A Pragmatic Approach to the Modeling of Nonlinear Rheological Networks for Polymers

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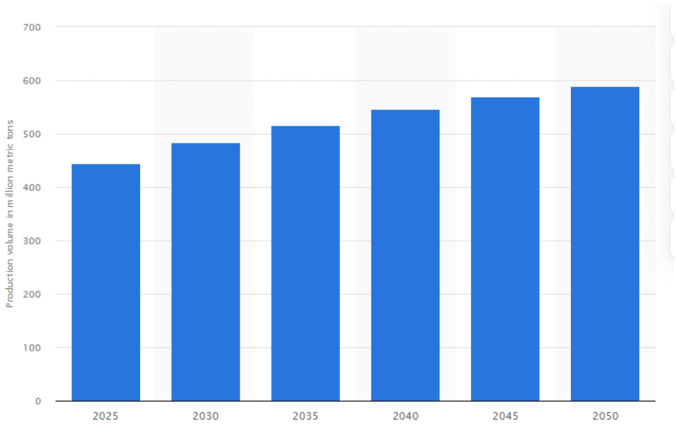
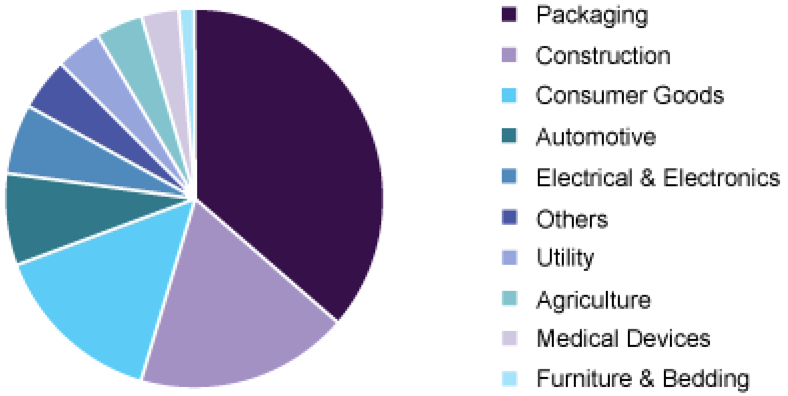
Ansys

Introduction





- Thermoplastics are widely used in many industries
  - Packaging solutions, consumer goods, medical devices, furniture, electronic devices, vehicles, …
  - Predicted global production is 445.25 Mt in 2025 and 590 Mt by 2050 (Statista)
- To meet competition and sustainability agendas, the need for realistic constitutive polymer models has never been greater
  - Ultrasonic processes, long duration loads, strain recovery and material damping

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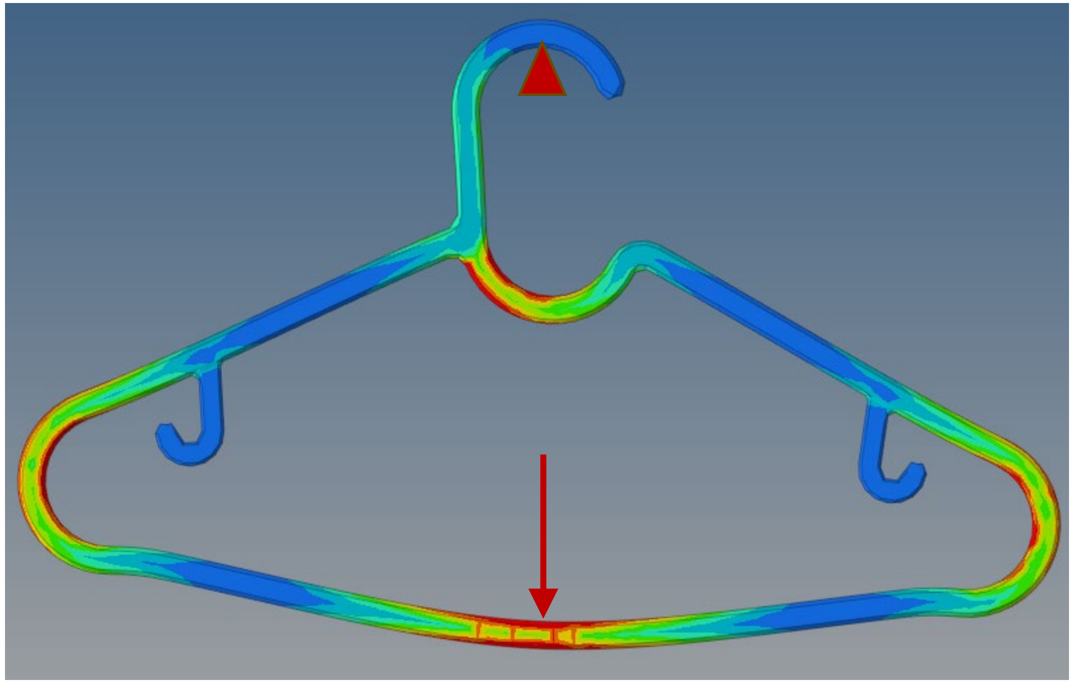
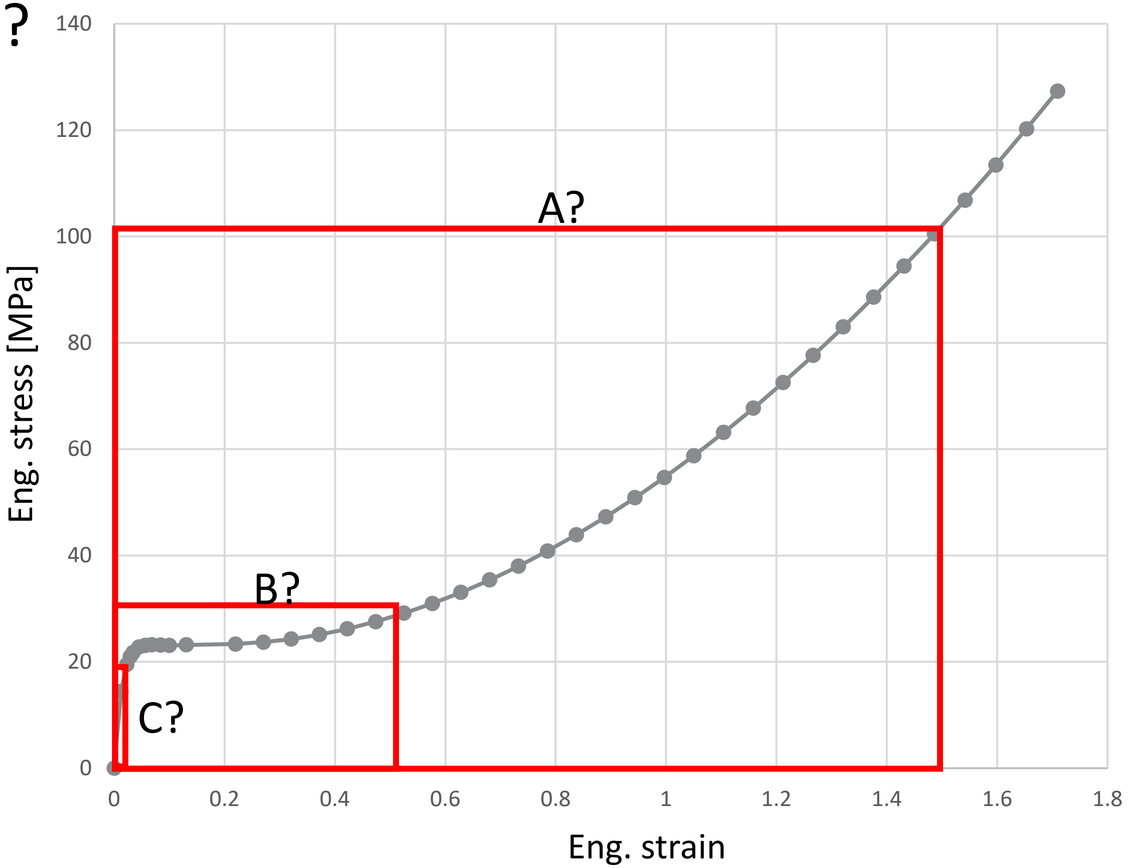
Introduction

- Which strain range is relevant for a polymer product that is designed to *withstand* a certain load (keep its shape and function)?

Example – deformation borderline unacceptable

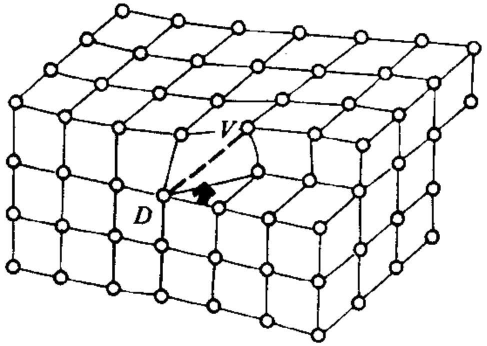


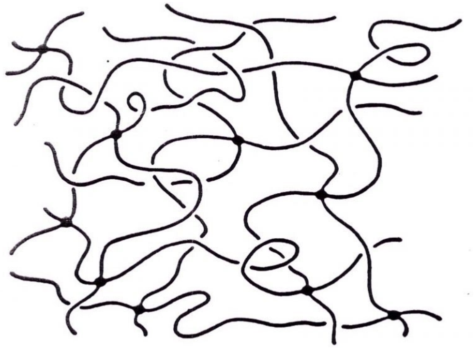
Hanger subjected to 1 kg for 3 weeks



IKEA has been on a journey away from elastic-plastic models and towards *rheological framework models*

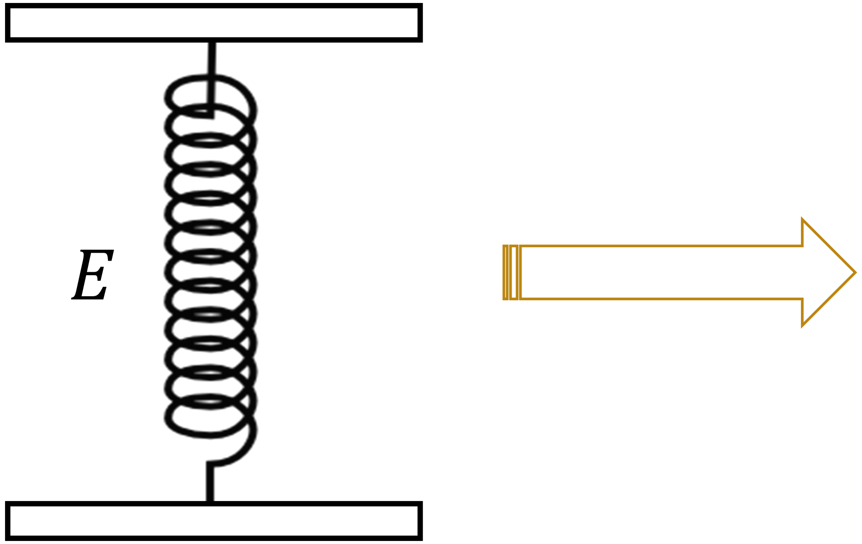
Rheological Networks

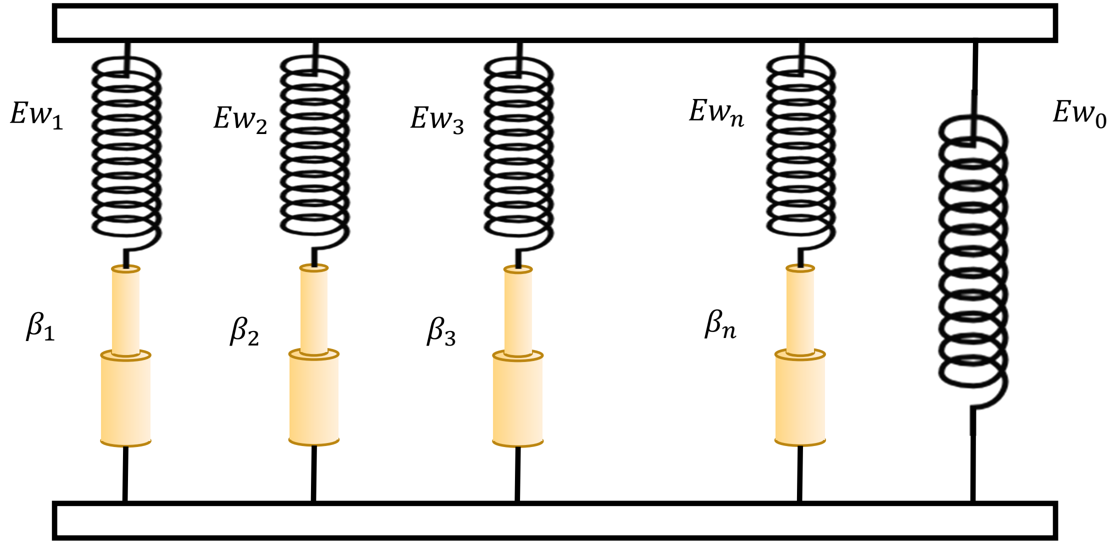




- Elastoplastic models are good for predicting dislocation movement in crystalline metal structures
- Polymers are built up as chains with crosslinks, and the response is more like fluids with time, temperature and stress dependency
- Rheological network models on the other side are fundamentally closer to the micro mechanics of the polymer chain interactions
  - Handles impact, stress relaxation, creep and recovery in any order and any time span by design
- Potential of consolidating many existing single purpose models of the same material into one material model

Rheological Network Principle





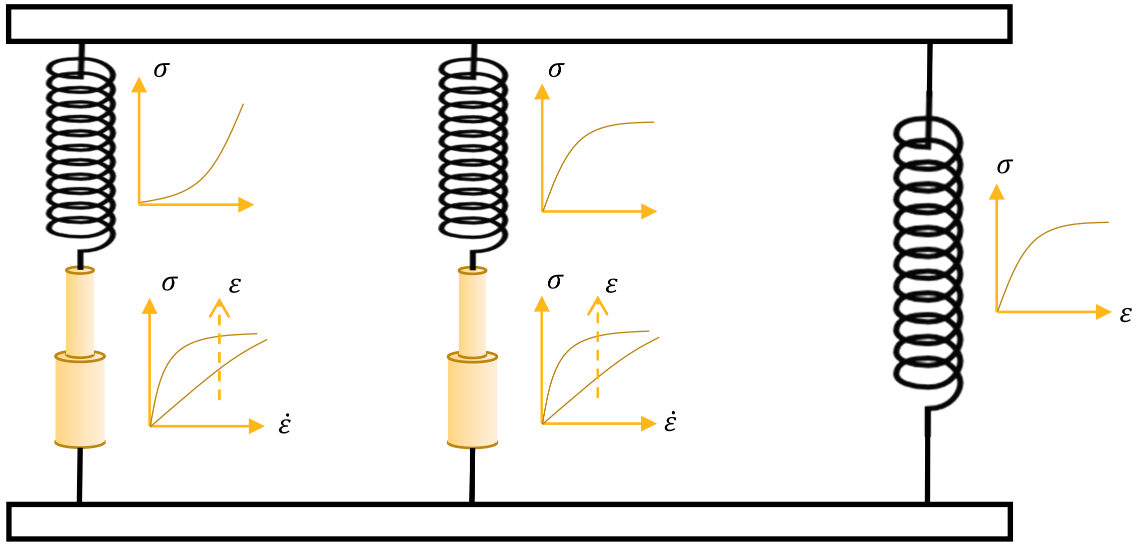
- A base material is “split” in terms of stiffness into a number of “weighted contributions”
  - $\sigma = w_0\sigma_0 + w_1\sigma_1 + w_2\sigma_2 + \cdots$ *(stiffness contributions)*
- Except for the “0th” contibution, impose stress decay by adding a damper
  - $\dot{\sigma}_i = \dot{\sigma}_0 - \beta_i\sigma_i$ *(viscoelasticity)*
- If β_i depends on the response itself, we have *nonlinear* viscoelasticity
  - $\beta_i = \frac{E}{\sigma_i}\dot{\varepsilon}_i \quad \dot{\varepsilon}_i = \left(\left(\frac{\sigma_i}{\sigma_*}\right)^{p_*}\left((q_*+1)(\varepsilon_* + \varepsilon_i)\right)^{q_*}\right)^{\frac{1}{q_*+1}}$ *(Norton-Bailey creep)*

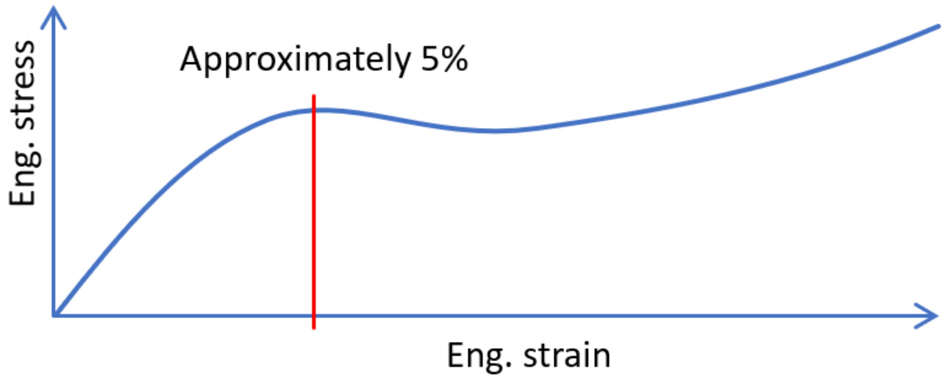
- Each contribution is “activated” at certain “range” of stress and strain levels
  - $p_* = 1$ corresponds to linear viscoelasticity while $p_* \gg 1$ corresponds to perfect plasticity with σ_* as yield
- With sufficiently many contributions, with each contribution spanning independent ranges of stress and time, many loading scenarios can be considered
- This extension from linear to nonlinear viscoelasticity was popularized by Jörgen Bergström and is the principle behind *MAT_ADD_INELASTICITY
- An important aspect is the ability to fit the model to experiments, which requires a simulation on its own (Mcalibration)

Motivation

- Goal for IKEA is to model time dependency within the functional range of a thermoplastic furniture component
  - Strains below uncontrolled yield in layman terms
- Concerns with existing approaches
  - Generic problems fitting experiments including both strain-rate variation and stress relaxation at varying stress levels
  - Lack of mimicking natural recovery after unloading
- Increasing number of links is unattractive as the number of parameters grow and makes the fitting procedure unnecessarily complicated
- Two discoveries constitute the base for a proposed model in this context

Motivation

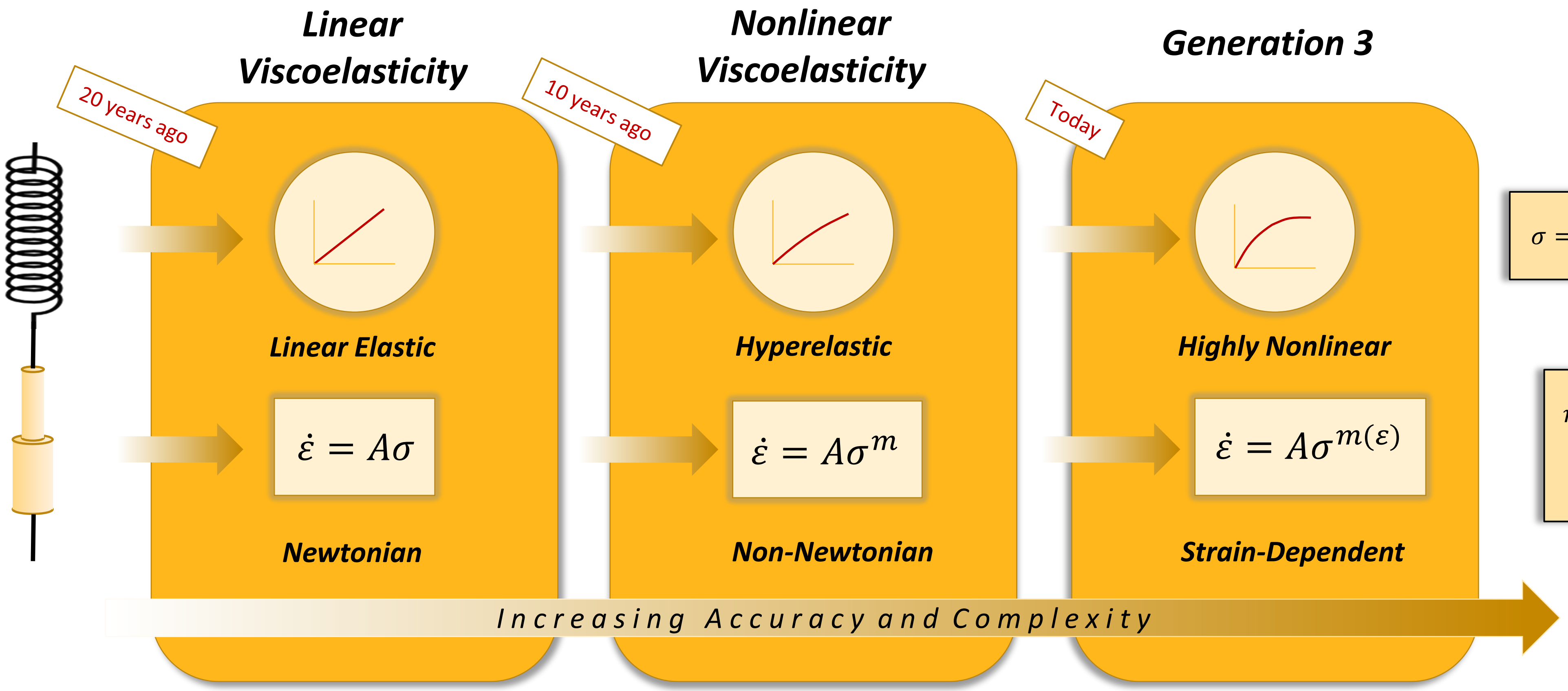




- To achieve the basic anatomy of a thermoplastic tension test, highly nonlinear stiffness is required for low strains
  - Typically, not applicable with a classical hyper-elastic approach
- Fitting relaxation tests at both low and high stress seems impossible
  - The dampers need more degrees of freedom

Generalization of Spring and Damper Response

- Allow both springs and dampers to be influenced by the level of strain
- Improvements were observed, without the need for more links



$$\sigma = E_s\varepsilon_e + \bar{\varepsilon}_e(E_e - E_s)\ln\left(\cosh\left(\frac{\varepsilon_e}{\bar{\varepsilon}_e}\right)\right)$$

$$m = m_s + (m_e - m_s)\ tanh\left(\frac{\varepsilon_v}{\bar{\varepsilon}_v}\right)$$

$$\dot{\varepsilon}_v = \left(\frac{\sigma}{\bar{\sigma}}\right)^m$$

Implementation

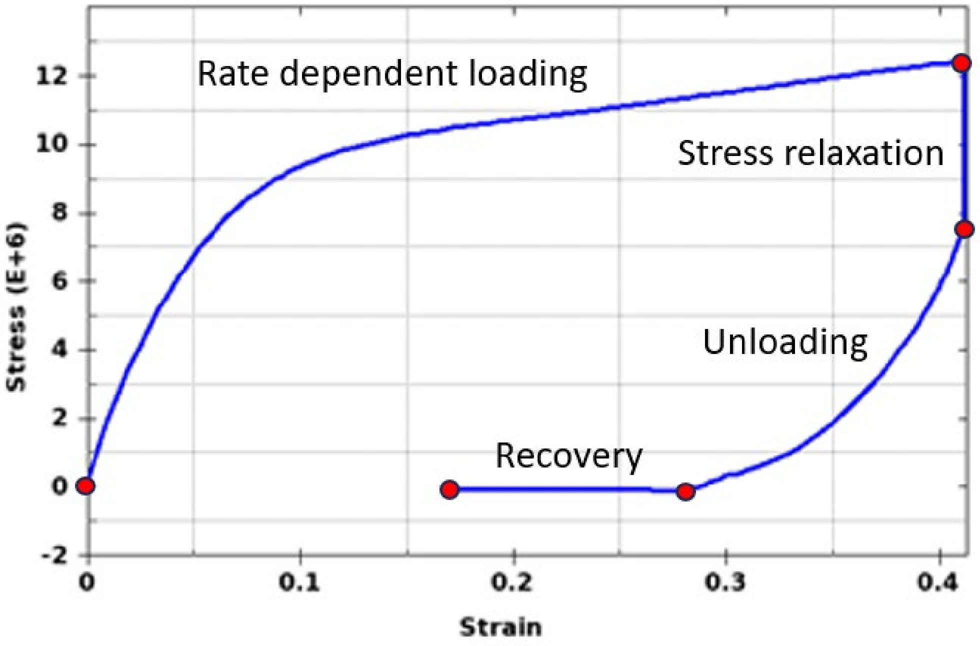
- Inspired by the conceptual outline, a 3D constitutive model was implemented
- Hypo-elasto-viscoelastic approach, using an incremental formulation
  - $\dot{\boldsymbol{\sigma}} = \boldsymbol{C}(\varepsilon_e)(\dot{\boldsymbol{\varepsilon}} - \dot{\boldsymbol{\varepsilon}}_c)$
  - $E(\varepsilon_e) = E_s + (E_e - E_s)\tanh\left(\frac{\varepsilon_e}{\bar{\varepsilon}_e}\right)$
  - $\dot{\boldsymbol{\varepsilon}}_c = a\left(\frac{\sigma^{\text{eff}}}{\bar{\sigma}}\right)^{m(\varepsilon_c)} \frac{3}{2}\frac{\boldsymbol{s}}{\sigma^{\text{eff}}}$
  - $m(\varepsilon_c) = m_s + (m_e - m_s)\tanh\left(\frac{\varepsilon_c}{\bar{\varepsilon}_c}\right)$
- A total of 22 material parameters
  - $E_s^i, E_e^i, \nu^i, \bar{\varepsilon}_e^i$ for $i = 1,2,3$
  - $a^i, \bar{\sigma}^i, m_s^i, m_e^i, \bar{\varepsilon}_c^i$ for $i = 1,2$

Part of the pragmatism lies in steering away from using deformation gradients and a total formulation, and not impose thermodynamic restrictions that may result in unnecessary cost and inability to capture the characteristics of real-world materials, but instead follow the traditional ls-dyna approach, allowing for a relaxation of theory and assuming that with proper material testing and parameter fitting the resulting material model will in practice be physically justified

Parameter Fitting

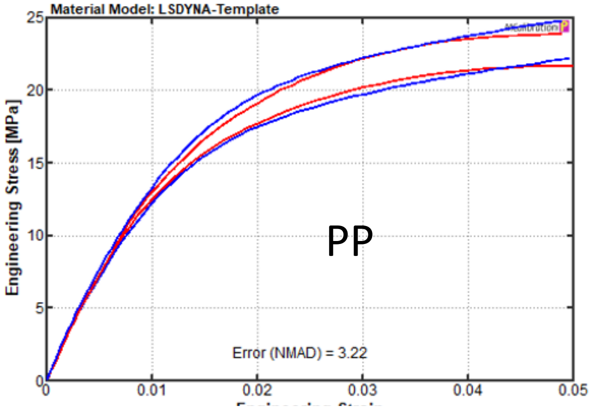
PolyPropylene

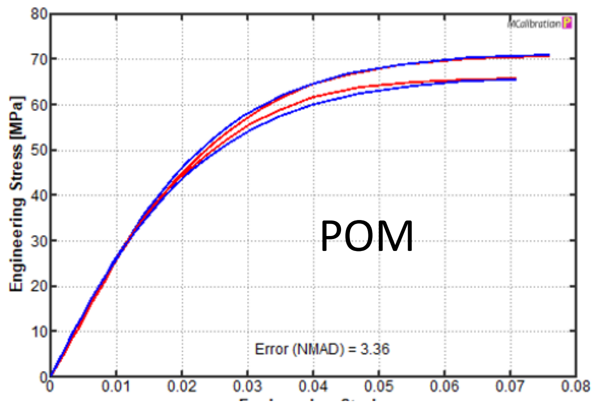
PolyOxyMethylene

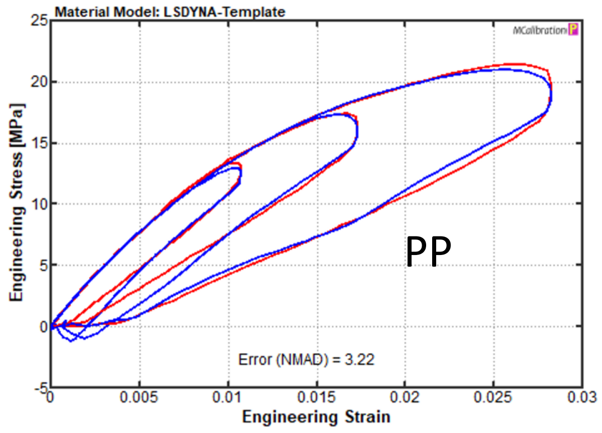


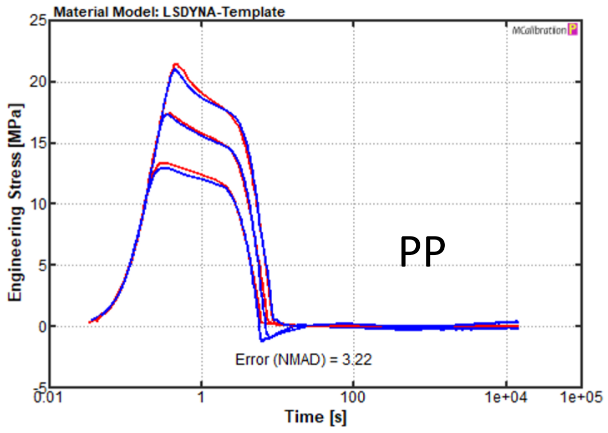
- To make proper use of a material model of this complexity, fitting test data is crucial
  - Using some kind of optimization tool is inevitable, here MCalibration from PolymerFEM is the product of choice
- Tests of thermoplastics are variants of the anatomy shown above
  - The objective of the material model is the ability to match all types of IKEA thermoplastics for all types of loading scenario occurring in everyday use
- PolyPropylene and PolyOxyMethylene were used, with strain levels below necking

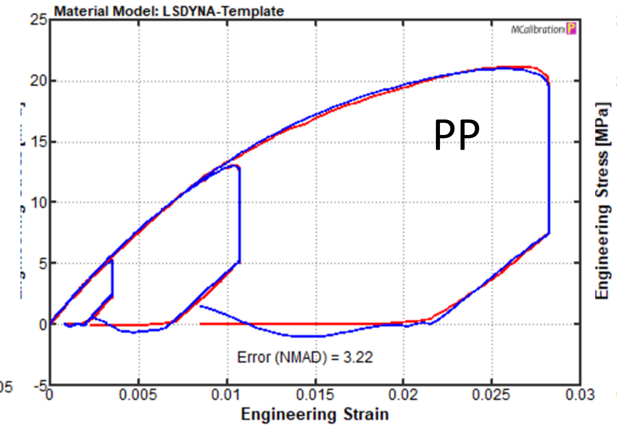
Tensile tests at 800mm/min and 50mm/min
Relaxation tests at 800mm/min with 20h relaxation and 4h recovery
Loading/unloading tests at 800mm/min without relaxation but with 4h recovery
Fitting error is 3.22% (PP) and 3.36% (POM)

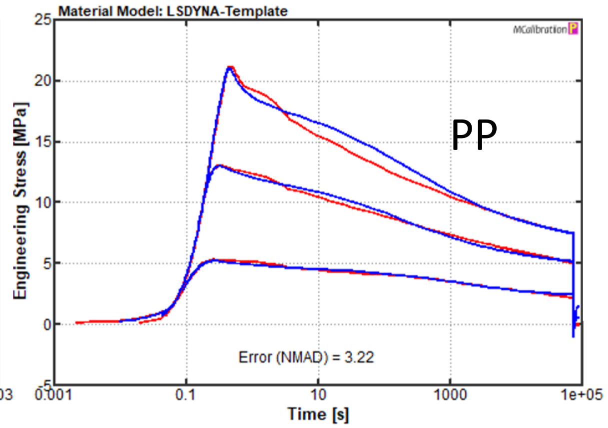


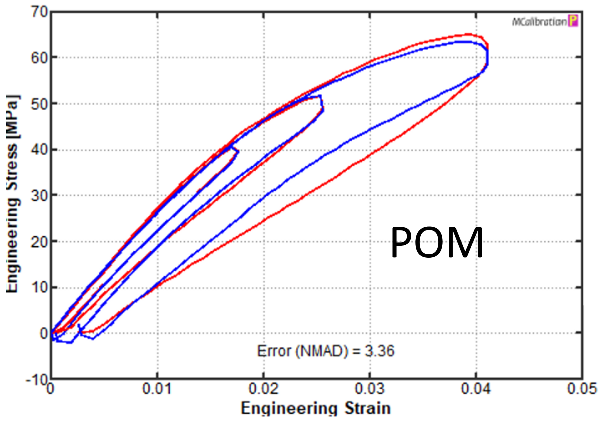


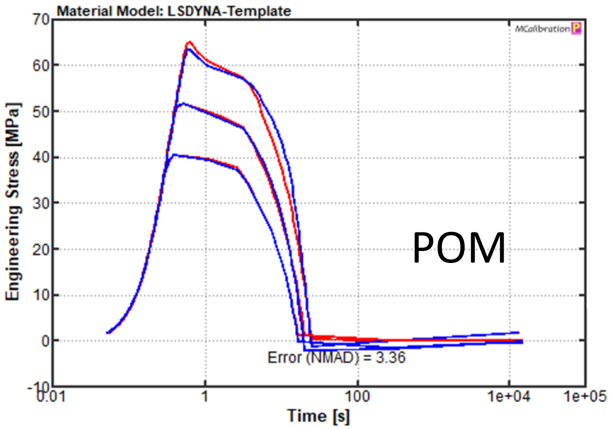


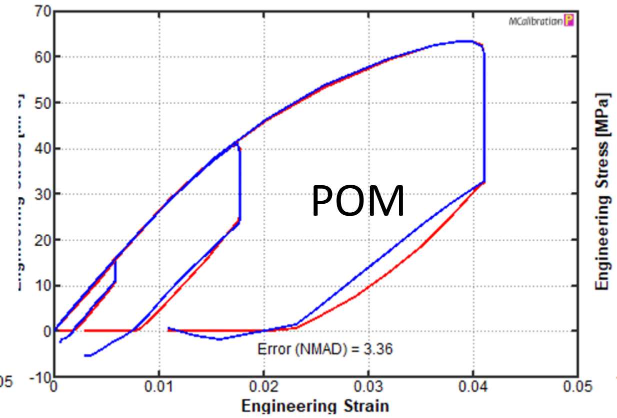


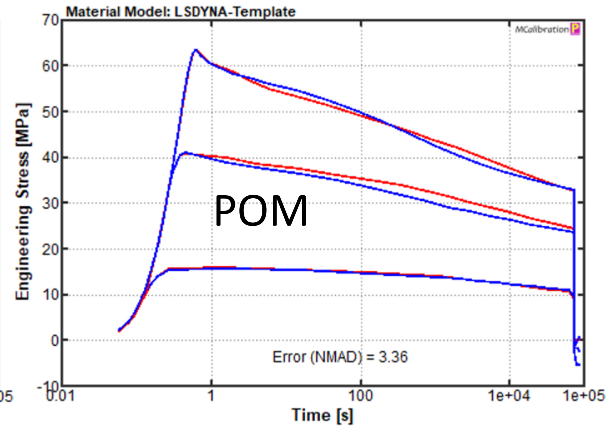








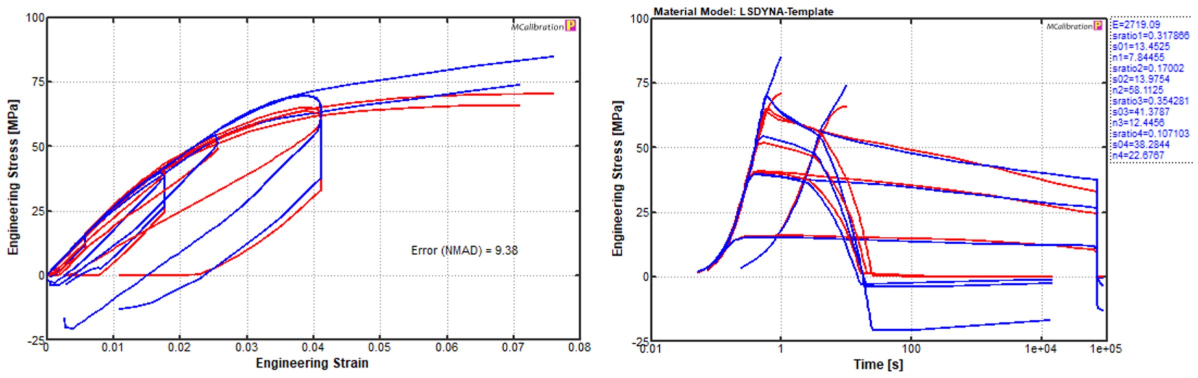




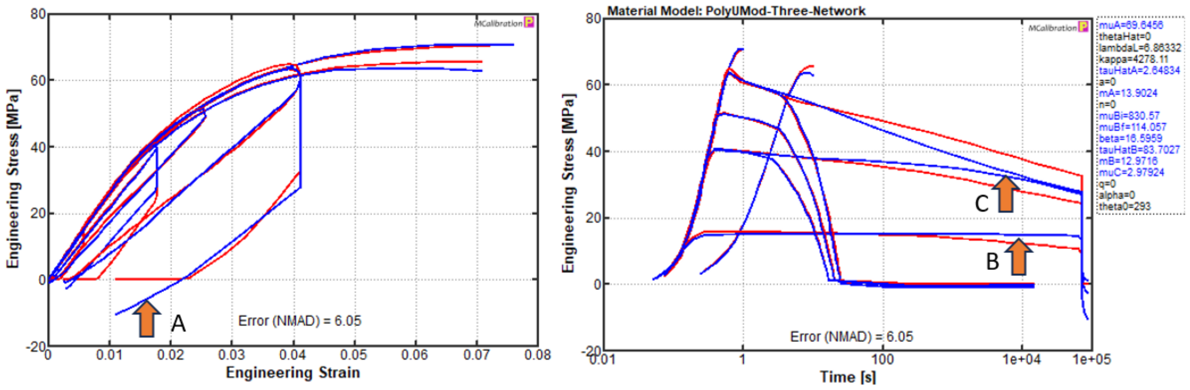
Comparison to MAI and TNM

- To assess the results of fitting, the same was done to a 5-link MAI network and the TNM model for POM
- While MAI isn't even visually promising, TNM shows overall decent results except for the inability to properly represent recovery (A) and relaxation (B,C)
- The error in these fits are 9.38% (MAI) and 6.05% (TNM), concluding that the proposed model is superior in the context of fitting the investigated thermoplastics

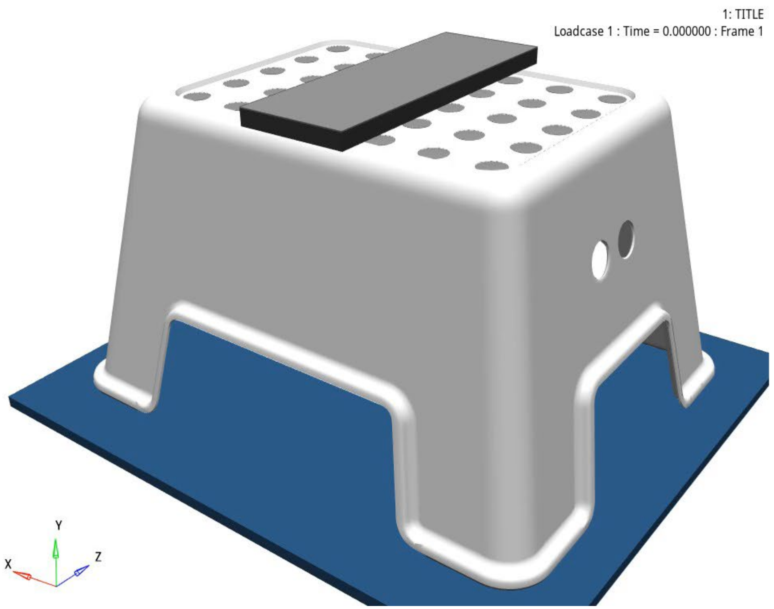
MAI

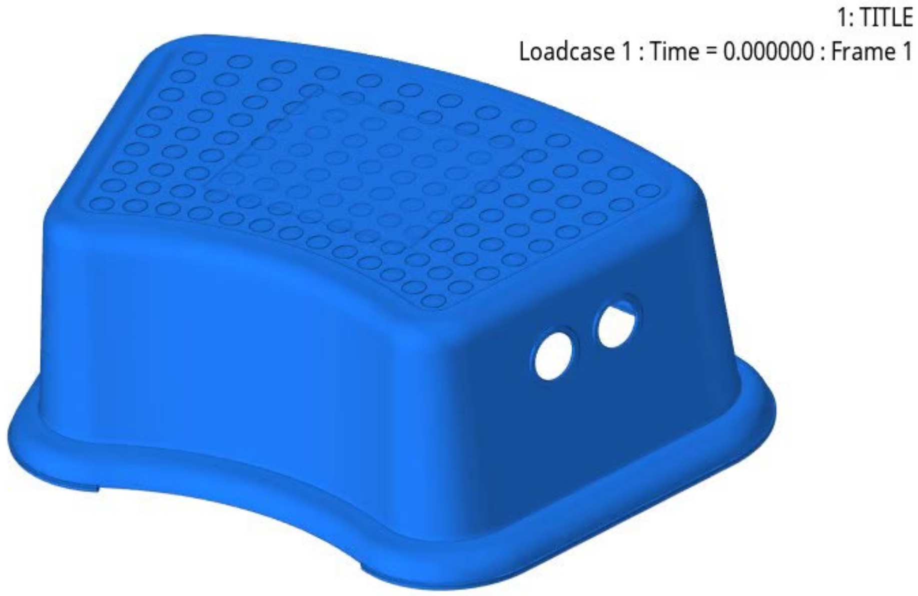


TNM



Application Examples





- The application examples serve the purpose of testing the model for robustness, speed and accuracy by comparing it with commercially available correspondents
- Indicative speed up when compared to MAI and TNM is roughly a factor of 3
- No robustness issues thus far, and results compare visually well with TNM

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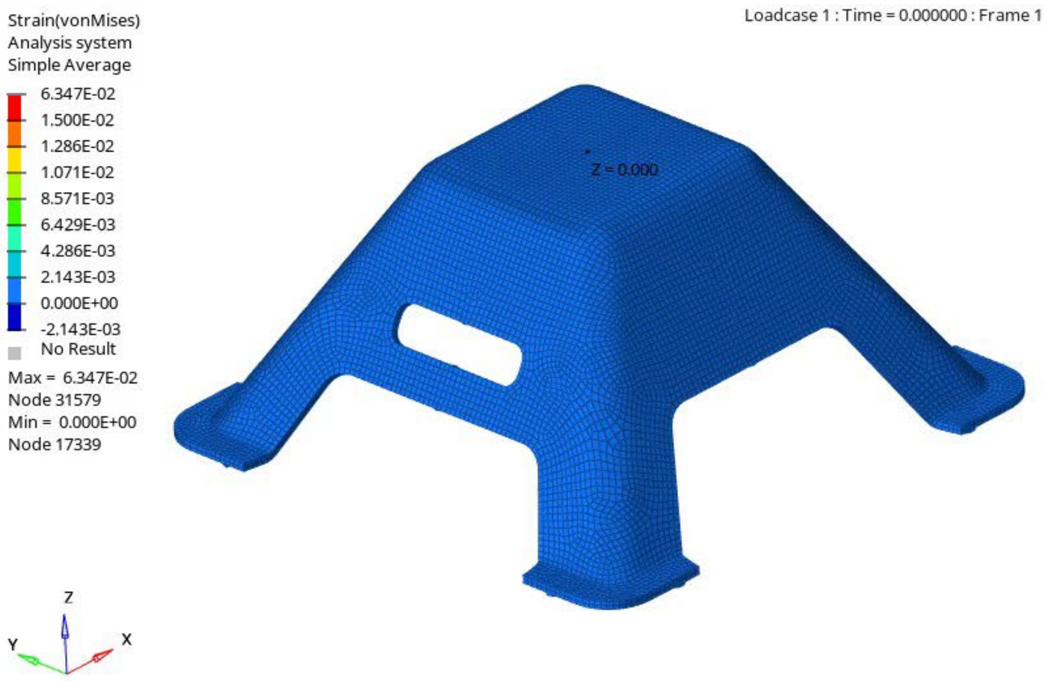
Application Examples



- The application examples serve the purpose of testing the model for robustness, speed and accuracy by comparing it with commercially available correspondents
- Indicative speed up when compared to MAI and TNM is roughly a factor of 3
- No robustness issues thus far, and results compare visually well with TNM and MAI

Summary

- The industry is constantly demanding more sophisticated polymer components to meet competition and sustainability agendas
- Established material models within the family of rheological frameworks are widely adopted due to their natural capability to mimic time effects in polymers
- A few shortcomings in commercial models have been presented and addressed in this paper, by means of proposing an alternate (pragmatic) constitutive approach to the rheological framework
- The proposed model shows highly desired accuracy combined with efficiency and robustness necessary for conducting the application simulations
- Some issues remain to be resolved, but the overall assessment is that the model is a promising candidate for virtually representing a wide variety of thermoplastics