UNIVERSIDADE D COIMBRA
FACULDADE DE CIÊNCIAS E TECNOLOGIA

THE ROLE OF VISCOELASTICITY IN THE MECHANICAL MODELLING OF RUBBERS

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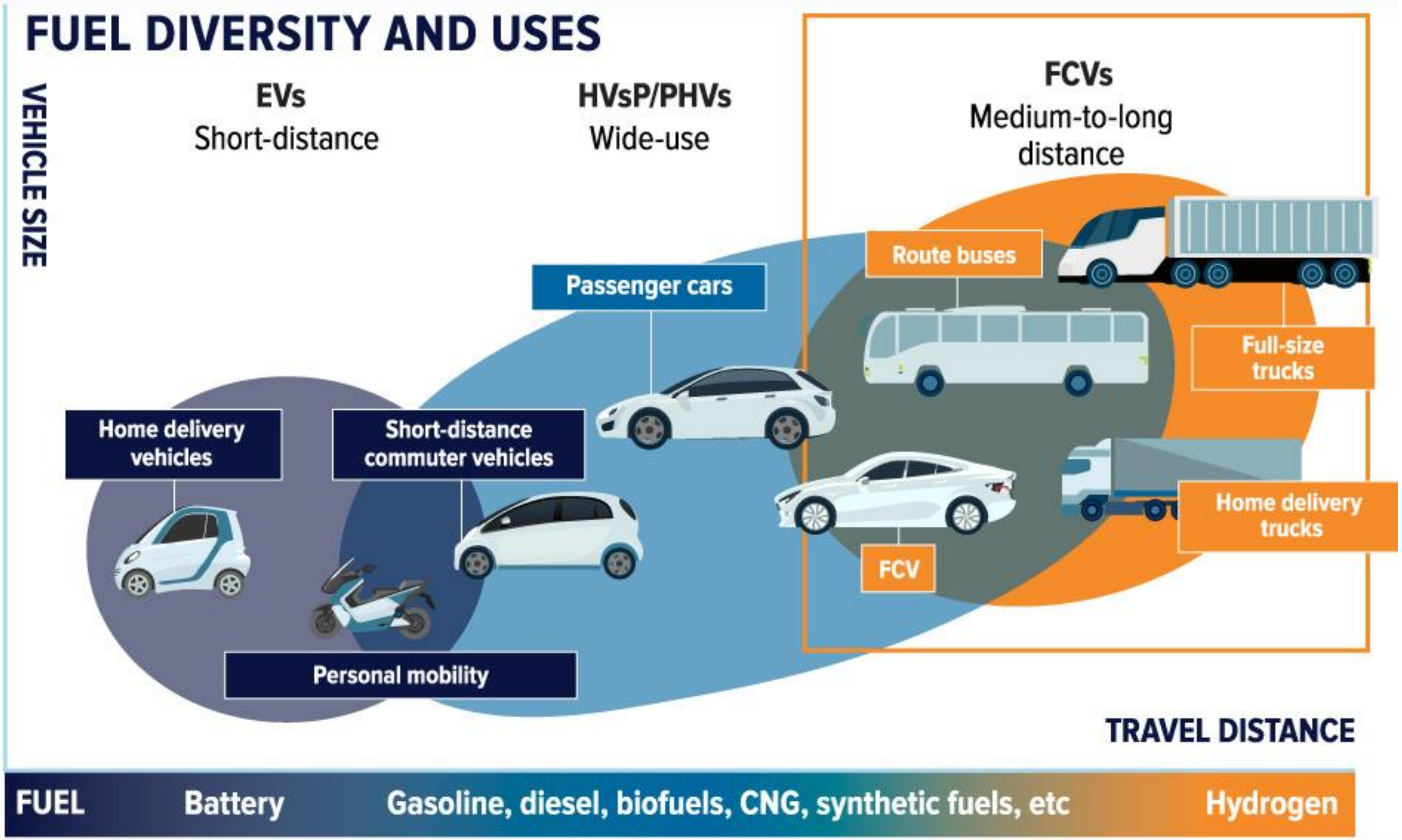
Vehicles utilization according with the type of fuel

Battery vehicles are appropriate for short-distance travels

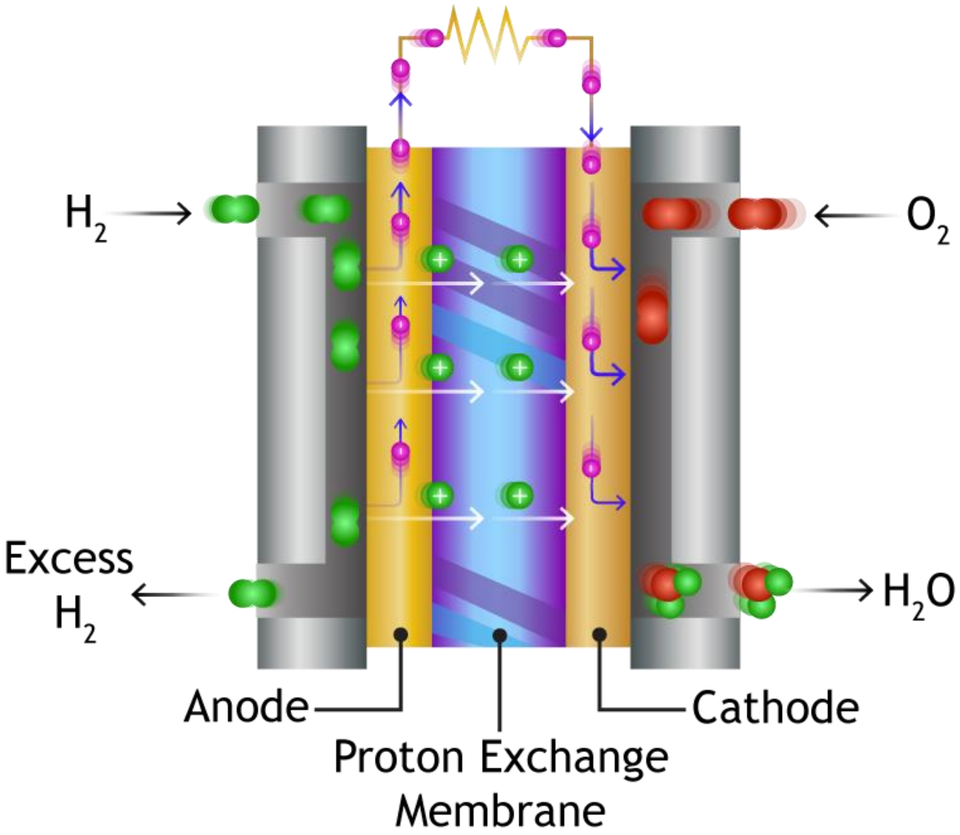


Hydrogen vehicles are appropriate for long-distance travels

Hydrogen Electric Vehicles

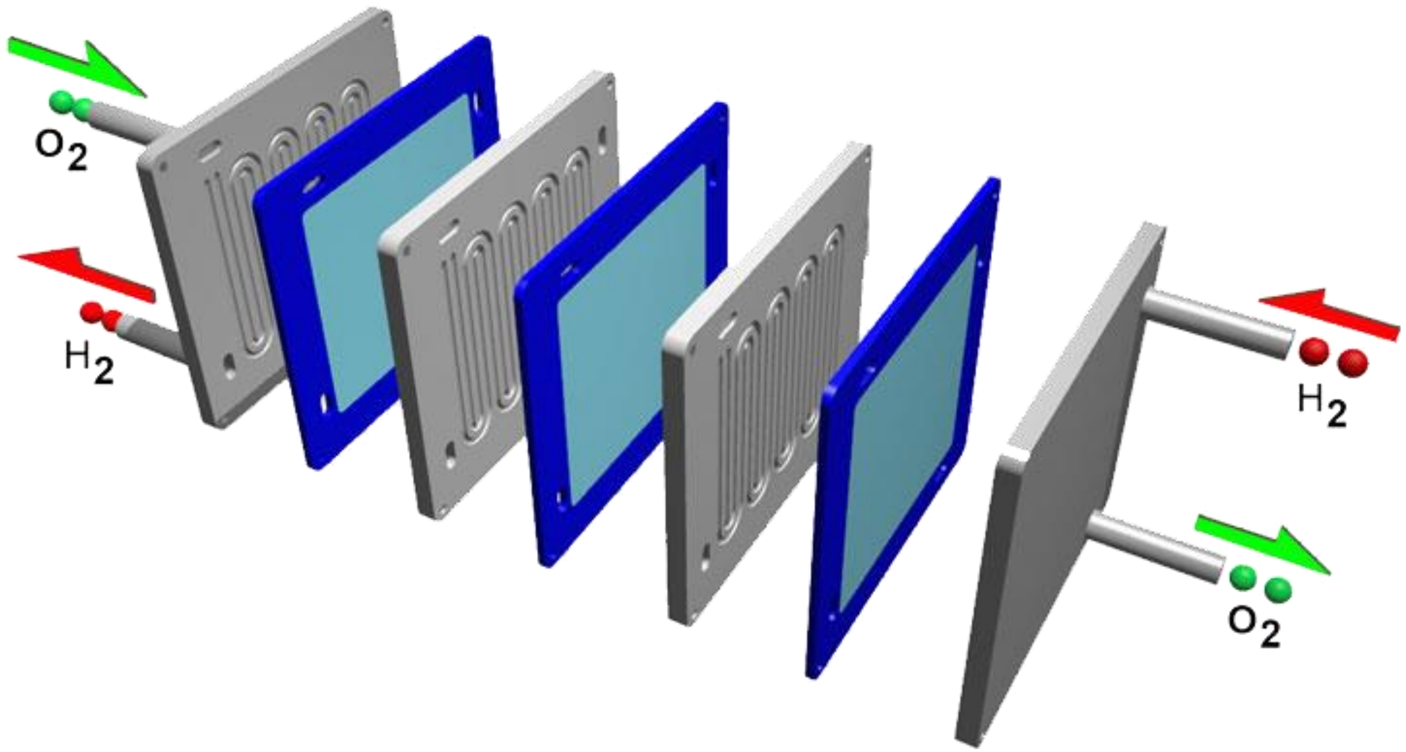
- **Proton exchange membrane (PEM) fuel cells** are electrochemical devices that convert the chemical energy of a fuel (hydrogen) directly to electrical energy

- **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**



PEM Fuel Cells

- Fuel cell is comprised of a series arrangement of “**repeating cell units**” stacked together
- A PEM fuel cell for a typical **passenger car** contains about **400–500 bipolar plates**

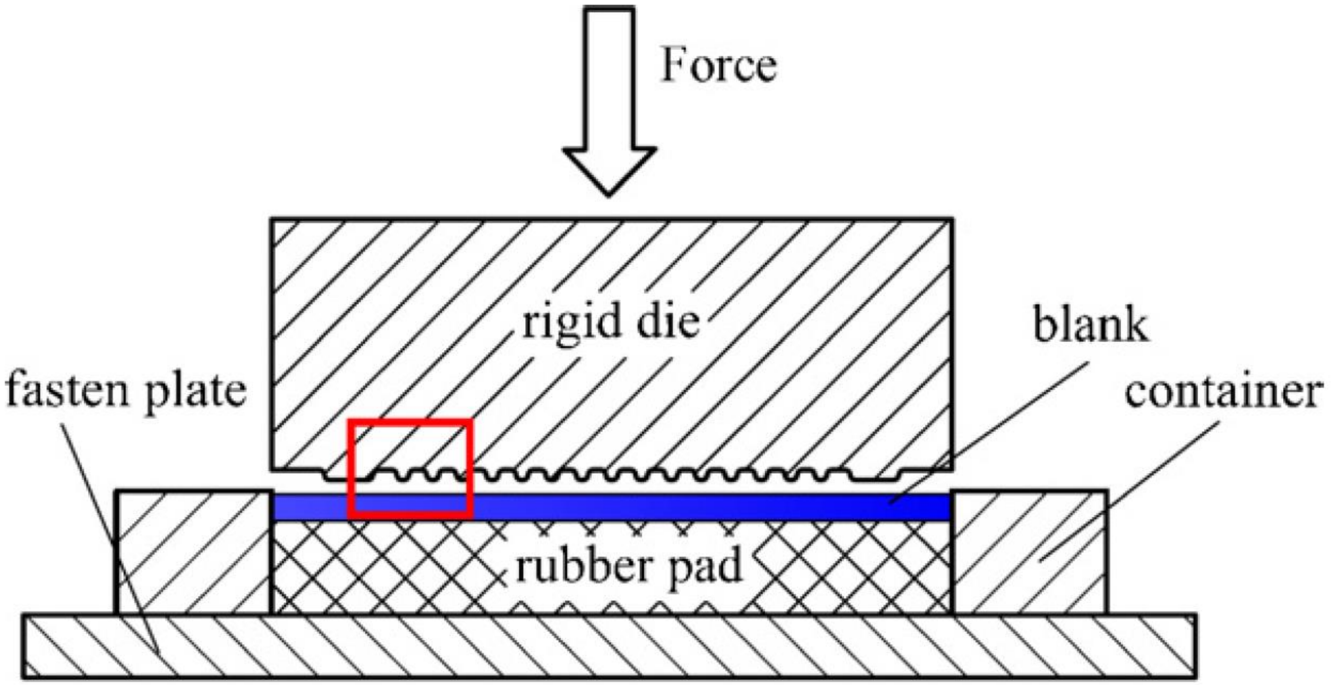


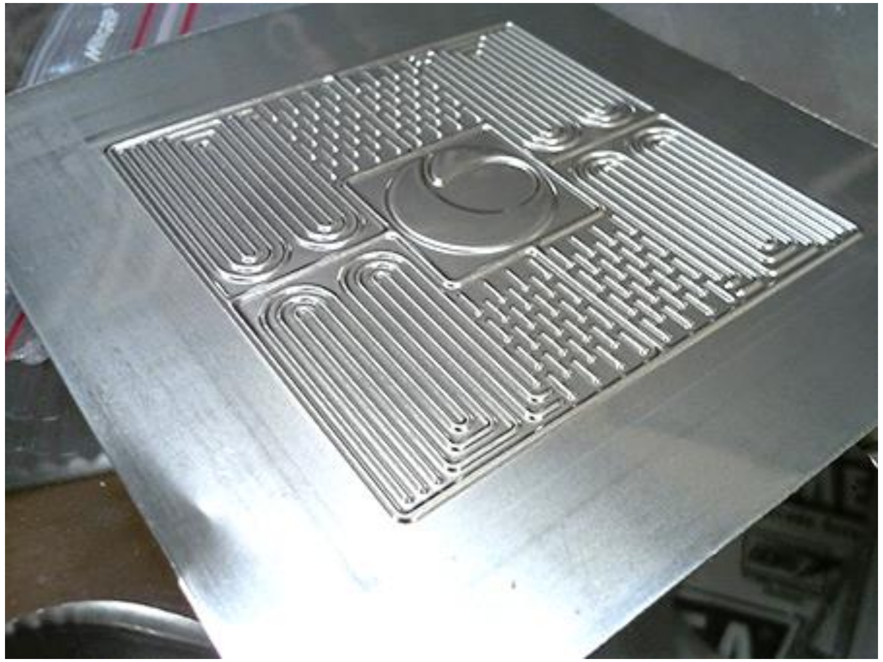
Bipolar plates

- Bipolar plate materials are broadly divided into **metallic** (e.g. titanium, stainless steel, aluminum) and **carbon-based** (e.g. graphite)
- Several manufacturing techniques are used to produce metallic bipolar plates (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



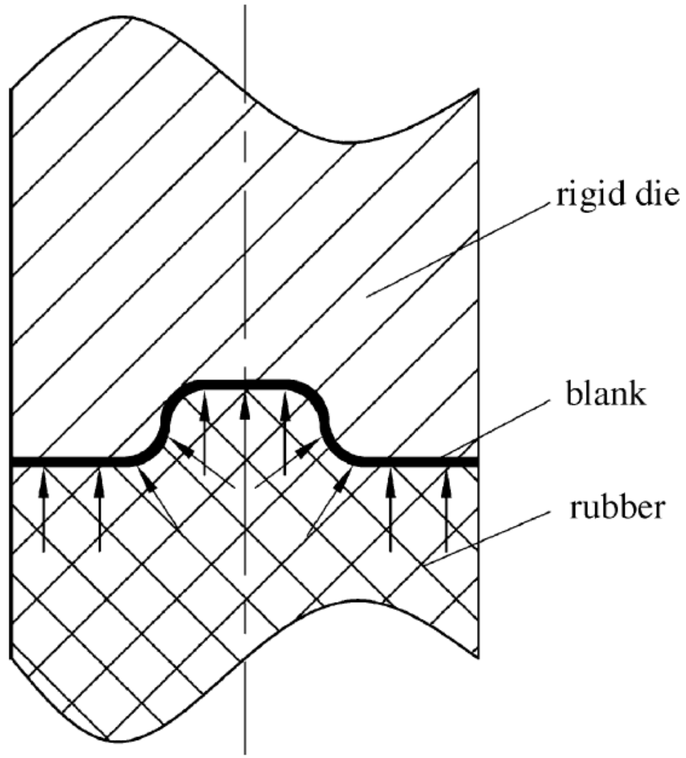


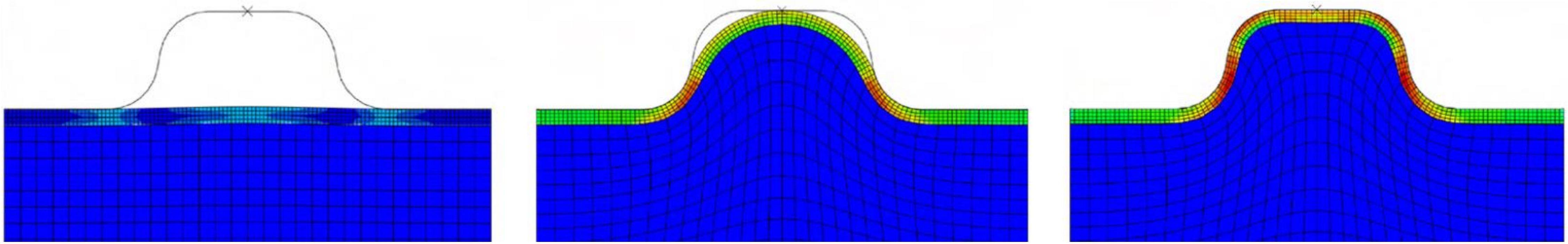
Introduction

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

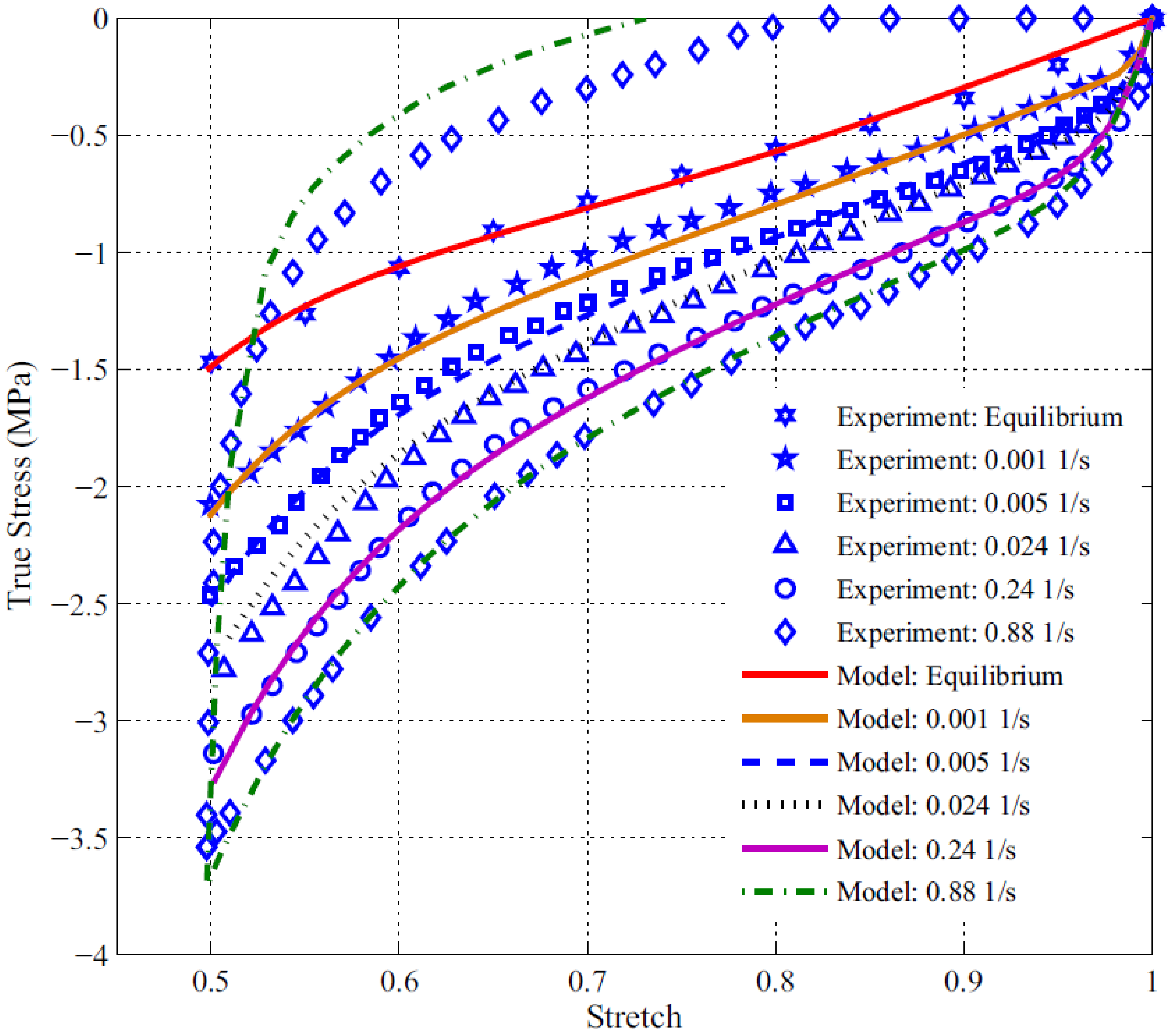




Visco-hyperelastic constitutive model

- The **rate-dependent** behavior of the rubber pad at **large deformations** is modelled by a **visco-hyperelastic constitutive model**

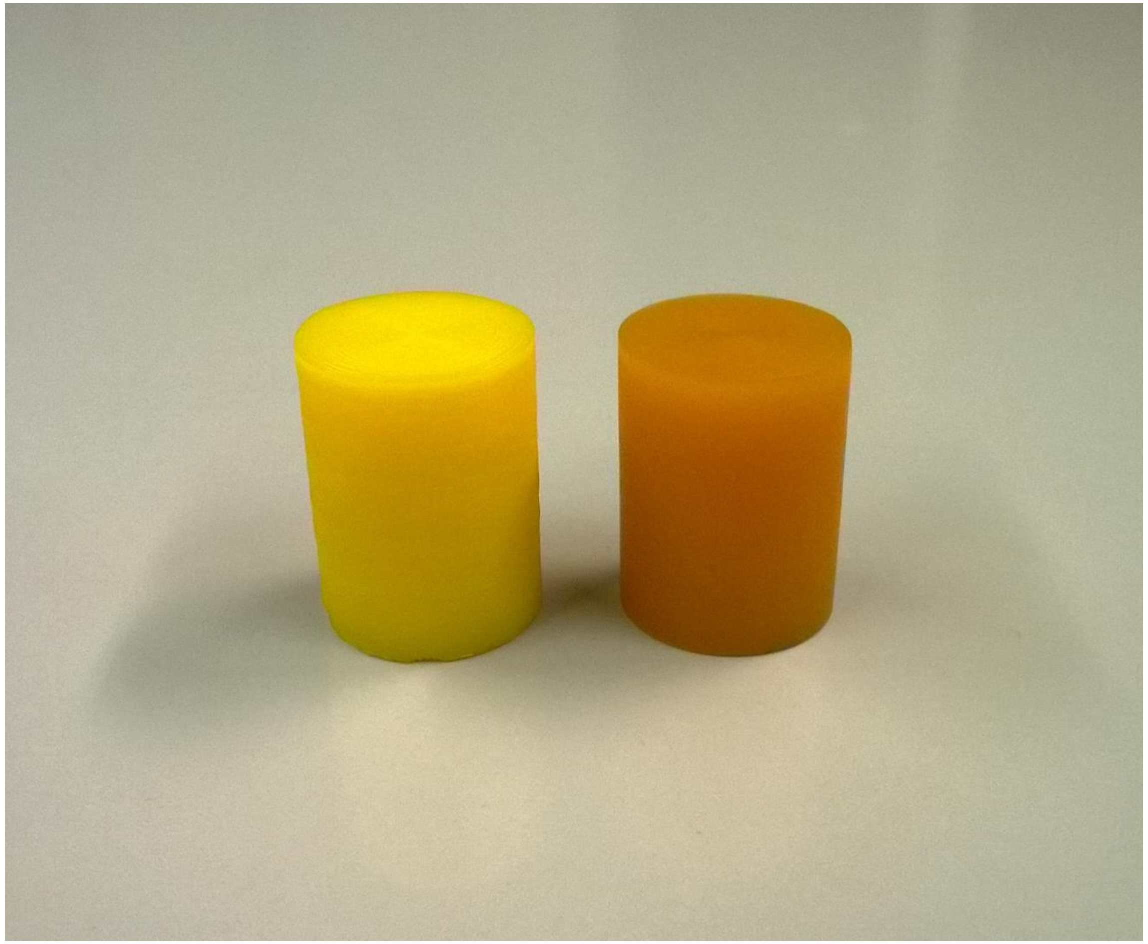
- The main objective of this study is to evaluate the **importance of the viscous effect** on the global behavior of the rubber pad during the forming process



Rubber materials studied

- 2 different **polyurethane (PUR) rubbers** with different values of hardness:
  - ❑ **70 Shore A** (yellow specimen)
  - ❑ **95 Shore A** (orange specimen)

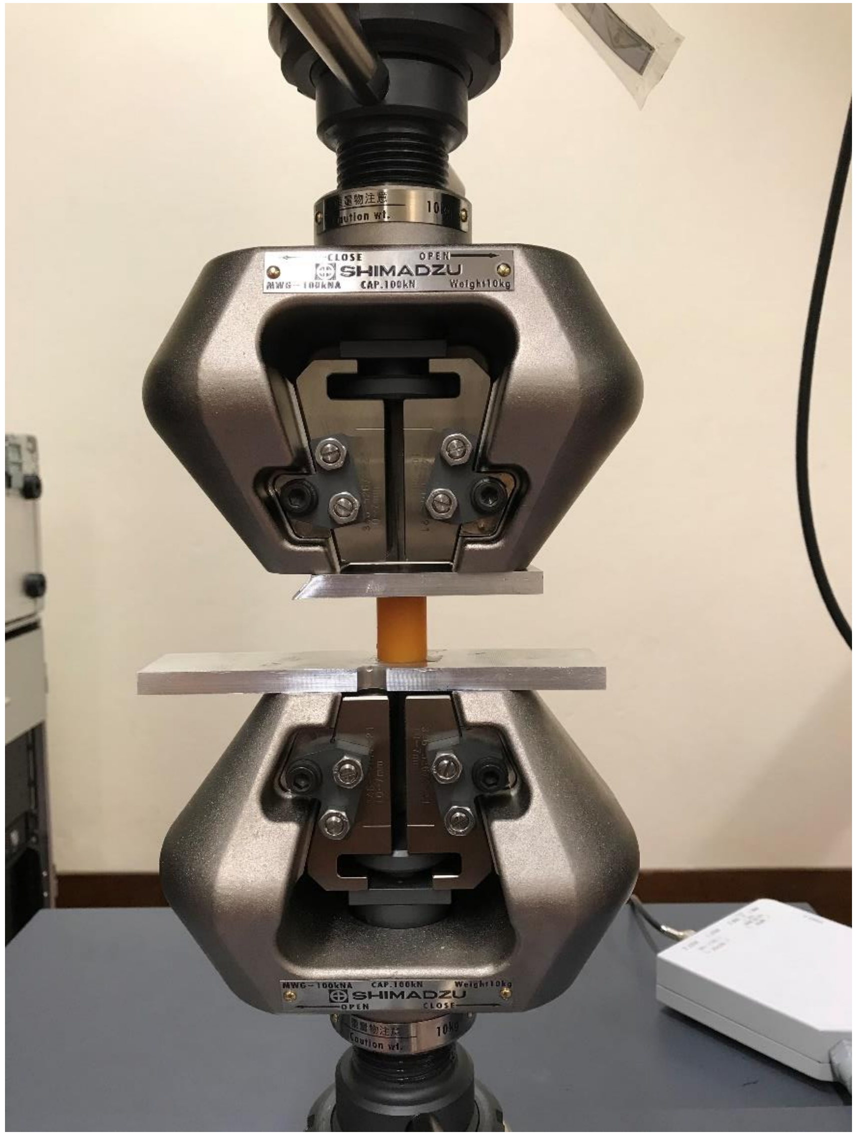
- Cylindrical specimens with 18 mm of diameter and 25 mm of height



Mechanical tests performed

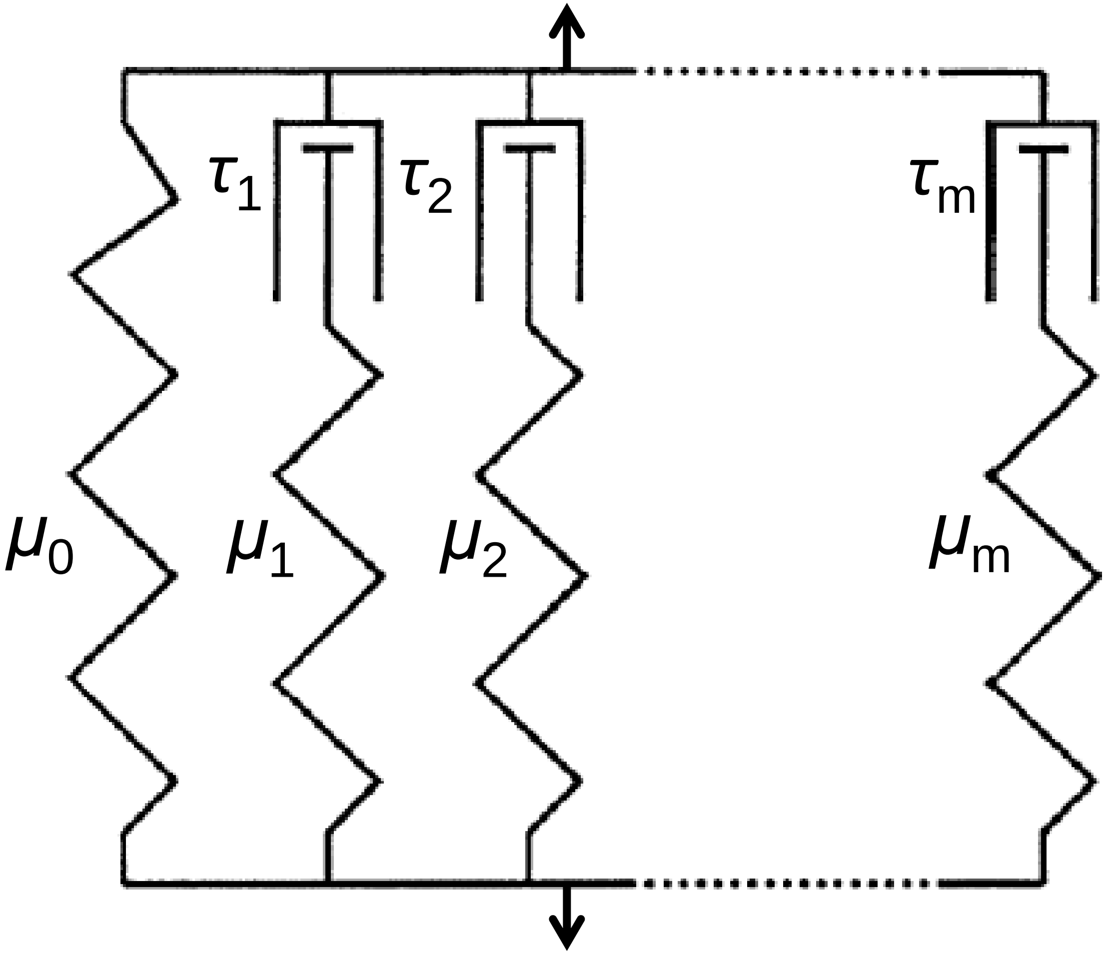
- **Uniaxial compression tests** comprising loading, permanency and unloading
  - ❑ 3 values of **grip speed** during the loading-unloading stage (0.05 mm/s, 0.5 mm/s and 5 mm/s)

- **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)



Visco-hyperelastic constitutive model

- The **hyperelasticity** is described by the Mooney-Rivlin model (2 parameters in the strain energy density function)
- The **viscoelasticity** is described by *m* Maxwell elements
- Each Maxwell element is defined by 2 parameters:
  - ❑ Relaxation time (τ)
  - ❑ $ak_i = \dfrac{\mu_i}{\mu_0}$

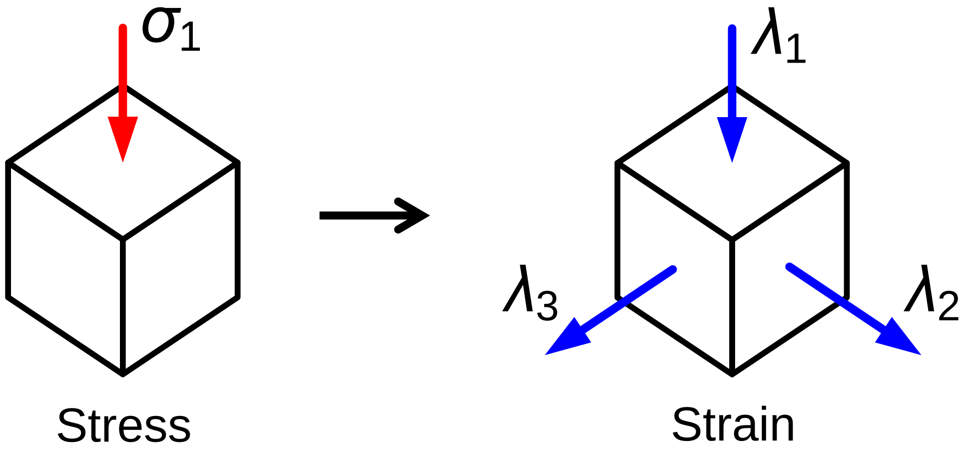


Rheological spring-dashpot model

Numerical 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:

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

- 2nd Piola-Kirchhoff stress from viscoelasticity:

$$P_{\mathrm{MW}_i}{}^{n+1} = \exp\left(-\frac{\Delta t}{\tau_i}\right) P_{\mathrm{MW}_i}{}^{n} + \frac{a k_i \tau_i}{\Delta t}\left[1 - \exp\left(-\frac{\Delta t}{\tau_i}\right)\right](P_{\mathrm{MR}}{}^{n+1} - P_{\mathrm{MR}}{}^{n})$$

$$P_{\mathrm{Total}} = P_{\mathrm{MR}} + \sum_{i=1}^{m} P_{\mathrm{MW}_i}$$

Calibration of Material Parameters

Least Squares fitting

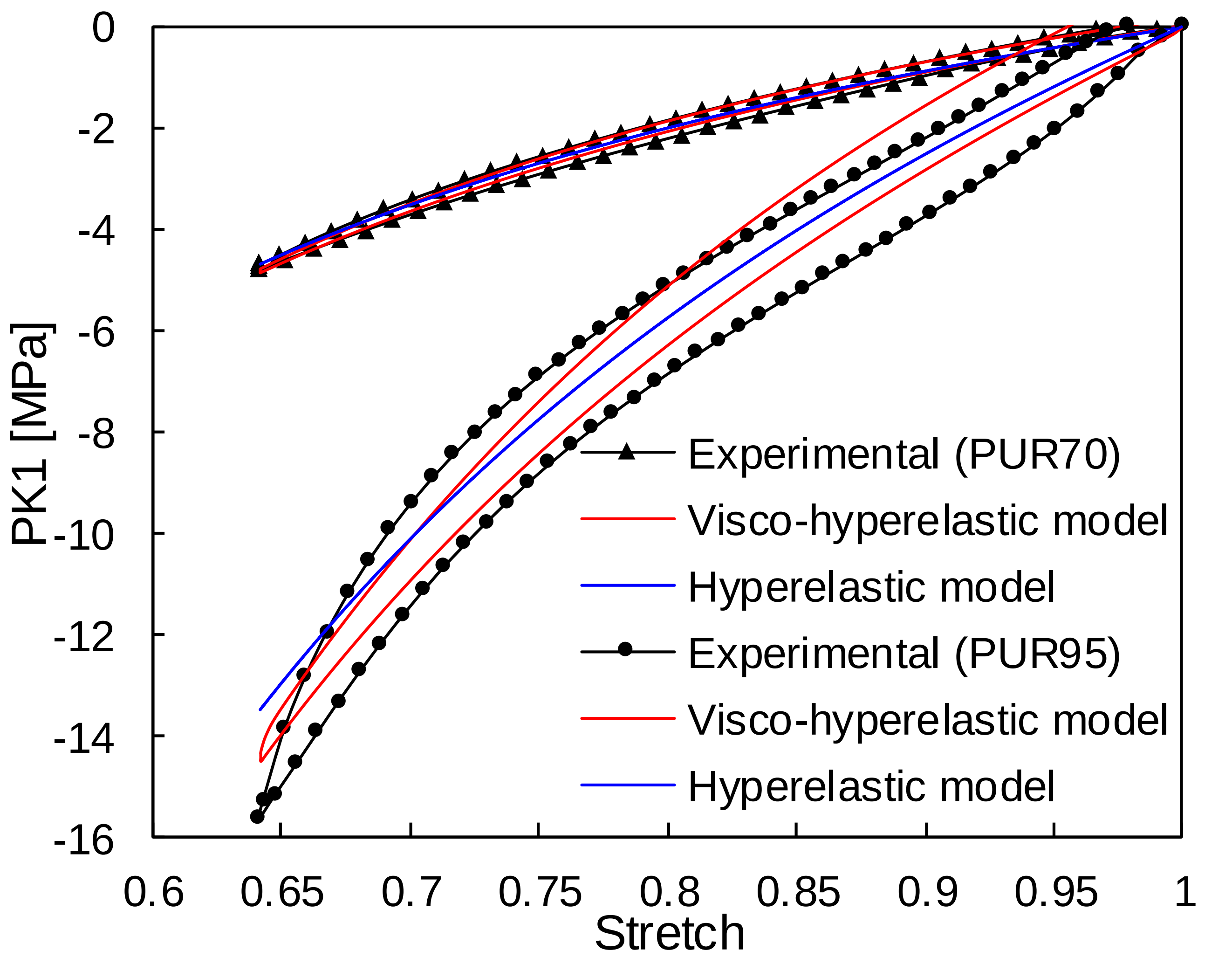
- Minimization of the difference between numerical and experimental stress, considering **all tests simultaneously** (3 uniaxial compression tests + 1 stress relaxation test)
  - **Visco-hyperelastic model** (2+2x2=6 material parameters)
  - **Hyperelastic model** (2 material parameters)

	C_{10}	C_{01}	ak_1	ak_2	τ_1	τ_2
PUR70 visco-hyperelastic model	1.196	0.000	0.0956	0.0719	634.9	10.01
PUR70 hyperelastic model	1.317	0.000	-	-	-	-
PUR95 visco-hyperelastic model	3.485	0.000	0.1945	1.5170	19.25	0.090
PUR95 hyperelastic model	3.776	0.000	-	-	-	-

Experimental and Numerical Stress

Uniaxial compression tests

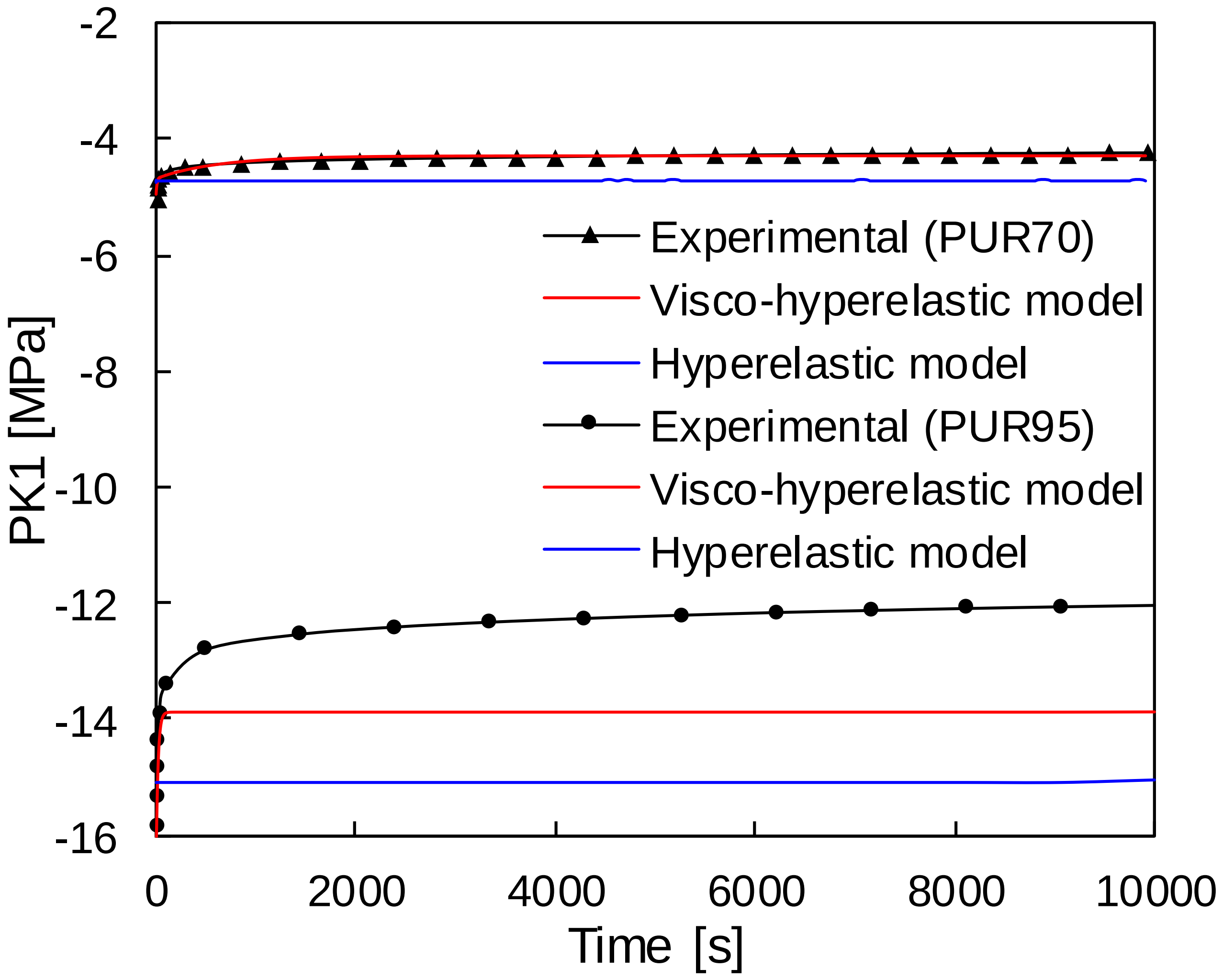
- Loading and unloading at 0.5 mm/s grip speed
- Influence of the rubber hardness on the stress values
- The largest difference between loading and unloading curve occurs for the PUR95 (more pronounced viscous effect)



Experimental and Numerical Stress

Stress relaxation tests

- Constant value of stretch = 0.65
- Improved prediction of the stress relaxation using the visco-hyperelastic constitutive model (PUR70)
- Regarding the PUR95, the experimental stress relaxation is underestimated by the numerical model (consequence of the relaxation time of each dashpot defining the Maxwell elements)



Conclusions

- Mechanical characterization of two polyurethane (PUR) rubbers
- The uniaxial loading/unloading shows that the viscous effect is more significant in the polyurethane with higher hardness value (PUR95)
- The adoption of the visco-hyperelastic model improves accuracy of the predicted stress
- Calibration of material parameters considers only the uniaxial stress state, but several strain paths arise in the rubber pad forming process

Acknowledgements

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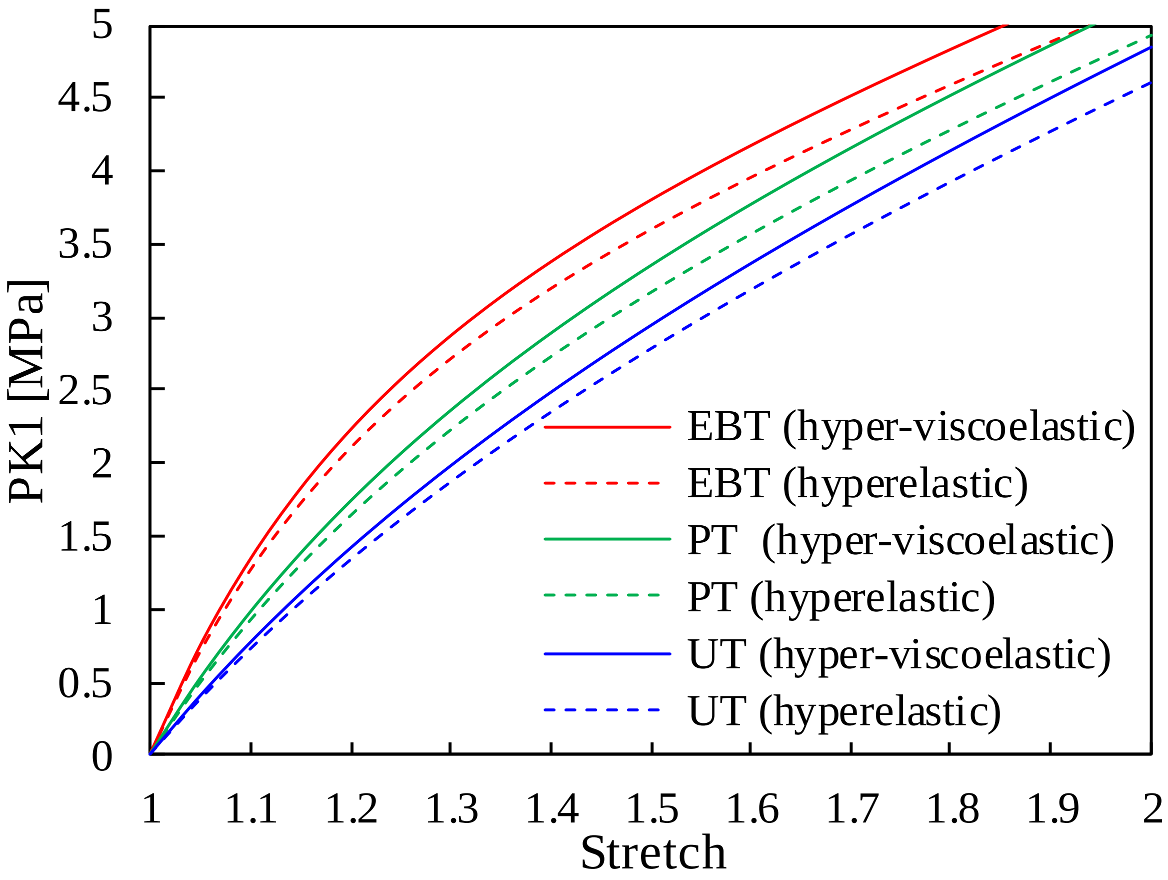
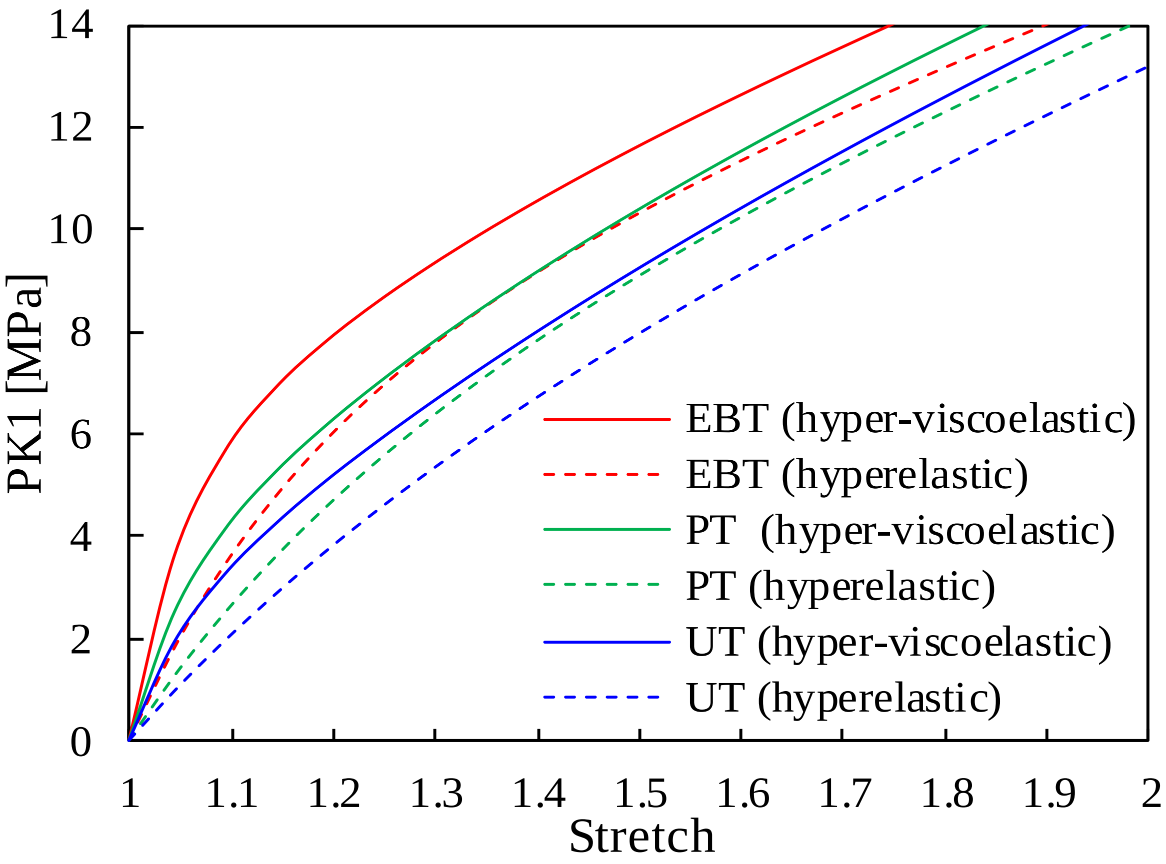
Thank you for your attention!

Numerical prediction of stress evolution

- Uniaxial tension; Equi-biaxial tension; Planar tension



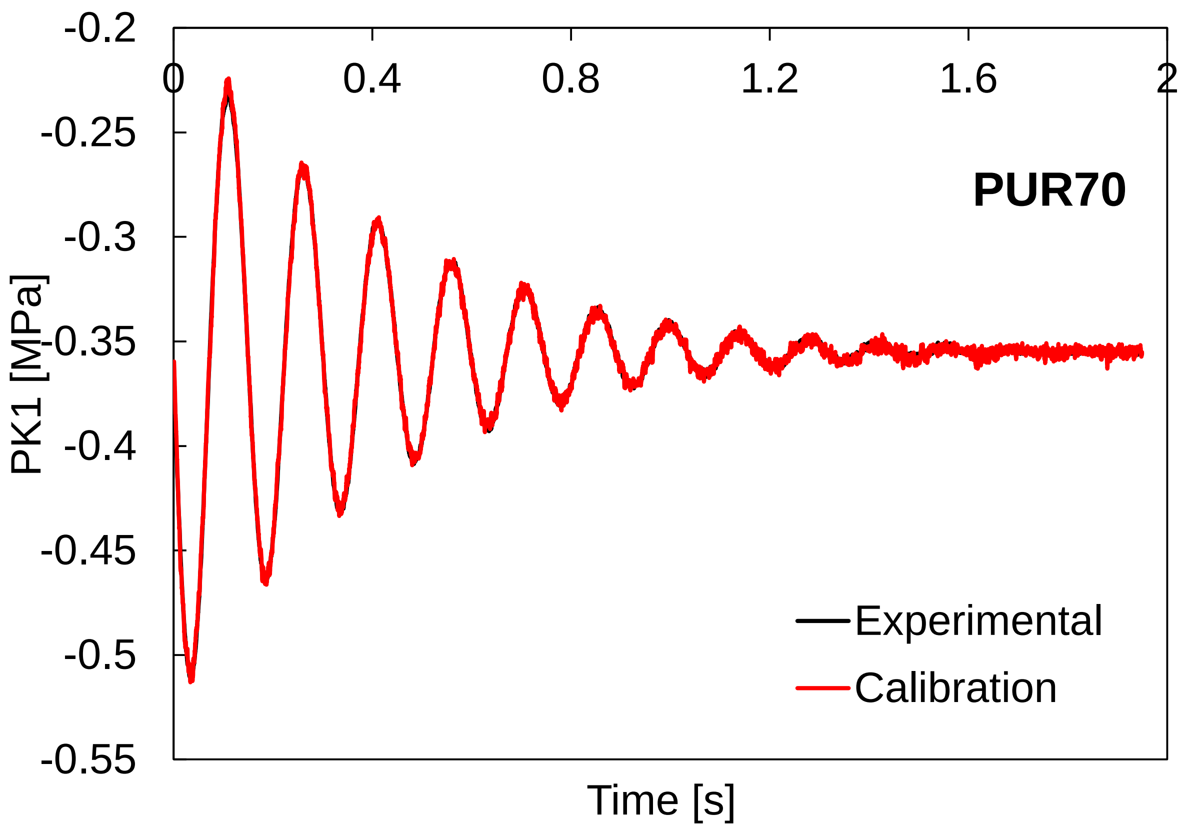


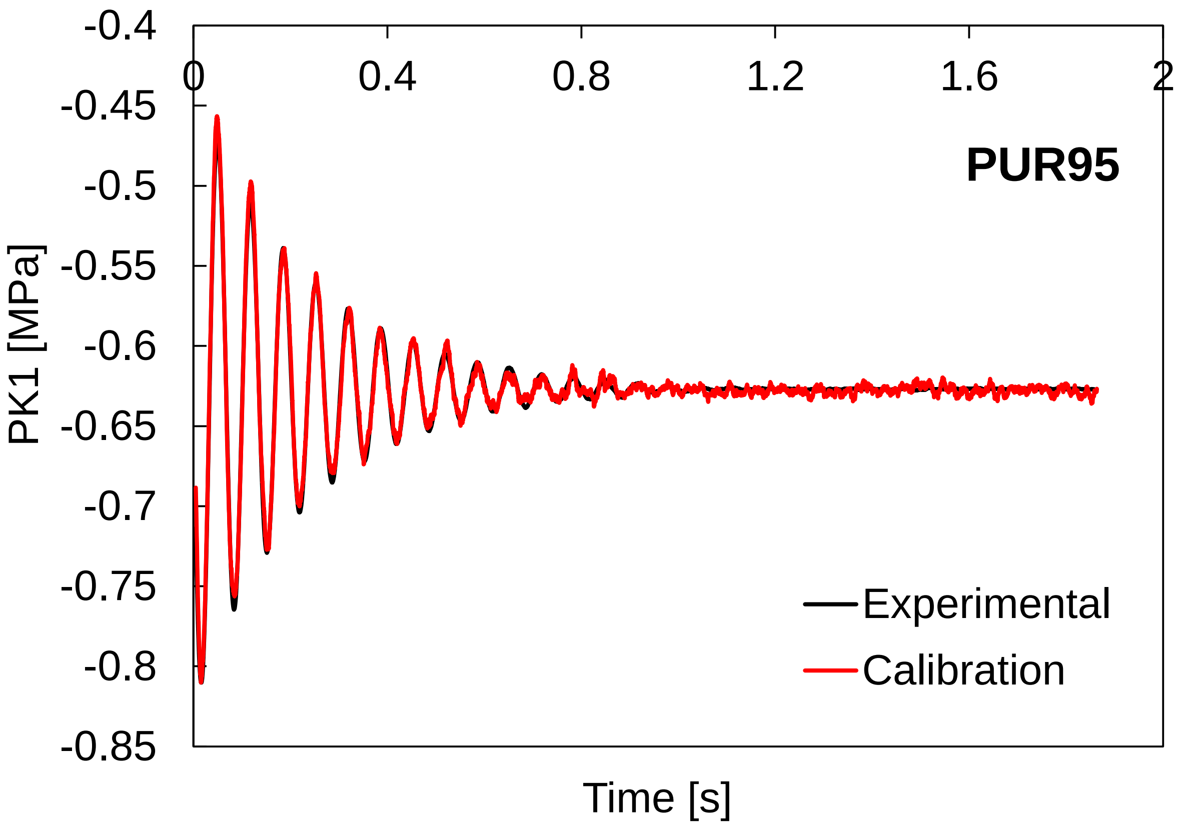
Yerzley's oscillograph

- A mass is placed on one arm of the beam at a distance L_m of the fulcrum
- The specimen is placed on the opposite side of the added mass at a distance L_p 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

Free Vibration Tests

Yerzley's oscillograph





C_{10}	C_{01}	ak_1	ak_2	τ_1	τ_2
0	1.1474	2.5024	0.1199	0.00198	1.25274

C_{10}	C_{01}	ak_1	ak_2	τ_1	τ_2
5.4882	0	0.4213	2.0021	482.665	0.00327