UNIVERSIDADE DE COIMBRA
FACULDADE DE CIÊNCIAS E TECNOLOGIA

Mechanical characterization of a polyurethane using a hyper-viscoelastic constitutive model

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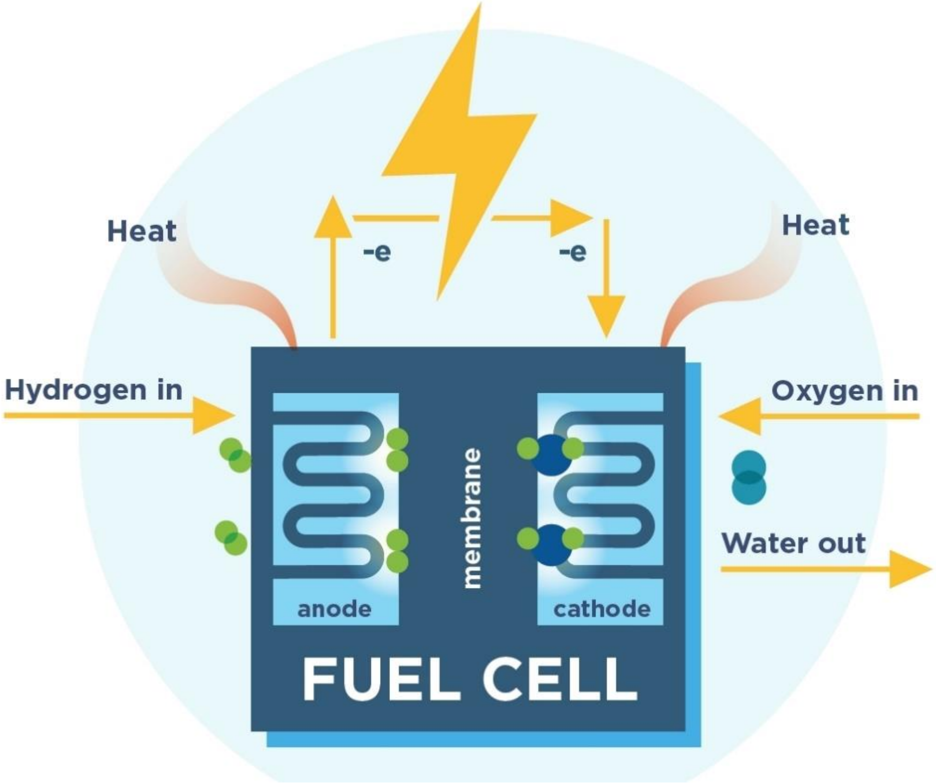
Fuel cell technology

- Unlike traditional combustion technologies that burn fuel, **fuel cells** undergo a chemical process to convert hydrogen-rich fuel into electricity

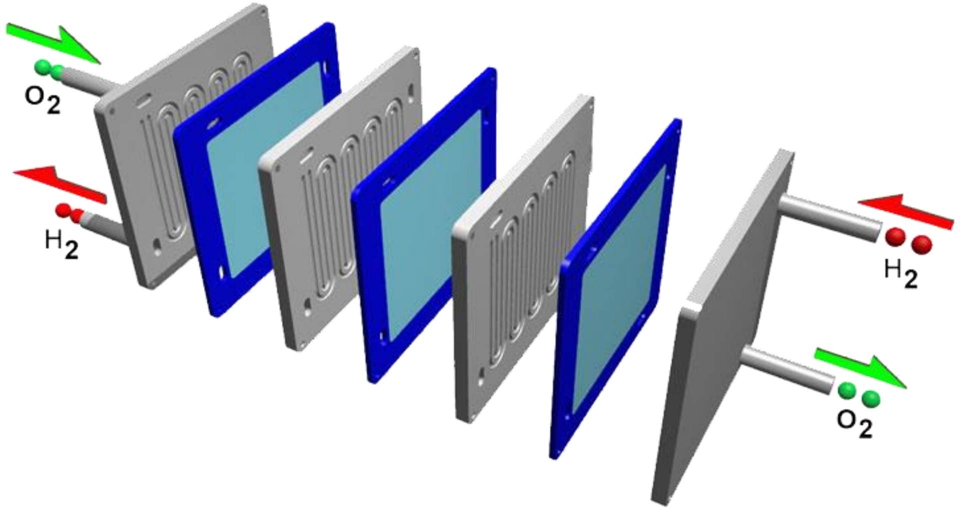


Advantages:

- Low-to-Zero Emissions
- High Efficiency
- Reliability
- Fuel Flexibility
- Energy Security
- Durability
- Scalability
- Quiet Operation

PEM Fuel Cells

- Among the most commonly used types of fuel cells are the **Proton exchange membrane (PEM) fuel cells**
- **Bipolar plates** are one of the main components of the PEM fuel cells, contributing to about 60–80% of the stack **weight** and 25–45% of the stack **cost**
- A PEM fuel cell for a typical **passenger car** contains about **400–500 bipolar plates**

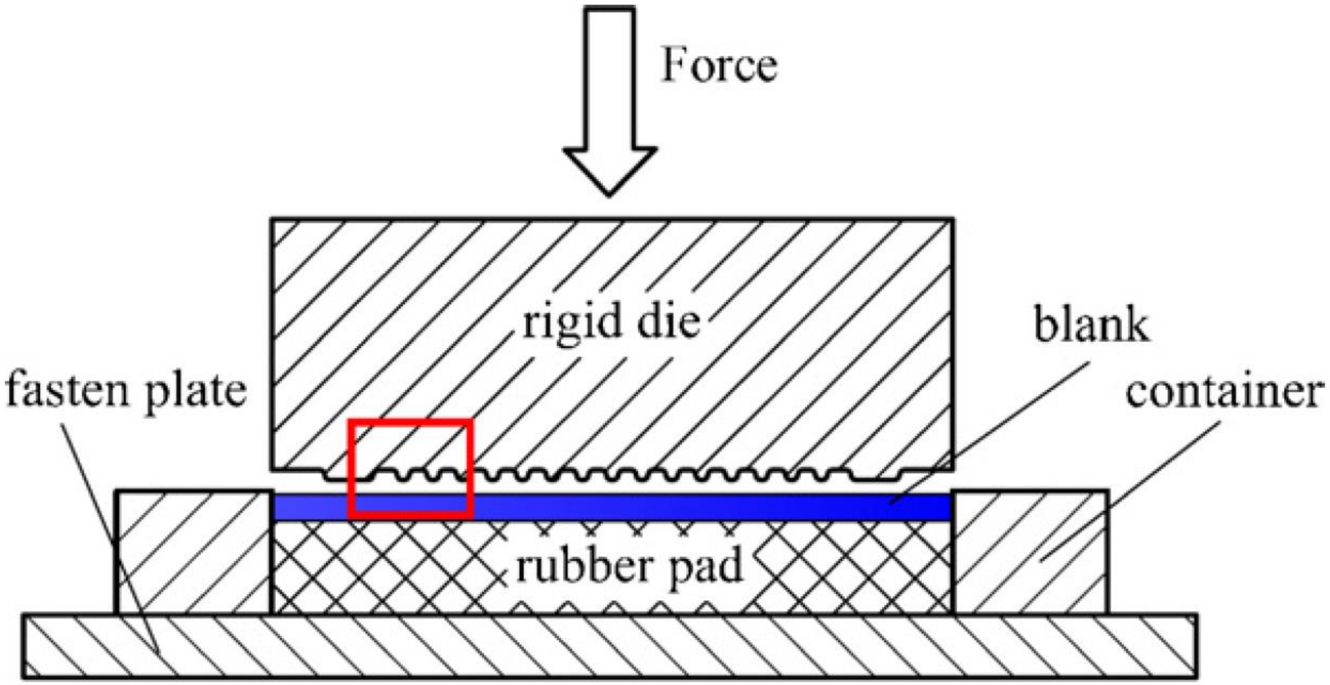


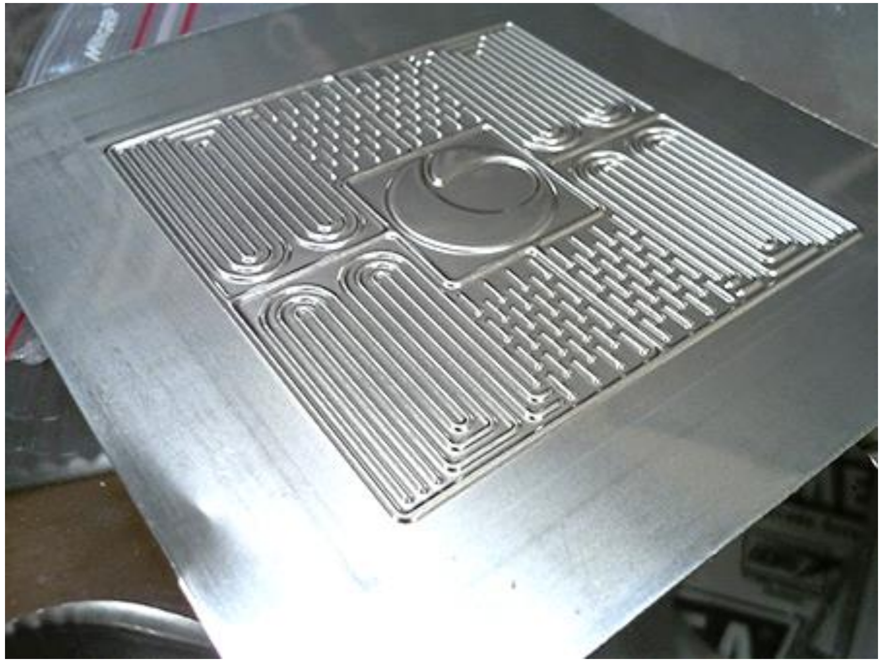
Bipolar plates (BPPs)

- Bipolar plate materials are broadly divided into **metallic** (e.g. titanium, stainless steel, aluminum) and **carbon-based** (e.g. graphite)
- BPPs can be produced by several manufacturing techniques like forming, milling and casting
- **The rubber pad forming process** is adopted in the manufacturing of **thin stamped bipolar plates**

Stamped bipolar plates by rubber pad forming

- The main advantages are **low tooling costs**, **mark-free surface** of the workpiece and **better formability** when compared to conventional press technology
- The **wear of the rubber** is an issue in large quantity manufacturing





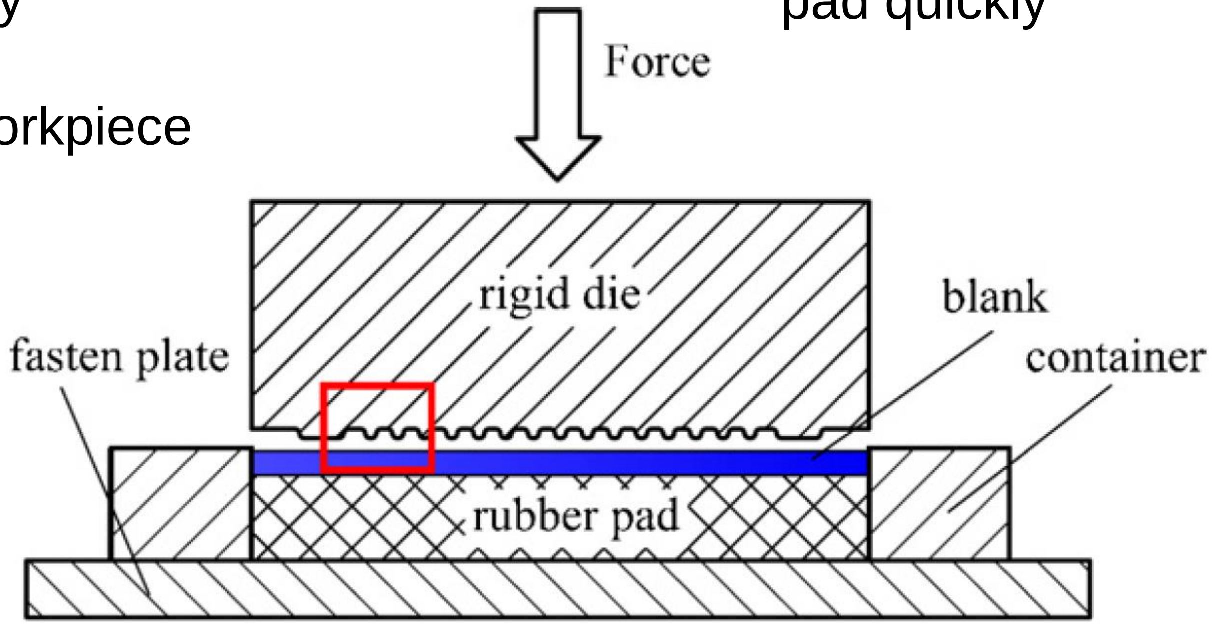
Stamped bipolar plates by rubber pad forming

Advantages:

- A single rubber pad can be used with **different die shapes**
- **Better formability** when compared to conventional press technology
- **Mark-free surface** of the workpiece
- **Low tooling costs**

Disadvantages:

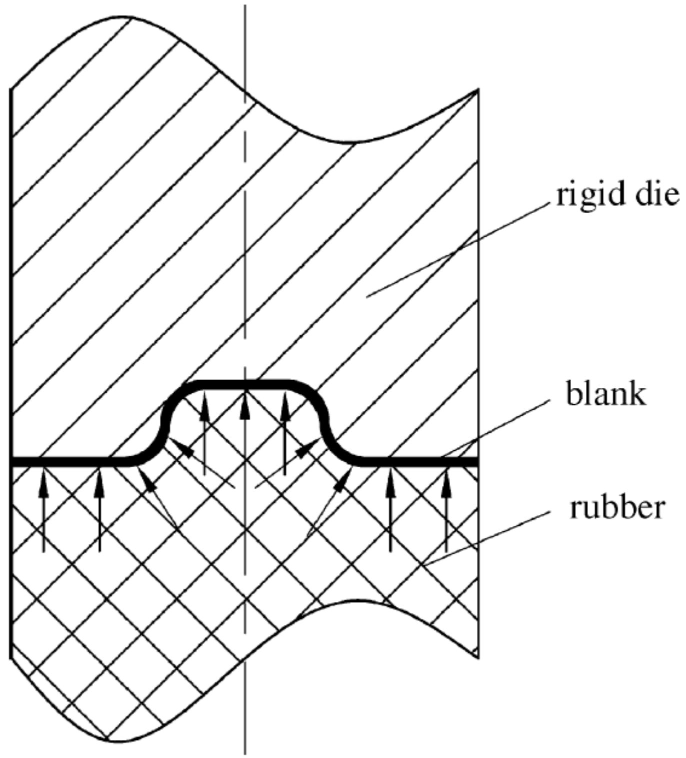
- The **wear of the rubber** is an issue in large quantity manufacturing
- Sharp projections **wear out the rubber** pad quickly

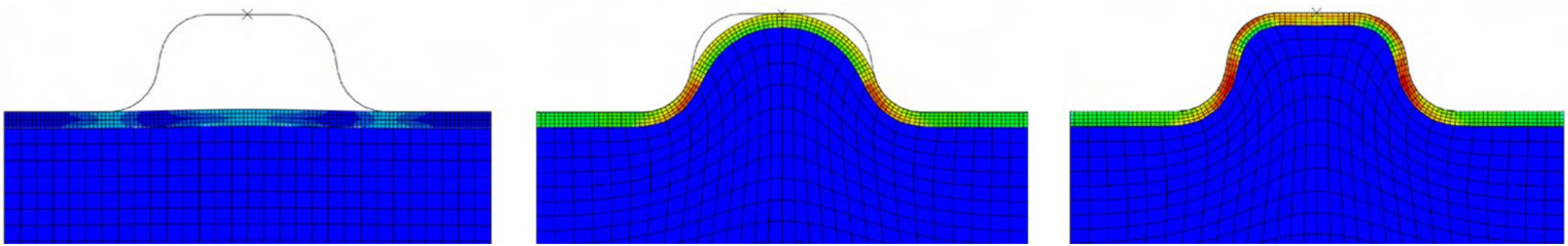


Numerical simulation of the rubber forming process

- **Numerical simulation** tools are adopted in the design and optimization of the forming processes to reduce **development cost** and **time-to-market** for new bipolar plates

- The accuracy of the numerical solutions is strongly dependent on the numerical models (**constitutive laws** for the **blank** and for the **rubber pad**) adopted in the finite element simulation



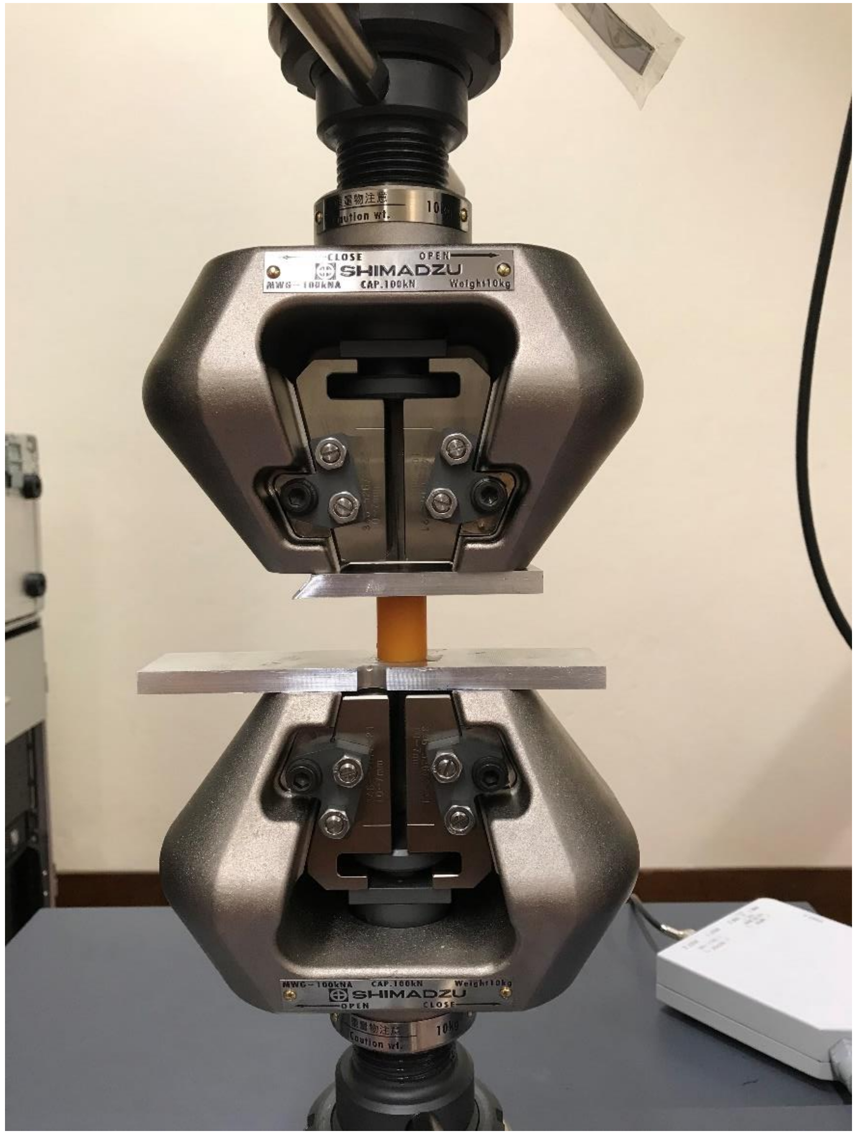


Rubber material specimens

- **Polyurethane (PUR) rubber** with **70 Shore A** of hardness
- Cylindrical specimens with D = 18 mm and H = 25 mm

Mechanical tests performed

- **Uniaxial compression tests** (loading, permanency and unloading)
  - ❑ 3 values of **grip speed** during the loading-unloading stage (0.05 mm/s, 0.5 mm/s and 5 mm/s)
- **Stress relaxation tests**
  - ❑ A stretch of 0.65 is kept constant for 10.000 seconds
  - ❑ Loading stage performed with the largest grip velocity (5 mm/s)



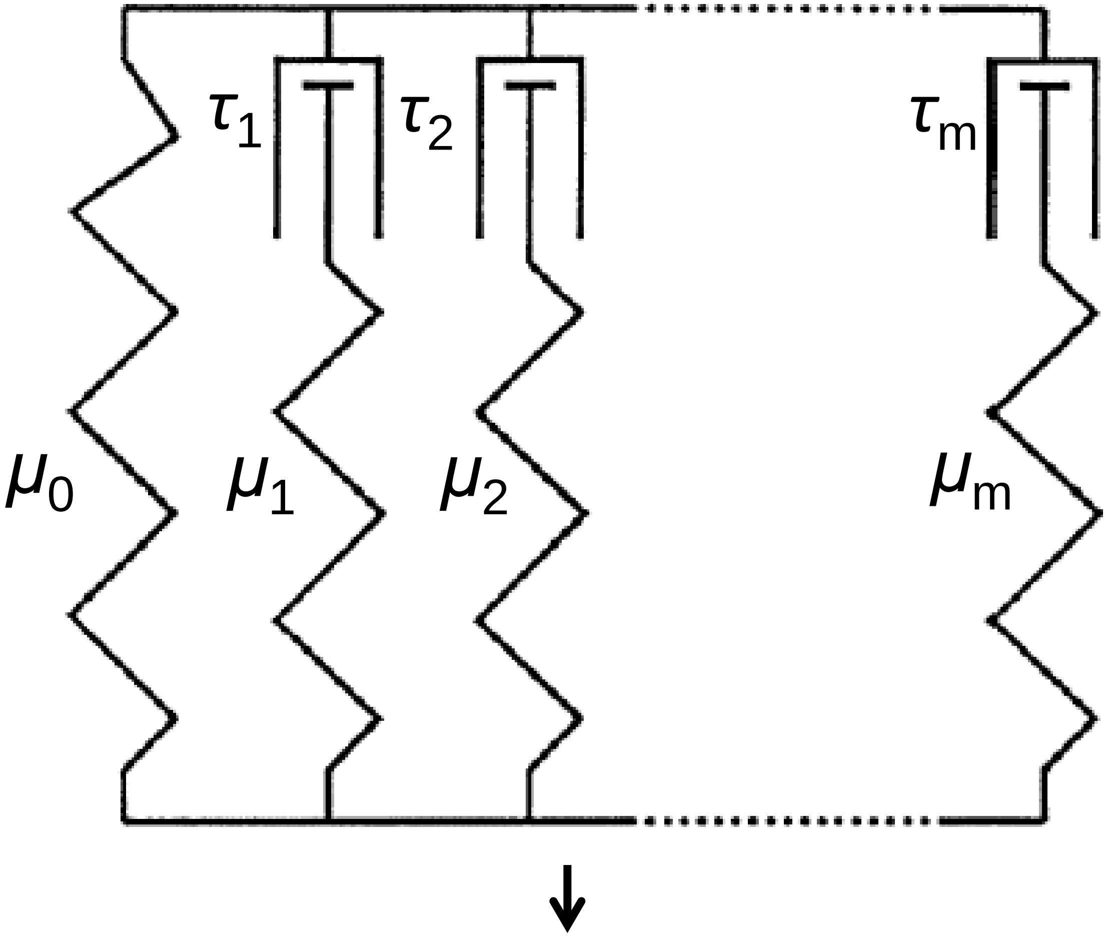
Mechanical tests performed

- **Free vibration tests**

  - Equipment: **Yerzley's oscillograph**
  - A mass is placed on one side of the beam at a distance L_m of the fulcrum while the specimen is placed on the opposite side at a distance L_s of the fulcrum
  - The unbalanced arms of the beam produce a pre-compression force on the specimen
  - An external perturbation applied to the beam makes the system oscillate
  - Displacement and force values are recorded

Hyper-viscoelastic constitutive model

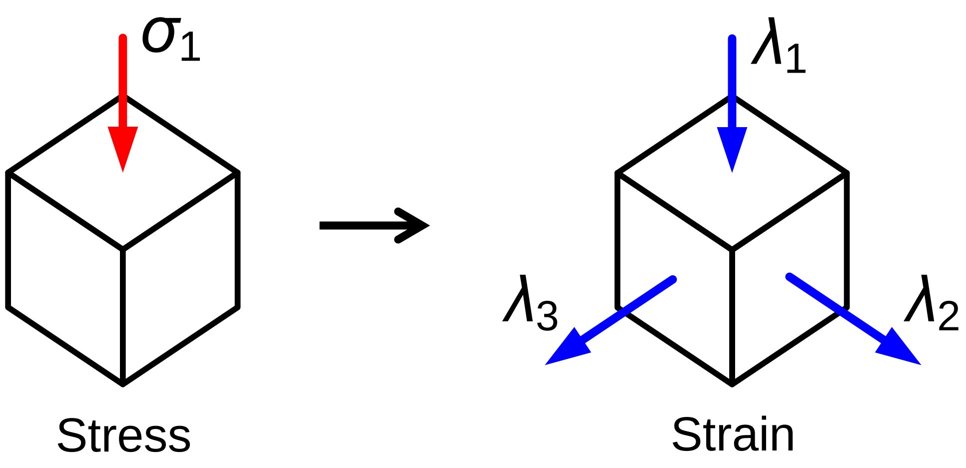
- The **hyperelasticity** is described by the Mooney-Rivlin model (2 parameters – C_{10} and C_{01})
- The **viscoelasticity** is described by *m* Maxwell elements
- Each Maxwell element is defined by 2 parameters:
  - ❑ Relaxation time (τ)
  - ❑ $ak_i = \frac{\mu_i}{\mu_0}$



Rheological spring-dashpot model (Generalized Maxwell Model)

Uniaxial compression stress state

- Assumptions:
  - ❑ Incompressible material
  - ❑ Isotropic material



$$\begin{cases} \lambda_1 = \lambda \\ \lambda_2 = 1/\sqrt{\lambda} \\ \lambda_3 = 1/\sqrt{\lambda} \end{cases}$$

- 2nd Piola-Kirchhoff stress from hyperelasticity:

$$\Pi_{\text{MR}} = 2(\lambda^{-1} - \lambda^{-4})(C_{10}\lambda + C_{01})$$

- 2nd Piola-Kirchhoff stress from viscoelasticity:

$$\Pi_{\text{MW}_i}^{\;n+1} = \exp\left(-\frac{\Delta t}{\tau_i}\right)\Pi_{\text{MW}_i}^{\;n} + \frac{ak_i\tau_i}{\Delta t}\left[1 - \exp\left(-\frac{\Delta t}{\tau_i}\right)\right](\Pi_{\text{MR}}^{\;n+1} - \Pi_{\text{MR}}^{\;n})$$

$$\Pi_{\text{Total}} = \Pi_{\text{MR}} + \sum_{i=1}^{m} \Pi_{\text{MW}_i}$$

Least Squares fitting

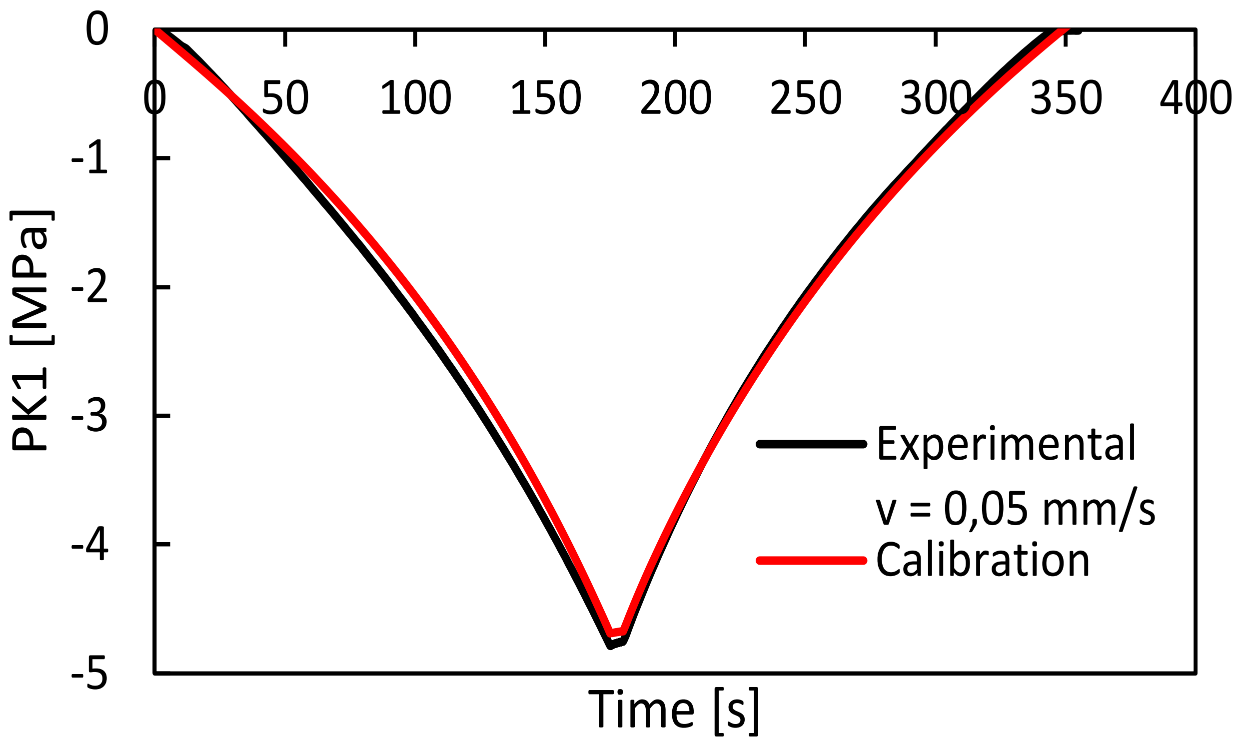
- Minimization of the difference between numerical and experimental PK1 stress, considering **all tests simultaneously** (3 uniaxial compression tests + 1 stress relaxation test + 1 free vibration test)

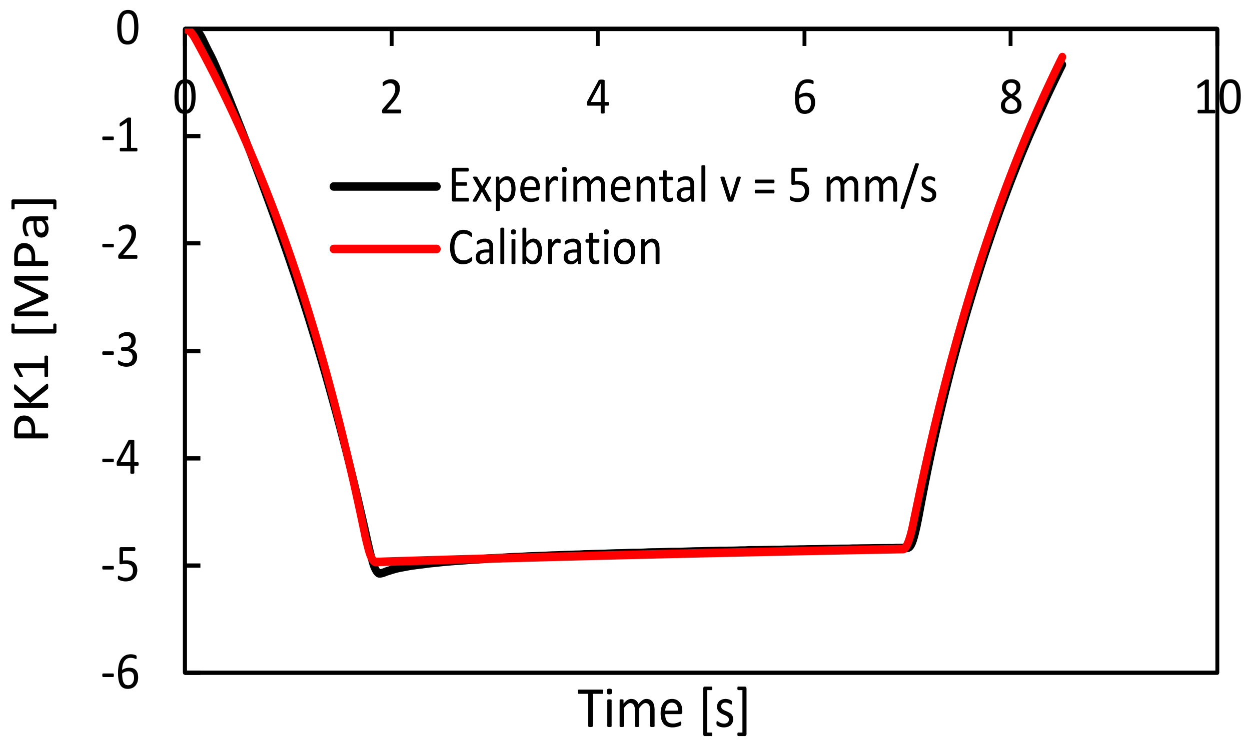
  - **Hyper-viscoelastic model** (2 + 2 x 4 = 10 material parameters)

C_{10}	C_{01}	ak_1	ak_2	ak_3	ak_4	τ_1	τ_2	τ_3	τ_4
1,19882	0	10^{-5}	0,069804	0,64690	0,09290	12763,88	9,38	0,00437	726,02

Uniaxial compression tests

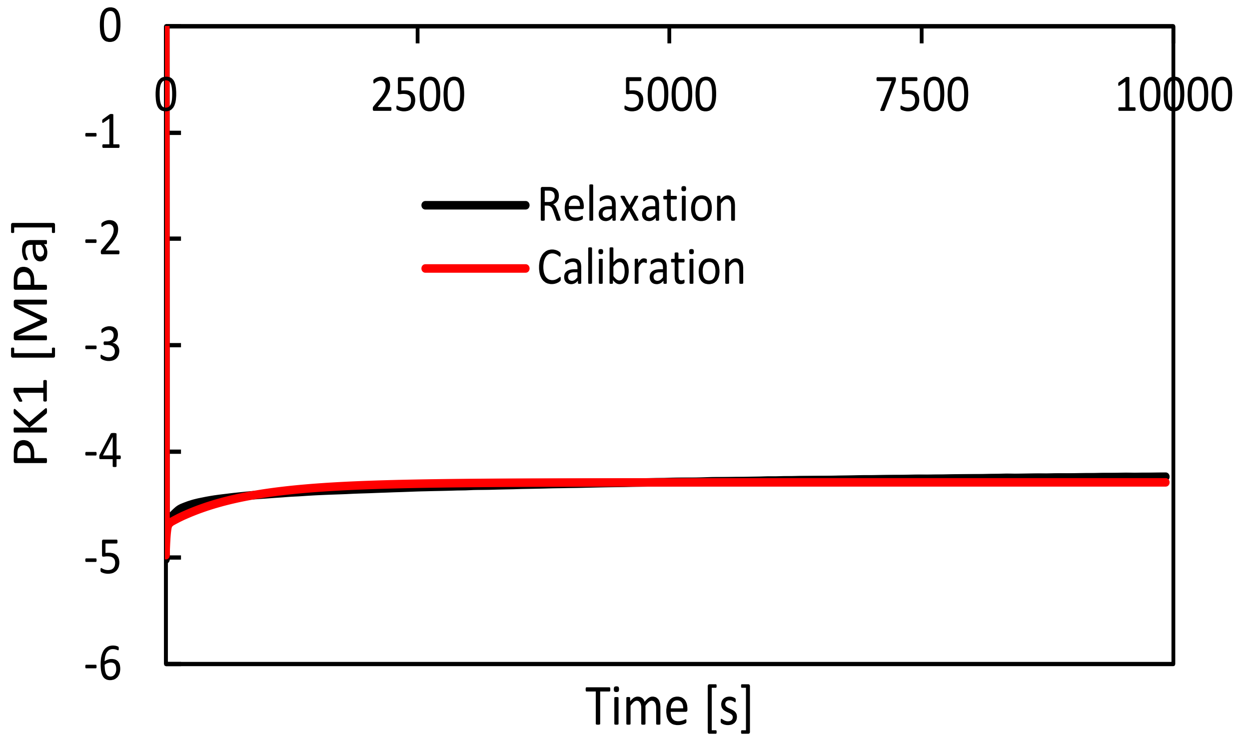
- Loading and unloading at 0.05 mm/s and 5 mm/s grip speed





Stress relaxation test

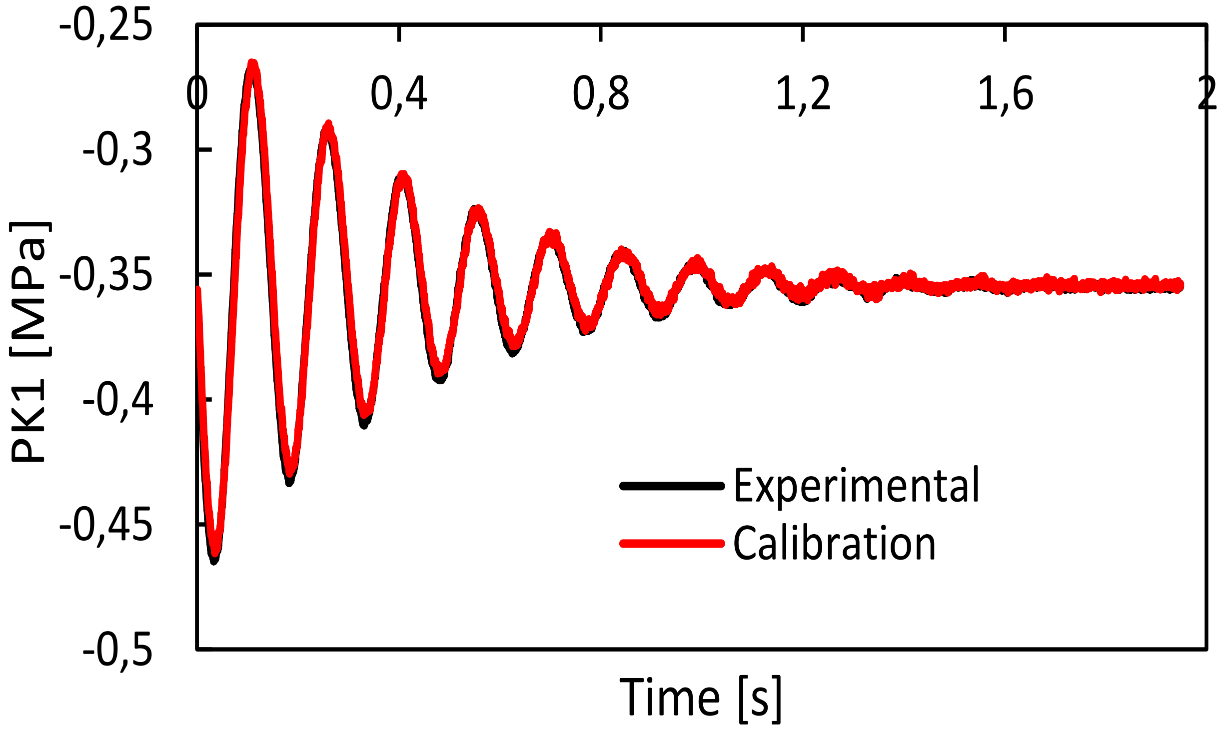
- Constant value of stretch of 0.65
- Relaxation of 10 000 s



Experimental and Numerical Stress

Free vibration test

- Evolution of PK1 stress for approximately 2 seconds
- The mean value of the curve represents the stress imposed by the pre-compression force



Conclusions

- Mechanical characterization of a polyurethane (PUR) rubber
- The identified material parameters can predict very accurately the mechanical behavior of the polyurethane in all tests performed
- This model will be applied in the numerical simulation of rubber pad forming of thin BPPs
- Calibration of material parameters considers only the uniaxial stress state, but several strain paths arise in the rubber pad forming process
- Further mechanical tests are required for a more complete characterization

Acknowledgements

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Thank you for your attention!