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Simulation of the elastic properties of 3D printed plastic tension rods using Fused Deposition Modeling (FDM)

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ABSTRACT: *The aim of this work is to simulate the elastic properties of 3D printed plastic rods using the Fused Deposition Modeling method (FDM). The plastic material PETG was used to 3D print the plastic rods according to the norm DIN EN ISO 527-2 Typ 1A. Different infill percentages were tested on the plastics rods in order to know their influence on the elastic properties. Tensile tests were conducted on the plastics rods based on the standard EN ISO 527-2, to obtain the stress-strain-curve of all the samples. It was observed that the Young´s Modulus of the printed rods increases linearly with the increase of the infill percentage. The software ANSYS together with the plugin Material-Designer was used to predict the elastic properties of the printed samples. Material-Designer uses RVE (Representative elementary volume), where it requires the creation of a geometry as well as the definition of the material properties. The RVE is exposed to several load cases and the homogenized data is computed from the results of the analysis. A correlation between the Young´s Modulus of the printed rods and the simulated RVE Young´s Modulus is found.*

KEYWORDS: *3D-Printing; FDM; Simulation; Young´s Modulus; Mechanical Properties;*

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I. INTRODUCTION

Additive Manufacturing is one of the greatest invention of this new era, giving new possibilities on obtaining fast prototypes [1]. Fused Deposition Modelling is one of the most popular and low cost methods among the wide range of 3D-Printing methods [2]. However, there are hardly any industrial applications in the field of high-precision plastic parts, since the component properties, unlike classic injection molding, cannot be simulated and predicted. Works from [2], [3], [4], [5] and [6] have been done to better understand the FDM 3D-printing method, but none of them uses simulation to predict the mechanical properties upon change of process parameters. In the FDM method the 3D printed plastic components are built up in layers [7]. This automatically leads to anisotropic material properties [8], therefore the mechanical properties of the component depend heavily on how the component was constructed in the 3D printer. Due to the lack of cross-linking of the individual layers, the strength of the 3D printed components is reduced compared to classic injection molded parts. In addition, plastic components manufactured using 3D printing have the disadvantage that they only result from the mechanical properties of the materials that is being used, such as PLA (polylactide), ABS (acrylonitrile-butadiene-styrene) or PETG (Polyethylene Terephthalate).

When it comes to additive manufacturing of components, the choice is limited compared to injection moulding. ABS or PLA are mostly used. For the 3D printing of metal, it is possible to use the iron-carbon diagrams to simulate which structures can be achieved at given temperatures during the entire process. The simulation models can calculate the warpage for metal and thus allow the geometry to be adjusted during the process to compensate for this warpage.

Simulating the 3D printing process of plastic samples will help to better understand the performance of 3D printed parts. The aim of this work is to use the simulation method to not only better understand the 3D printing process by simulating different parameter and thus seeing the effect on the sample, but also to predict the elastic properties of 3D printed components. For this reason during this work several specimens were printed and tested in order to obtain enough experimental data. Further on, the Simulation of the elastic mechanical properties of the 3D printed parts was conducted and the results obtained from the simulation were compared with the experimental tests.

II. MATERIALS AND METHODS

1.1 Experimental procedure

For the experiments, a Fused Deposition Modeling (FDM) 3D-Printer was used to print the plastic rods. In this method, a continuous filament of thermoplastic material is extruded from a heated printer extruder head (nozzle) and is deposited layer-by-layer on a heated building plate. The movement of the printing head is computer controlled in order to stop and start the deposition of material, to successfully build the printed shape. In this research the 3D-Printer Prusa i3 MK3S [9] was used, where the building plate was heated up to 85°C and the material was injected through the nozzle with a temperature of 235°C for PETG. The geometry was sliced in the PrusaSlicer Software [10].

The printed geometry was the tensile rod 527-2 Type 1A, which is used in the norm DIN EN ISO 527-2, to determine tensile properties that are obtain from a tensile test using a tensile testing machine. Figure 1 shows the dimensions and shape of the tensile rod 527-2 Type 1A, that was used and investigated during this research.

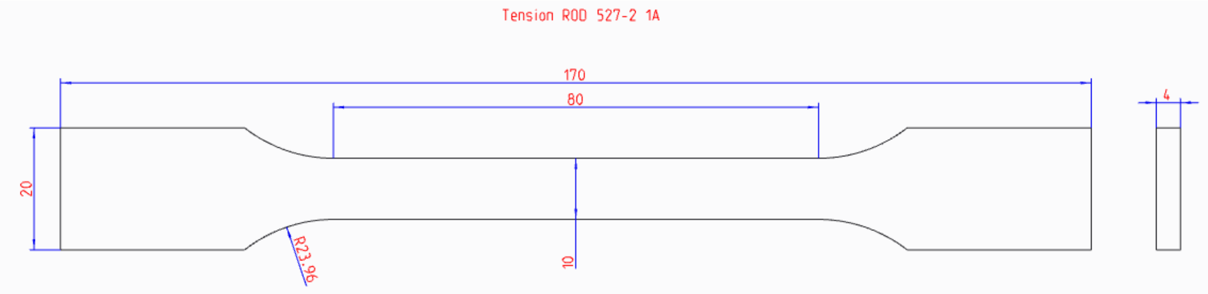

Fig. 1. Schematic representation of the tensile rod 527-2 Type A, with dimensions in mm

In this research the parameter that was investigated was the infill percentage of the plastic rods, meaning the amount of material that fills the inside of the sample. The infill percentage was varied in the following values 20%, 40%, 60% and 80%. The following

Table 1.

Table 1Overview of the 3D printing process settings for the Prusa i3 MK3S

	PETG
Nozzle size (mm)	0.4
Slice height (mm)	0.2
Infill (%)	20,40,60,80
Melting Temperature (°C)	235
Building plate temperature (°C)	85

1.2Tensile tests & Results

The plastics rods were tested using a tensile testing machine Zwick Z100 [11]. The testing norm as already mentioned was the DIN EN ISO 527-2 with a testing speed of 50 mm/min and a clamping length of 120 mm. For each infill percentage 7 samples were tested in order to see the reproducibility of the results as well as the capability of the 3D-Printer to produce samples with constant mechanical properties. The following Figure 2 shows the results obtained from the tensile tests. It can be observed that the elastic field of the stress-strain-curve is pretty constant and reproducible. The plastic field also shows a good reproducibility of results in terms of the maximum tensile strength.

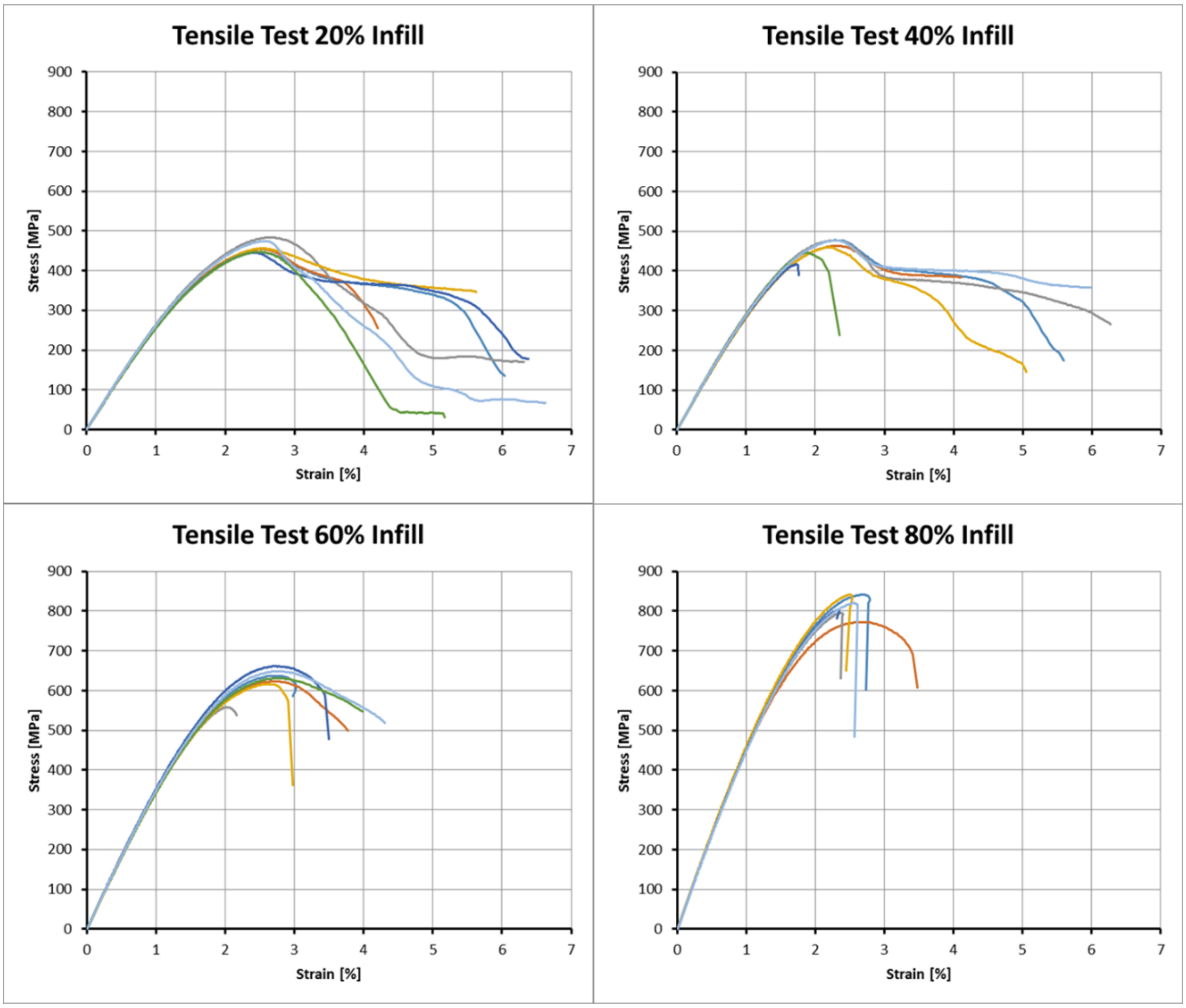

Fig. 2. Stress-Strain-Curveforplasticrodsmadeof PETG with different infillpercentages 20%, 40%, 60% and 80%

However, for the aim of this research only the elastic field was considered for the comparison between simulation and experiments. One reason for this is that the used software ANSYS, does not have a simulation feature for the 3D-Printing of plastic samples, only for metals. The other reason is that the new plugin from ANSYS “Material Designer” can only make the prediction of linear material properties. ANSYS is still further developing the software in order to be able to simulate nonlinear material properties in a near future. In the following Table 2 it can be seen the results for the Young-Modulus from the stress-strain-curves conducted in the experimental phase. The Young-Modulus of the PETG filament, given by the manufacturer, is completely different from the Young-Modulus of the produced samples upon infill percentage variation. For this reason, it is not to expect that 3D-printed samples will behave with the same elasticity as the manufacturers given Young-Modulus of the filament. Figure 3 shows the results from Table 2 into a diagram. It is observed that with the increase of the infill percentage, the value of Young-Modulus is increasing. However, the values were always below the manufacturers given Young-Modulus of the PETG filament. This shows that with different infill percentages it is possible to obtain different types of deformation during the performance of 3D-printed parts. Since the Young-Modulus was constant and reproducible, these results can now be used for the comparison between simulation and experiments.

Table 2Young-Modulus results from the stress-strain-curves of PETG plastic rods

Infill Percentage	Young-Modulus PETG	Young-Modulus PETG Filament
20%	680 MPa	1940 MPa
40%	760 MPa	
60%	910 MPa	
80%	1200 MPa	

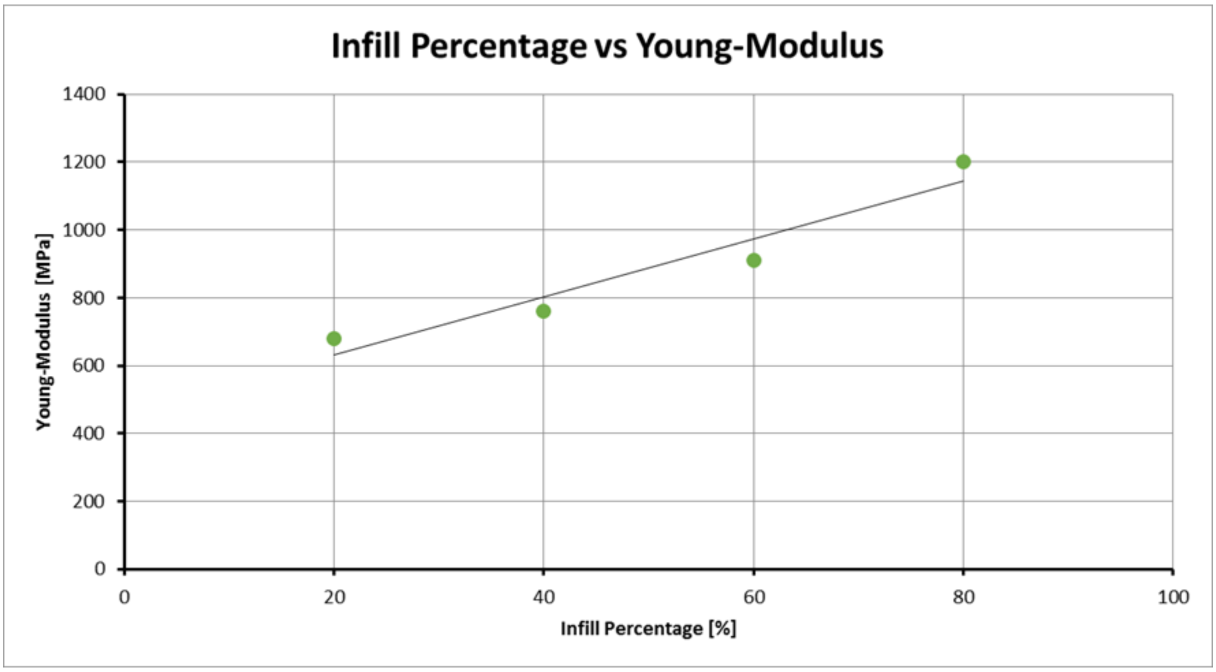

Fig. 3. Linear behaviourbetweenthe Young-Modulusofplasticrodsmadeof PETG andtheirinfillpercentage

III. ANSYS SIMULATION – MATERIAL DESIGNER

For the simulation of the mechanical properties of the 3D-printed tension rods, the software ANSYS [12] was used. ANSYS has since the 19.2 version, a new feature called "Material Designer". The 3D-printed geometry cannot be exported from the slicer and directly imported to ANSYS. For this to happen, it would be extra programming necessary to have the exactly same geometry. On the other hand, even if we would have the geometry, the 3D-printed layers of 0.2 mm are extremely small, which would result in a model with a large number of elements, as well as the computing time.

Material Designer is capable to make an average of the mechanical properties instead of simulating the full microstructure. In this plugin, a finite element analysis is conducted on the macrostructure of the material, which requires to model a RVE (Representative Volume Element). For this reason, the creation of the geometry, as well as the definition of the material properties of this structure are necessary. Further, the geometry is meshed and the RVE goes under macroscopic loads, and the new material data is computed, based on these load responses. Material designer allows the calculation of material properties of an RVE based on different types of structures: Lattice, UD Composite, Random UD Composite, Chopped Fiber Composite, Woven Composite and User Defined.

Table 3 shows the material properties of the PETG Filament, which was used during the experiments. In this research, the user defined RVE was used to define the geometry of the microstructure of the plastic rods. Figure 4 shows the geometry concept of the RVE during this research. As shown in Figure 4.A, the printed geometries were sliced using the software PrusaSlicer changing the infill percentages in the values mentioned in chapter 2.2. Afterwards the dimensions of the yellow structures were analyzed and drawn in the software Creo-Parametric 3.0 (Figure 4.B), in order to obtain the CAD-Geometry of the RVE. Subsequently the CAD-Geometry was saved as a *Step-file and imported into ANSYS-Material Designer (Figure 4.C). The material properties of the filament were input into the material library of ANSYS and the RVE was meshed and subjected to the loads.

Table 3Material Properties of the PETG filament

Material	**PETG**
Density (g/cm^3)	1.27
Young-Modulus (MPa)	1940
Tensile Strength (MPa)	50
Printing Temperature (°C)	195-225

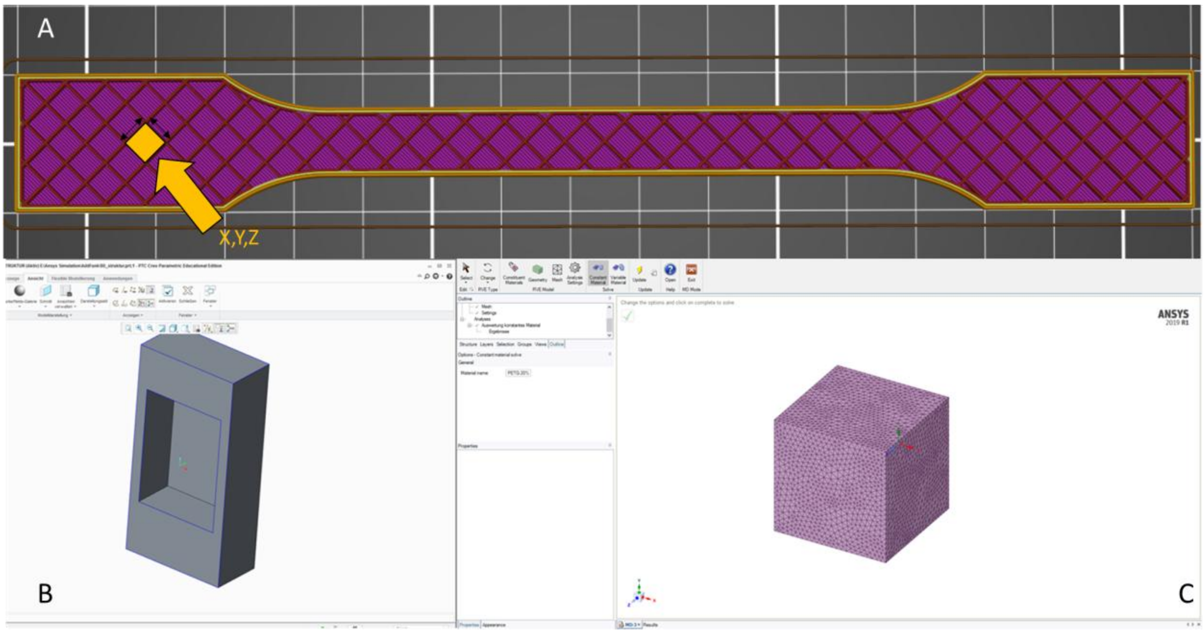

Fig. 4. Representative Volume Element (RVE) geometry concept; A. PrusaSlicer; B. Sectional cut of the CAD Geometry in Creo Parametric 3.0; C. RVE in ANSYS – Material Designer

IV. RESULTS & DISCUSSION

After all the geometries were designed for the different infill percentages, the Material-Designer subjected these geometries to some loads and the new material properties were calculated. The new calculated materials are presented in Table 3. It is seen that the values obtained from the experiments are very similar with the results obtained from the simulation. However, there is still space for improvement since the simulation results don´t match exactly the experiment results. The actual error between simulation and experiment is 17, 5, 6 and 10% for the infill percentage 20, 40, 60 and 80% respectively.

Table 4Young-Modulus comparison between the tensile experiments and the simulation for PETG plastic rods

Infill Percentage	Young-Modulus PETG-Experiment	Young-Modulus PETG-Simulation	Young-Modulus PETG Filament
20%	680 MPa	564 MPa	1940 MPa
40%	760 MPa	718 MPa	
60%	910 MPa	877 MPa	
80%	1200 MPa	1074 MPa	

The new calculated material properties from Table 4, were input in the ANSYS-Workbench simulation in order to predict the deformation of the plastic rods according to the new material properties. An elastic analysis was conducted on the same geometry as the plastic rod´s geometry, however to facilitate, the geometry was simplified to match the clamping length. This length is where the tensile tests were conducted and where the measurements for the stress-strain-curves were analyzed. Figure 5 shows the simulated elastic deformation obtained on the plastic rod after inputting the new calculated material properties from Material Designer.

For the experiments, the infill percentage of the 3D-printed plastic rods was varied in the following values: 20, 40, 60, and 80%. It was observed that with the increase of the infill percentage the Young-Modulus increases linearly, therefore the deformation decreases. From the experiments it was also observed that the maximum tensile strength also increased, giving more stability to the samples. However for this study, only the elastic field was taken into consideration since the Material Designer feature, does not allow the prediction of non-linear properties. The material properties of the used PETG Filament were input in Material Designer as well as the geometry of each individual structure of the plastic rods.

The new calculated material properties show a good match between experiment and simulation with an average error of 9%. There are still space for improvement to reduce the error between simulation and experiment. The difference between the results obtained from the experiments and the simulation can be explained duo to the fact that the material designer doesn´t cover entirely the 3D-Printing process mechanism.

This means that parameters like geometry perimeters, thermal expansions or residual stresses are not taken into consideration.

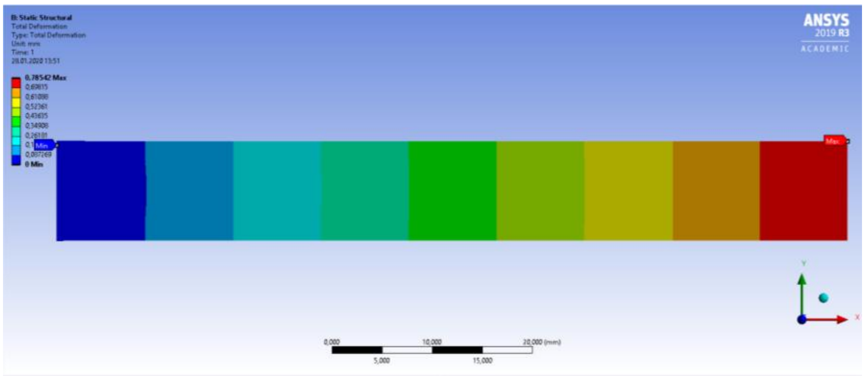

Fig.5. Simulation of the elastic deformation of plastic rods using new calculated properties from ANSYS-Material Designer

The following figure 6 shows the comparison of the deformation results between simulation and experiment. It is seen the prediction from the simulation in ANSYS-Workbench with the results from the stress-strain-curves upon variation of the infill percentage. The prediction of the elastic deformation has a very good match between simulation and experiment.

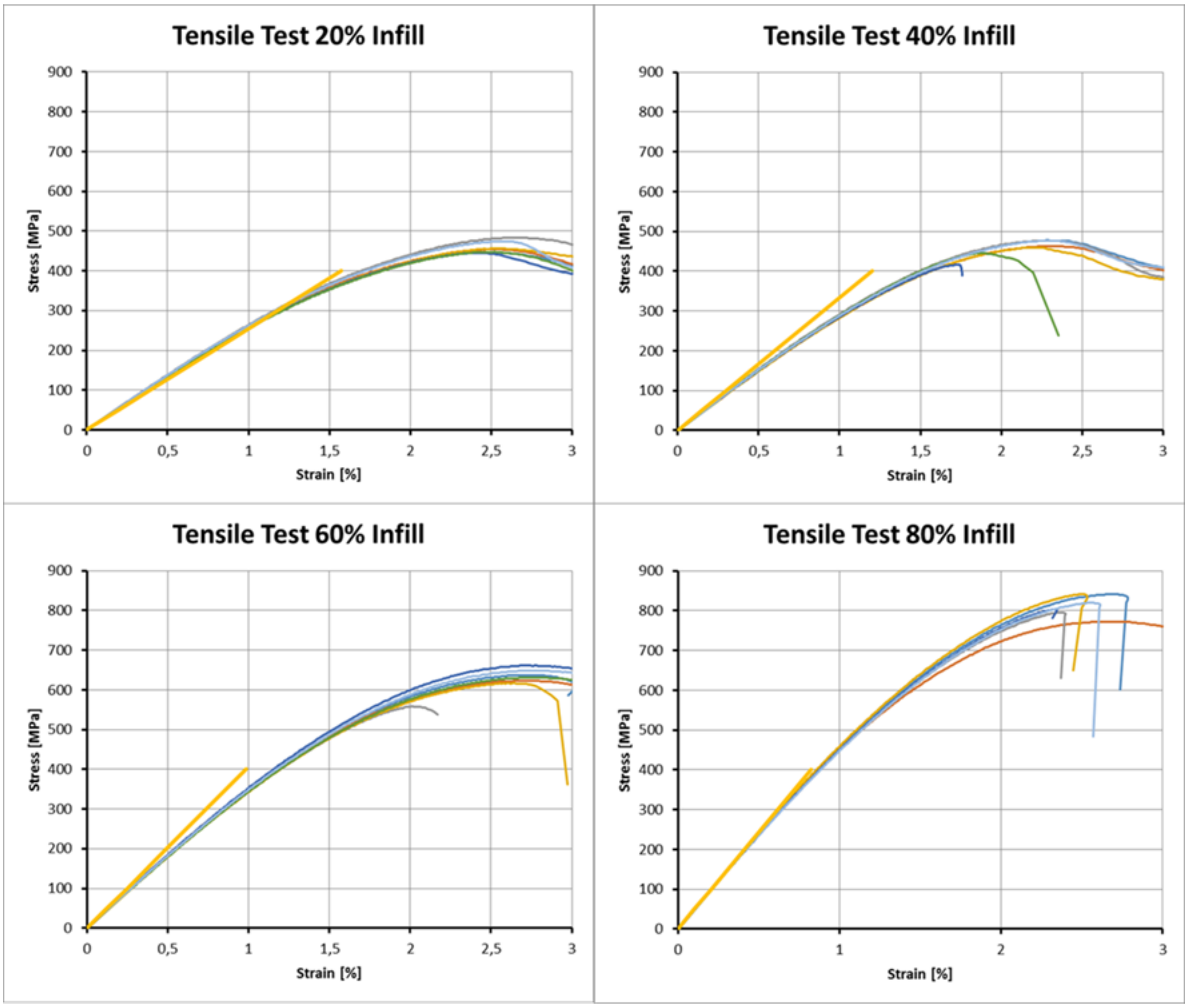

Fig.6. Comparison between Simulation and Experiment for the elastic field of the stress-strain-curve of PETG plastic rods

V. CONCLUSIONS

This research successfully leads to the development of a simulation model for 3D-printed plastic rods. This simulation model enables the prediction of the elastic properties of 3D-printed plastic rods, which can help to better understand the performance of 3D-printed samples upon variation of infill percentages. This helps the user to make predictions on the future deformation that the sample will have during its performance, according to the respective infill percentage.

Using the knowledge of this research, future experiments will be conducted on real and practicable samples. It will also be further investigated how to predict the plastic properties of 3D-printed parts. Further, a new simulation model is being developed to predict the thermal expansion and the residual stresses that are originated from the thermoplastic melting process, in order to understand and represent the real 3D-Printing mechanism. This new simulation model shows a good potential as it can also be used and further expanded not only to 3D-Printing but also to 6D-Printing.

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