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ISOTROPIC ELASTIC AND PLASTIC DEFORMATION IN PARALLEL RHEOLOGICAL FRAMEWORK MODELS

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Abstract: This paper deals with the calibration of the polymer material PPC3TF2 using the PRF (Parallel Rheological Framework) material model implemented in the commercial software Abaqus. In order to reduce computational time, the unit cube model was used for the simulations. The coefficients initially calculated in Excel were used as input values to create the material model. For the most accurate results, the coefficients were optimized in Isight software.

KEYWORDS: material model; calibration; PRF; hyperelasticity; viscoelasticity; unit cube

1 Introduction

Finite element simulations have a fundamental role in modern engineering development, requiring the use of a suitable constitutive model to simulate material properties. Bocko et al. in their paper dealt with the estimation of material properties of carbon nanotubes using the finite element method [1]. For designing components from polymeric materials, it is important to consider that their mechanical behaviour is considerably different to conventional metals [2]. In additional to their low density, polymers are also characterised by their high elastic deformation capability, which allows them to absorb and release energy without permanent changes in shape [3]. Many polymeric materials are viscoelastic, i.e. they exhibit a combination of viscous and elastic response under external loading. Due to their properties, polymeric materials are nowadays considered as reliable and modern materials.

In this paper, the calibrated material is PPC3TF2, a polypropylene copolymer grade, filled with 20% talc by weight. PPC3TF2 finds applications in the production of HVAC (heating, ventilation, and air conditioning) components and in the automotive industry as interior trim [4].

In the commercial software Abaqus, the PRF (Parallel Rheological Framework) model can be used to represent specific polymer properties such as hyperelasticity, non-linear viscoelasticity and plasticity. PRF provides the ability to represent the material behaviour of polymers comprehensively, which allows more realistic simulations, but on the other hand requires more complex calibration methods [2], [3], [5].

Data from two types of tests - relaxation tests at three different levels of strain, and four uniaxial tensile tests for four different rates of strain - were used to calibrate the coefficients of the PRF model.

The Isight optimization tool and optimization algorithm AMGA - Archive based Micro Genetic Algorithm was used to optimize these coefficients. Isight is a software tool used for the integration and automation of the repetitive analytical design process. Isight automatically substitutes design input parameters, executes simulation code, and extracts searched output

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values until it finds the required solution [6]. The genetic algorithm was discussed by Élesztős et al. in their paper where they used it to optimize the welding process [7].

2 Estimation of PRF model parameters

The chosen PRF model (Fig. 1) consists of one equilibrium elastoplastic network 0 and three viscoelastic networks 1, 2, 3. For the calibration of plastics, considering the number of parameters, it is generally advisable to choose a number of viscoelastic networks $N = 3$.

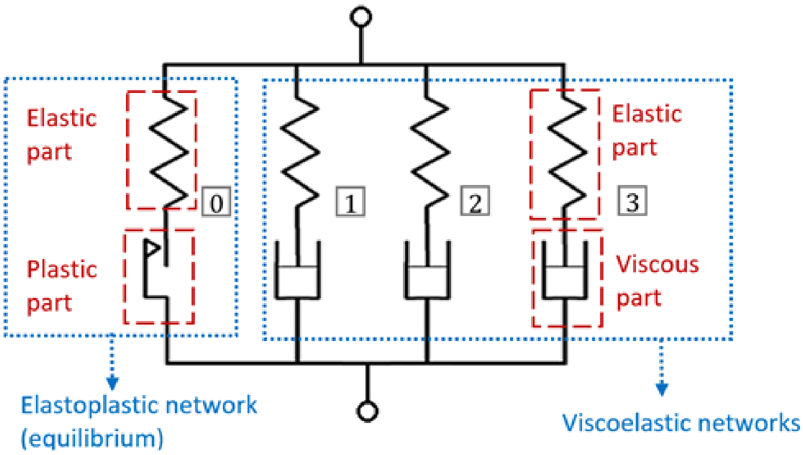

Fig. 1 The applied PRF model.

Calibration data

Calibration data from uniaxial tensile tests and relaxation tests were provided by Axel Products, Inc.

- **Hyperelasticity parameters**

The elastic part of the response is specified for all networks by using a hyperelastic material model. Since the same definition of hyperelastic material is used for each network, the model requires only one definition of hyperelasticity along with the stiffness ratio for each network. The Yeoh model was chosen for defining the hyperelastic behaviour. The choice of this model is based on its suitability for calibration using uniaxial tensile test data. Since the material is isotropic, two material constants are required to represent the material properties. Based on the Young's modulus of elasticity determined from the tensile curves and the Poisson's number for polypropylene, the constants C_{10} and D_1 of the Yeoh model were calculated.

- **Viscoelasticity parameters**

Viscoelasticity defines the behaviour of viscous dampers as well as the ratio of the stiffness of each spring to the total stiffness. Relaxation test data were used to estimate the viscoelasticity parameters and the Prony series was defined. The Prony series parameters were then converted to the PRF model parameters SR and A.

With the use of the estimated parameters from Tab. 1 and for $n = 1$, $m = 0$ for each of the three networks, the PRF model is linearly viscoelastic.

Tab. 1 Estimated parameters of material model.

Hyperelasticity	$C_{10} = 474.87$ MPa	$D_1 = 0.000309$ MPa^{-1}
Viscoelasticity	$SR_1 = 0.0228$	$A_1 = 0.0154$ MPa^{-1}
	$SR_2 = 0.0876$	$A_2 = 0.000236$ MPa^{-1}
	$SR_3 = 0.1540$	$A_3 = 0.0000144$ MPa^{-1}

Calibration of the material model

For the purpose of calibration of the resulting material model four material models M0, M1, M2, M3 were created. These models in sequence form the resulting PRF model, which includes a description of hyperelasticity, viscoelasticity, plasticity and strain rate dependent plasticity.

A simplified model of the test specimen is a unit cube, with a reference point in the centre of the top wall (Fig. 2). The load is controlled by the displacement prescription of this node. The advantage of this model is a significant reduction in computational time.

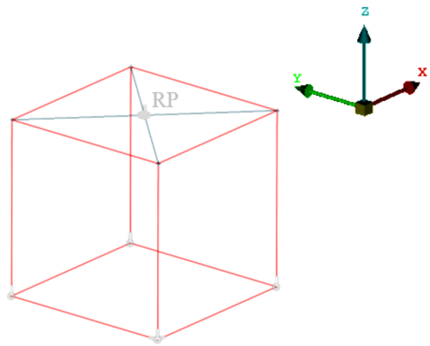

Fig. 2 Finite element model.

- **Material model M0**

The purpose of this model is to refine the hyperelasticity parameter C_{10}. The specification in Abaqus:

```
*Material, name=M0; PPC3TF2
*Hyperelastic, yeoh, moduli=INSTANTANEOUS
 <C10>, <C20>, <C30>, <D1>, 0., 0.
```

- **Material model M1**

The material model includes the definition of hyperelasticity and viscoelasticity.

```
*Material, name=M1; PPC3TF2
*Hyperelastic, yeoh, moduli=INSTANTANEOUS
 <C10>, <C20>, <C30>, <D1>, <D2>, <D3>.
*Viscoelastic, Nonlinear, NetworkId=1, SRatio= <SR1>, Law=STRAIN
<A1>, <n1>, <m1>
*Viscoelastic, Nonlinear, NetworkId=2, SRatio=<SR2>, Law=STRAIN
<A2>, <n2>, <m2>
*Viscoelastic, Nonlinear, NetworkId=3, SRatio=<SR3>, Law=STRAIN
<A3>, <n3>, <m3>
```

- **Material model M2**

This is a continuation of the M1 model with the following extension to the definition of plasticity with isotropic hardening:

```
*PLASTIC, HARDENING=ISOTROPIC
<Sigma0>,0
<yieldStress_01>, <plStrain_01>
<yieldStress_02>, <plStrain_02>
<yieldStress_03>, <plStrain_03>
<yieldStress_04>, <plStrain_04>
<yieldStress_05>, <plStrain_05>
```

```
<yieldStress_06>, <plStrain_06>
<yieldStress_07>, <plStrain_07>
<yieldStress_08>, <plStrain_08>
<yieldStress_09>, <plStrain_09>
<yieldStress_10>, <plStrain_10>
```

- **Material model M3**

This is the M2 model, which is extended to strain rate dependent plasticity. The plasticity curve in this model is scaled using the Chaboche model:

```
*RATE DEPENDENT, TYPE=CHABOCHE
<eps0Dot_Ch>, <K_Ch>, <n_Ch>
```

Simulation

Three relaxation tests and a tensile test were simulated in Abaqus by using the M1 material model. The input values of the used coefficients are given in Tab. 1. A comparison of the results of the first simulation is shown in Fig. 3.

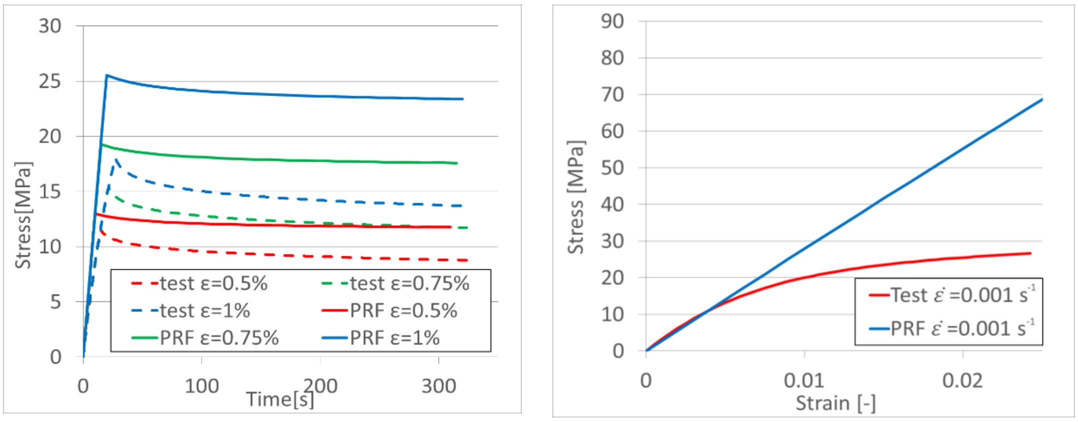

Fig. 3 PRF model response (before parameter optimization) compared to test data.

From the comparison of the responses, the need for the adjustment of the model parameters is evident. The optimization requires modification of the shape of the tensile curve, which can be done primarily by changing the hyperelasticity parameter C_{10}. At earlier times, stress relaxation also needs to be emphasized. This can be achieved by optimizing the n, m parameters.

3 Optimization in Isight

The objective of the PRF model parameter optimization is to approximate the tensile and relaxation curves obtained by simulation with the curves from material tests.

Optimization scheme

In Design Gateway, optimization scheme shown in the Fig. 4 was created. Two types of material tests were used in the Isight material coefficient fitting process. In the calibration scheme, one network for uniaxial test and three networks for relaxation tests are used.

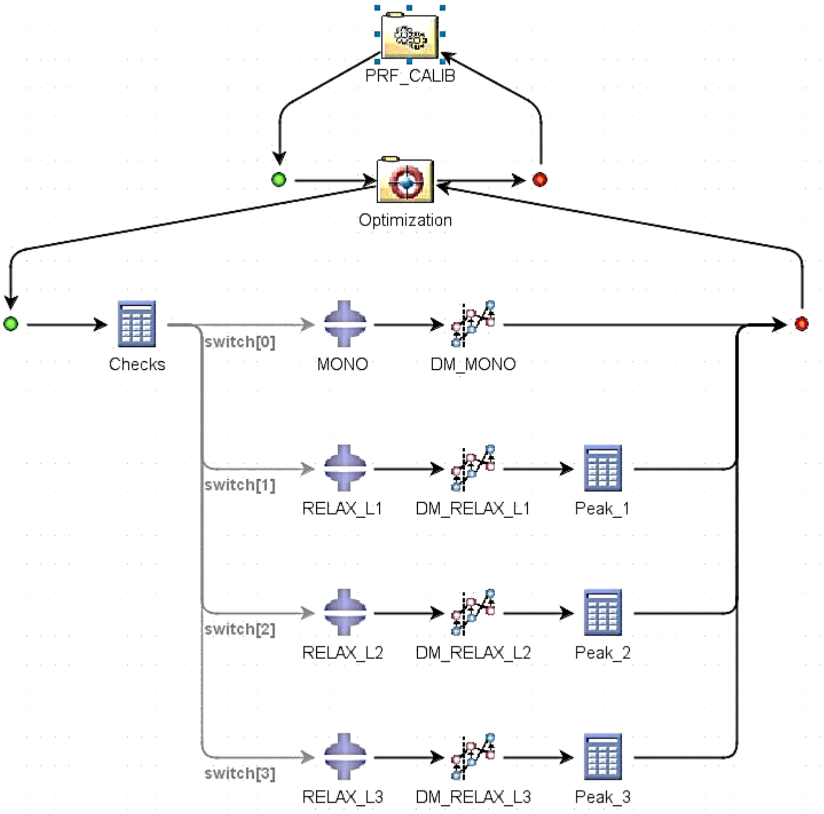

Fig. 4 Optimization scheme No. 1.

Optimization variables

Fig. 5 shows all the parameters that enter the optimization as variables. In the optimization process, variables were selected according to the used material model (M0, M1, M2, M3). For all optimized variables it was necessary to set boundary values and initial value, from which the optimization will be started. The set boundary values are based on parameter definitions, separate tests of the model's sensitivity to extreme values of the variables and experience.

Optimization

General | Variables | Constraints | Objectives

	Parameter	Lower Bound	Value	Upper Bound
☑	A1	1.0E-7	0.0154	0.01
☑	A2	1.0E-7	2.36E-4	0.01
☑	A3	1.0E-7	1.44E-5	0.01
☑	C10		474.87	
☑	K_Ch	1.0	10.0	100.0
☑	K_JC	0.01	10.0	100.0
☑	m1	-0.9	-0.2	-0.1
☑	m2	-0.9	-0.3	-0.1
☑	m3	-0.9	-0.5	-0.1
☑	n1	0.5	1.0	5.0
☑	n2	0.5	1.0	5.0
☑	n3	0.5	1.0	5.0
☑	n_Ch	1.0	3.0	10.0
☑	n_JC	0.05	0.3	0.95
☑	Sigma0	0.5	16.0	25.0
☑	SR1	0.0	0.0228	0.4
☑	SR2	0.0	0.0876	0.4
☑	SR3	0.1	0.154	0.25

Fig. 5 Optimization variables.

The objective function is a linear combination of the partial objective functions. The objective function is in the form of relative error or sum of squared difference on each branch of the optimization scheme.

Due to the number of variables to be optimized, this is a multicriteria optimization problem. Therefore, the result will be a number of solutions that produce a Pareto front or set of optimal solutions.

The optimization algorithm AMGA - Archive based Micro Genetic Algorithm was used to optimize the coefficients in Isight. The M0 model was only used for the optimization of the hyperelasticity parameter C_{10}. In the next optimization (model M1) the viscoelasticity parameters $SR_1, SR_2, SR_3, A_1, A_2, A_3, n_1, n_2, n_3, m_1, m_2, m_3$ were refined. Since only the viscoelasticity parameters were optimized, the optimization was performed only on the branches [1], [2], [3]. The used parameter values are shown in Tab. 2. A comparison of the results from Fig. 6 and Fig. 3 shows that the optimization provided an approximation of both the tensile and relaxation curves.

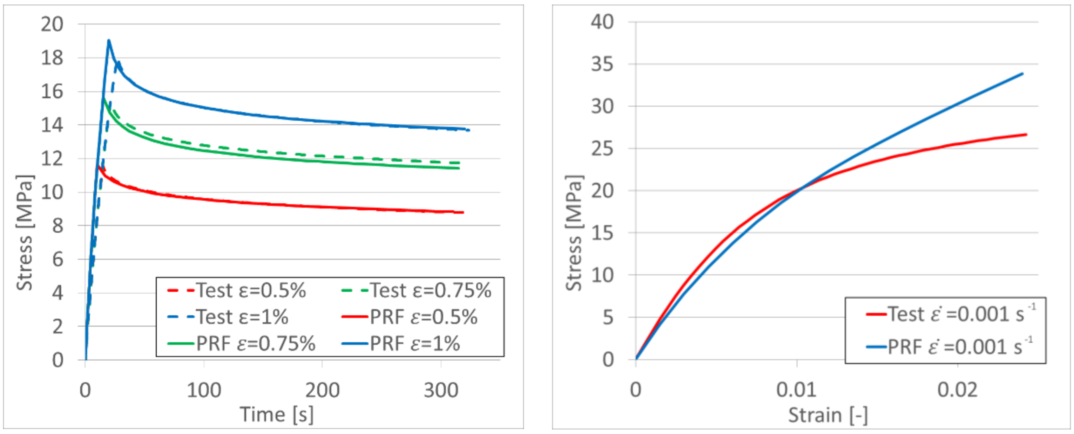

Fig. 6 PRF model M1 response compared to test data.

Tab. 2 Optimized parameters of material model M1.

Hyper-elasticity	$C_{10} = 493.62$ MPa		$D_1 = 0.000309$ MPa^{-1}	
Visco-elasticity	$SR_1 = 0.0979$	$A_1 = 0.0000226$ MPa^{-1}	$n_1 = 4.708$	$m_1 = -0.335$
	$SR_2 = 0.3720$	$A_2 = 0.0000151$ MPa^{-1}	$n_2 = 3.47$	$m_2 = -0.524$
	$SR_3 = 0.2470$	$A_3 = 2.15 \cdot 10^7$ MPa^{-1}	$n_3 = 4.45$	$m_3 = -0.369$

The M2 material model follows the M1 model, with the optimization variables extended to include the parameters of the Johnson-Cook plasticity model. Hence, all four branches, including branch [0], were run. The optimized variables are the viscoelasticity parameters $SR_1, SR_2, SR_3, A_1, A_2, A_3, n_1, n_2, n_3, m_1, m_2, m_3$ and parameter of the Johnson-Cook plasticity model K_{JC}, n_{JC}, σ_0.

In the process of evaluating the results, the objective function in the form of relative error was found to be appropriate in the case of approximation of tensile curves, but it did not find adequate solutions for relaxation tests. Therefore, an objective function in the form of sum of Y-axis area differences was used. By comparing the areas of differences and considering a uniform distribution of errors on the individual branches, an optimal solution was selected from the set of allowable solutions with the parameters listed in Tab. 3 and with the results shown in Fig. 7.

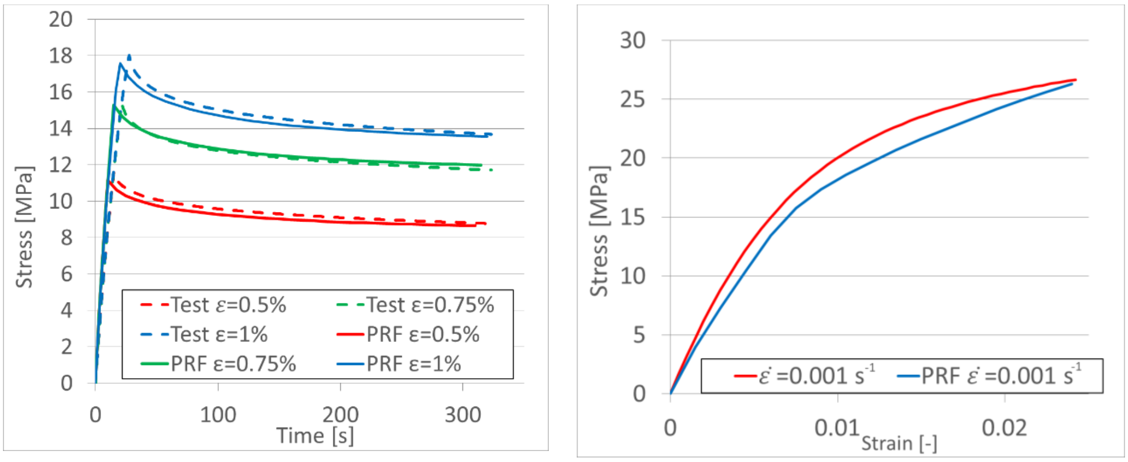

Fig. 7 PRF model M2 response compared to test data.

Tab. 3 Optimized parameters of material model M2.

Hyperelasticity	$C_{10} = 493.62$ MPa		$D_1 = 0.000309\ \text{MPa}^{-1}$	
Viscoelasticity	$SR_1 = 0.0684$	$n_1 = 1.77$	$m_1 = -0.209$	$A_1 = 0.000716\ \text{MPa}^{-1}$
	$SR_2 = 0.24$	$n_2 = 4.87$	$m_2 = -0.204$	$A_2 = 0.00132\ \text{MPa}^{-1}$
	$SR_3 = 0.129$	$n_3 = 1.21$	$m_3 = -0.205$	$A_3 = 5.22 \cdot 10^{-5}\ \text{MPa}^{-1}$
Plasticity	$\sigma_0 = 10.7$ MPa			
	$K_{JC} = 83.6$			
	$n_{JC} = 0.584$			

For calibration of the strain rate dependent plasticity parameters, the optimization scheme No. 1 (Fig. 4) was extended with three more branches, for three higher strain rates (Fig. 8).

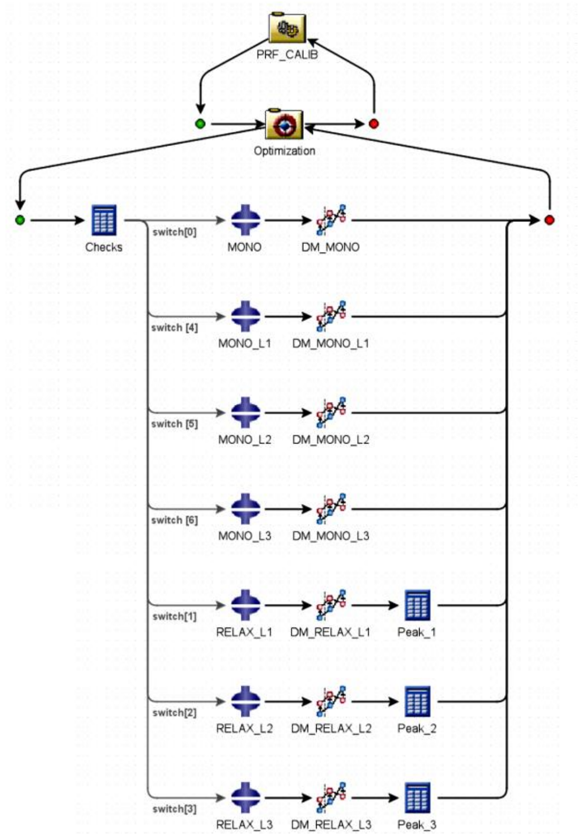

Fig. 8 Optimization scheme No. 2.

Only the branches for the tensile test [0], [4], [5], [6] were run. The objective function is the sum of the relative errors of the target and computed curves. The optimization variables are the Johnson-Cook model parameters K_{JC}, n_{JC} and Chaboche model parameters K_{ch}, n_{ch}.

From the set of allowable solutions, the optimal solution was chosen with a focus on the uniformity of the error distribution on the individual branches and minimization of the error for quasi-statics. A comparison of the tensile simulation results for the four relative strain rates with the test results is shown in Fig. 9. The resulting parameter values of the PRF model are shown in Tab. 4.

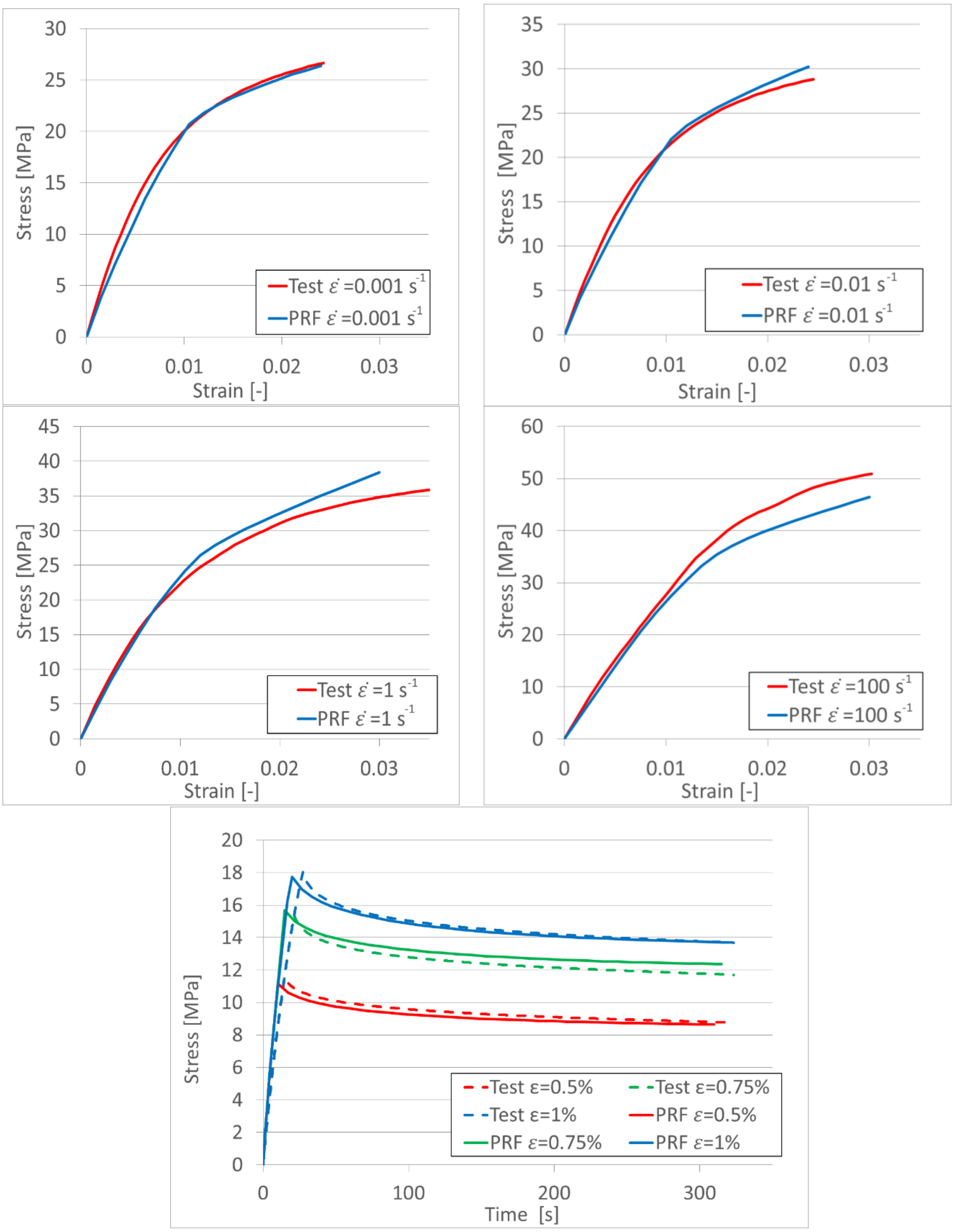

Fig. 9 Comparison of tensile curves and relaxation curves for the resulting M3 model.

Tab. 4 Resulting values of the optimized parameters of the M3 model.

Hyper-elasticity	$C_{10} = 493.62$ MPa		$D_1 = 0.000309$ MPa^{-1}	
Visco-elasticity	$SR_1 = 0.0684$	$n_1 = 1.77$	$m_1 = -0.209$	$A_1 = 0.000716$ MPa^{-1}
	$SR_2 = 0.24$	$n_2 = 4.87$	$m_2 = -0.204$	$A_2 = 0.00132$ MPa^{-1}
	$SR_3 = 0.129$	$n_3 = 1.21$	$m_3 = -0.205$	$A_3 = 5.22 \cdot 10^{-5}$ MPa^{-1}
Plasticity	$\sigma_0 = 10.7$ MPa			
	$K_{JC} = 11.4$			
	$n_{JC} = 0.139$			
Strain rate plasticity	$K_{ch} = 2.16$			
	$n_{ch} = 3.89$			
	$\dot{\varepsilon}_{Ch}^{0} = 1$			

Since the parameters of the PRF model are mutually related, the relaxation curves were also scaled using the Chaboche model. The authors consider that although there may be some deviations on these branches, the application of the methodology used is acceptable for practical use. Initial parameter estimation and calculation was performed in Excel.

CONCLUSION

The paper dealt with the estimation of the material model parameters of the PPC3TF2 polymer. The PRF model implemented in the FEM software Abaqus was used to represent the viscoelastic-plastic behaviour of this polymer. Material test data were measured and provided by Axel Products, Inc. Tensile test data were used to determine the constants of the isotropic material. Relaxation test data were used to determine the viscoelasticity parameters. The constants of the Yeoh hyperelasticity model were calculated from the Young's modulus and Poisson's number of polypropylene.

The finite element model and four material models were created in Abaqus. Comparison of the simulation results in Abaqus with the real test data showed that the estimated parameters of the PRF model needed to be refined. Since the PRF model parameters are interrelated, their refinement was carried out by sequential optimization using the Isight optimization software.

The resulting material model M3 includes a description of hyperelasticity, viscoelasticity, plasticity defined by the model Johnson-Cook and plasticity dependent on plastic strain rate, defined using the Chaboche model. This model, in application with the PRF model, achieves satisfactory results.

This work can be built on in the future by extending the material model to temperature dependence.

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