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Modelling and Testing of 3D Printed Flexible Structures with Three-pointed Star Pattern Used in Biomedical Applications

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Abstract. The objective of this work is to determine, using laboratory testing and computer modelling, the stiffness of flexible structures with three-pointed star pattern made by 3D printing method. In this paper, we present the design of the experiment and the development of the computer model as well as evaluating the structure's stiffness. At the end of the work, a validated computer model is used for a parametric study of the three-pointed star pattern. The obtained results can be used for designing of the biomedical applications.

Introduction

The flexible structure (FST) represents a thin shell with openings pattern that decreases the structure's stiffness in the normal direction. With such a structure, parts with desired deformation behaviour or aesthetically modified parts with preserved structural integrity can be designed [1, 2, 3]. Due to the enormous advantages of 3D printing methods such as Selective Laser Sintering (SLS) or Multi-Jet Fusion (MJF), the complicated shape of FST can be printed without supports and the final shape is created without additional machining. By using Polyamide 12 (PA12), also known as nylon, the resulting smooth structure can be used for biomedical applications. These applications for their purposes must meet strictly stiffness requirements which are established using the medical examination because FST must adapt to the user body.

In this paper, the determination of the stiffness of designed FST with three-pointed star pattern printed by SLS method using material PA12 is presented. Firstly, the stiffness of FST is determined by experiment. In the second part, the computer model using the Finite Element (FE) method simulating the experiment is created. The results of the FST stiffness obtained from the computer model are validated by the experiment results. Parametric study of the stiffness of FST with three-pointed star pattern is done with this validated computer model.

Experiment and stiffness determination

The experiment is inspired by the laboratory testing of Cranial Orthoses published in [4]. The specimen representing FST with a half sphere-shape with inner radius R_1 = 65.0 mm is clamped into testing device and gradually loaded by plunger with dimension R_2 = 65.0 mm and h = 18.0 mm, see Fig. 1. The load is generated and measured using TESTOMETRIC 500-50CT universal testing machine.

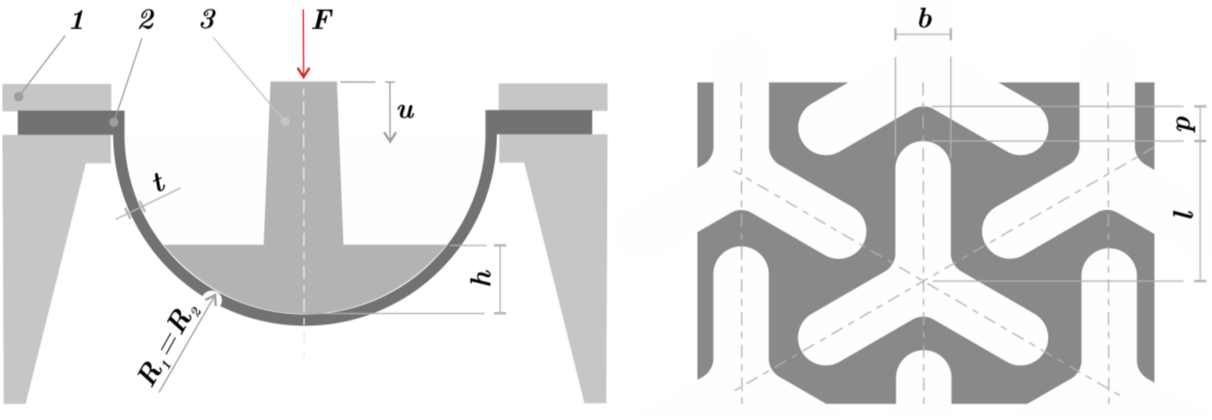

Fig. 1: Three-pointed star pattern (right) and scheme of testing device (left):
1 – testing device, 2 – specimen, 3 – plunger

For experiment purposes, two specimens marked by letter A with three-pointed star pattern employing parameters b = 2.00 mm, l = 5.00 mm and p = 2.35 mm were printed, see Table 2. The designed thickness of the first specimen A is t = 1.00 mm, the thickness of the second specimen A is t = 1.25 mm. The measured relationship between applied force F and deflection u of specimens A is depicted on Fig. 2. The stiffness of specimen A is determined by the linear approximation of the measured data with excluded nonlinear part in the beginning of loading.

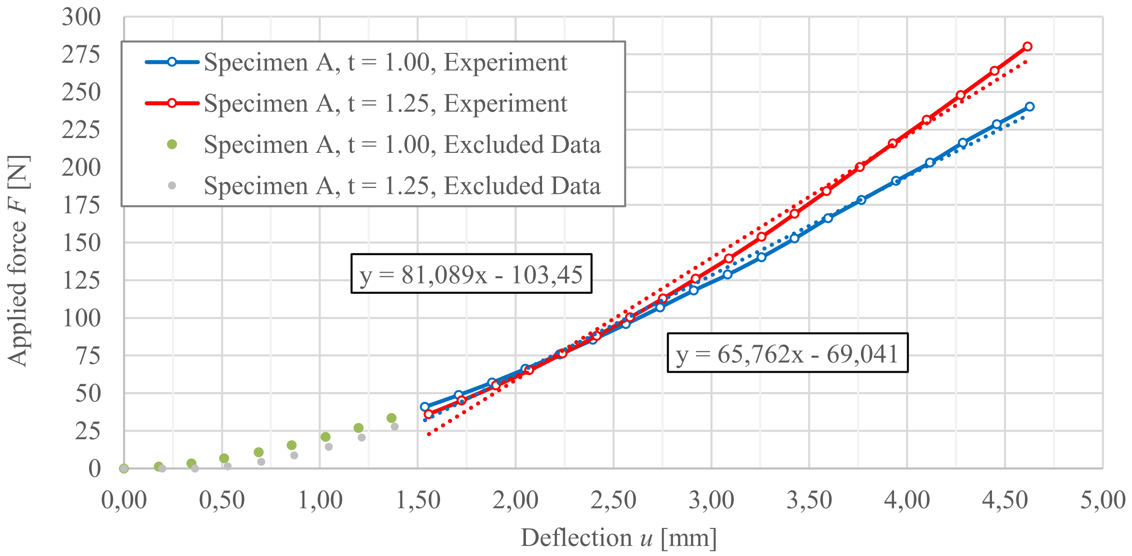

Fig. 2 The relationship between applied force F and measured deflection u with stiffness determination

Simulations

To be able to replace FST experiment measuring with a virtual one, a computer model is developed. This model uses the Finite Element (FE) method for mathematical description and is created in SW ANSYS Workbench 2019 R3 and it consists of two parts. The first part represents the parametric geometrical model of the specimen with subjected three-point star pattern, second one is used for prescribing boundary conditions corresponding to the specimen loading by plunger. Since plunger is much stiffer than tested structure, static loading is gradually increased and applied on a contact area by using ANSYS remote force function with deformable behaviour. The friction between plunger and specimen is neglected. Loading of the structure is gradually increased until loading force value F = 200 N is reached. Measured thicknesses of printed Specimen A are lower than required, which was caused by manufacturing tolerances. As a result of SLS printing process, real thicknesses t_r are decreased by 0.20 mm.

To capture specimen physical behaviour together with large deformations and deflection, nonlinear static structural analysis using finite elements for shell discretization (SHELL181) are used in computer model [5]. Linear isotropic elastic material model of material is used with Young's modulus E = 1 224 MPa and Poisson ratio μ = 0.39 [6, 7]. FE model consisted of 100 000 elements and 90 000 nodes.

The calculated result from a computer model is relationship between applied force F and deflection u, from which stiffness is determined by linear approximation again. The high-quality calibration between experiment and simulation is achieved (Table 1). The vector displacement field correspond to loading force F = 200 N is shown in Fig. 3.

Table 1: Comparison of determined stiffness k from experiment and simulation

Designed thickness t [mm]	Real thickness t_r [mm]	Experiment k [N/mm]	Simulation k [N/mm]	Difference [%]
1.00	0.80	65.76	68.97	4.90
1.25	1.05	81.09	88.48	9.10

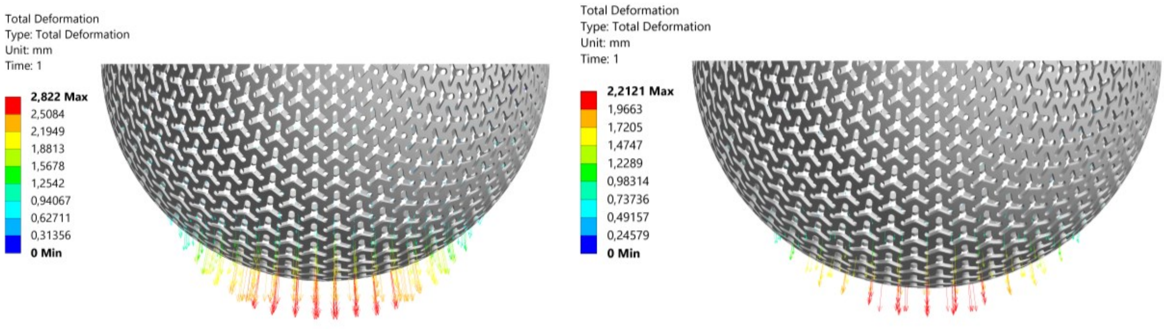

Fig. 3 The vector displacement fields corresponding to the applied force F = 200 N for specimen A, real thickness t_r = 0.80 mm (left) and t_r =1.05 mm (right)

Parametric study

Parametric study of the FST stiffness employing the presented computer model was done. The stiffness is evaluated all together for fifteen variants of the pattern and real thicknesses. Three geometries of specimens with different tree-point star pattern were designed. The pattern geometry of first specimen A is described above. The pattern of the second specimen B has increased width between pattern openings p by 0.25 mm corresponding to parameters b = 2.00 mm, l = 5.00 mm, p = 2.60 mm. In case of the pattern of third specimen C, pattern openings parameters *b* and *l* were increased by 0.25 mm, i.e. $b = 2.25$ mm, $l = 5.25$ mm, $p = 2.35$ mm. Each specimen was thought in five real thicknesses ranging from 0.80 mm to 1.80 mm with the step size 0.25 mm. The pattern parameters are presented in Table 2.

Table 2: Tree-point star pattern parameters

Pattern parameters	Opening parameter *b* [mm]	Opening parameter *l* [mm]	Width between pattern openings *p* [mm]
Specimen A	2.00	5.00	2.35
Specimen B	2.00	5.00	2.60
Specimen C	2.25	5.25	2.35

Obtained results are listed in Table 3. It could be seen, that the influence of the determined stiffness *k* grows with increasing the real thickness t_r. Also, it is apparent from Fig. 4, the changing of the opening parameters *b*, *l* and the width between pattern openings *p* has a significant effect on the stiffness.

Table 3: Evaluation of determined stiffness from parametric study

Real thickness [mm]	0.80	1.05	1.30	1.55	1.80
Flexible structure	Determined stiffness *k* [N/mm]				
Specimen A	68.97	88.48	107.64	126.41	144.85
Specimen B	83.68	107.88	131.68	155.02	177.91
Specimen C	62.02	79.37	96.40	113.10	129.51

Conclusions

In this paper, two ways of determining the stiffness of the 3D printed FST are presented. A new experimental jig was constructed replacing traditional tensile and flexural testing techniques used for internal structure properties testing [8, 9]. The second one is a numerical analysis based on FE method. It was demonstrated that developed computer model is able to describe behaviour of FST and as such could be used to evaluate the FST stiffness. The high-quality calibration between experiment and simulation is achieved. In the end of the work, the computer model has been used for parametric study including three-point star pattern parameters and real thickness variation (Fig. 4). The proposed experimental technique has been found as an important complementary tool in the design of the 3D printed FST with tree-point star pattern by non-linear computer modelling, employing FE method.

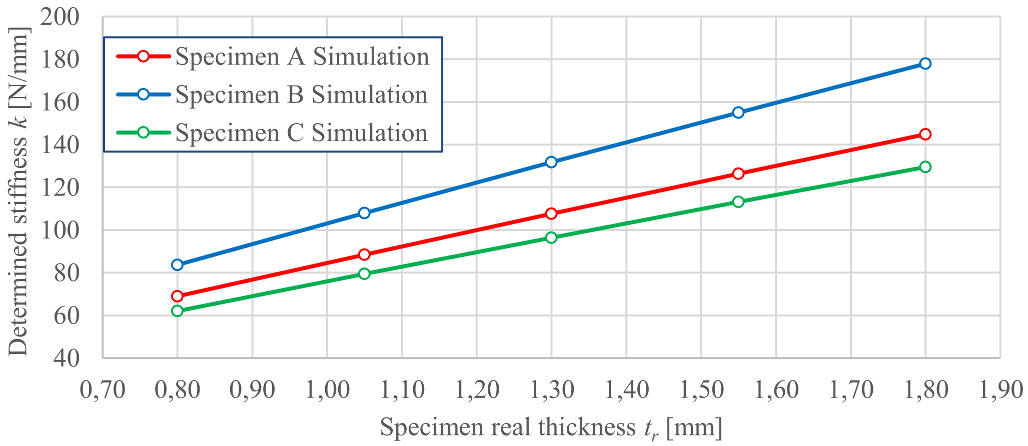

Fig. 4 Relationship between determined stiffness *k* and specimen real thickness t_r

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