

Review of the FeFp Model



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Summary

The recent Extended Functionality release of ABAQUS (v6.7-EF) contains a new material model for “permanent set in rubber-like materials”. This model is also referred to as the FeFp model, which is a peculiar name since virtually all viscoplastic material models are based on the F^eF^p decomposition. The ABAQUS manuals do not provide much information about the theory of the new model, or give guidelines about when it is useful. It is simply stated that the model can be used to predict permanent set in filled elastomers and thermoplastics. In order to learn more about this model I compared the predictions from the new FeFp model to other existing models. The results from this study show that the FeFp model is not able to accurately predict the response of either elastomers or thermoplastics. In fact, the predictions from this model are not very different from the old metal plasticity models, which are known to not work well for polymers. I have also shown that much more accurate material models exists, for example the dynamic Bergstrom-Boyce model (DBB) for elastomers, and the three-network model (TNM) for thermoplastics.

If you are interested in learning more about selecting an appropriate material model for a polymer, then I recommend that you attend one of my training classes.

Introduction

The FeFp model is an extension of currently available material models in ABAQUS. Specifically, it allows you to combine hyperelasticity, metal plasticity, and the Mullins effect. In ABAQUS terms, you can combine `*Hyperelastic`, `*Plastic`, and `*Mullins Effect`. Note that the new model does not work with the linear viscoelastic model or the hysteresis model.

The FeFp model is based on an interesting modular idea, the question that I am trying to answer in this study is how well does it work in practice?

To answer that I tried to calibrate the model to experimental data for:

- a chloroprene rubber with 25 vol% carbon black,
- an ultra-high molecular weight polyethylene (UHMWPE).

The following sections summarize the calibration results and a general discussion and comparison with other material models.



Modeling of Elastomers

To evaluate how the FeFp model can predict the behavior of elastomers I applied it to a chloroprene rubber with 25 vol% carbon black. The experimental data that I used in this study is summarized in Figure 1.

The experimental data set consisted of uniaxial compression to a true strain of -0.8 followed by unloading back to zero stress. Three different strain-rates were tested, and the experiments were performed at room temperature. The samples were conditioned to remove the Mullins effect before the tests.

I then attempted to fit the FeFp model this experimental data set. The ABAQUS manuals mentions a fitting tool that is available on the Simulia support web site. I downloaded those files, but for some reason I could not activate the tool. It is possible that I did something wrong during the installation. If someone has experience with the provided fitting tool I encourage you to provide that feedback on the PolymerFEM.com [forums](#). Fortunately, I have developed my own general purpose material parameter calibration [tool](#), and was able to fit the new model using this Matlab tool. The best fit I could get of the experimental data is shown in Figure 2.

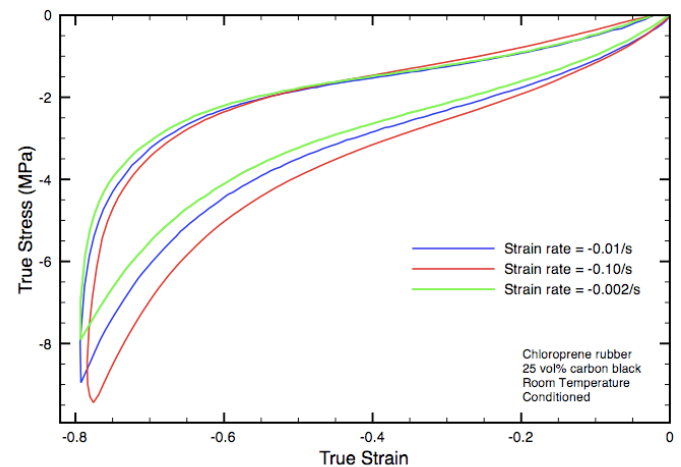


Figure 1. Experimental data for a chloroprene rubber tested in uniaxial compression at three strain rates.

The model predictions shown in Figure 2 were obtained using the following material parameters:

```
*Hyperelastic, Arruda-Boyce
2.5036, 1.9842, 0.01
*Plastic, hardening=isotropic
1.9981, 0
2.8545, 0.05
5.605, 0.1
4.8531, 0.2
5.3678, 0.3
5.5914, 0.4
6.0387, 0.5
6.5979, 0.6
7.157, 0.7
19.234, 0.8
*Rate Dependent
0.55914, 0.79678
```

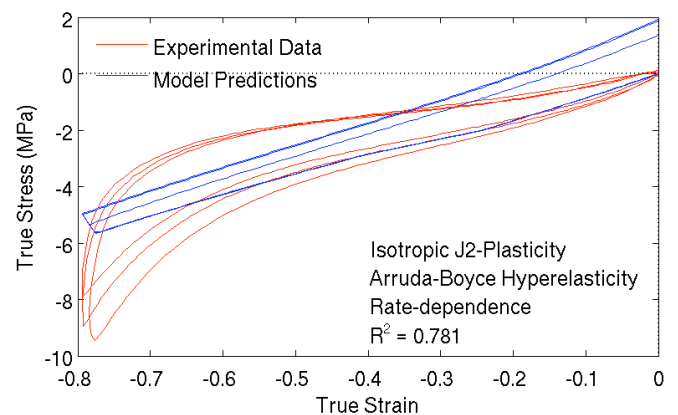


Figure 2. Comparison between the experimental data for a chloroprene rubber and the best model predictions from the FeFp model.

Note that kinematic hardening plasticity does not work any better in this case.

Figure 2 shows that the new FeFp model does *not* accurately predict the response of the elastomer. In fact, the predictions are not much better than the old elastic-plastic model in ABAQUS. I welcome anyone to try to find a better fit using the new model.

A more accurate model for elastomers is the dynamic Bergstrom-Boyce (DBB) [model](#). This is a model that can capture both the small strain dynamic response, and the large-strain, time- and temperature-dependent response. I also used my Matlab material parameter calibration [tool](#) to fit this model to the experimental data. The results of the calibration are shown in Figure 3. This figure shows that the dynamic Bergstrom-Boyce (DBB) model accurately predicts the response of this elastomer.

The relative error of the DBB model predictions, as expressed in terms of $1-R^2$, is 0.019. The corresponding error value for the FeFp model is 0.219. In other words, in this case the DBB model is 11 times more accurate than the FeFp model!

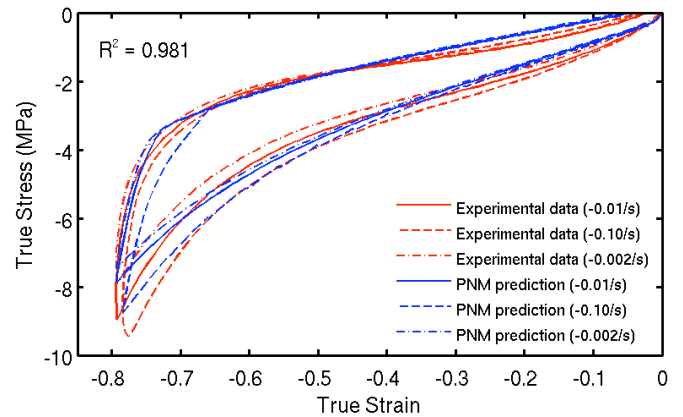
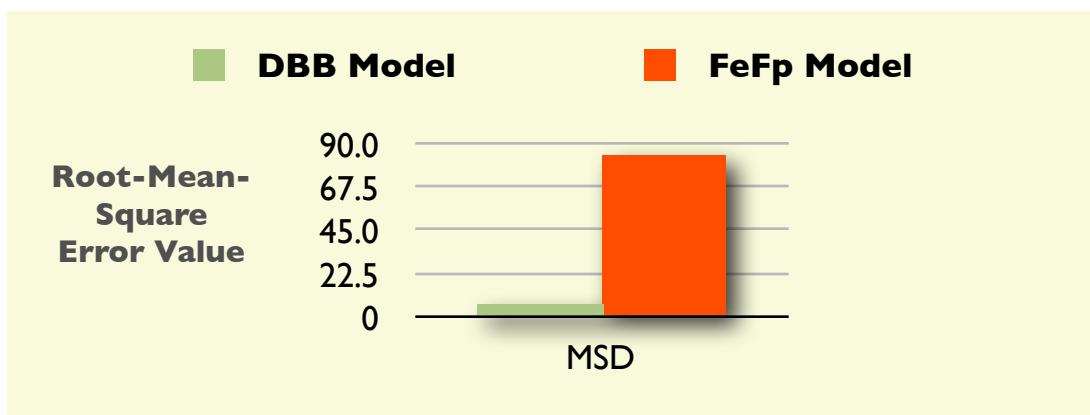
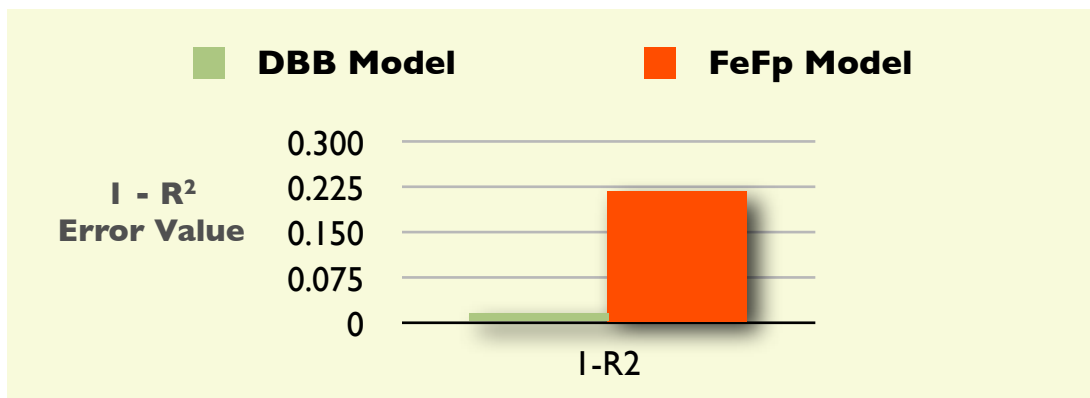


Figure 3. Comparison between the experimental data for a chloroprene rubber and the best model predictions from the DBB model



Modeling of Thermoplastics

To evaluate how the FeFp model can predict the behavior of thermoplastics I applied it to experimental data for an ultra-high molecular weight polyethylene (UHMWPE). The experimental data that I used in this study is summarized in Figure 4.

The experimental data consisted of:

- uniaxial tension to failure at three different strain rates,
- uniaxial compression to a true strain of -1,
- uniaxial cyclic loading at three different strain rates.

Note that UHMWPE is a material that does not neck even at large uniaxial tensile strains.

The best fit of the FeFp model to the experimental data set is shown in Figure 5. The results in this figure were obtained using the following material parameters:

```
*Hyperelastic, arruda-boyce
120.54, 1.9677, 0.01
*Plastic, hardening=isotropic
13.118, 0
26.149, 0.01
27.904, 0.03
25.143, 0.05
29.515, 0.08
29.208, 0.1
32.734, 0.15
41.249, 0.5
65, 0.7
163.97, 1
*Rate Dependent
0.54658, 0.87453
```

Note that kinematic hardening plasticity does not work any better in this case.

A more detailed comparison of the cyclic loading data and the corresponding FeFp model predictions are shown in Figure 6. Figures 5 and 6 show that the FeFp model has a number of weaknesses, for example, it cannot capture both the large-strain tension and compression data at the same time. The model also has problems with cyclic loading predictions.

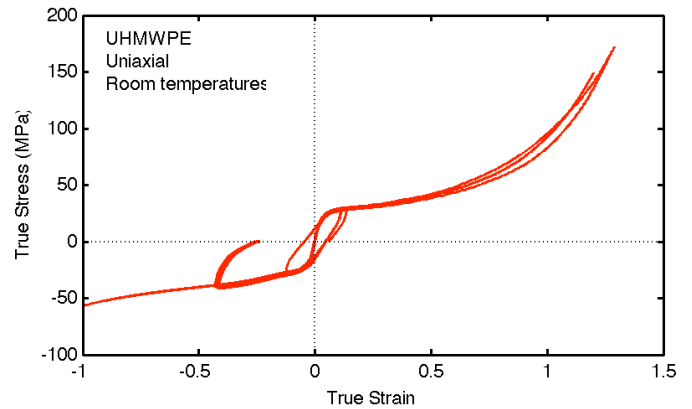


Figure 4. Experimental data for a UHMWPE material.

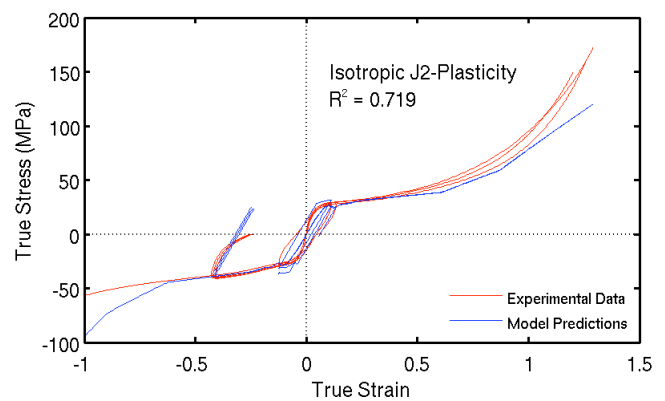


Figure 5. Comparison between the experimental data for an UHMWPE and the best model predictions from the FeFp model.

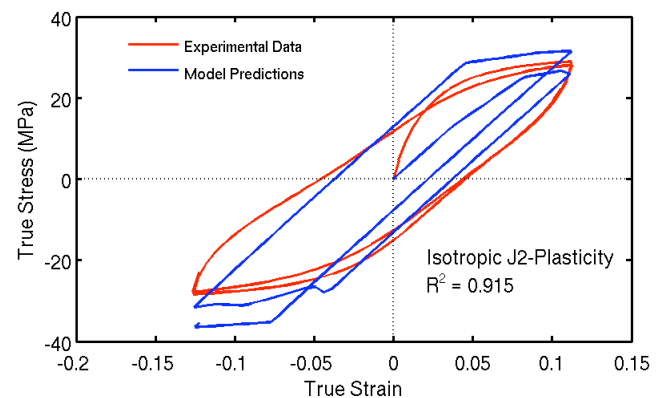


Figure 6. Comparison between the experimental data for an UHMWPE and the best model predictions from the FeFp model.

The plasticity component that I used in this study was based on isotropic hardening. This type of plasticity formulation is not suitable for cyclic loading of polymers. The problem that occurs when applying this type of plasticity model to cyclic loading is illustrated in Figure 7. As is shown in the figure, the predicted stress magnitude in each load cycle keeps increasing, a phenomenon that is clearly not physical for plastics.

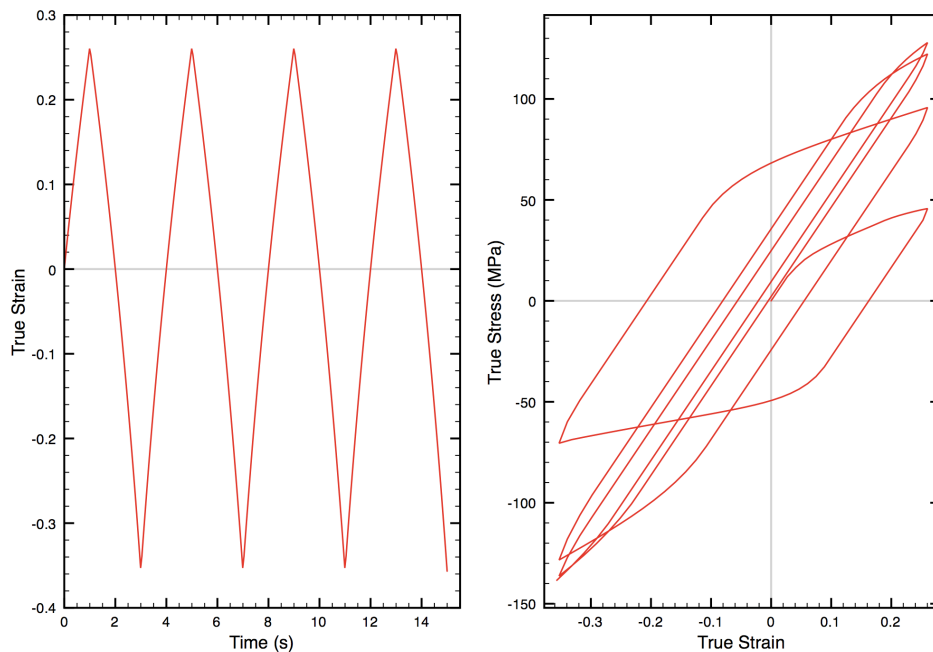


Figure 7. Cyclic loading predictions using an isotropic plasticity model. The figure to the left shows the applied strain history, and the figure to the right shows the resulting stress response.

A more advanced material model for UHMWPE is the three-network model (TNM). The results from calibrating this model are shown in Figures 8 and 9.

It is clear from Figures 5-6, and 8-9, that the three network model is significantly more accurate than the FeFp model at predicting the response of UHMWPE.

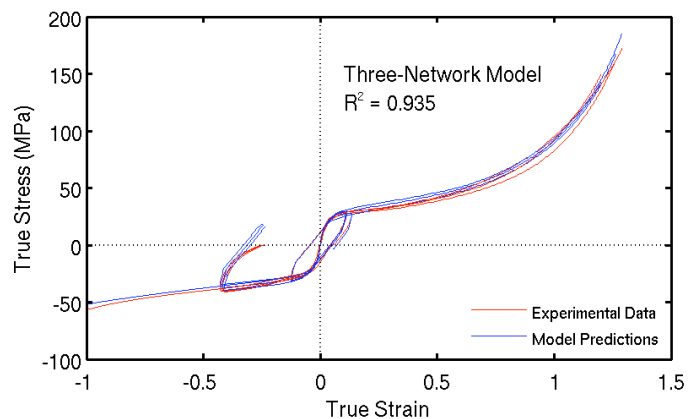


Figure 8. Comparison between the experimental data for an UHMWPE and the best model predictions from the TN model.

The FeFp model is not a good general purpose model for any polymer. There are other much more accurate models available.

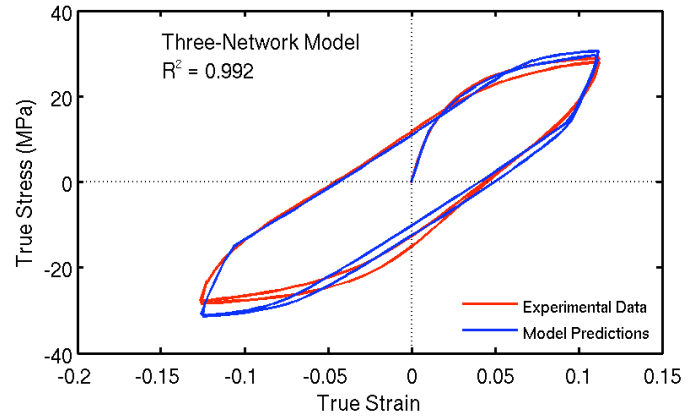
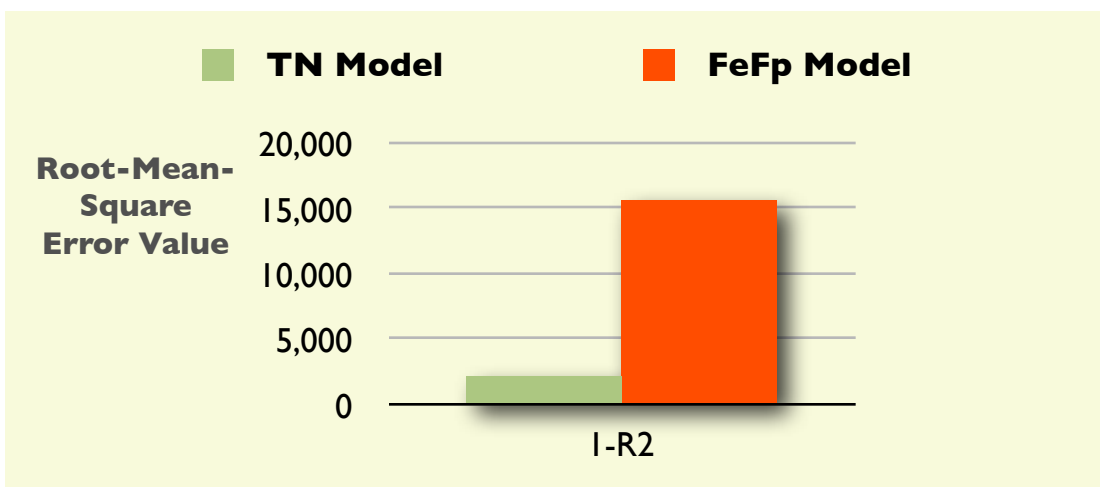
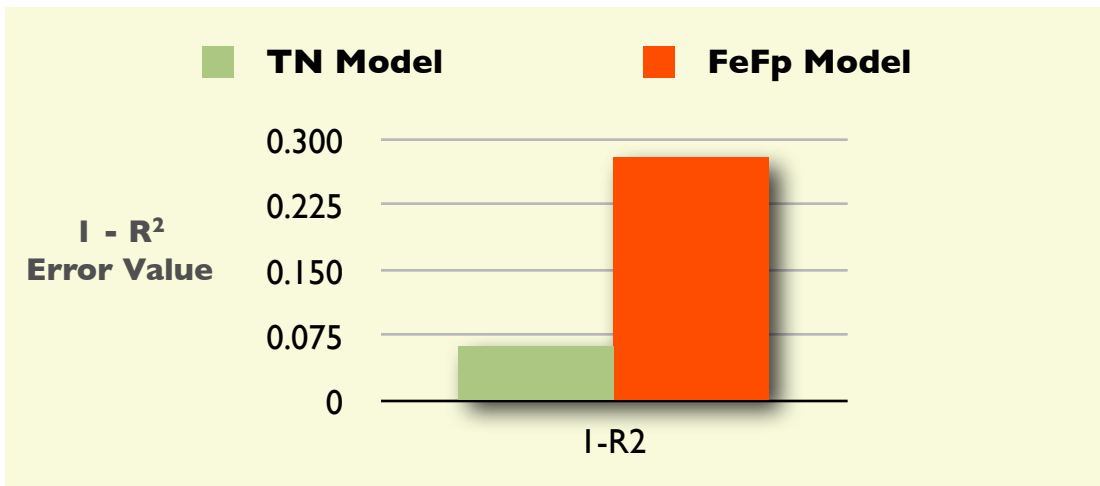


Figure 9. Details of the three network model predictions of the cyclic data.

The relative error of the model predictions, as expressed in terms of $1-R^2$, is 0.281 for the FeFp model, and 0.065 for the three network model. In other words the error in the FeFp model predictions are more than 4 times larger than the error in the TNM predictions.



Official Response from SIMULIA

After publishing this review of the FeFp model I received the following official response form SIMULIA:

“The material model currently implemented in Abaqus is intended to capture permanent set in filled rubber subject to cyclic loading under multi-axial stress states and mild load reversal. Working closely with an industrial partner this capability has been validated against experimental results. Details of the validation procedure, including test data, input files, an Abaqus/CAE plug-in for calibration, and a paper presented at ECCMR 2007 are available through Answer 3522 on the SIMULIA Online Support System (www.simulia.com -> Support -> My Support). We acknowledge that the material model currently implemented in Abaqus is not suitable for complete load reversal and is limited in its ability to capture effects such as plasticity and rate dependence. We expect to relax these limitations and extend the polymer modeling capabilities of Abaqus in future releases.”
