Design and Behaviour of 3D Printed Joint Connecting Various Polymer Materials

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Abstract: This paper deals with the design and modelling of a joint made by a 3D printing method. The aim of the work is to test and prepare a suitable connection between two printed materials. To determine the best-performing type of joint, Load capacity is used as main criterion. For evaluation, two materials (PA12 and TPU) are used for performing experiments using a universal testing machine. After obtaining data, a mathematical model was developed to correspond with the experiment. A parametric study was performed to evaluate suitable modifications of the design. A computational model was done in the software ANSYS Workbench 2020 R2. The conclusion is the evaluation of the obtained knowledge and comparison of the experimental testing with the FEM analysis. The obtained results can be used for designing biomedicine aids.

Keywords: Joint connection; Load-bearing capacity; Additive manufacturing; Finite Element Method

1 Introduction

Additive manufacturing is becoming more popular for making personalized biomechanical applications such as orthosis or prostheses which have typically complex geometries [1, 2]. The typical material for printing such applications is currently PA12 (Polyamide 12). However, some materials used directly with skin are rough and cause calluses, therefore there is a need for softer materials. These days, manufacturers are experimenting with TPU (Thermoplastic Polyurethane), which could replace foams. Current SLS (Select Laser Sintering) printers cannot print made of two materials.

This paper deals with the design and testing of a joint that can connect two parts made of two materials with different mechanical properties, see Table 1 (the material data were obtained from articles [3, 4]). The main aim of the new joint is to have a strong enough connection of two parts for application and an additional but not mandatory requirement is to be able to dismantle the joint. The first part of the aim is to have a large load-bearing capacity for forced detaching. The second part is due to the ability to wash softer parts of the assembly to minimize health issues.

This work is based on previous results of flexible structures which are used in biomechanical applications [5]. However, the applications were made of one material. due to the higher demand for using multiple materials, this work is aimed for investigating connecting these materials in various places of the part.

Table 1. Material properties of PA12 and TPU.

Material	E [MPa]	ν [-]	σ_Y [MPa]	E_T [MPa]	A [%]
PA12	1 224	0.39	21	334	18
TPU (1301)	60	0.4	5	0.06	250

2 Method

The first step was to design two types of joints for this application base on different concepts [4]. The first joint is a customization of the dovetail joint (see Fig. 1) but applied for polymer materials. This type of joint is typical in wood applications (it is a standardized joint). However, it was necessary to slightly alter it due to the manufacturing process (3D printing), which meant removing sharp edges. The second joint was the annular joint (see Fig. 2), which has no standard. For each joint, three variants were created which different dimensions (see Table 2 and **Table** Table 3). It should be noted that the left part of the joint from Fig. 1 and Fig. 2 was made of PA12, and the right part was made of TPU (1301). Both parts were printed from virgin powder. Depending on the design of the joint, there is a possibility of limited movement (rotation) of connected parts. In our application, it was necessary to restrict this movement.

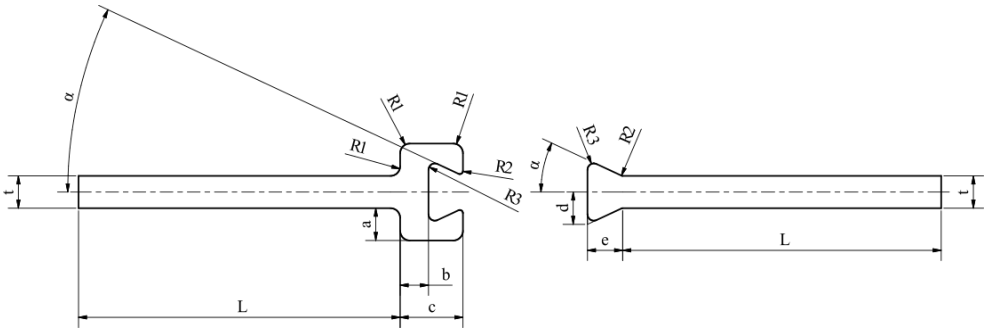

Fig. 1 Scheme of dovetail joint.

Table 2. Dimension of dovetail joint (left part PA12, right part TPU).

Dimensions	a [mm]	α [°]	b [mm]	c [mm]	d [mm]	e [mm]	L [mm]	$R1$ [mm]	$R2$ [mm]	$R3$ [mm]	t [mm]
Variant 1	1.00	25	0.88	1.95	1.00	1.07	10.0	0.30	0.10	0.20	1.00
Variant 2	1.50	25	0.90	3.02	1.50	2.14	10.0	0.30	0.10	0.20	1.00
Variant 3	1.50	40	0.88	1.95	1.50	1.19	10.0	0.30	0.10	0.20	1.00

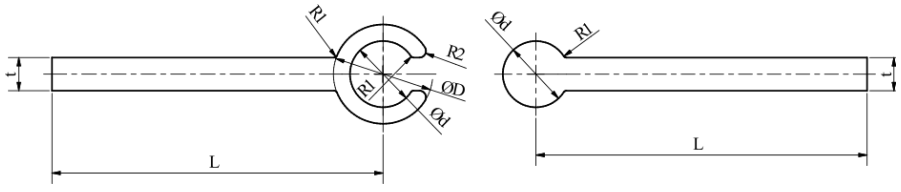

Fig. 2 Scheme of the annular joint (left part PA12, right part TPU).

Table 3. Dimensions of annular joint.

Dimensions	*a* [mm]	*α* [°]	*b* [mm]	*L* [mm]	*R1* [mm]	*R2* [mm]	*t* [mm]
Variant 1	1.07	25	1.00	10.0	0.20	0.10	1.00
Variant 2	2.14	25	1.50	10.0	0.20	0.10	1.00
Variant 3	1.19	40	1.50	10.0	0.20	0.10	1.00

In the second step after manufacturing these variants, experiments were performed using the universal testing machine (TESTOMETRIC M500-50CT) with the force sensor (S2M). The force sensor is in the range of 0 – 100 N. Specimens were thoroughly cleaned and put in jaws of the machine (see the example presented in Fig. 3). The velocity of the jaws was set to v = 5 mm/min. The machine was running until disjointing. From the experiment, we obtained a relation between acting force and displacement. In the beginning, joints had linear characteristics. However, it was not linear in full range. The experiment was performed for each variant using five specimens. The presented results in Fig. 4 represent Variant 2 of the annular joint (specimen O) and Variant 3 of the dovetail joint (specimen L).

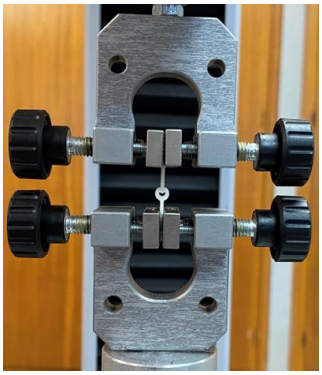

Fig. 3 Clamping of the annular joint in the universal testing machine.

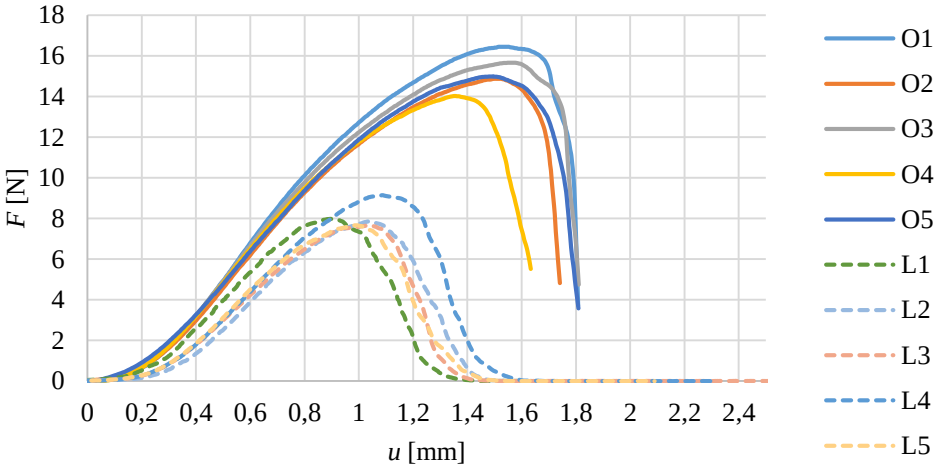

Fig.4 Force displacement diagram of specimens O and specimens L.

As it is apparent from Fig. 4, specimen L had a smaller load-bearing capacity for disjointing than specimen O. For the following study, we focused on the annular join. In the third step,

we performed numerical modelling using the finite element method. The numerical model contained multiple nonlinearities, such as material model, contacts, and large deformation, similarly as previous research of load-bearing capacity of wires ropes [6]. Because of these nonlinearities, we chose plane stress analysis, which is a simplified simulation than volume one, but it provided us with enough accurate results for our case. The numerical model used symmetry and had 5 948 nodes and 1 864 elements. Material models were elastic-plastic materials using bilinear isotropic hardening. The used mechanical properties are listed in Table 1. This model aimed to get the same load-bearing capacities as the experiment. For evaluation of difference between numerical modelling and experiment, following expression is used

$$err = \frac{F_{LAB_{ave}} - F_{FEA}}{F_{FEA}} \cdot 100\ (\%), \tag{1}$$

where $F_{LAB_{ave}}$ is average load capacity obtained from experiment and F_{FEA} is load capacity obtained from numerical modelling. Evaluated difference was 7.7 %. Additionally, we obtained a field of stresses (Fig. 5) and mainly plastic strains after disjointing using the finite element method. Comparison of experimental data and of numerical model is presented in Fig. 6.

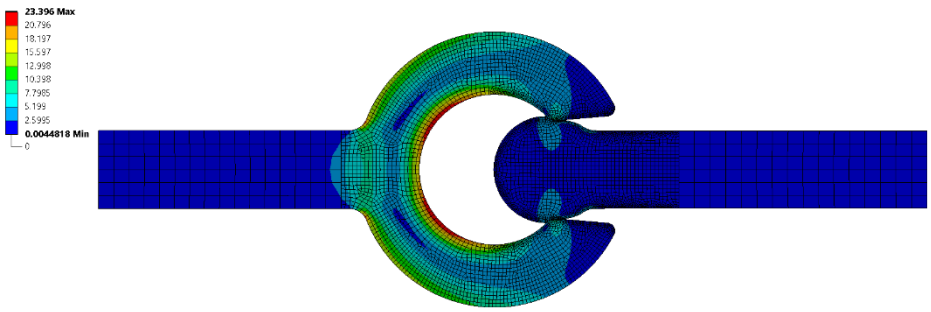

Fig. 5 Field of equivalent von Mises stress during maximal load corresponds to the load-bearing capacity.

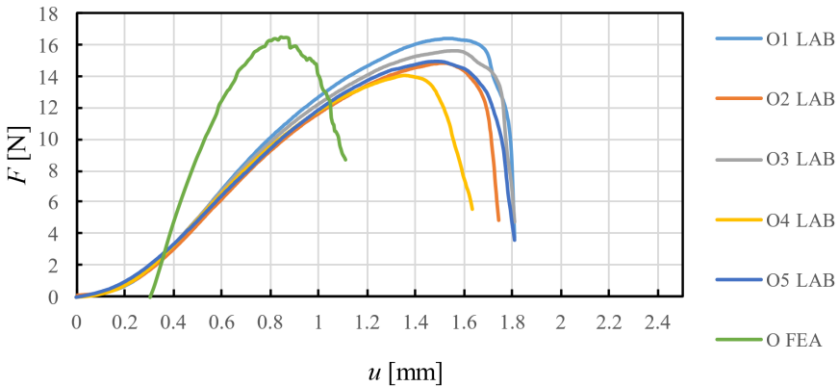

Fig 6 Comparison of experimental data with finite element analysis.

The fourth step was a parametric study of the key parameter. The parametric study dealt with investigating the change in the load-bearing capacity due to resizing the filler's radius ***R1***, see Fig. 7. Radius ***R1*** was assumed as an important geometrical parameter influencing load-bearing capacity. The rest of the dimensions was not the task of the parametric study even though they might affect stiffness or the load capacity. Totally 6 values of the radius were

studied. The dimension is limited due to the limitation of manufacturing (a small radius is difficult to manufacture) and larger values are affected by dimension ***d.*** The study resulted in lowering the radius enlarged the load-bearing capacity which is apparent from linear regression in Fig. 7. For the larger load-bearing capacities during disjointing, it is crucial to have it caught by the slot of the tougher part.

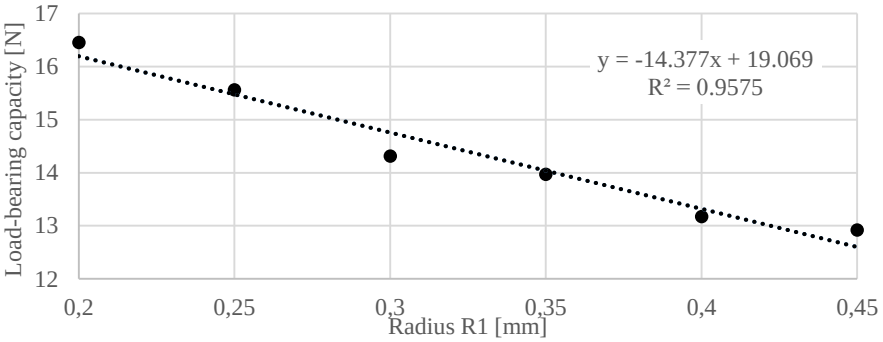

Fig. 7 Parametric study of radius R1.

Conclusions

With the advent of new types of biomechanical application, it is necessary to research possibilities of connecting various 3D printed material. We designed joint connections made of two materials (PA12 and TPU) with main aim to maximized possible load-bearing capacity. In this paper, we presented two types of joints (dovetail and annular). We performed experimental measurement of two possible variants and prepared numerical model which was later used for parametric study.

Comparing the experiment load-bearing capacity with one obtained from the numerical model, the error is 7.7 %. However, numerical modelling had different characteristics than experimental ones, see Fig. 6. Our explanation of this phenomenon was manufacturing inaccuracies, which can be minimized by precious printing. Numerical modelling used simplified analysis which might have affected results. The material models used rather a simple plasticity model. The contact was also simplified since the surface of the part is affected by heat treatment. In this study, we focused only on maximal force before disjointing, therefor model was enough suitable for parametric study. After the parametric study, it was apparent that radius ***R1*** affects load capacity greatly because it might allow a smoother transition of parts (which led to lower values of load capacity).

The presented numerical model is suitable for fast parametric studies but has a lot of shortcomings. For better evaluation of the whole characteristic, one should the material model and prepare a volume analysis of the joint. After treating these shortcomings, a numerical model can be used for preparing a better design of joints.

Acknowledgments

This work was supported by Specific Research „Application of Modern Computational and Experimental Approaches in Applied Mechanics“ (SP2023/027).

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