SIMULATION MODEL OF POLYCARBONATE MATERIAL FOR ADDITIVE TECHNOLOGY FDM

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The Department of Robotics at the VSB-TU Ostrava has been long-term involved in the improvement of parameters in parts produced by additive technology. It primarily concerns component parts as well as bigger functional units of mobile robots. However, it is not exceptional to produce a complete bearing frame of a mobile robot or an effector with the majority of parts produced by additive technology. This paper follows up previous publications from the area of material properties of "printed" polycarbonate, where, on the basis of tensile and bend tests, basic mechanical properties of printed polycarbonate were verified. Based on these paper-described performed tests, values have been acquired and subsequently a simulation model for the above-material has been designed. The simulation model and found out mechanical properties of the material should primarily serve to designers at the phase of drafting parts or functional units produced by additive technology FDM.

KEYWORDS

rapid prototyping, polycarbonate, bend tests, tensile tests, shear tests, simulation model

1 INTRODUCTION

The Department of Robotic primarily uses additive technology to produce final parts for functional units. It does not only concern second-rate parts, such as protective covers and view parts, where mechanical properties of the used materials do not play any important role with respect to the part functions. A large number of parts has been produced in a form of functional parts, such as gear trains, chassis of a mobile robot, or a complete effector, which constitute the main parts of the whole unit. When designing such constructions, it has been found out that there is a lack of available foundations to create a quality simulation model. Thus, it was necessary to produce some part by the method of try-mistake, which negatively influences the creation of the future unit. It primarily concerns time and financial losses when repeatedly producing modified parts. Real properties became evident only after additional measurements.

A typical example of using additive technology are jaws of robot's effector (see Fig. 1). Additive technology enables to produce effector jaws quickly irrespective of the shape of the manipulated object. Thus, this opens space, mainly in mobile robotics, for fast reaction to newly occurred conditions, when the shape of the manipulated object does not have to be known in advance. Therefore, jaws can be designed and produced within hours. Such an approach can also be used for quick repairs of the system in a mission.

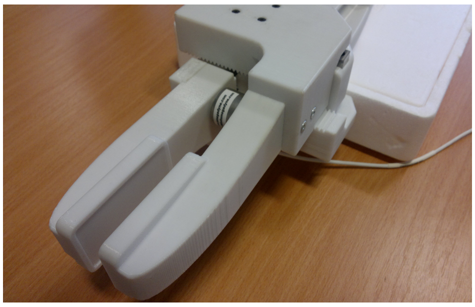

Figure 1. Measuring the grip force of the jaws on an effector designed at the Department of Robotics [Lipina 2011]

However, there is an issue of jaws' load capacity, when the performed modifications can result in a significant intervention into the solidity of the original or newly created construction of the jaws. A quality design when there is no possibility to perform verification measurements requires a quality simulation model of the given material.

2 TESTS OF MECHANICAL PROPERTIES

The experiment used additive technology from company Stratasys, namely printer FORTUS 360 mcL [Stratasys 2018]. The printer uses the FDM printing technology to produce parts [Chua 2003, Spisak 2014, Beniak 2014, Beniak 2015]. The pre-processing phase used software Insight, which is supplied with the printer. Apart from the standard setting of printing of the internal structure, such as Solid, Sparse, and Sparse – double dense, the software enables individual setting both of the internal structure and contours. The building material was polycarbonate PC-10, supplied by the printer producer. Selected printing parameters and material properties provided by the producer are listed in Table 1 and Table 2.

Parameter	Value [mm]	Parameter	Value
Contour width	0.508	**Nozzle type**	T 16
Slice height	0.254	**Extruder temperature**	368 [ºC]
Part sparse fill air gap	2.286	**Heated-bed temperature**	145 [ºC]

Table 1. Print parameters

Parameter	Value	Parameter	Value
Tensile Strength	68	**Flexural Strength**	104 [MPa]
Tensile Modulus	2 280 [MPa]	**Flexural Modulus**	2 200 [MPa]
Heat Deflection	138 [°C]	**Tensile Elongation**	5 [%]

Table 2. Selected mechanical properties of PC-10 material provided by the producer - Stratasys

Individual tests were performed for three standard types of internal structure composition (solid, sparse and sparse - double dense). However, in order to create a simulation model, only the internal structure Solid was further worked with due to the measured parameters.

Solid is a type of 3D-print where a cross-section of the part is printed using the maximum density of the material from which it is made. First, the perimeter of the part is printed, and then the inner space is filled by layering the fibres in a pre-defined position (see Fig. 2).

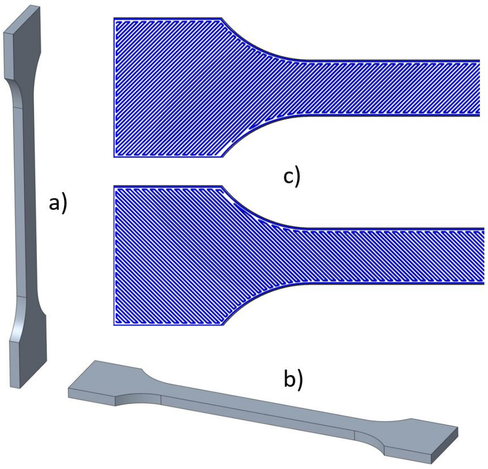

Figure 2. Orientation of a sample on a building sheet during production a) vertically and b) horizontally. Orientation of fibres in consecutive layers c) when printing type Solid Horizontally.

2.1 *Tensile tests*

The tensile tests [Lipina2014, Lipina 2015] used a series of samples Solid, Sparse and Double Sparse with basic dimensions (see Fig. 3) and the thickness of 4 mm. There was also a series of samples printed vertically for the internal structure Solid. For the purposes of a comparison with regularly produced polycarbonate, the samples were cut out of a board from material MARLON FSX Longlife.

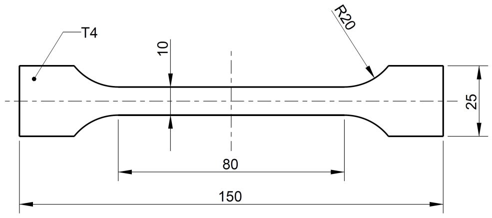

Figure 3. Dimensions of the test sample with a standard structure.

The tests were conducted on a M500-50CT bench-top twin-column universal materials testing machine, which is capable of exerting forces up to 50 kN and measuring sample elongation with a precision of 0.001 mm. The machine was connected to and controlled by a computer using WinTest Analysis software. The reported parameters are averages obtained from sample sections (see Fig. 4 and 5).

The numerical model used values of tensile strength, flexibility module (see Fig. 6 and 7). The plasticity threshold was set to the tension value of 0.2 % prolongation. These values were then used for the numerical model. The value of 1850 MPa was used as the flexibility module.

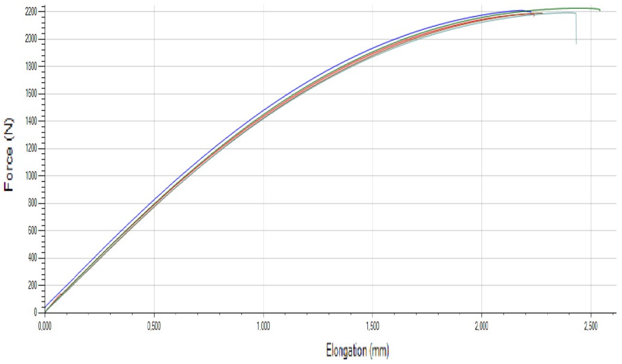

Figure 4. Plot from the tensile test of the Solid sample, horizontally.

Figure 5. Tensile test of a Solid sample, horizontal.

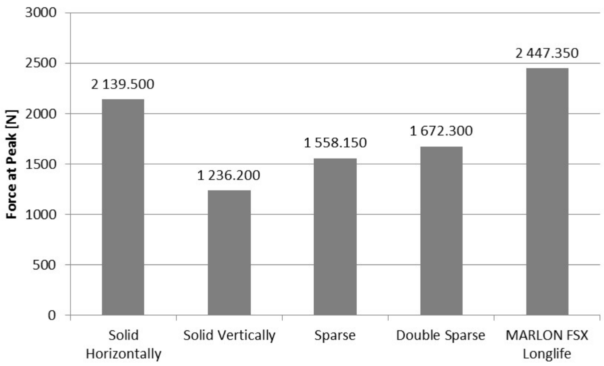

Figure 6. Force at peak for the samples tested.

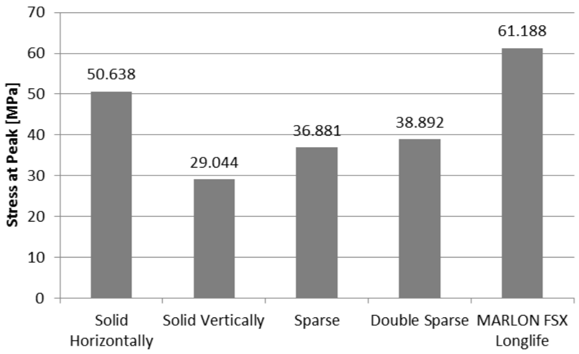

Figure 7. Stress at peak for the samples tested.

2.2 *Shear tests*

A shear test [Lipina2017] completes the parameters necessary for the creation of the numerical model. The prepared samples of dimensions 10 x 10 x 100 mm were printed horizontally as Solid. With respect to the way of producing parts (samples) by RP technology by layering, there are two possible ways of force acting during a shear test. First, it concerns perpendicular force acting and when the sample is rotated by 90°, there are tangent forces acting on the printed planes. For the purposes of test completeness, one sample was printed vertically in order to find out the shear value between individual layers of the print.

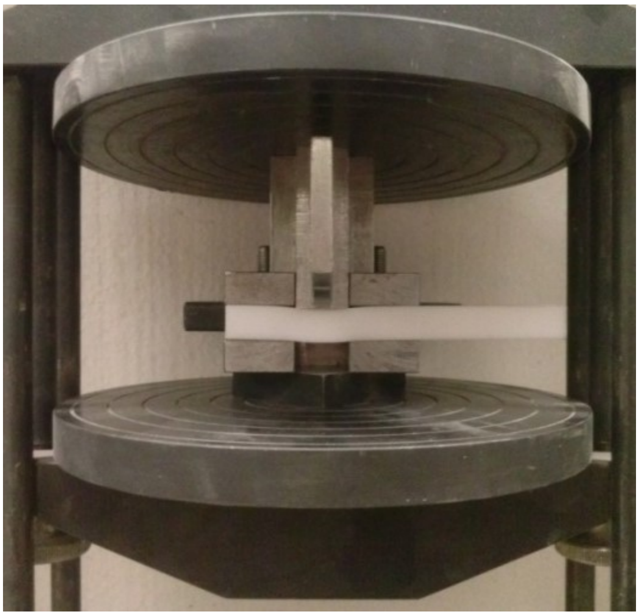

Figure 8. Shear test of a sample with printed layers oriented perpendicularly to the acting force.

The shear tests were performed on a mechanically controlled testing device FP10 at the peak force of 10 kN and on hydraulic drive device EU40 with the peak force of 400 kN (see Fig. 8). First, one-shear load test was performed. However, this test was influenced by acting tensile and bend component. Thus a double-shear load test was performed, where those forces were eliminated resulting in much more relevant results (see Fig. 9).

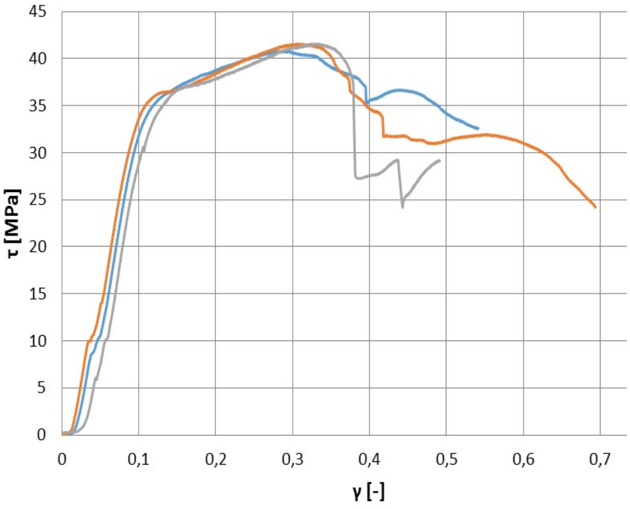

Figure 9. Plot: Results of a double-shear test for a set of three samples with printed layers oriented perpendicularly to the acting force.

3 SIMULATION MODEL

The numerical models used values acquired when testing mechanical properties of the material, particularly:

E – tensile elasticity module 2130 MPa,

G – shear elasticity module 470 MPa.

$$\begin{bmatrix} \frac{1}{E} & -\frac{\upsilon}{E} & -\frac{\upsilon}{E} & 0 & 0 & 0 \\ -\frac{\upsilon}{E} & \frac{1}{E} & -\frac{\upsilon}{E} & 0 & 0 & 0 \\ -\frac{\upsilon}{E} & -\frac{\upsilon}{E} & \frac{1}{E} & 0 & 0 & 0 \\ & & & \frac{(2+2\upsilon)}{E} & 0 & 0 \\ & & & & \frac{(2+2\upsilon)}{E} & 0 \\ 0 & 0 & 0 & 0 & 0 & \frac{(2+2\upsilon)}{E} \end{bmatrix} \quad (1)$$

Adding the above-stated values into the formula

$$\frac{E}{2G}-1 \quad (2)$$

determines the value which is a borderline value for the behaviour of an isotropic elastic material. For modelling itself, it is suitable to use a lower value which is provided in tables, for example:

$$\upsilon = 0.39 \quad (3)$$

Some values were estimated or taken over from tables. Since the material is not of isotropic nature, not all parameters can be read out from the performed tests.

Modelling itself was performed in program suite Salome-Meca with processor Code-Aster designed for numerical analysis using the Finite element method. The suite is composed of a standard set of programs pre-processor-processor-postprocessor. Therefore, a complete preparation of the model, its computation and subsequent result evaluation can be performed.

Having performed mechanical tests of polycarbonate for 3D printing, the acquired information was applied into a numerical model. The main focus was on tests in bend and shear. A sample for these tests is a simple cuboid with a length of 200 mm, a height of 25 mm and a thickness of 10 mm. Tensile test is difficult to model with local stress increase as in linear flexibility it stretches in its whole length and cross-section, which does not correspond with reality when imperfections result in an increase in local stress and subsequent damage. The material itself was modelled as elastic-plastic conditioned by Von-Mises plasticity with hardening. Due to the fact that having achieved plasticity of 0.2 % deformation, there is quite a quick loss of load capacity and a high deformation increase, thus using this condition is a sufficient approximation of material behaviour. The hardening module is determined from the plastic area of a working diagram of the tensile tested sample. Unlike the elasticity module to the 0.2 % deformation level, the curve inclination decreases by app. one third. The selected value is then 660MPa. The real diagram is of a non-linear nature. In the model, the non-linear branch is approximated linearly. Placement of the sample in bend and shear needs to be modelled as contact areas in order to ensure one-sided supports and to achieve behaviour close to a real test.

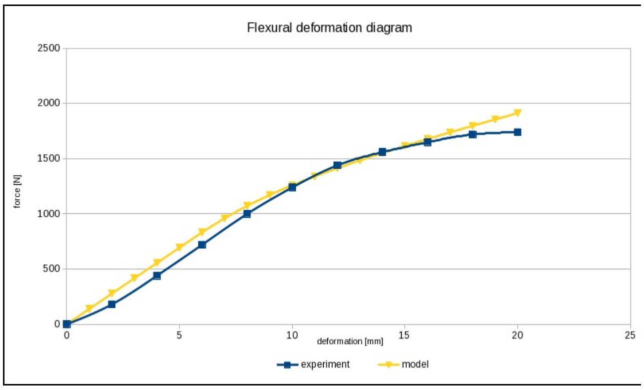

Figure 10. Comparison of experimental and model deformation from flexural test.

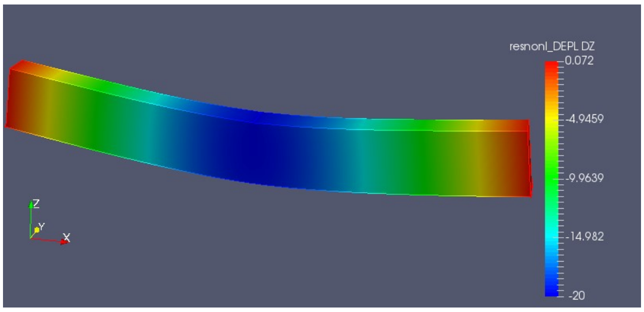

Figure 11. Deformation of flexural model.

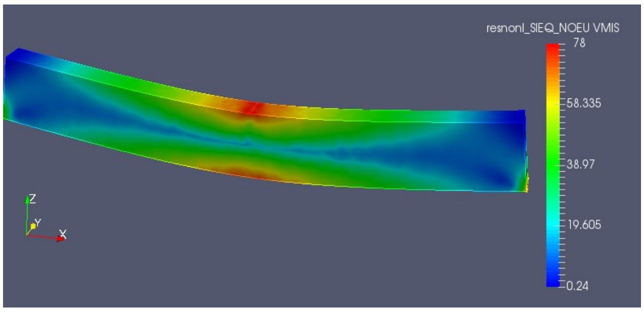

Figure 12. Deformation of flexural model.

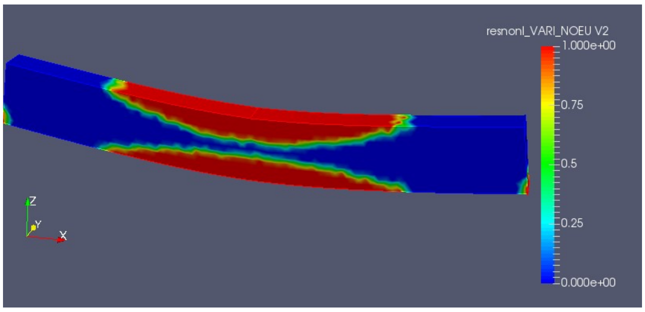

Figure 13. Deformation of flexural model.

The results achieved on the bent sample (see Fig. 10-13) reveal that the elastic-plastic model with balanced hardening quite well approximates the bend behaviour. The advantage is the sample in bend does not demonstrate damage which would locally weaken the cross-section which would result in significant local non-linearities. This issue is primarily noticeable in shear tests.

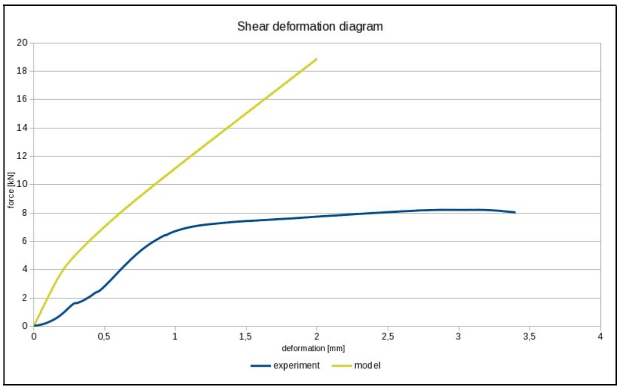

Figure 14. Comparison of experimental and model deformation from shear test.

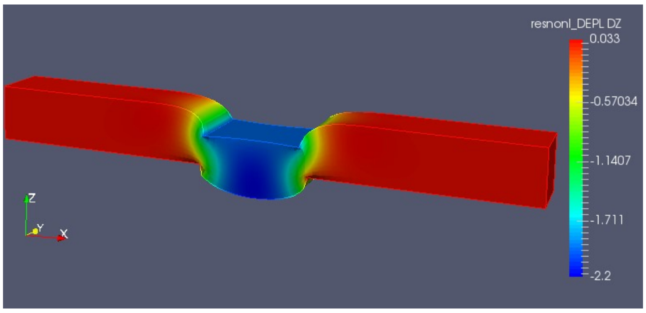

Figure 15. Deformation of shear model (mm).

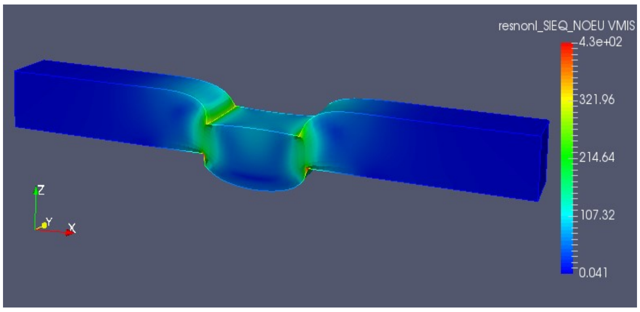

Figure 16. Von-Mises stress at deformation of 2mm.

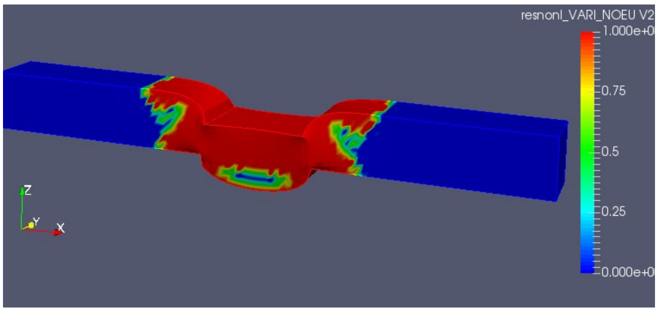

Figure 17. Indication of plastic state at deformation 2mm.

The shear test model (see Fig. 14-17) notably shows the influence of damage on the achieved results. As only a small deformations result in tensile damage on the upper surface of the sample, the elastic-plastic model does not allow such behaviour. Due to the influence of hardening, there is an unreal stress increase on the upper surface of the sample (see Fig. 17). The model, however, well reveals tensile deformation on the upper surface of the sample and bulging on the bottom surface. It is necessary to state that the standard elastic-plastic model with hardening, though with no damage, only partially approximates behaviour in almost clear shear. In a real part produced by 3D printing, occurrence of such direct shear load is highly improbable and it is also advisable to avoid such load.

4 CONCLUSION

Based on the acquired values from tests of mechanical qualities of the polycarbonate material (tensile, shear, bend tests) and added values from tables, a simulation model was created in a software suite Salome-Meca with Code-Aster for numerical analysis using the method of finite elements.

The important aspect of 3D print is the price of a part. It means that the first considered orientation of the printed part is the most cost-effective one. The simulation model primarily serves for verification of the cost-effective part orientation by prediction of critical locations in the model with respect to anticipated forces acting on the part. In addition it helps to find correct orientation for printing of the part or shows areas which have to be redesigned with respect to given stress conditions.

According to the tests, the tested plastic has almost isotropic behaviour unless the tension reaches an area of plastic deformation or damage. There are visible differences, primarily in tensile tests perpendicularly to the planes of printing. Although the modulus of elasticity is almost identical, there is significantly lower coherence between individual layers stressed perpendicularly to the planes of printings. This becomes evident by slight damage without any substantial material extension.

Such behaviour results in possible material damage if there are higher tensions perpendicularly to the printed layers. The material is not able of plasticity or non-linear elasticity (not tested which case corresponds to this) in this direction and the layers separate from each other. The acquired results are applied in constructing parts produced by RP technology at the Department of Robotics.

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