A Study of Strain Rate Effects on the Mechanical Response of PolyJet Printed Elastomer Composites

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Abstract: This article presents the experiments and finite element analysis on PolyJet Digital Material. The aim of this work is to demonstrate the mechanical properties of a mixture of two materials Agilus30 and VeroClear at various strain rates. The identification of the visco-hyperelastic material model is based on the shear experiment. The calibration model that has been used is the Parallel Rheological Framework model (PRF). One branch of PRF represented the hyperelastic material; the other branch of PRF defines nonlinear viscoelastic properties, known as the Bergstrom-Boyce (B-B) model. The material parameters were used as material input in Marc Mentat software for finite element analysis (FEA) to predict the compressive stress response of cylindrical samples under various strains. Subsequently, these FEA results were compared with the experimental data.

Keywords: PolyJet composite elastomer; Parameter calibration; Bergstrom-Boyce (B-B); Mechanical properties

1 Introduction

The PolyJet Matrix technology is a 3D printing technology that uses a jetting process to deposit droplets of photopolymer materials layer by layer to create a 3D object. One of the advantages of this technology is the ability to use two model photopolymers simultaneously, which can be mixed to create new materials with varying properties known as composite materials [1,2]. Polymeric materials are widely used in 3D printing and can be produced using various 3D printers with a broad range of properties. Soft polymer is widely utilized in additive manufacturing digital material robotics. These materials can be used in various industries, including robotics, as they enable the creation of soft and compliant robotic components [3,4].

Recent researches are focused on understanding and optimizing the mechanical properties of additive manufacturing materials including also computational modeling. This plays a crucial role in predicting and simulating the mechanical behavior of additively manufactured materials. Computational methods such as finite element analysis (FEA) were used to simulate the mechanical response, thermal properties, and other behavior of these materials [5,6].

For hyperelastic materials, the most commonly used constitutive model is the strain energy density function as a relation of the stress and strain of the material. The material parameters that define this function can be determined through a variety of experimental techniques, such as uniaxial tension or compression tests, biaxial tension tests, or shear tests [7-9]. The results of these experiments can be used to fit the strain energy density function to the experimental data, allowing the determination of the material parameters.

The aim of this work is to determine the mechanical properties of 3D printed Digital Material DM40 (Agilus30 and VeroClear). The material exhibits a remarkable nonlinear visco-hyperelastic response that depends on the strain and strain rates. The Bergstrom-Boyce (B-B) model was used to describe the nonlinear behavior of the material [10]. The identification

of the visco-hyperelastic material parameters is based on the cyclic loading shear test experimental data of 3D-printed samples.

2 Experimental methods

The Stratasys500 was used to print the specimen, the printed digital material referred to as DM40 is a mixture of two different materials, Agilus30 and VeroClear. The print direction is the vertical z-direction and the Infill percentage of the material is 100%.

2.2 Shear cyclic test

The specimen dimension (length 20 mm, width 20 mm, and height 5 mm). The INSTRON Electropuls E3000 testing machine with a load cell of 1 kN was utilized for the shear test. The load-unload shear tests were performed on the specimen and then the last cycle was held for relaxation. The applied different strains as followed 0.3, 0.4, and 0.5 with various strain rates: 0.2 s^{-1}, 0.4 s^{-1} and 0.6 s^{-1}, respectively, see Fig. 1a. The experiments were repeated three times by allowing the sample to rest for 10 minutes before the next test. The temperature chamber during the test was set to 30° C, see Fig. 1b.

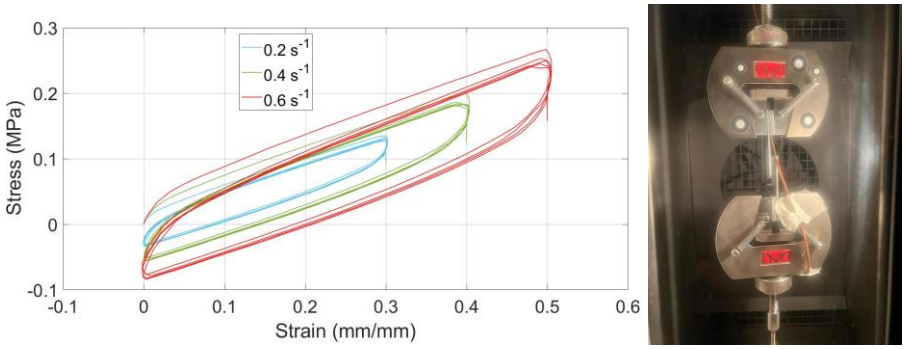


Fig. 1 (a) Shear cyclic test under various strain and strain rates, (b) shear test.

2.3 Uniaxial compression test

The uniaxial compression tests were performed on the cylinder sample (diameter 17.8 mm, height 25 mm). The samples were compressed to 50% of the hight with different strain rates of 0.4 10^{-2} s^{-1}, 0.2 s^{-1}, 0.4 s^{-1}, and 0.6 s^{-1}. The experiments were repeated three times and the average was calculated. The results are presented in Fig. 2. The temperature chamber during the test was set to 30° C because the material stiffness is affected by the small change in the temperature and also the need to investigate the material to be softer (flexible). The upper compression plate and lower compression plate were lubricated to reduce the barrelling effect of the samples.

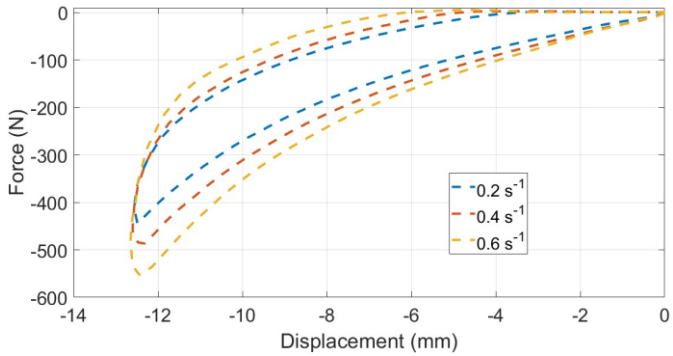


Fig. 2 Uniaxial compression at different strain rates.

3 Constitutive modelling and equation

The Parallel Rheological Framework was used to model the response of the material. The constitutive material modelling includes decoupling a material's behavior into different parallel chains, each with a given individual constitutive behavior, see Fig. 3.

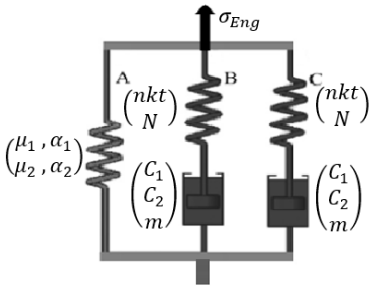


Fig. 3 Three-unit Parallel Rheological Frameworks (Bergstrom 2015).

3.1 Hyperelastic model

The Ogden model that has been selected in this study was fitted by shear experimental data. The strain energy is presented in Eq 1.

$$W = \sum_{i=1}^{N} \frac{\mu_i}{\alpha_i}\left(\lambda_1^{\alpha_i} + \lambda_2^{\alpha_i} + \lambda_3^{\alpha_i} - 3\right) + \frac{K}{2}(J-1), \quad (1)$$

where λ_1, λ_2, and λ_3 are principal stretches, μ_i are moduli and α_i are non-dimensional material constants. J and K are the elastic volume ratio and the material bulk modulus respectively.

3.2 Eight-Chain hyperelastic model

The Eight Chain model considers eight orientations of chains in space, which can be visualized using the eight-chain network system. This system is a representation of how polymer chains are arranged in a specific configuration, the function is expressed as a series of appropriate terms in expansion Eq. 2. [11]

$$\mathcal{W}_{EC} = nkt\left[\frac{1}{2}(I_1 - 3) + \frac{1}{20N}(I_1^2 - 9) + \frac{11}{1050N^2}(I_1^3 - 27) + \frac{19}{7000N^3}(I_1^4 - 81) + \frac{519}{673750N^4}(I_1^5 - 243)\right], \quad (2)$$

where *nkt* represents initial modulus and *N* is limiting chain extensibility are the model parameters, I_1 also corresponds to the first invariant of the right Cauchy-Green deformation tensor.

3.3 Nonlinear viscoelastic element of Bergstrom-Boyce model

The B-B model is used to describe the time-depending behavior of elastomeric materials for large strains. The flow rate rule of the nonlinear viscous element is presented in Eq. 3.

$$\dot{\gamma}=c_1[\lambda^i_{chain}\text{-}1]^{c_2} \parallel \tau^V_{ISO} \parallel^m , \tag{3}$$

where C_1, C_2 and m are material parameters, λ^i_{chain} is the inelastic network stretch, and τ^V_{ISO} is the deviatoric Kirchhoff stress representing viscous behavior.

4. Material parameter calibration results

The shear cycle test results were used for fitting Bergstrom-Boyce (B-B) model and the hyperelastic and viscoelastic material constants were determined. The fitting results are presented in Tables 1 and 2. The total parameters are 14. The two-terms Ogden model, represented by chain A, is identified by constants μ_1, μ_2, and α_1, α_2. The constants of nonlinear viscous elements are then *nkt*, *N*, C_1, C_2, m for chain B and C respectively.

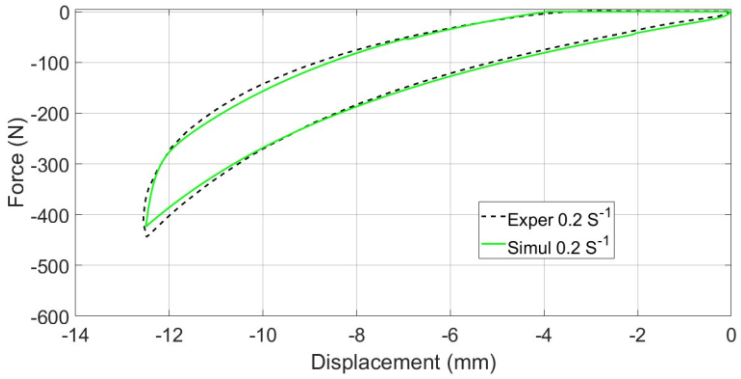
Table 1. Ogden Model constants.

Term *i*	Moduli μ_i	Exponents α_i
1	0.0566	0.274
2	0.293	2.090

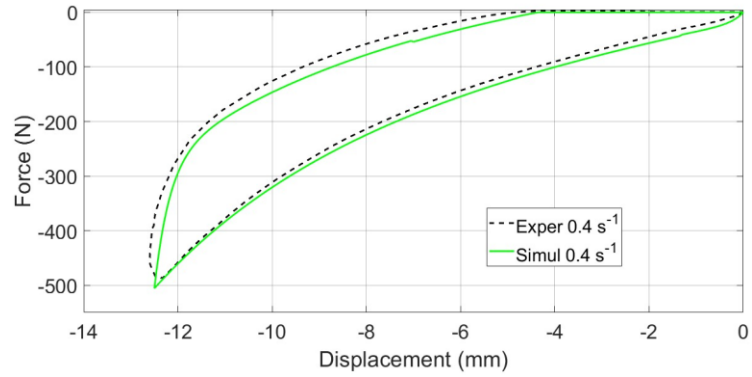
Table 2. Viscoelastic Model constants.

Viscoelastic parameters	Bergstrom-Boyce (Chain B)	Bergstrom-Boyce (Chain C)
nkt	0.152	2.9077
N	3.559	27.262
C_1	1.1251	4.798
C_2	-0.1027	-0.0554
m	0.8924	0.961

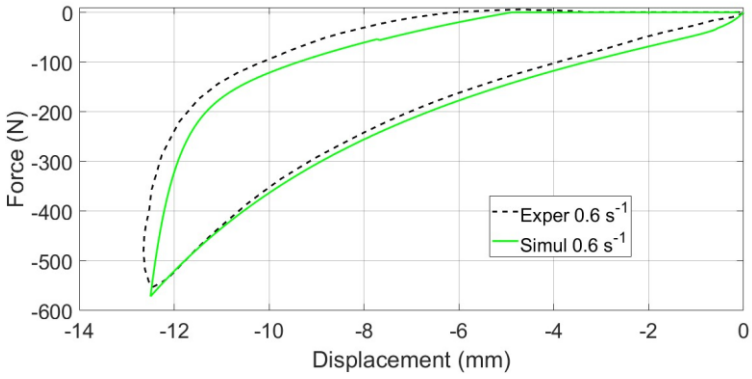
The material model identified in this way was used for simulation of compression test and results were compared with experimental data. This comparison shows a very good correlation as it is seen in Fig. 4 (a), (b) and (c) where nonlinear force-displacement characteristics are displayed.



(a)



(b)



(c)

Fig.4 Experiment validation with FEA at different strain rates.

Conclusion

This study presents the mechanical response of new composite PolyJet material Agulus30 and VeroClear and the description of the hyperelastic and nonlinear viscoelastic properties. The cycle shear experiments were performed to determine the parameters of the hyperelastic and nonlinear viscoelastic model. The validation of the model was verified by a compression test with cylindrical sample. The comparison between experimental data and simulation results, in general, shows a good agreement, which is confirmed the accuracy and applicability of the PRF model.

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