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STRAIN-RATE DEPENDENT MECHANICAL BEHAVIOUR AND CONSTITUTIVE MODELLING OF FFF-PRINTED STRONGMAN AND SLA-PRINTED FLEXIBLE 80A

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Abstract

Fused Filament Fabrication (FFF) is a versatile additive manufacturing technology due to the wide range of materials available for this process. However, selecting an appropriate material for a given application can be challenging. Understanding the mechanical behaviour of materials, especially polymeric materials, is vital for determining their suitability for specific applications. In this regard, characterizing their mechanical properties at different strain rates is essential as polymeric materials exhibit rate dependent behaviour. Physical testing using universal testing machines is one of the most commonly used methods for characterizing the mechanical behaviour of polymers. In this study strain rate dependent mechanical behaviour of two 3D printed polymer materials, Strongman (STR) and Formlabs Flexible 80A, was investigated. Strongman, a thermoplastic material produced using FFF, and Flexible 80A, an elastomeric photopolymer produced using stereolithography (SLA) were experimentally tested at different strain rates. Influence of strain rate on the mechanical properties and stress strain response of both materials was analysed. Furthermore, different constitutive material models were calibrated for each material using the experimental data obtained at different strain rates. Statistical metrics were employed to quantitatively assess the agreement between the experimental and predicted responses to identify the best constitutive model for each material.

Keywords: Additive manufacturing; FFF; SLA; Strain rate dependence; Constitutive modelling.

1. Introduction

Additive Manufacturing (AM) has recently gained a large attention from the industry as well as the academic community, while it is considered to be in the forefront of industrial manufacturing processes either for prototyping or mass production procedures. Especially FFF technology, which has been mainly used for prototyping purposes until now, opens new avenues expanding its capabilities to small batched mass production [1].
Additive manufacturing technology has shown huge potential in the advanced production of complex hierarchical and topological structures with single or multi material designs. Innovative applications of additive manufacturing are

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especially prevalent in biomedical, aerospace, construction and protective structures offering key benefits such as design freedom, mass customisation, waste minimisation and rapid prototyping while enabling the printing of metal alloys, polymer composites, ceramics, concrete and even organic structures. Over the past decades, various additive manufacturing techniques have been developed including fused deposition modelling, powder bed fusion, inkjet printing, contour crafting, stereolithography, direct energy deposition and laminated object manufacturing [2].

Among the various AM technologies, stereolithography (SLA) has gained particular prominence due to its high geometric fidelity, surface quality and accessibility. SLA operates on the principle of vat photopolymerization, where a liquid photopolymer resin is selectively cured layer by layer using a specific light source, typically a UV laser or projector [3].

Alongside this hardware accessibility, commercial material catalogues are expanding to include resins that mimic standard engineering thermoplastics and new elastomeric materials. Formlabs Elastic 50A (E50A) and Flexible 80A (F80A) are widely used in soft robotics, consumer goods and electronics [4], [5]. F80A is often used for impact resistant seals and mimicking biological organs [6], while E50A is used in soft robotics and for simulating cardiovascular soft tissues [7].

Mechanical properties of SLA printed polymers are influenced by several manufacturing parameters, including layer height, build orientation, washing conditions, and post curing parameters [8].

Although these materials have been used in various applications, a critical gap exists in understanding their mechanical responses under different loading conditions, as well as in developing validated constitutive models that accurately predict their behaviour at varying strain rates and under different loading types.

However, because these materials exhibit highly nonlinear, visco-hyperelastic responses that are sensitive to loading velocity establishing accurate constitutive models is a prerequisite for reliable dynamic simulations [9].

Unlike conventionally manufactured rubbers, additively manufactured elastomers exhibit process induced heterogeneity, anisotropy and rate dependent behaviour arising from layer wise photopolymerization and non-uniform curing histories. These effects are especially critical under large deformations and dynamic loading conditions [9], [10].

Elastomers are polymer materials with module of elasticity typically between 1 and 500 MPa and are characterized by large strains under small stresses [11].

Mechanical response of 3D printed polymer materials is influenced not only by material and manufacturing parameters but also by the strain rate applied during mechanical testing [12]. Previous research has demonstrated that changes in strain rate can affect tensile strength, yield strength, Young's modulus, and strain of FDM printed polymers [13]. Mechanical properties of PLA Strongman also depend on manufacturing parameters such as infill density, printing orientation, nozzle diameter and layer height [14].

For PLA material increase in strain rate results in a nearly linear increase in ultimate tensile strength and elastic modulus, indicating that the material becomes stronger and stiffer under faster loading conditions. In the investigated range, the UTS increased from 40.41 MPa at 0.8 mm/min to 52.62 MPa at 20 mm/min, while the elastic modulus increased from 1.54 GPa to 2.21 GPa. In contrast, ultimate strain remained nearly unchanged, indicating that the strain rate primarily affects the strength and stiffness of the material rather than its ultimate elongation [15].

Strain rate sensitivity of 3D printed polymers is material dependent and cannot be characterized by a single universal response. In particular, PLA showed high strain rate sensitivity, whereas PETG and PA6 exhibited considerably lower sensitivity, highlighting the need to account for material specific rate dependent behaviour when developing constitutive models for FFF printed polymers. Mechanical properties of FFF printed polymers are strongly affected by the applied strain rate and this dependence varies between different polymer materials and strain rate levels. Modifications in mechanical properties caused by strain rate should be further investigated and appropriately modelled, especially to improve prediction of material behaviour under different loading conditions [16].

3D printed polymers exhibit significant strain rate sensitivity with increasing strain rates leading to higher yield stresses. Results also show that conventional constitutive models such as the Johnson-Cook model may have limitations in accurately capturing complex deformation mechanisms of polymeric materials, especially at high strain rates. Authors therefore highlight the relevance of alternative constitutive models, including the Bergström-Boyce and Maxwell (Prony series) models, for more accurately describing the strain rate dependent behaviour of 3D printed polymers [17].

Results demonstrate that strain rate has a significant influence on the mechanical response of FFF printed polymers, affecting their tensile strength, stiffness and overall deformation behaviour. Increasing the strain rate resulted in a pronounced increase in stiffness for TPU, while the effect on tensile strength was smaller. Study further showed that the strain rate sensitivity of the material is strongly influenced by FFF processing parameters, nozzle temperature and layer height indicating that both material characteristics and manufacturing conditions must be considered when evaluating the mechanical response of 3D printed polymers. These findings highlight the importance of incorporating strain rate dependent behaviour into constitutive modelling as conventional hyperelastic models without rate dependence may not adequately capture the experimentally observed response over different loading rates. Therefore, rate dependent constitutive formulations capable of representing viscoelastic and/or viscoplastic effects should be considered when developing predictive material models for FFF printed polymers [18].

Mechanical response of polymer materials can involve several distinct deformation mechanisms including elastic and nonlinear elastic deformation, permanent deformation, strain rate dependence, hysteresis, stress relaxation and creep. Selection of an appropriate constitutive model is strongly dependent on the dominant mechanisms observed experimentally. Constitutive models can generally be divided into elastic, elastic plastic, hyperelastic, linear viscoelastic, and nonlinear viscoelastic/viscoplastic formulations with increasing model complexity providing the ability to represent a wider range of material phenomena.

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Flexible 80A exhibits pronounced nonlinearity, strain rate dependence and significant viscoelastic behaviour. Increasing strain rate leads to higher stress levels and UTS, while stress relaxation can reduce the initial stress by up to approximately 75% after 1000 s. Material also exhibits hysteresis and energy dissipation with an average dissipated energy of approximately 36% per loading cycle. In addition, orientation dependent anisotropy was observed, especially under compression and at higher strain rates. For Flexible 80A, a visco-hyperelastic formulation combining a piecewise four term Ogden model with a four term Prony series was found to adequately capture the material pronounced nonlinear and strain rate dependent response. Model achieved a maximum NRMSE of 10.69% in tensile loading across the investigated strain rates demonstrating good agreement with the experimental data. However, authors noted that the Prony-series approach relies on strain time separability and strain and rate independent relaxation times, which may limit its accuracy for large deformations, multiaxial cyclic loading and high strain rates. Therefore, while the Ogden-Prony formulation provides a suitable approximation within the calibrated strain and rate range, more advanced nonlinear viscoelastic models may be required when extrapolating beyond this range [19].
Bergström and Bischoff proposed a Three Network Model (TNM) to describe nonlinear, time and temperature dependent behaviour of thermoplastic polymers. Model represents material response through three parallel networks, each describing a different deformation mechanism. Compared with conventional plasticity and other constitutive models, TNM provided improved description of polymer behaviour under tension, compression, cyclic loading and large strains. TNM parameters were initially estimated from characteristic features of the experimental stress strain response and then optimized using complete uniaxial experimental data. The model provided a better overall description than the Bergström-Boyce model, with R^2 values of 0.977 and 0.859, respectively, for uniaxial loading. When both uniaxial and small punch data were considered, the corresponding R^2 values were 0.986 and 0.714, highlighting the potential of TNM for describing complex polymer deformation [20].

2. Materials and methods

Experimental study was carried out on two polymer materials: STR and Flexible 80A. STR material used in this study were supplied by AzureFilm and Flexible 80A by Formlabs. Stress strain curves obtained from tensile tests were used to determine parameters of several material models. Calibrated material models were evaluated using statistical metrics to quantify their agreement with the experimental data and to identify the model providing the most accurate overall representation of the material behaviour.
Tensile specimen was designed in SolidWorks according to ISO 527-2. Technical drawing of specimen is presented in Fig. 1. CAD models were exported in STL format and imported into the slicer software for specimen fabrication. Specimens of STR are imported into Bambu Studio V2.6.0.51 slicer and manufactured using FFF printing technology with parameters presented in Table 1.
Specimens of Flexible 80A are imported into PreForm slicer and manufactured using SLA printing technology with parameters presented in Table 2. All specimens of Flexible 80A material are washed after 3D printing in IPA alcohol and post cured. In the end all specimens are tensile tested, collected data was analysed and results are presented. All specimens are printed in flat orientation.

Material	3D Printer	Layer height [mm]	Printing temperature [°C]	Build plate temperature [°C]	Infill density [%]	Nozzle diameter [mm]
Strongman (STR)	Bambulab X1 Carbon	0.2	220	55	100	0.4

Table 1. Test specimens printing parameters (STR)

Material	3D Printer	Print settings	Layer height [mm]
Flexible 80A	Form 3B	Default v3.0	0.1

Table 2. Test specimens printing parameters (Flexible 80A)

Specimens are 3D printed on Bambulab X1 Carbon and Form 3B printers. For STR twelve and for Flexible 80A nine tensile specimens were 3D printed and then tested.

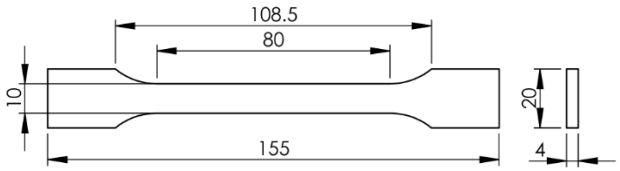

Fig. 1. Tensile test specimen

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Tensile testing was performed using Shimadzu AGS-X universal testing machine with maximum load of 10 kN (Fig. 2) by applying different strain rates.

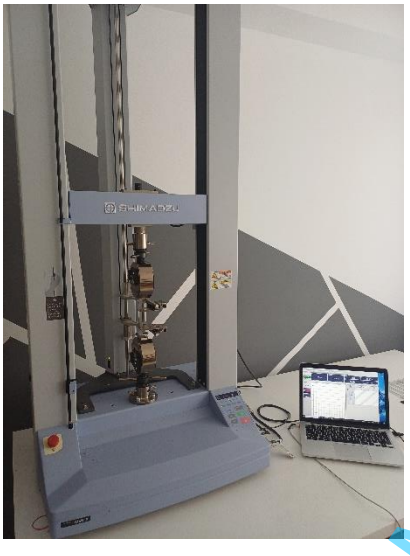

Fig. 2. Shimadzu AGS-X Universal testing machine

Mechanical properties data monitoring was performed using Trapezium-X software by Shimadzu. Tests were conducted at different strain rates for both materials. For each strain rate, three specimens were tested to obtain three individual stress strain curves. For STR applied strain rates were 0.0005, 0.002, 0.02, and 0.1 s^{-1}, while for Flexible 80A tests were performed at strain rates of 0.0002, 0.002 and 0.2 s^{-1}. This range of strain rates was selected to investigate the rate dependent mechanical response of the investigated materials.
Different constitutive models were calibrated using the MCalibration software by PolyUMod. Statistical metrics were used to evaluate the quality of each model and to compare their ability to reproduce the experimental response. Based on these results most suitable model was identified for each of the investigated materials.

3. Results and discussion

For each strain rate, three specimens were tested and mean stress strain curve obtained from the specimens is presented. Experimental data for the STR material are presented in Fig. 3, while the results for Flexible 80A are shown in Fig. 4.

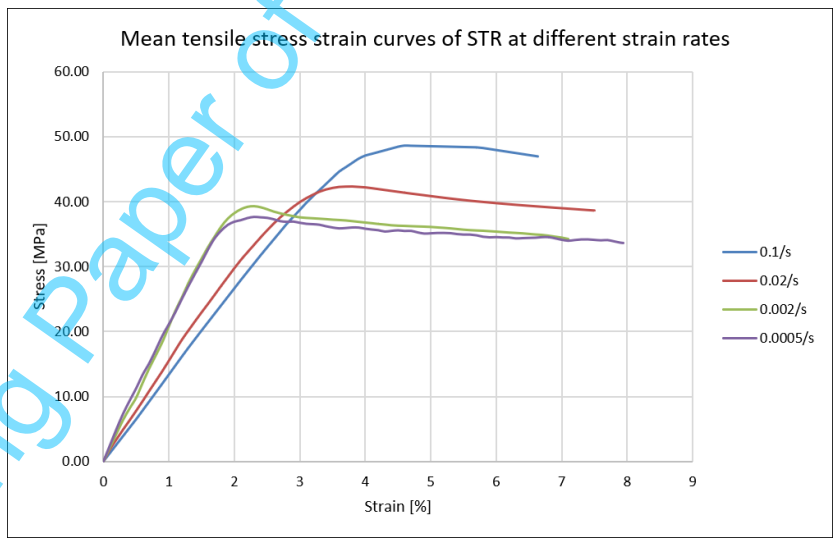

Fig. 3. Mean tensile stress strain curves of STR at different strain rates

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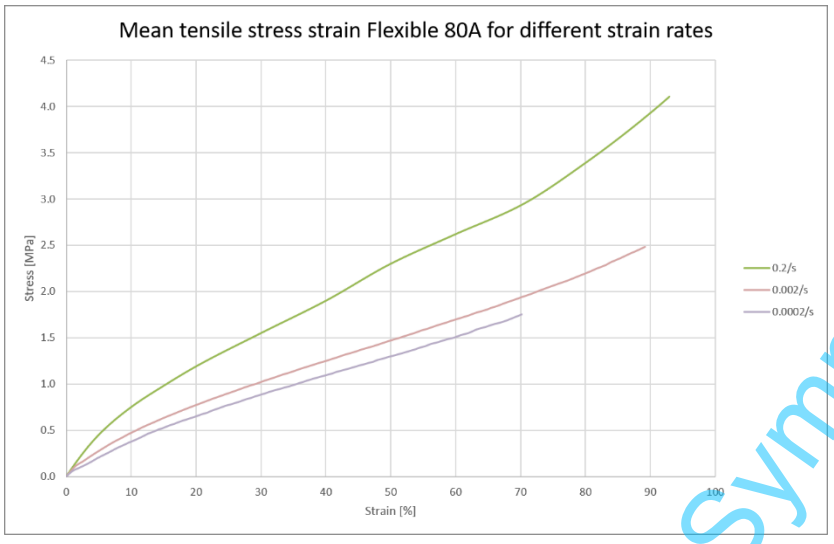

Fig. 4. Mean tensile stress strain curves of Flexible 80A at different strain rates

Experimental results demonstrate a clear dependence of the tensile response on strain rate for both investigated materials, although the effect differs between STR and Flexible 80A. As shown in Fig. 3, increasing the strain rate for STR from 0.0005 to 0.1 s^{-1} results in a higher stress response. At the two lowest strain rates, 0.0005 and 0.002 s^{-1}, the curves reach maximum stress values of approximately 37-39 MPa, while the maximum stress increases to about 42 MPa at 0.02 s^{-1} and nearly 49 MPa at 0.1 s^{-1}. Effect of strain rate can also be observed in the post peak region where the lower strain rates show a more gradual decrease in stress after reaching the maximum value. This indicates that STR offers greater resistance to deformation when subjected to faster loading.

A different stress strain response is observed for Flexible 80A, as presented in Fig. 4. Material shows a continuous nonlinear response over a much larger strain range with no clearly defined yield point. Influence of strain rate is especially evident when comparing the curves obtained at 0.0002 and 0.002 s^{-1} with one at 0.2 s^{-1}. At the same strain, higher strain rates produce considerably higher stress values indicating an increase in the apparent stiffness of the material with increasing loading rate. This behaviour is consistent with the nature of Flexible 80A as an elastomeric material, where the mechanical response depends strongly on the time available for molecular rearrangement and stress relaxation.

Differences between the two sets of curves are also related to different intended uses of these materials. STR is a relatively stiff PLA based FFF material, where strength and dimensional stability are important, while Flexible 80A is intended for applications requiring flexibility and large deformation. Effect of strain rate has a different practical significance for the two materials. For STR, increase in strain rate mainly results in a higher stress level and tensile strength within a relatively small strain range, whereas for Flexible 80A it changes stress required to achieve large deformations and therefore has a direct effect on its apparent stiffness. These results also show why the strain rate should be considered when defining the material behaviour for numerical modelling, since using a stress strain curve obtained at only one strain rate may not adequately represent the response of either material under different loading conditions.

Strain rate sensitivity index, m, was calculated as a function of strain for each investigated material. Equation (1) was used to determine the index m [21].

$$m = \frac{\Delta ln(\sigma)}{\Delta ln(\dot{\varepsilon})} \tag{1}$$

where σ is the stress and $\dot{\varepsilon}$ is the strain rate. Strain rate sensitivity index m is a parameter used to quantify the dependence of the material stress response on the applied strain rate.

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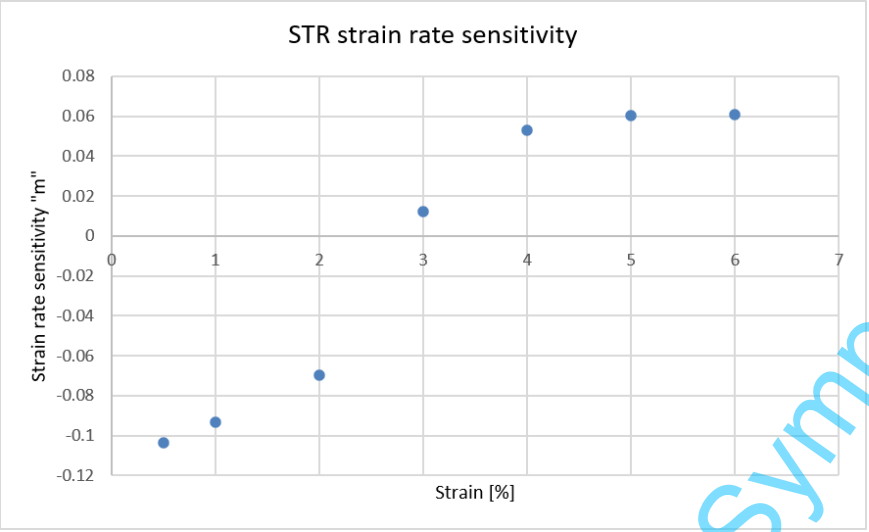

Fig. 5. STR strain rate sensitivity

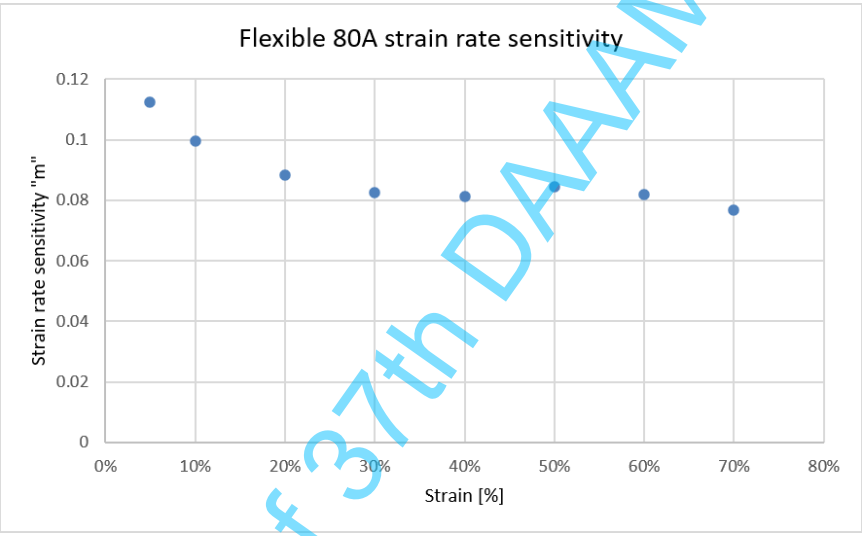

Fig. 6. Flexible 80A strain rate sensitivity

As shown in Fig. 5, the strain rate sensitivity index m for STR changes with strain. At low strains, negative values are obtained, reaching approximately -0.10 at 0.5% strain and -0.07 at 2% strain. Index then increases and becomes positive at around 3% strain, reaching approximately 0.05 - 0.06 between 4% and 6% strain. Negative values at low strain indicate a slight decrease in stress with increasing strain rate in this region. At higher strains positive values indicate the expected increase in stress with increasing strain rate.

For Flexible 80A, Fig. 6 shows positive *m* values over the entire investigated strain range. Index is highest at approximately 5% strain with a value of about 0.11 and gradually decreases with increasing strain. Above approximately 30% strain, *m* remains relatively stable at around 0.08. This indicates that the stress response of Flexible 80A is consistently affected by the strain rate, although the magnitude of this effect decreases slightly as the deformation increases.

Overall, Figs. 5 and 6 show different strain rate sensitivity behaviour for the two materials. Flexible 80A exhibits positive *m* values throughout the investigated strain range, while STR shows a transition from negative to positive values with increasing strain. At higher strains, *m* values for Flexible 80A remain around 0.08, while STR reaches approximately 0.05-0.06. These results indicate that strain rate affects the stress response of both materials, with Flexible 80A showing a more consistent strain rate sensitivity over the investigated strain range. Direct comparison of the sensitivity magnitude should, however, be considered in relation to the different strain rate ranges used for the two materials.

Selection of an appropriate constitutive model is important for obtaining a reliable representation of the material response, as different models are capable of capturing different aspects of nonlinear and rate dependent polymer behaviour. Using experimental data obtained at multiple strain rates allows the calibration to account for the rate dependence of the material and to obtain a single set of material parameters capable of describing the response over the investigated range of loading rates.

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Conventional hyperelastic models such as Neo Hookean, Mooney Rivlin and Ogden provide an effective starting point for describing nonlinear large strain behaviour of elastomeric materials. Their main limitation is that they are rate independent formulations and therefore cannot inherently capture changes in mechanical response associated with different strain rates, hysteresis, stress relaxation or creep. Bergström-Boyce model extends the hyperelastic description by introducing rate dependent deformation mechanisms and is therefore especially suitable for elastomeric materials exhibiting nonlinear time and rate dependent behaviour. Performance of Bergström-Boyce model will be investigated not only for the elastomeric material for which this type of formulation is primarily intended but also for the thermoplastic material. This will determine how effectively an elastomer-oriented model can reproduce thermoplastic behaviour.
Three Network (TN) model which was primarily developed to describe nonlinear viscoplastic response of thermoplastic polymers will be evaluated for both thermoplastic and elastomeric materials. This approach assesses whether constitutive models developed for specific classes of polymers can also provide an adequate description of materials outside their primary intended application. Study aims not only to identify the model providing the best fit for each material but also to investigate limitations of different nonlinear rate dependent constitutive formulations across elastomeric and thermoplastic polymer systems.

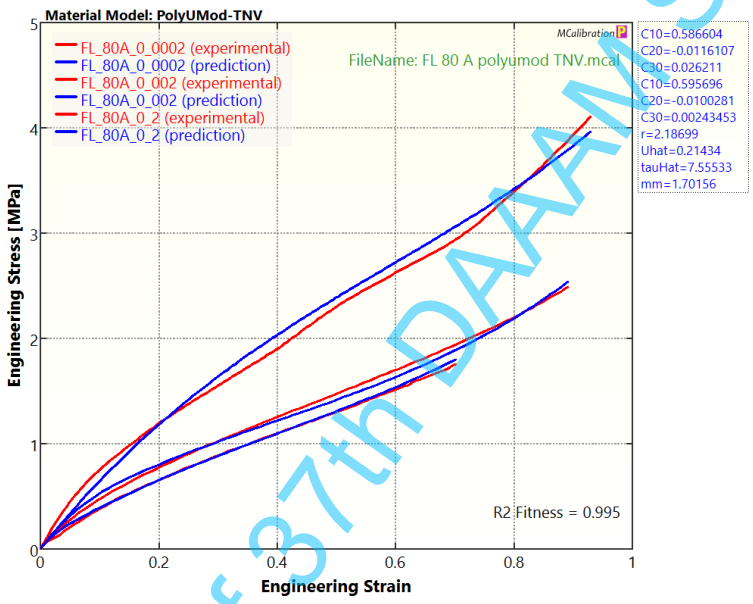

Fig. 7. Calibration of the POLYUMOD Three Network Viscoelastic model in MCalibration for Flexible 80A

An example of constitutive model calibration for Flexible 80A with different strain rates is presented in Fig. 7 showing good agreement between the experimental and predicted responses. Flexible 80A is considered representative of an elastomeric material while Strongman is considered representative of a thermoplastic material. Their respective material behaviours provide a basis for investigating applicability of different constitutive models across distinct classes of polymeric materials. Accordingly, Bergström-Boyce (BB) and Three Network (TN) models will be investigated using both PolyUMod and ANSYS implementations. Their performance will be assessed for both material classes. In addition to these models, study will consider Three Network Viscoplastic (TNV) model available in PolyUMod. This combination encompasses conventional hyperelastic, viscoelastic, viscoplastic and nonlinear rate dependent constitutive formulations and provides a broad basis for comparison. Selected models will be evaluated for both Flexible 80A and Strongman regardless of the material class for which a particular formulation was primarily developed. Significance of this approach lies in determining not only which constitutive model provides the best agreement with experimental data for each material but also whether models developed primarily for elastomeric or thermoplastic materials can be successfully applied to the other material class.

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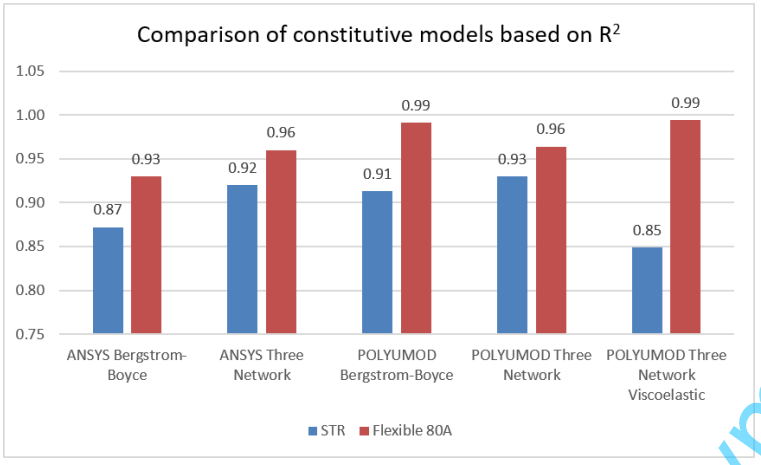

Fig. 8. Comparison of constitutive models based on coefficients of determination (R^2)

Coefficients of determination (R^2) values obtained for the different constitutive models are presented in the Fig. 8. For STR, highest R^2 value is obtained with the PolyUMod Three Network model (0.93), followed by the ANSYS Three Network model (0.92) and the PolyUMod Bergstrom-Boyce model (0.91). ANSYS Bergstrom-Boyce and PolyUMod Three Network Viscoelastic models give lower values of 0.87 and 0.85, respectively. For Flexible 80A, all investigated models provide higher R^2 values, ranging from 0.93 to 0.99. Highest values of 0.99 are obtained with the PolyUMod Bergstrom-Boyce and PolyUMod Three Network Viscoelastic models. These results indicate that the selected constitutive models reproduce the experimental response of Flexible 80A better than that of STR while the best performing model differs between the two materials.

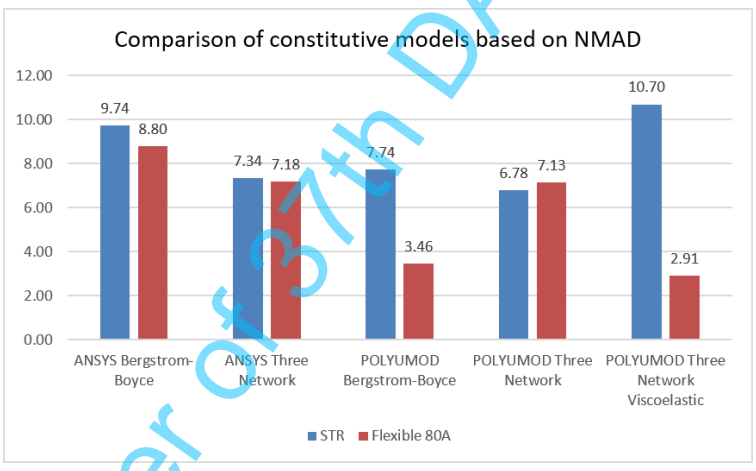

Fig. 9. Comparison of constitutive models based on Normalized mean absolute deviation (NMAD)

Normalized mean absolute deviation (NMAD) values obtained for the investigated constitutive models are presented in the Fig. 9. For STR, lowest NMAD value is obtained with the PolyUMod Three Network model (6.78), while the ANSYS Three Network model gives a similar value of 7.34. Highest NMAD values are obtained for the PolyUMod Three Network Viscoelastic and ANSYS Bergstrom-Boyce models with values of 10.70 and 9.74, respectively. For Flexible 80A, lowest NMAD value is obtained with the PolyUMod Three Network Viscoelastic model (2.91), followed by the PolyUMod Bergstrom-Boyce model (3.46). ANSYS Three Network and PolyUMod Three Network models give similar values of 7.18 and 7.13, respectively, while the ANSYS Bergstrom-Boyce model gives a value of 8.80.

Comparison of the R^2 and NMAD metrics shows that the performance of the constitutive models depends on the investigated material. For STR, the PolyUMod Three Network model gives the highest R^2 (0.93) and the lowest NMAD (6.78). For Flexible 80A, the PolyUMod Three Network Viscoelastic and PolyUMod Bergstrom-Boyce models provide the highest R^2 (0.99), while the PolyUMod Three Network Viscoelastic model gives the lowest NMAD (2.91). Based on the obtained R^2 and NMAD values, the PolyUMod Three Network model provides the most suitable description of the tensile response of STR, while the PolyUMod Three Network Viscoelastic model is the most suitable for describing the tensile response of Flexible 80A over the investigated strain rate range.

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4. Conclusion

This study investigated strain rate dependent tensile behaviour of two additively manufactured polymer materials, Strongman (STR) and Formlabs Flexible 80A. STR represents a thermoplastic material produced using FFF while Flexible 80A represents an elastomeric material produced using SLA. Tensile tests were performed at four different strain rates for each material. Stress strain responses were analysed to determine the influence of strain rate on mechanical behaviour. Strain rate sensitivity index was also calculated. Several constitutive models were calibrated using experimental data and their performance was evaluated using coefficient of determination (R^2) and normalized mean absolute deviation (NMAD).

Experimental results showed that strain rate affects tensile response of both materials. For STR an increase in strain rate resulted in higher stress levels and tensile strength. Strain rate sensitivity varied with strain and changed from negative values at low strains to positive values at higher strains. Flexible 80A showed a nonlinear tensile response and positive strain rate sensitivity over the investigated strain range. Higher sensitivity of Flexible 80A indicates that its tensile response is more affected by changes in strain rate than STR. Comparison of constitutive models showed that model performance depends on material. For STR PolyUMod Three Network model provided the highest R^2 and lowest NMAD. For Flexible 80A PolyUMod Three Network Viscoelastic model provided the lowest NMAD and was among models with the highest R^2. Based on obtained results PolyUMod Three Network model is most suitable for describing tensile response of STR while PolyUMod Three Network Viscoelastic model is most suitable for describing tensile response of Flexible 80A within investigated strain rate range.

It should also be noted that multi network constitutive models, such as the Three Network Viscoelastic model involve increased parameter and formulation complexity compared with simpler constitutive formulations. Although this complexity can provide improved representation of nonlinear and rate-dependent material behaviour, it may also increase computational cost, particularly in large scale explicit finite element simulations. Therefore, model selection should consider not only predictive accuracy but also the required computational efficiency for the intended numerical application.

An advantage of this study is comparison of constitutive models developed for different classes of polymer materials. Models were evaluated using experimental data obtained at multiple strain rates. This provides information about their ability to describe rate dependent tensile behaviour of materials produced using different additive manufacturing technologies. Main limitation of study is that model calibration and evaluation were based only on uniaxial tensile data. Results therefore describe model performance for tensile loading within investigated strain rate range. Other loading conditions such as compression cyclic loading stress relaxation and creep were not investigated. Influence of printing orientation and other manufacturing parameters was also not systematically studied.

Future research should include additional loading conditions such as compression, tensile cyclic loading, compressive cyclic loading and stress relaxation to enable more comprehensive calibration and validation of constitutive models. Further investigation of printing orientation, manufacturing parameters and a wider range of strain rates could provide additional information about mechanical behaviour of additively manufactured polymers. Such results could improve application of constitutive models in numerical simulations under different loading conditions.

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