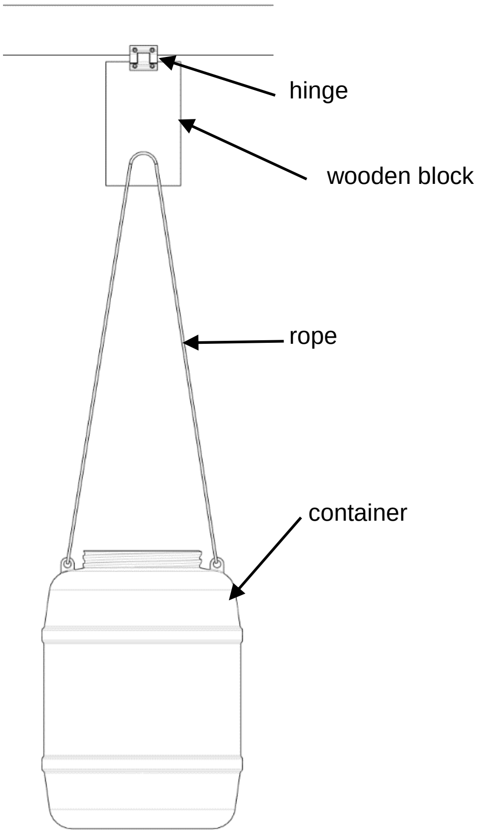

Fig. 13: Scheme of research stand.

Photographs of typical damaged hinges are shown in the figures (Fig. 14, Fig. 15).

Fig. 14: Hinge with 60% density hexagonal filling.

Fig. 15: Hinge with60% density linear filling.

The test results are presented in a (Tab. 2)

Tab.2. Summary of experimental results.

Filling		Breaking load [kg]
[%]	Pattern	
100	Full	>160
60	Linear	158
60	Hexagonal	141
30	Linear	96
30	Hexagonal	85

For the hinge with solid infill, no damage occurred under a 160 kg load (Fig. 16). In other cases, it was observed that the load-bearing capacity of the hinge with linear infill was approximately 10% greater than with hexagonal infill, regardless of the infill density used.

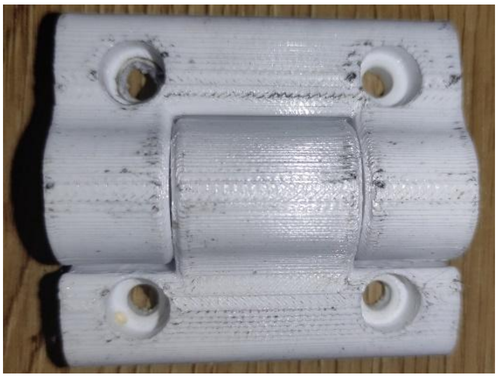

Fig. 16: Hinge with full filling after the test.

5.2 Bench Testing for Real-World Conditions

Tests simulating real-world working conditions were conducted on a dedicated test rig. These experiments aimed to determine the maximum load (Fig. 17). that a pair of hinges could withstand during operation and to measure wear by evaluating the gap change between the door and the top rail (x1, x2). The performance of the hinge under various loads was also analyzed during the tests.

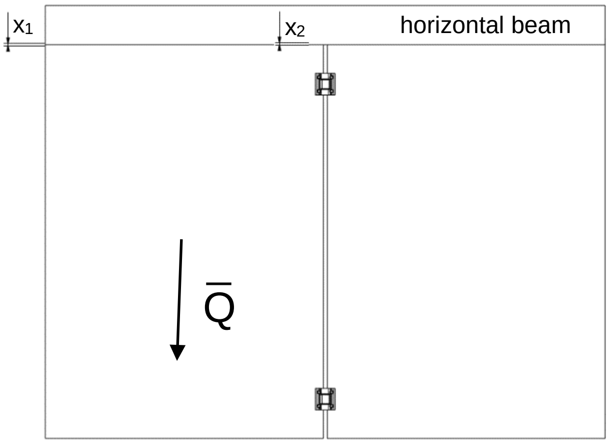

Fig. 17: Schematic diagram of the experimental stand for measuring clearances.

Hinges with a 30% linear infill density were tested for maximum load capacity. After applying or changing the load, a full cycle of hinge operation, including opening to a 90˚ angle and returning to the starting position, was performed. The load was increased in 3.5 kg increments, and the hinge failed under a 28 kg load (Fig. 18), corresponding to a torque of approximately 202 Nm on the hinges.

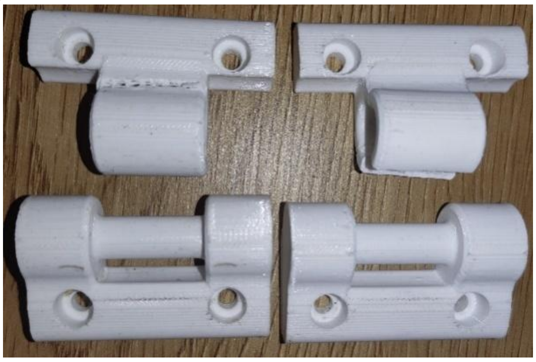

Fig. 18: Damaged hinge.

To assess hinge wear, the door was loaded with a set force, and a specified number of cycles were performed, measuring the gaps after each cycle. The loads were 7 kg and 14 kg. For the 14 kg load, tests were conducted both with and without lubrication, as the hinge tended to seize and plasticize of material after approximately 120 cycles due to localized temperature increases (Fig 19).

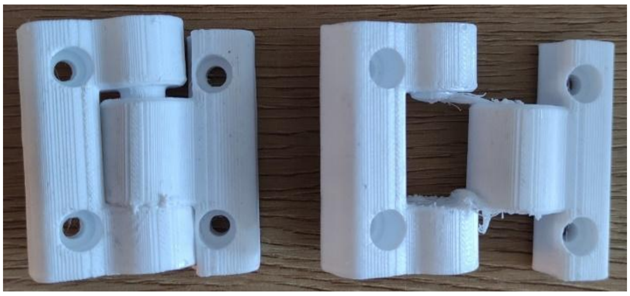

Fig. 19: Hinge damaged by temperature increase.

The results of the wear rate test, depending on the number of load cycles and lubrication, are presented in a table (Tab. 3).

Tab. 3: Summary of durability test results

	Load 7kg		Load14kg Without lubrication		Load 14kg With lubrication	
Cycles no. [-]	x_1[mm]	x_2[mm]	x_1[mm]	x_2[mm]	x_1[mm]	x_2[mm]
10	0	0	0,6	0,4	0	0,5
20	0	0	1	0,8	0	0,6
50	0,2	0,2	1,3	1,1	0,2	1
75	0,5	0,4	1,5	1,2	0,5	1,3
100	0,5	0,5	1,7	1,4	0,5	1,5
150	0,6	0,6	-	-	0,6	1,6
200	0,6	0,7	-	-	0,9	1,8

6 SUMMARY

W The article presents the results of studies verifying the feasibility of producing functional components using the popular FFF additive manufacturing method [[Ian 2021]. A uniaxial furniture hinge, manufactured entirely using additive techniques, was chosen as the research model. The results of bench tests confirmed the suitability and practical applicability of additively manufactured components. Analysis of the data indicates that such hinges can be successfully used in constructions subjected to low and medium loads with low usage intensity.

When designing and using these hinges, it is important to consider the specific characteristics of additively manufactured components, particularly the deformations resulting from the layered structure of the product and the impact of the manufacturing direction on its strength properties. A significant impact of the infill pattern and density on the hinge's load-bearing capacity was observed. As predicted, the best results were obtained with 100% infill. For different infill patterns, 10% better results were achieved with linear infill oriented perpendicularly to the applied load. The tests were conducted for unidirectional loading; in the case of a complex load state, the results may differ, which needs to be verified in further research.

During durability tests, a positive effect of lubricating the cooperating surfaces was observed. Without lubrication, clearances appeared after just a few operating cycles.

Another consideration is the layer thickness, which in this case determined the smallest possible pin diameter. With a layer thickness of 0.2 mm, a pin diameter of 10 mm was used; smaller diameters might cause operational issues. To achieve smaller diameters, a thinner layer thickness should be applied. This is one of the planned research directions.

The obtained results can be practically applied in the design, manufacturing, and operation of elements subjected to small and medium loads operating at low speeds. The work was conducted on dimensions considered minimal for the assumed printing parameters. In practical applications, it is possible to produce larger components designed to carry greater loads. In future work, the influence of selected printing parameters on load-bearing capacity and minimum clearance will be determined. Additionally, the possibility of conducting topological optimization of the components is being considered, to improve the material-to-load-bearing capacity ratio, which will positively impact the practical use of such solutions.

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