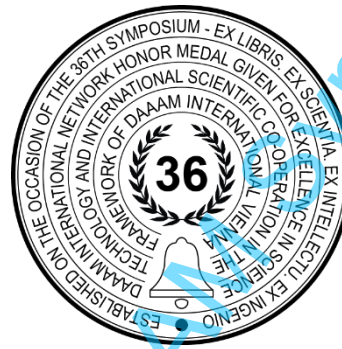


COMPARATIVE EVALUATION OF HYPERELASTIC CONSTITUTIVE MODELS FOR FDM PRINTED POLYMER MATERIALS

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Abstract

Additive manufacturing (AM) or 3D printing technology creates a tangible object by adding successive layers of materials. Nowadays, 3D printing is used for developing both metal and non-metal products. Advances in 3D printing technology have made design, modification, and testing of 3D-printed parts much simpler especially for thermoplastics and rubber-like materials. However, proper material modelling and validation are required for the finite element analysis of these types of materials. Accurate constitutive material models for polymers are essential for reliable stress and deformation analysis within finite element methods. Without a proper representation of their nonlinear mechanical behaviour numerical predictions may significantly deviate from experimental responses limiting their applicability in engineering design and analysis. This study presents an experimental investigation of mechanical properties of 3D-printed PLA, ABS, PETG, Strongman (STR), PLA CF, PET CF and PC materials followed by numerical analysis used to validate and verify different material models. The study also aims to evaluate the precision of different hyperelastic models using experimental data. These models rely on parameters obtained through curve-fitting functions.

Keywords: Additive manufacturing; FDM; Material model; Numerical analysis.

1. Introduction

Today, one of the most popular and fast-growing production technologies are surely additive technologies (AM). On the market there is a huge interest in AM technologies and certainly key factor in the development of AM technologies is the development of AM materials. In addition to a large number of different technologies one of the most frequently used is Fused Deposition Modeling (FDM) technology also known as Fused Filament Fabrication (FFF) or material extrusion [1]. Additive manufacturing (AM) increases the design freedom to the level not possible by conventional manufacturing methods. Engineers may create or invent more sophisticated geometries leading to tailor made structures to distinct applications in the future. In AM, also called 3D printing the approach is a layer-by-layer production. CAD models are prepared by using a “slicer” software for each layer. Unlike traditional subtractive manufacturing methods which involve material removal to shape products, 3D printing manufacture objects layer by layer using materials such as polymers, metals and ceramics. This layer by layer approach enables complex geometries and customization which are unattainable

with traditional manufacturing techniques [2]. Applications span industries like aerospace, automotive, healthcare and consumer goods where the technology is valued for its ability to shorten lead times, reduce tooling costs and enable rapid prototyping [3]. Moreover, 3D printing facilitates creation of lightweight structures such as lattice designs which maintain strength while minimizing material usage making it especially advantageous for industries prioritizing energy efficiency [4]. A wide range of materials is available for 3D printing with PLA, ABS, PETG, STR, PLA CF, PET CF and PC representing only some of the most used options among many others.

Mechanical properties of FDM-printed polymer components depends not only on the material itself but also on manufacturing parameters which significantly influence the tensile and flexural properties of printed parts [5].

Alongside the development of new materials for additive manufacturing there is a growing need for advanced and reliable material models that can accurately describe their mechanical behaviour. Such models are essential for enabling efficient design, simulation, and optimization of components in real engineering applications where polymers often exhibit complex nonlinear mechanical behaviour.

Study of hyperelastic models for 3D printed materials has become crucial due to its applications in additive manufacturing and materials science. Those models combined with material advancements open new opportunities for designing lightweight and durable components [6].

Reliable characterization of FFF-printed polymers remains a significant research challenge due to the combined influence of material properties, printing parameters and manufacturing induced anisotropy on their mechanical response [7].

Finite element simulations have become an indispensable tool for predicting the mechanical behaviour of FDM-printed components enabling efficient design optimization while reducing the need for extensive experimental testing [8]. Development of numerical models for describing the mechanical behaviour of polymeric materials has progressed in recent years driven by the widespread application of the finite element method and additive manufacturing technologies [9], [10]. Studies have demonstrated that linear elastic models are insufficient to accurately represent the response of polymers under large deformations leading to the increasing use of hyperelastic and viscoelastic constitutive models such as the Neo-Hookean, Mooney–Rivlin, Yeoh, Gent and Ogden models [2], [10]. Considerable research efforts have focused on calibrating these constitutive models using experimental data obtained from tensile and compression tests, validating those models through finite element simulations has become a standard practice [10]. Particular attention has been devoted to FDM-manufactured polymer materials where printing parameters such as infill density, raster orientation and extrusion temperature have been shown to influence both the mechanical properties and the constitutive model parameters [2] [10]. Recent investigations have reported that higher order constitutive models particularly the Mooney–Rivlin and Yeoh models generally provide better agreement with experimental results than simpler hyperelastic formulations. Advanced viscoplastic models including the Bergström–Boyce and Three-Network models have proven effective in describing the nonlinear response of polymeric materials [9], [10].

Majority of published studies have focused on a limited number of polymer materials, dominantly PLA and TPU, while comprehensive comparisons of multiple hyperelastic models across a broader range of FDM polymers combined with experimental validation was left out. This gap in existing literature highlights the need for further research in this area. Existing studies mainly focus on one or two FDM materials while systematic comparisons of several hyperelastic constitutive models across a broader range of commercially available polymers remain limited.

Layer height has a significant influence on the mechanical properties of FDM-printed PLA. Specimens manufactured with layer heights of 0.2 mm and 0.1 mm exhibited higher stiffness and ultimate tensile strength than those produced with a 0.3 mm layer height, increasing the loading rate further enhanced both the elastic modulus and ultimate tensile strength. Authors also developed constitutive material models using MCalibration and successfully validated them in Abaqus. An excellent agreement between numerical and experimental results ($R^2 > 0.999$) confirmed that the proposed modelling approach can be reliably applied in future finite element analyses of polymer materials [11].

Neo-Hookean and Mooney–Rivlin models provide best agreement with the experimental data across different infill densities for PLA+ material with the Neo-Hookean model being preferable due to its simpler parameter identification. Authors further proposed a new equation for determining the Neo-Hookean material parameter as a function of infill density. They also highlighted the need for future studies to consider advanced hyperelastic models such as Ogden and Arruda–Boyce as well as the influence of printing parameters, viscoelasticity, temperature effects and multiaxial loading conditions on the mechanical response of PLA+ [12].

Selection of an appropriate hyperelastic constitutive model is crucial for accurately predicting the nonlinear mechanical response of elastomeric materials. Comparative analyses of several hyperelastic models have shown that their accuracy depends on the strain range, element formulation and calibration procedure with Mooney–Rivlin and Yeoh models generally providing more accurate predictions under large deformation conditions [13].

Primary objective of this research is to determine material parameters of different hyperelastic constitutive models using curve-fitting techniques applied to experimental data. In addition, study aims to identify hyperelastic model that best describes mechanical behaviour of each analysed polymer material. Unlike previous studies that primarily focused on one or two FDM polymer materials, present study systematically compares four hyperelastic constitutive models across seven commercially available FDM polymers using identical experimental procedures and finite element calibration. Obtained results provide practical recommendations for selecting constitutive models for finite element simulations of FDM-printed polymer components.

2. Materials and methods

Experimental study was carried out on seven polymer materials: PLA, ABS, PETG, STR, PLA CF, PET CF and PC. Materials used in this study were supplied by AzureFilm with the exception of the PC filament which was manufactured by Ultimaker. Stress–strain curves obtained from tensile tests were used to determine material parameters of several hyperelastic models by curve fitting. Those material models were then implemented in finite element simulations and results were compared with experimental data to evaluate their accuracy. Flexural tests were performed to determine flexural properties of the analysed materials.

Tensile and flexural specimens were designed in SolidWorks according to ISO 527-2 and ISO 178, respectively. Technical drawings of specimens are presented in Fig. 1. CAD models were exported in STL format and imported into the slicer software for specimen fabrication (Bambu Studio V2.6.0.51 and Cura 5.12.0). All specimens were manufactured using FDM printing parameters presented in Table 1.

Material	3D Printer	Layer height [mm]	Printing temperature [°C]	Build plate temperature [°C]	Infill density [%]	Nozzle diameter [mm]
PLA	Bambulab X1 Carbon	0.2	220	55	100	0.4
ABS		0.2	270	90	100	0.4
PETG		0.2	255	70	100	0.4
Strongman (STR)		0.2	220	55	100	0.4
PLA CF		0.2	230	55	100	0.4
PET CF	Ultimaker S5	0.2	230	80	100	0.6
PC	Ultimaker S3	0.15	280	110	100	0.4

Table 1. Test specimens printing parameters

Specimens are 3D printed on Bambulab X1 Carbon, Ultimaker S3 and Ultimaker S5 desktop FDM 3D printers. For each material five tensile and five flexural specimens were 3D printed and then tested.

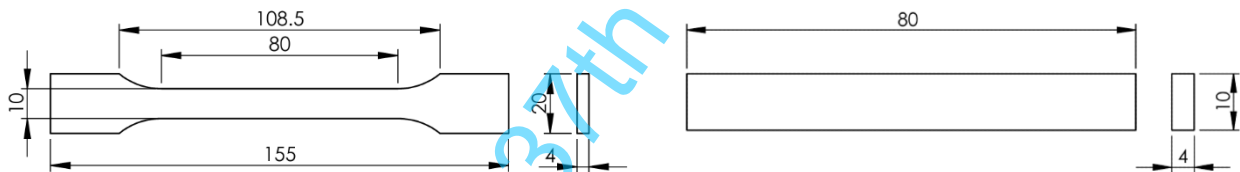


Fig. 1. Tensile (left) and flexural (right) test specimen

Tensile and flexural testing was performed using Shimadzu AGS-X universal testing machine with maximum load of 10 kN (Fig. 2) according to ISO 527-1 and ISO 178, respectively, both with testing speed 5 mm/min.

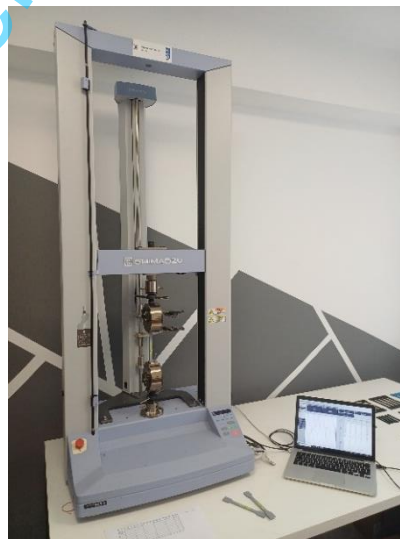


Fig. 2. Shimadzu AGS-X Universal testing machine

Mechanical properties data monitoring was performed using Trapezium-X software by Shimadzu. During the test tensile and flexural mechanical properties such as Ultimate tensile strength (R_m), yield strength (R_y), Elastic modulus (E) and Flexural strength (R_f) were analyzed.

Stress-strain curves obtained from the tensile tests were imported into ANSYS where material parameters were identified using the curve fitting procedure. Four hyperelastic constitutive models were considered: Mooney-Rivlin 2 Parameter, Mooney-Rivlin 3 Parameter, Gent and Yeoh 2nd Order. Analyzed hyperelastic constitutive models are based on strain energy density function where material response is defined through strain energy stored during deformation. Model calibration was performed using the experimental stress-strain data up to the ultimate tensile stress (UTS). Calibrated material parameters obtained for each model and each analyzed material are shown in Table 2.

Material model	Parameter	PLA	ABS	PETG	STR	PLA CF	PET CF	PC
Mooney–Rivlin 2	C10 [MPa]	-5700.5	-2608.9	-3262.6	-4406.8	-8188.8	-	-2608.9
	C01 [MPa]	6169.9	2933.5	3533.8	4841.9	8682.4	-	2933.5
Mooney–Rivlin 3	C10 [MPa]	589.9	1370.9	-1083.4	2976.3	-3873.7	-	487.6
	C01 [MPa]	-159.4	-1070.6	1341.6	-2574.5	4350.1	-	-220.6
	C11 [MPa]	-33446.8	-19942.2	-10886.5	-47571.7	-32566.6	-	-10189
Yeoh 2nd Order	C10 [MPa]	431.2	306.8	-	414.3	-	-	268.4
	C20 [MPa]	-31862.8	-14439.6	-	-31192.7	-	-	-9013.2
Gent	Initial shear modulus μ [MPa]	741.4	620.6	509.9	728.3	794.4	803.5	538.8
	Limiting value	1.62 e10	-0.008	-0.005	1.41 e10	1.27 e10	1.81 e10	-0.012

Table 2. Constitutive model parameters for different materials

Those parameters were used in finite element simulations to evaluate the ability of each constitutive model to reproduce experimental mechanical response and to identify the most suitable hyperelastic model for each analyzed material. Although the material parameters were successfully calibrated, finite element simulations using the Yeoh 2nd Order model for PETG and PLA CF and the Mooney–Rivlin models for PET CF did not converge due to the strain-softening response after the peak stress which caused numerical instability in the implicit Static Structural solver. Lack of convergence indicates that the selected constitutive formulation was unable to adequately represent experiment observed nonlinear response within the implicit solution procedure resulting in numerical instability during the analysis. Because of that those parameters sets are left out from results.

Tensile test simulation layout is presented in Fig. 3. Left end of the specimen was fully constrained and displacement was applied to the right end in the X-direction matching the displacement history used in the tensile experiments over the same loading period.

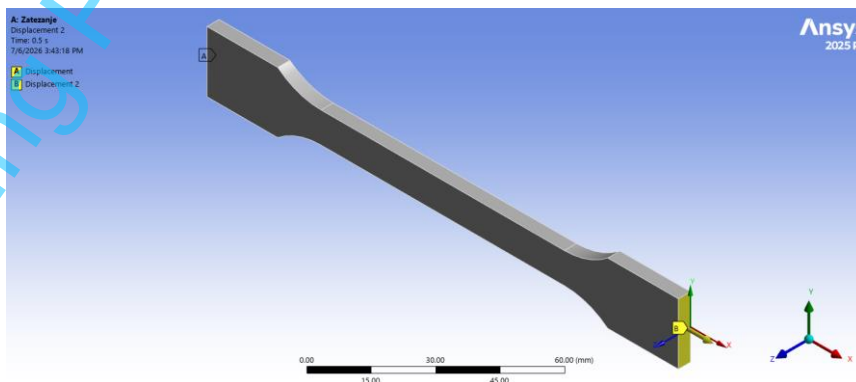


Fig. 3. Simulation layout in ANSYS

Tensile test was simulated in ANSYS using the same specimen geometry and loading conditions as in the experimental tests. This allowed numerical model to closely reproduce experimental testing conditions and enabled a direct comparison between the numerical and experimental results. Numerical results obtained from ANSYS were initially expressed as true stress-strain curves. They were then converted to engineering stress-strain curves based on the assumption of constant volume enabling a direct comparison with the experimental results.

3. Results and discussion

Experimental tensile and flexural stress-strain curves of the analyzed FDM-printed polymer materials are presented in Fig. 4 and 5. Fig. 4 shows tensile stress-strain curves and Fig. 5 presents flexural stress-strain curves. Stress-strain curves represent average experimental response of five specimens for each material. Mean curve was calculated only over the strain range where results from all five specimens were available. Shaded area indicates ± 1 standard deviation and illustrates variation of experimental results between the tested specimens.

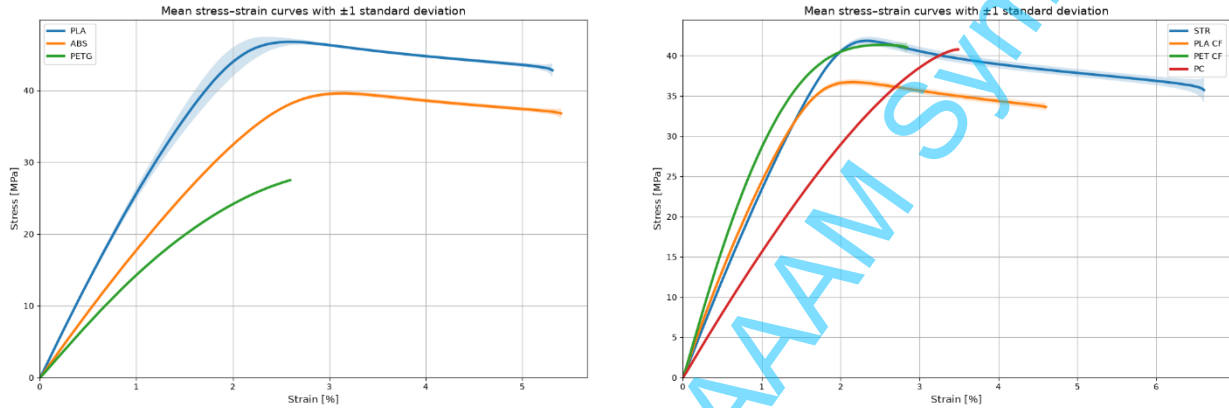


Fig. 4. Mean experimental tensile stress-strain curves with ± 1 standard deviation for PLA, ABS and PETG (left) and STR, PLA CF, PET CF and PC (right)

Tensile stress-strain curves reveal clear differences in mechanical response of analysed FDM printed materials. PLA and STR exhibited the highest stiffness and tensile strength, PETG showed the lowest strength among analysed materials. PC demonstrated largest deformation before reaching maximum stress indicating a more ductile behaviour. Narrow shaded regions indicate good repeatability of the experimental results.

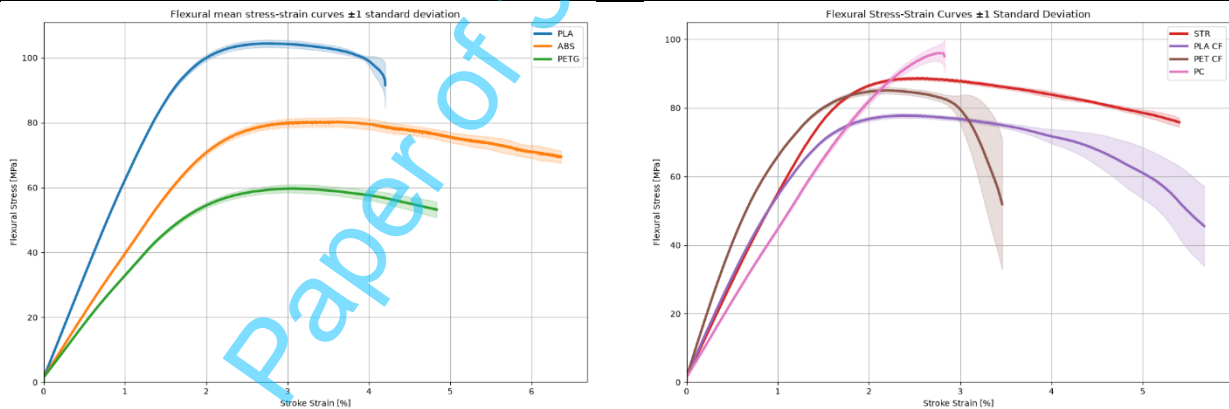


Fig. 5. Mean experimental flexural stress-strain curves with ± 1 standard deviation for PLA, ABS and PETG (left) and STR, PLA CF, PET CF, and PC (right)

PLA and PC achieved highest flexural performance, PETG and PLA CF showed lower resistance to flexural stress. STR maintained a stable load carrying capacity over a wide strain range, PET CF exhibited a more pronounced reduction in stress after reaching maximum value of stress. Experimental results showed good repeatability with greater scatter observed for PLA CF and PET CF at higher strain levels.

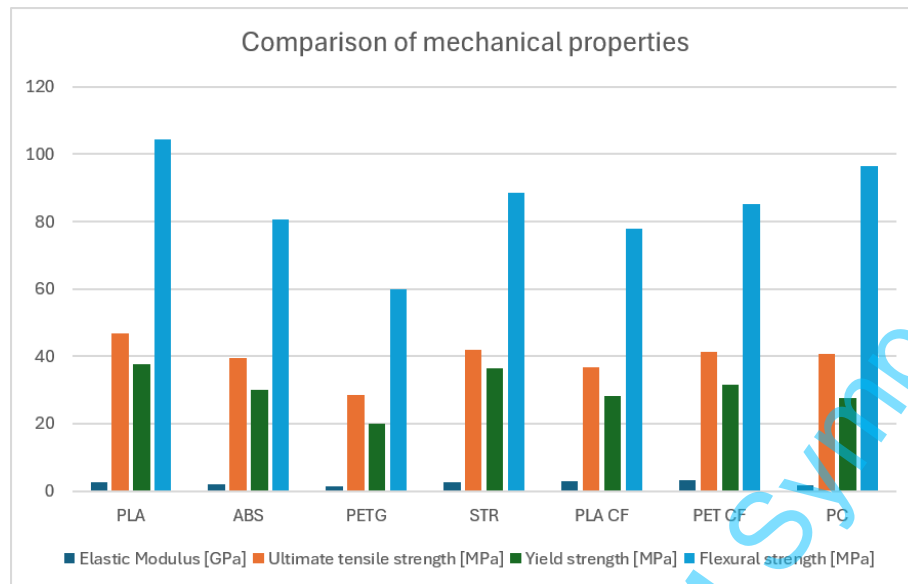


Fig. 6. Comparison of mechanical properties for different polymer materials

Fig. 6 compares main mechanical properties of the analysed FDM-printed polymer materials. PLA showed the highest tensile and flexural strength, PETG exhibited lowest mechanical performance, remaining materials demonstrated intermediate properties.

Since the material models were calibrated using experimental stress–strain data up to the ultimate tensile stress (UTS), comparison between numerical and experimental results was limited to this range.

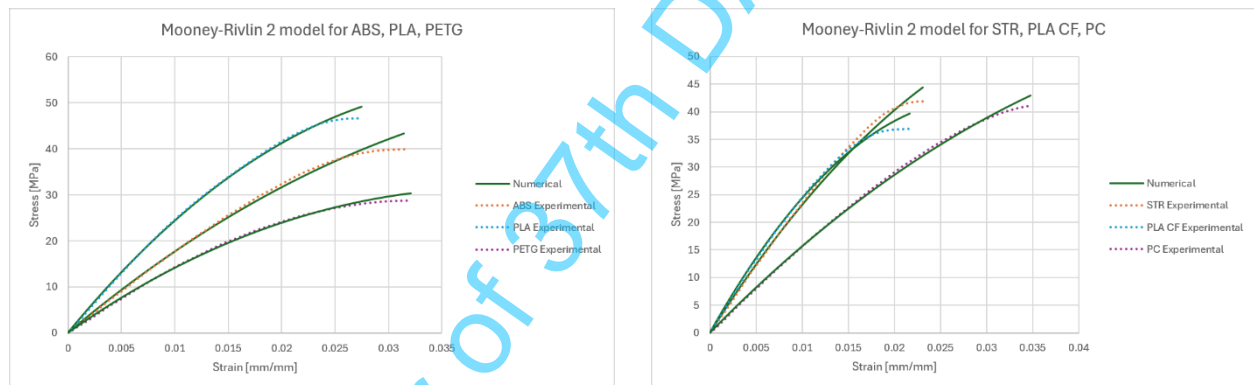


Fig. 7. Comparison of experimental and numerical tensile stress–strain curves using Mooney–Rivlin 2 Parameter model

Mooney-Rivlin 2 model provides good agreement for ABS, PLA and PETG as shown in Fig. 7. Simulation accurately reproduces nonlinear behaviour of all three materials. Only small differences are observed at higher strain levels, especially for ABS, where numerical model overestimates experimental response while the agreement for PLA and PETG remains very good. Mooney-Rivlin 2 model reproduces behaviour of STR, PLA CF and PC with generally good accuracy. Numerical curves closely follow the experimental trends throughout most of the analysed deformation range indicating that model adequately represent nonlinear mechanical response of those materials. Largest deviations are observed for STR and PLA CF at higher strain levels, numerical model overestimates response. Agreement for PC remains very good over the entire analysed range. Less accuracy at higher strain levels is related to limited flexibility of two-parameter strain energy function which cannot fully capture nonlinear stiffening observed in some materials.

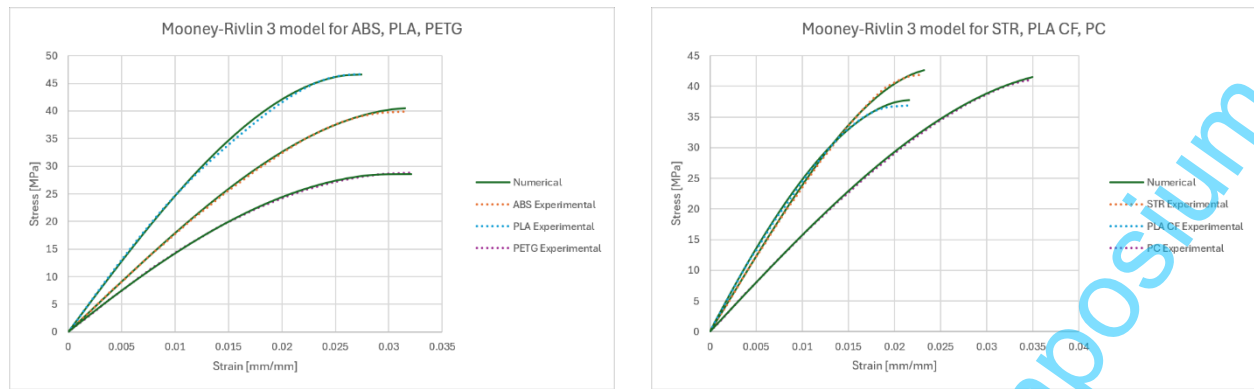


Fig. 8. Comparison of experimental and numerical tensile stress–strain curves using Mooney–Rivlin 3 Parameter model

Mooney–Rivlin 3 model (Fig. 8) provides excellent agreement between numerical and experimental stress–strain curves for STR, PLA CF and PC. Numerical responses follow experimental results throughout the analysed range demonstrating that calibrated material parameters accurately describe nonlinear mechanical behaviour of those materials. Only minor deviations are observed at higher strains where numerical model overestimates experimental stress especially for STR and PLA CF. Those differences are small while the agreement for PC is almost perfect over the entire analysed range confirming good capability of constitutive model. Mooney–Rivlin 3 model also accurately reproduces the experimental mechanical response of ABS, PLA and PETG. Very good correlation is observed between numerical and experimental curves indicating that calibrated model successfully captures nonlinear stress–strain behaviour of all three materials. Improved agreement of the Mooney–Rivlin 3 model can be attributed to its additional material parameter C11 which provides greater flexibility in describing strain energy function. This enables a more accurate representation of nonlinear material response, whereas simpler models may not fully capture the observed nonlinear behaviour.

Results demonstrate that Mooney–Rivlin 3 model provides a reliable representation of the analysed polymer materials within the considered deformation range.

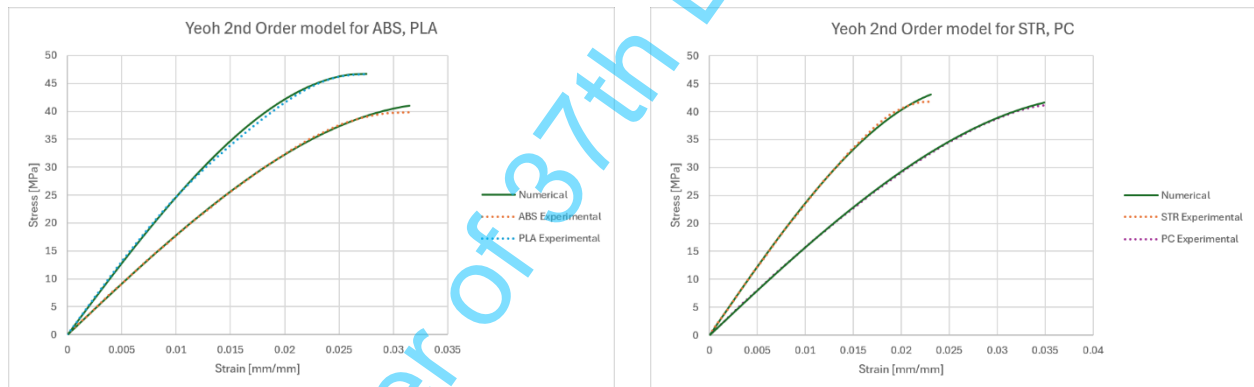


Fig. 9. Comparison of experimental and numerical tensile stress–strain curves using Yeoh 2nd Order model

Yeoh 2nd Order model (Fig. 9) provides good agreement between numerical and experimental stress–strain curves for ABS and PLA. Simulated curves closely follow experimental results over the entire analysed range. Only small differences appear at higher strain levels especially for ABS. Despite this, numerical and experimental curves show very good agreement indicating that Yeoh 2nd Order model can accurately describe those materials. Model also gives good results for STR and PC with only slight differences for STR at high strains while the agreement for PC is almost perfect.

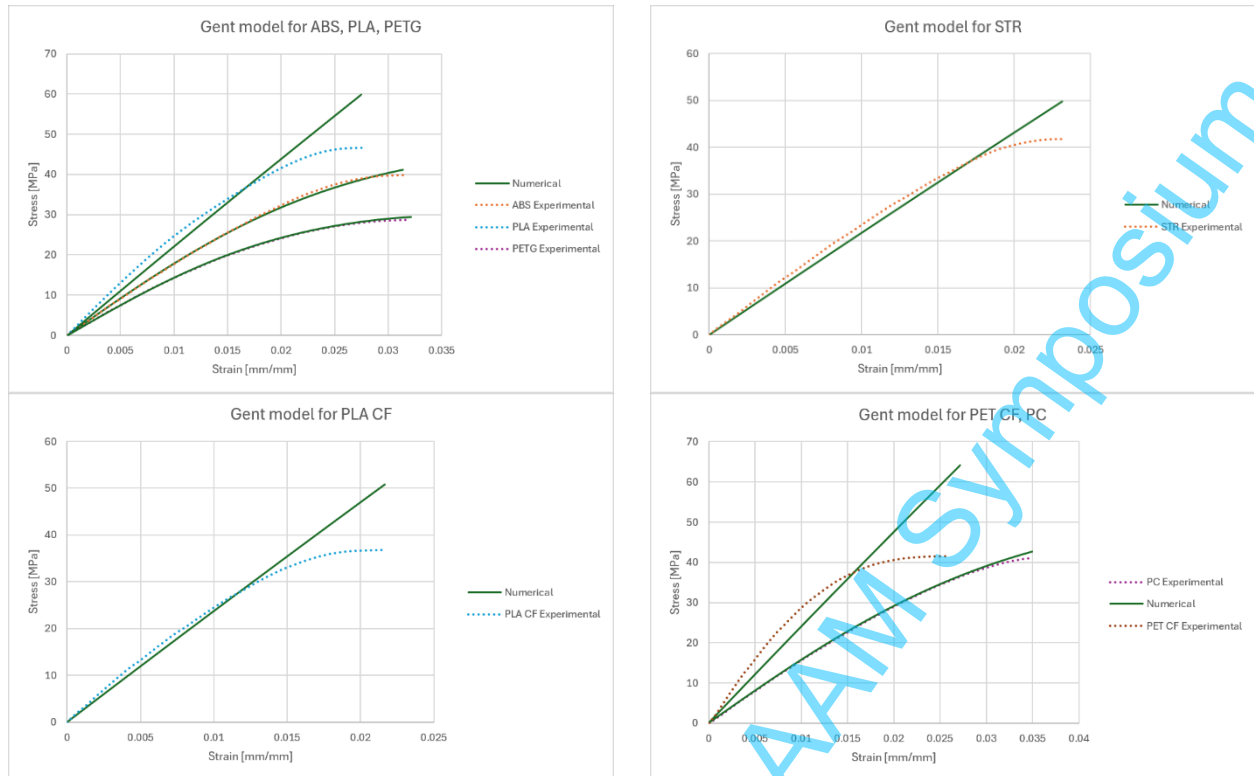


Fig. 10. Comparison of experimental and numerical tensile stress–strain curves using Gent model

Fig. 10 shows that Gent model exhibits different capabilities depending on the analysed material. Good agreement is observed for ABS, PETG, STR and PC where overall nonlinear mechanical response is reproduced with satisfactory accuracy. PLA, PLA CF and PET CF exhibit larger deviations at higher strain levels with the numerical model overestimating stress response. Larger deviations observed for PLA, PLA CF and PET CF indicate that strain energy function of Gent model is not sufficiently flexible to represent nonlinear behaviour of these materials throughout analysed strain range.

Results indicate that Gent model is suitable for describing behaviour of ABS, PETG, STR and PC within the analysed range. Capability is limited for PLA, PLA CF and especially PET CF where differences become more pronounced as the strain increases.

Results indicate that capability of a constitutive model depends not only on the selected formulation but also on the mechanical behaviour of analysed material. Models with a greater number of material parameters generally provided more accurate predictions while materials exhibiting pronounced strain-softening behaviour were more challenging to reproduce using conventional hyperelastic constitutive models.

Coefficient of determination (R^2) was used to evaluate overall quality of the numerical fit, whereas RMSE was employed to quantify the magnitude of prediction error between experimental and numerical stress values. Combined use of both metrics provides a more comprehensive assessment of model performance.

Table 3 shows that Mooney–Rivlin 3 model achieved the highest correlation with experimental results for almost all analysed materials followed closely by the Yeoh 2nd Order and Mooney–Rivlin 2 models, Gent model exhibited lower accuracy particularly for PLA CF and PET CF.

Model	Mooney–Rivlin 2	Mooney–Rivlin 3	Yeoh 2nd Order	Gent
PLA	0.998	0.999	0.999	0.908
ABS	0.995	1.000	1.000	0.999
PETG	0.998	1.000	-	1.000
STR	0.996	0.999	0.999	0.956
PLA CF	0.997	1.000	-	0.898
PET CF	-	-	-	0.759
PC	0.998	1.000	1.000	0.999

Table 3. Coefficients of determination (R^2) obtained for the analysed constitutive models

Table 4 presents RMSE values for analysed constitutive models. Mooney-Rivlin 3 and Yeoh 2nd Order models generally achieved lowest RMSE value demonstrating highest accuracy for most analysed materials. Mooney-Rivlin 3 model showed best agreement for ABS, STR and PLA CF while Yeoh 2nd Order model showed lowest RMSE values for PLA and PC. Gent model exhibited higher RMSE values for PLA, STR, PLA CF and PET CF indicating reduced accuracy in describing their behaviour, Mooney-Rivlin 2 model provided intermediate performance across all analysed materials.

Model	Mooney–Rivlin 2	Mooney–Rivlin 3	Yeoh 2nd Order	Gent
PLA	0.654	0.417	0.407	4.485
ABS	0.854	0.205	0.277	0.381
PETG	0.412	0.189	-	0.154
STR	0.874	0.307	0.382	2.881
PLA CF	0.591	0.25	-	3.61
PET CF	-	-	-	6.523
PC	0.556	0.188	0.186	0.498

Table 4. Root Mean Square Error (RMSE) values for the analysed constitutive models

4. Conclusion

This study analysed applicability of four hyperelastic constitutive models, Mooney–Rivlin 2 Parameter, Mooney–Rivlin 3 Parameter, Yeoh 2nd Order, and Gent, for describing behaviour of seven commonly used FDM-printed polymer materials: PLA, ABS, PETG, STR, PLA CF, PET CF and PC. Material parameters were identified by fitting experimental tensile stress–strain curves up to the ultimate tensile stress (UTS) after which calibrated models were implemented in finite element simulations and validated through comparison with the experimental results.

Experimental investigation demonstrated that selected materials exhibit different mechanical properties. While PLA and STR showed highest tensile strength and stiffness, PC showed good ductility, PETG demonstrated lowest tensile strength among the analysed materials. Experimental results also confirmed good repeatability as indicated by small standard deviations obtained from five tested specimens for each material.

Numerical analysis showed that the predictive capability strongly depends on both the constitutive model and analysed material. Mooney-Rivlin 3 Parameter model consistently provided closest agreement with experimental data and achieved the highest coefficient of determination (R^2) for almost all analysed materials. Yeoh 2nd Order model demonstrated excellent performance for materials for which calibration was successfully performed, while Mooney-Rivlin 2 Parameter model produced satisfactory results with larger deviations. Gent model showed acceptable agreement for ABS, PETG, STR and PC, but showed noticeably larger differences for PLA, PLA CF and particularly PET CF.

Evaluation using both coefficient of determination (R^2) and root mean square error (RMSE) confirmed graphical comparison between numerical and experimental data. While R^2 demonstrated the overall quality of fit, RMSE provided additional information regarding magnitude of prediction error enabling a more comprehensive assessment of model performance. Combined evaluation indicated that the Mooney-Rivlin 3 Parameter and Yeoh 2nd Order models provide highest overall accuracy for analysed polymer materials.

Although these hyperelastic constitutive models were originally developed for elastomeric materials, they demonstrated good predictive capability for most analysed thermoplastic polymers up to the ultimate tensile stress. They can also provide a useful phenomenological description of the nonlinear mechanical response of thermoplastics within the investigated strain range. However, their limitations become evident once damage and strain-softening behaviour begin to develop.

It should also be noted that the analysed hyperelastic constitutive models are primarily intended to describe nonlinear response under monotonic loading. They do not account for strain rate dependency, hysteresis, strain softening which are commonly observed in polymer materials.

Obtained results provide practical guidance for selecting constitutive models in finite element simulations of FDM-printed polymer components and may serve as a useful reference for future numerical analyses of additively manufactured thermoplastic structures.

Future research should include experimental investigations under different strain rates as well as cyclic loading unloading tests to capture hysteresis and stress softening to enable a more comprehensive calibration and validation of constitutive material models. Advanced constitutive models that incorporate damage evolution and post-peak strain softening should be analysed since hyperelastic constitutive models cannot reproduce damage evolution and post peak softening observed in several analysed polymers. Future research should also validate material models under different loading conditions and investigate the influence of FDM process parameters such as raster orientation, layer thickness and infill density on model parameters.

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