Evaluation and Improvement of Methods Characterizing the Young's Modulus of Refractory Materials at Room and High Temperature Applications

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Outline

- **Motivation:** Numerical modelling, applied to refractory masonries
- **State of the Art**: Determination of Young‘s Modulus – Dynamic method vs static methods, DIC measurements for deflection measurement
- **Goals**: Use of RUL tests to determine temperature dependant E static
- **Experimental Results**: RUL Tests, Stress-Strain Curves, DIC
- **FEM Validation**
- **Summary & Future Work**

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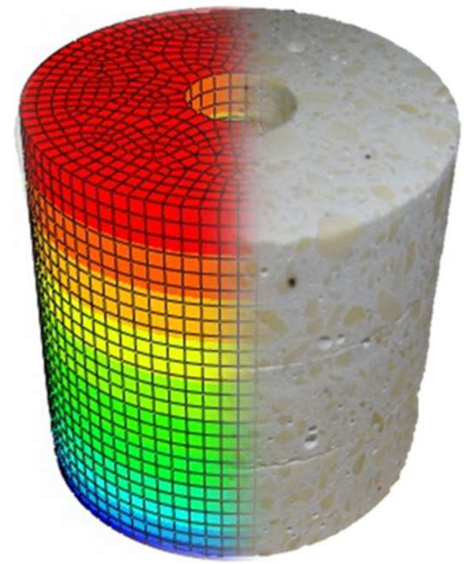
Motivation

- Refractories used wherever (in)direct contact with a high temperature process
- Simulations can help lower safety factors for plant design → static load cases
- Accurate material data needed for simulations
  - Thermal properties
  - Creep behavior
  - Elastic-plastic behavior
- Resonance Frequency Damping Analysis (RFDA) often used for temperature-dependent Young‘s Modulus $E_{dynamic}$
- How to determine temperature-dependent E_{static}?
  → New method proposed, utilizing Refractoriness Under Load (RUL) tests



RUL specimen and according FEM model

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High-Alumina Refractory model material

Model material: High-alumina refractory castable

Selected for its resemblance to **typical refractories** materials

Remains stable at **high temperatures** (no phase transformation)

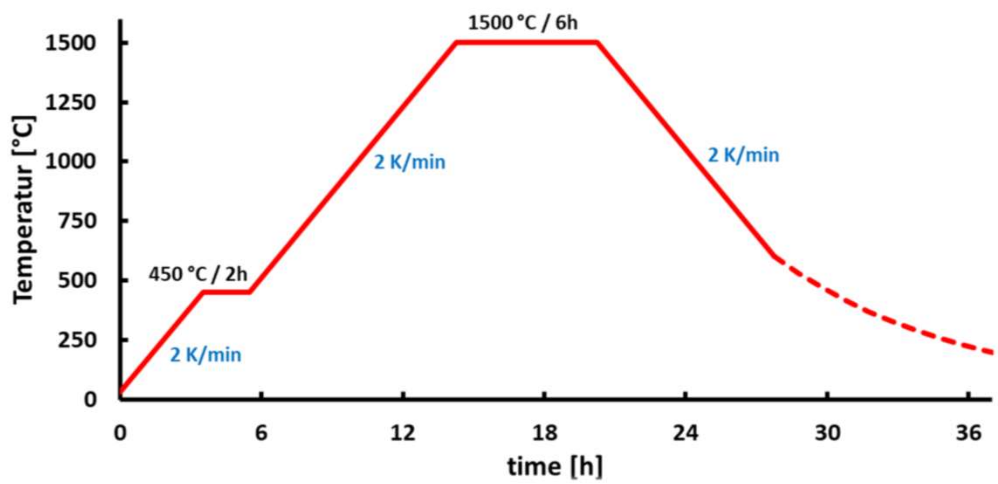
Open Porosity ≈ 17 %

Total Porosity ≈ 22 %

The expected Young's modulus of the material is around **100 - 150 GPa**

Standardized sample geometry

Material	Specification	Weight percent [%]
Tabular alumina	1-3 mm	35
	0,5-1 mm	17,5
	0,2-0,6 mm	10,5
	0-0,3 mm	10
	0-0,0045 mm	12,5
Reactive Aluminas	PFR	14
Sol-Gel	92% H_2O	5,5 – 8,5



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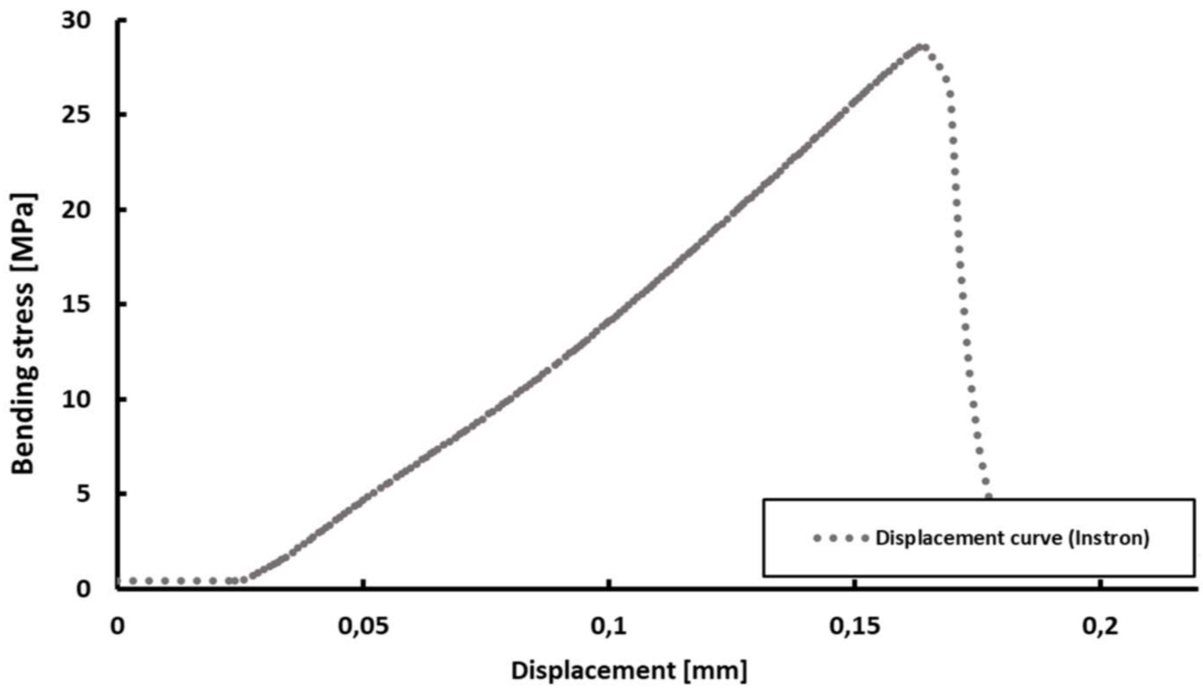
Instron 3-Point Bending Test



Exemplary measurement with Instron

Displacement measurements are too high mainly due to **test frame flexibility**

$$E = \frac{\sigma}{\varepsilon}$$

E-Modul = 17 GPa

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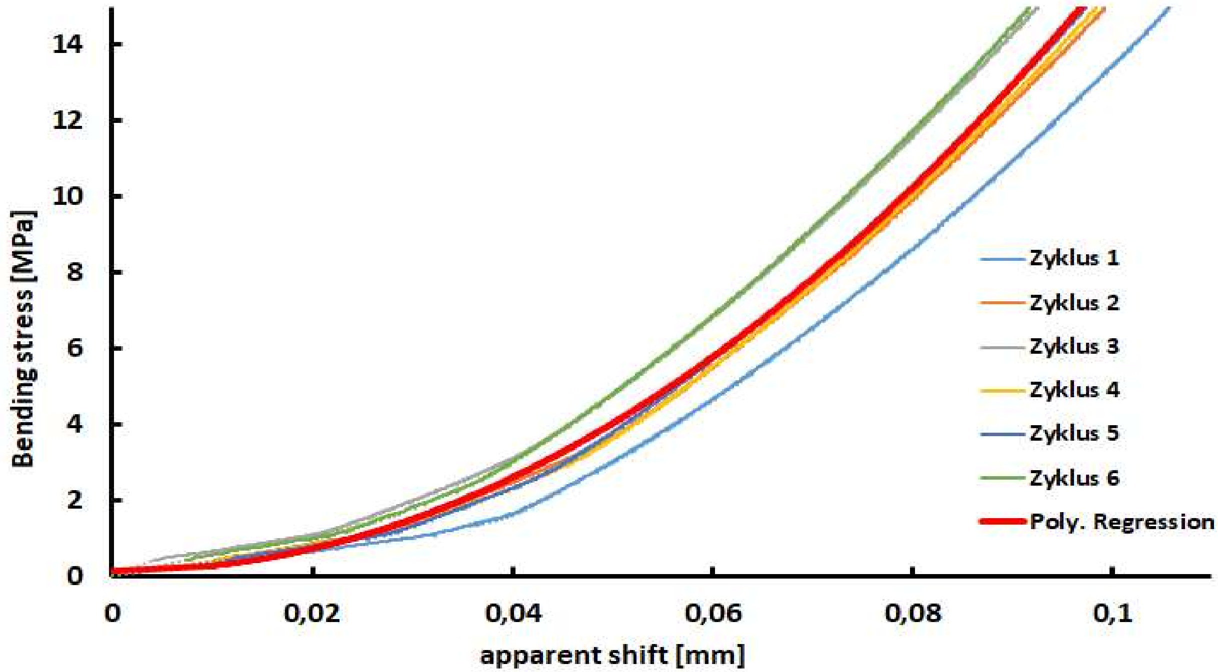
3-Point Bending Test – Apparent displacement of Instron



The **apparent displacement** of the **test frame** is determined

$$I = \frac{b * h^3}{12}$$

Area moment of inertia for the calibration rod is **1000x** that of the standard test bar.

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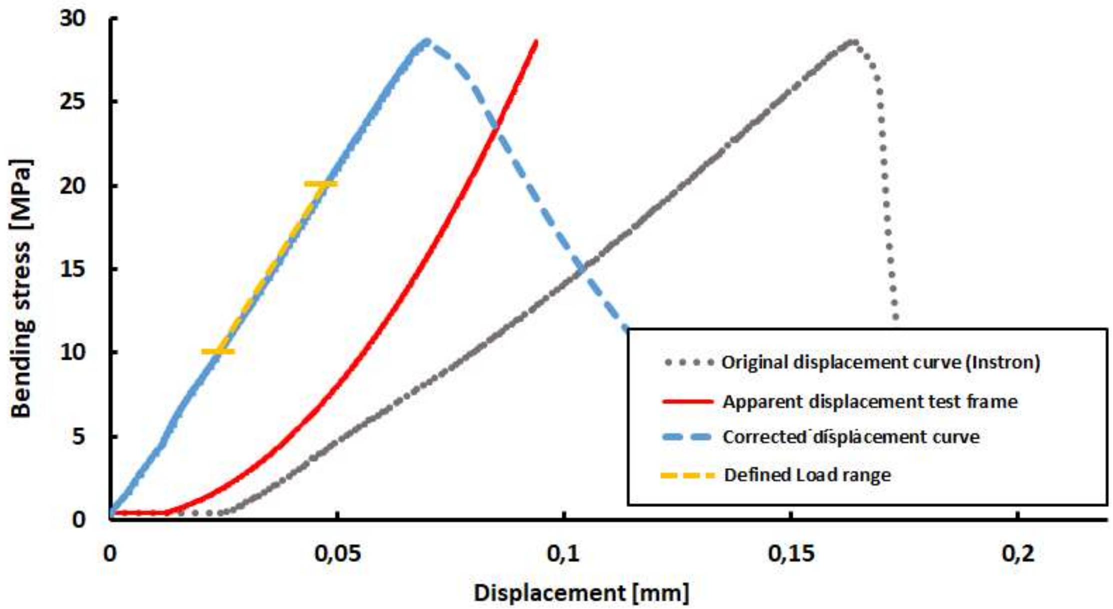
3-Point Bending Test – Apparent displacement correction

- We can now **subtract** the apparent displacement from the measured displacement
- The E-Modul is calculated within a defined load range
- Uncorrected E-Modul: 17 GPa
- **Corrected E-Modul: 132 GPa**



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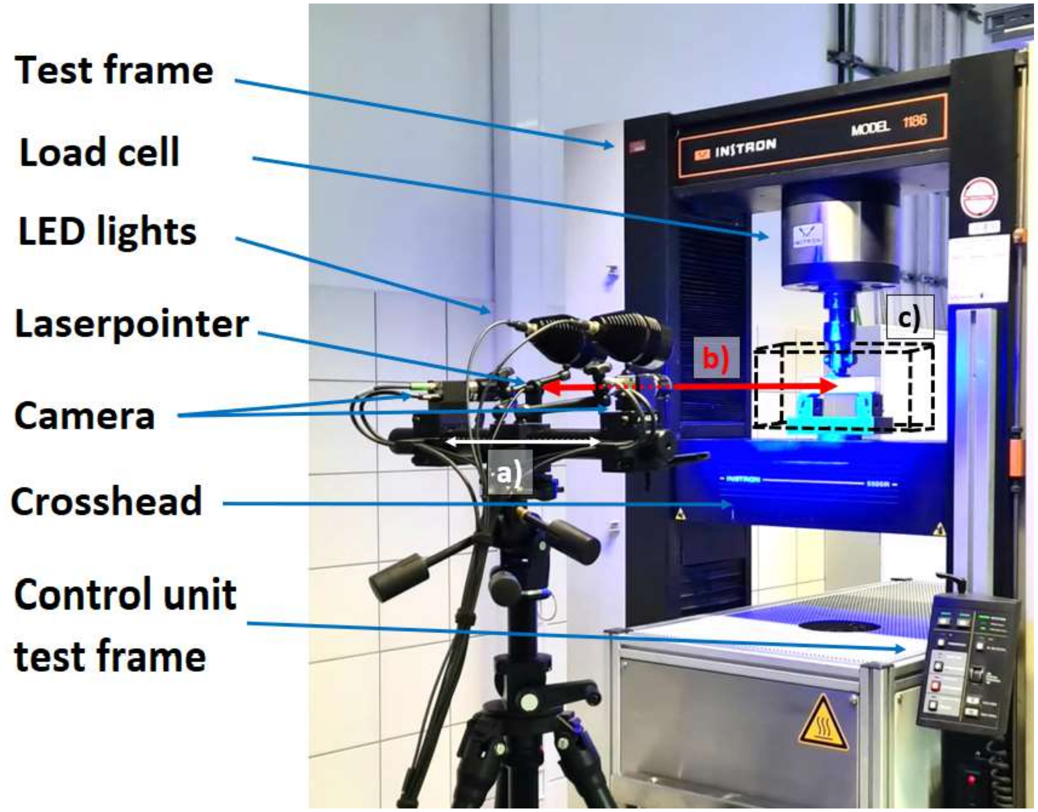
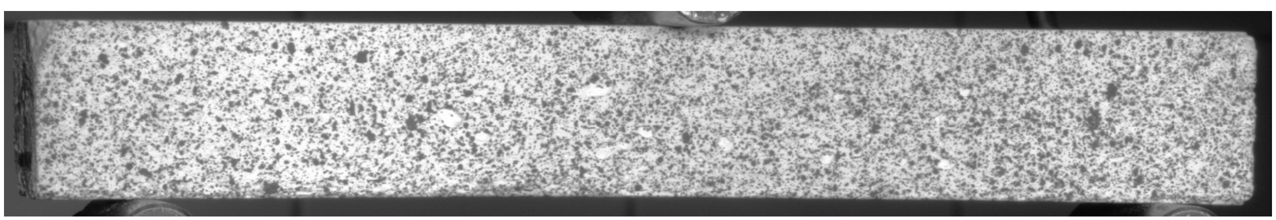
3-Point bending test – Digital Image correlation

- ARAMIS 12M adjustale by Zeiss
- Ignoring typical **spring-back** and **settling effects** in the experimental setup.
- **Direct measurement** of local strains on the sample surface
- Stochastic pattern enables complete **area analysis**.





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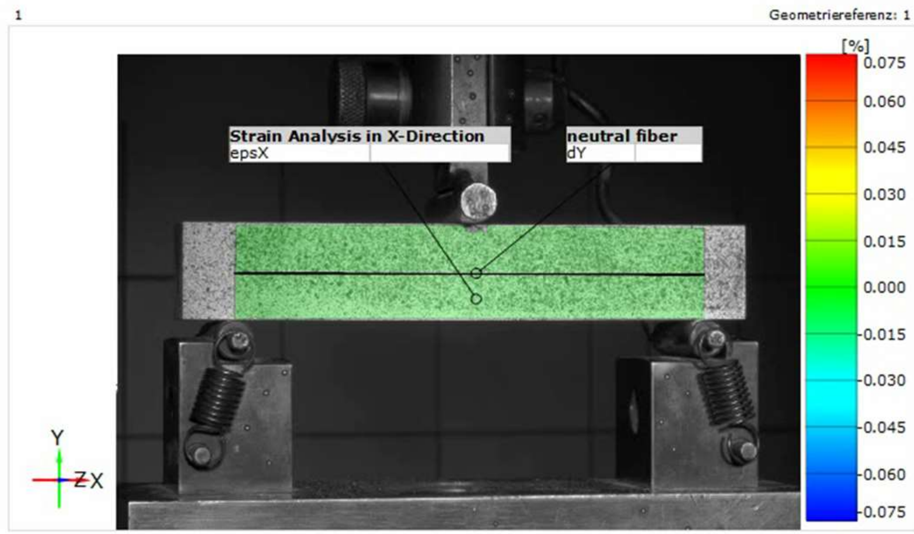
Reference Sample: Aluminum subjected to Load Range from 15N to 10,000N

Surface analysis:

Shows strain in the **X-direction** [%]

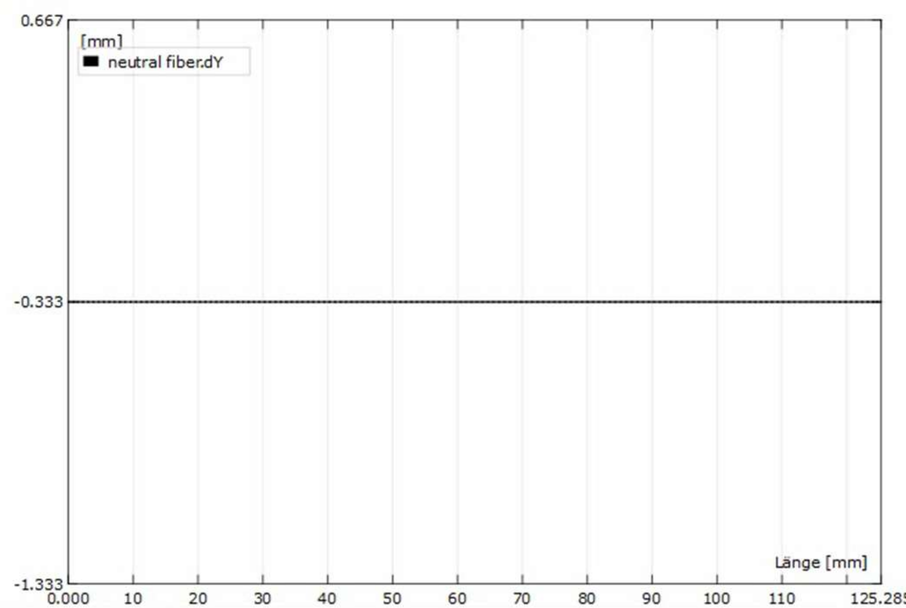
- Positive values signify tensile stress.
- Negative values signify compressive stress.



Bending Line:

Shows displacement in the **Y-Direction** [mm]

- Neutral fiber is in the sample's middle
- Load is applied at a rate of 0.15 MPa/s
  - [DIN 993-6]



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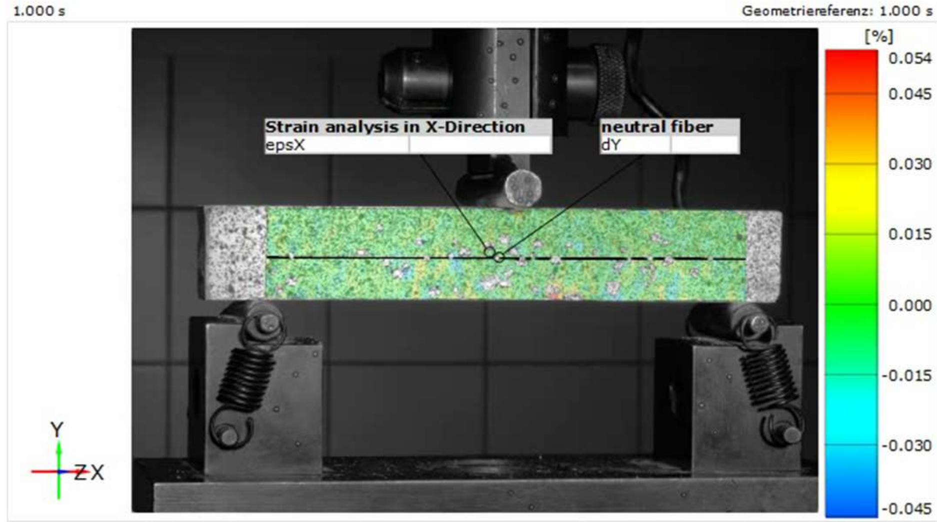
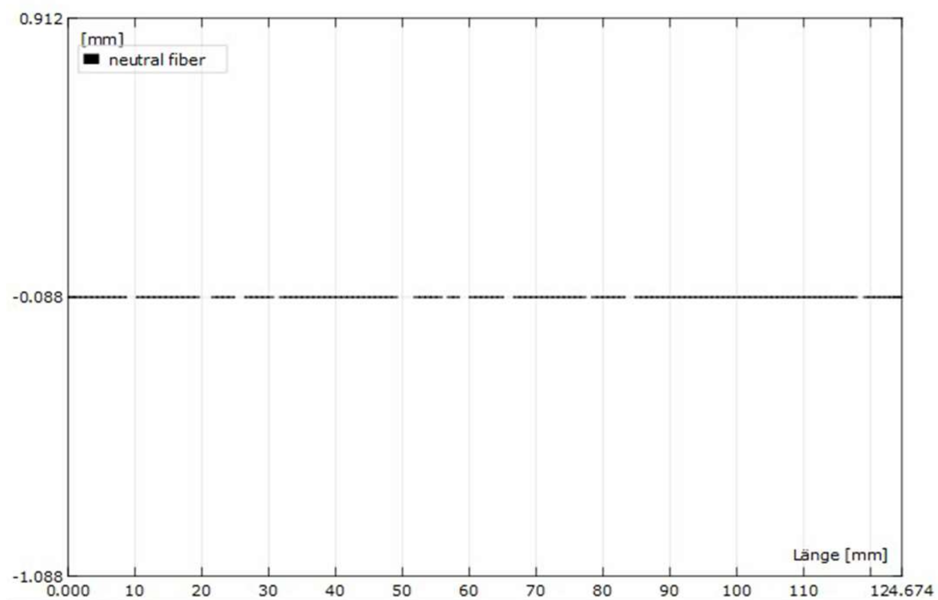
High-Alumina Refractory Sample: Load Applied Until Failure at 1858N

- The refractory sample exhibits a **smaller strain**
- Data quality decreases
- **Rotation around the Z-axis**
- The calculation can no longer be performed in the coordinate software
- **Export** the bending line and conduct the analysis in Python





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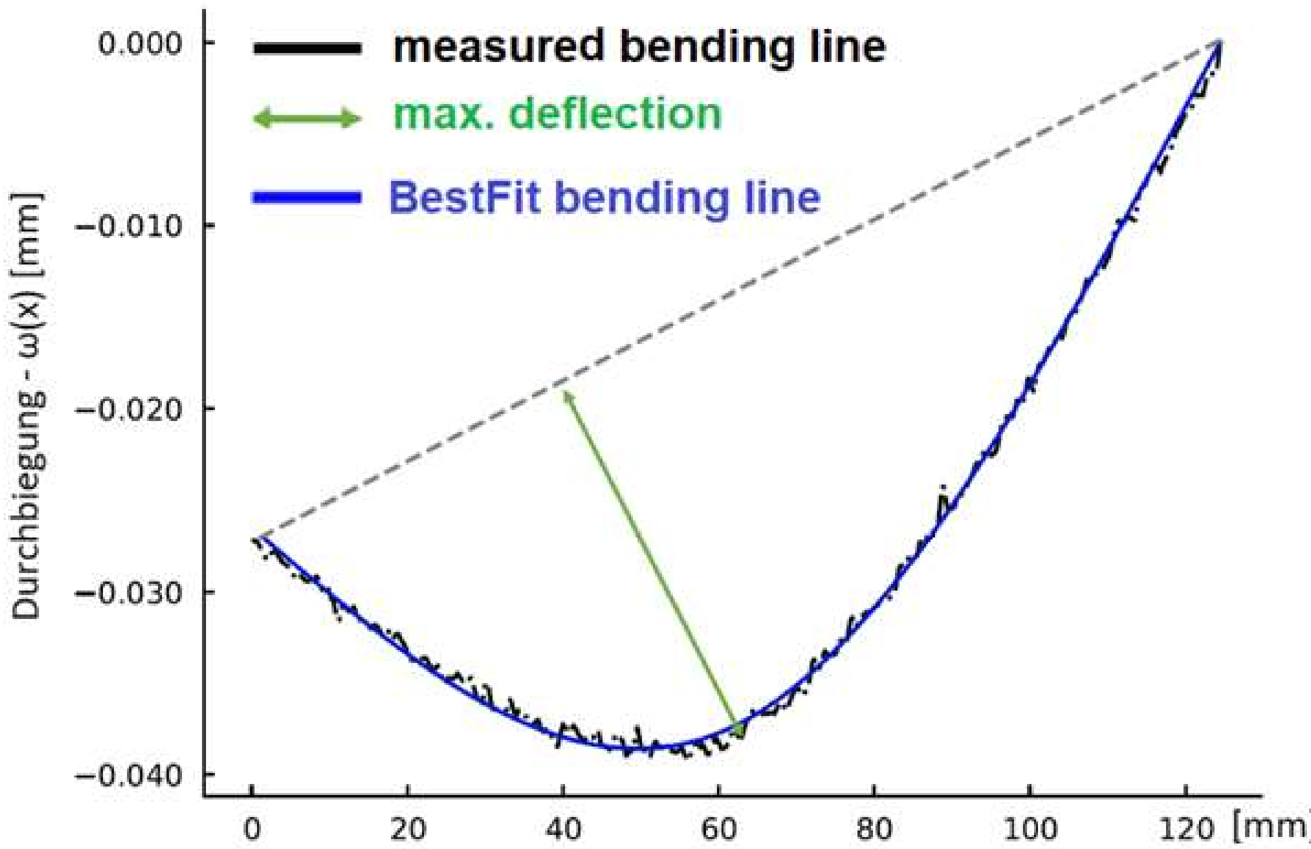
Bending line analysis in Python

- The **respective force** corresponds to the measurement value
- The E-Modul can be determined using the **maximum deflection** and the **BestFit** method.



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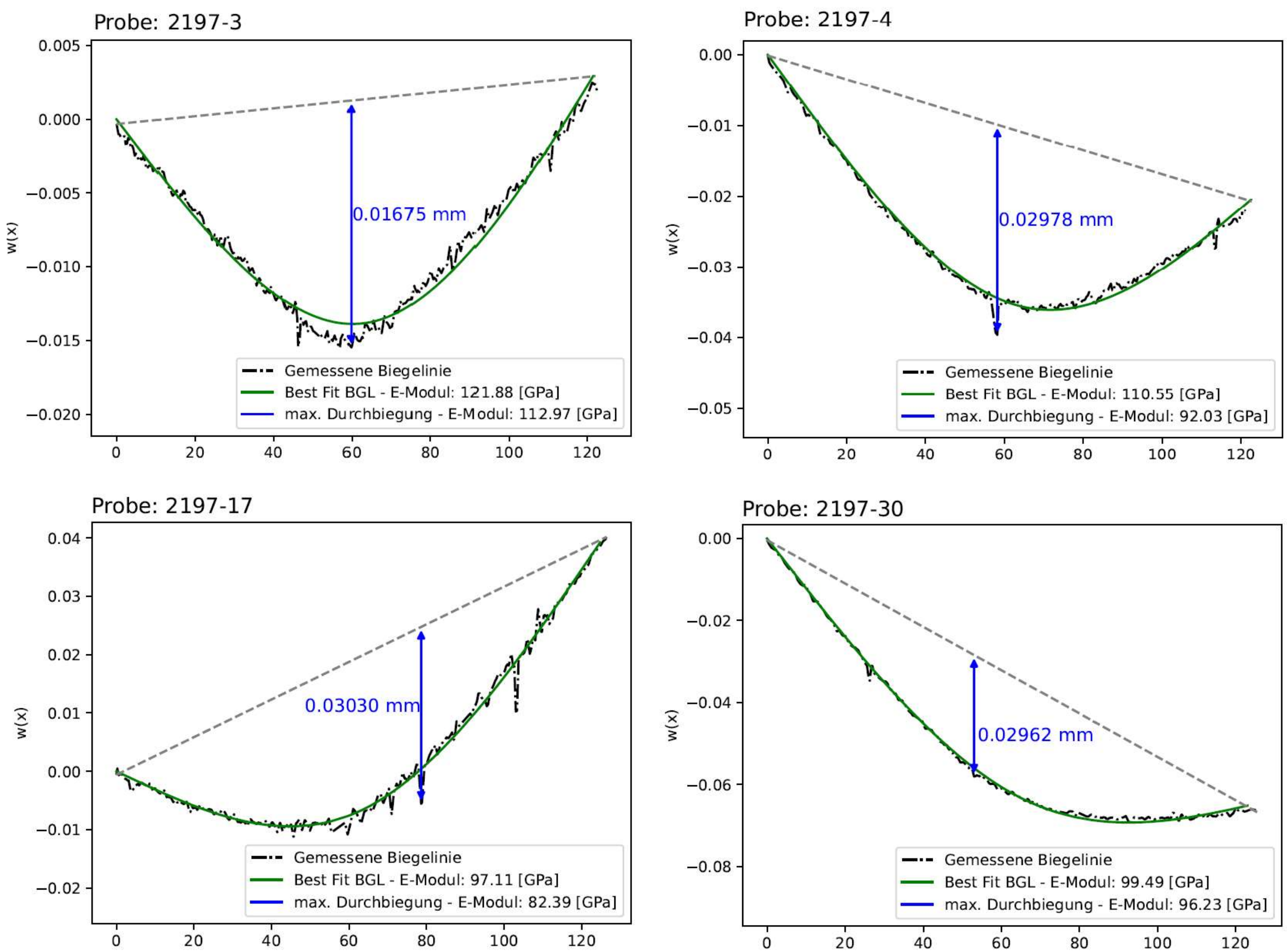
3-Point bending test – Digital Image correlation



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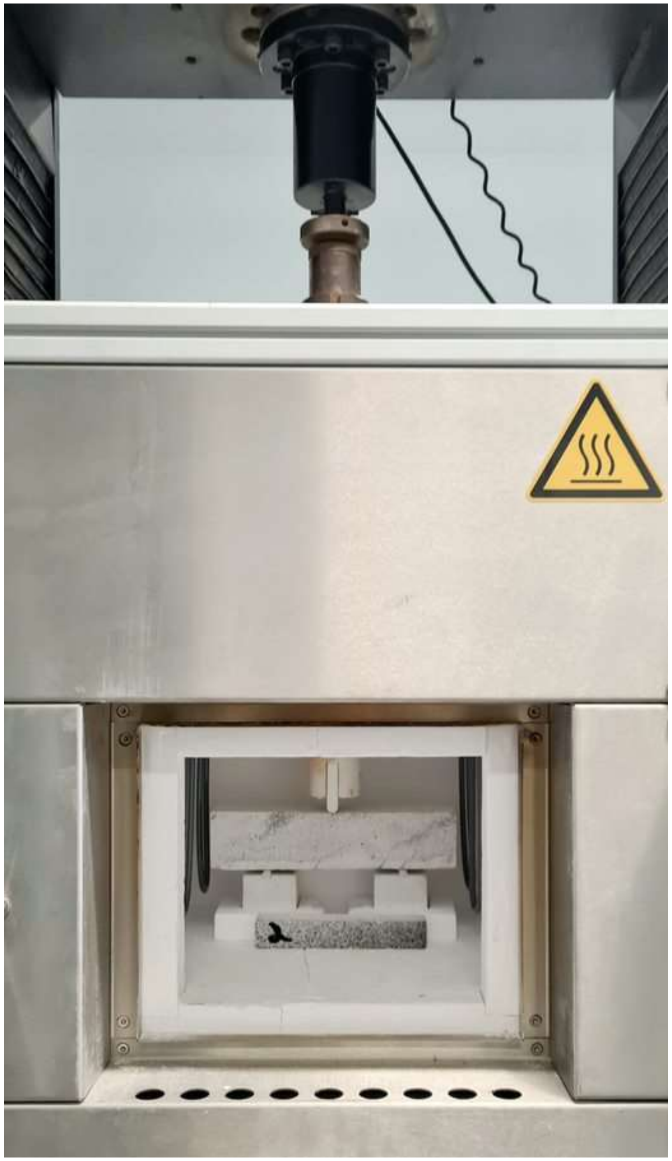
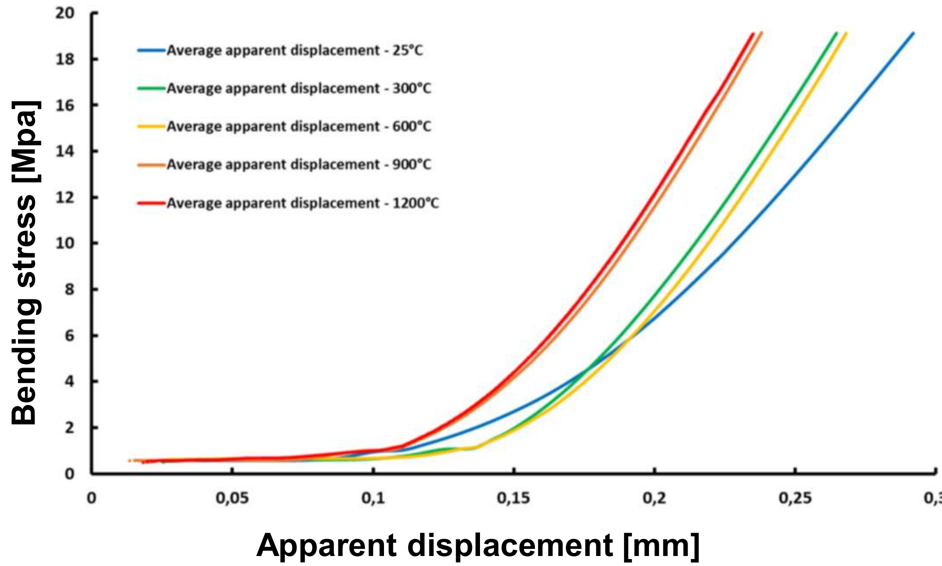
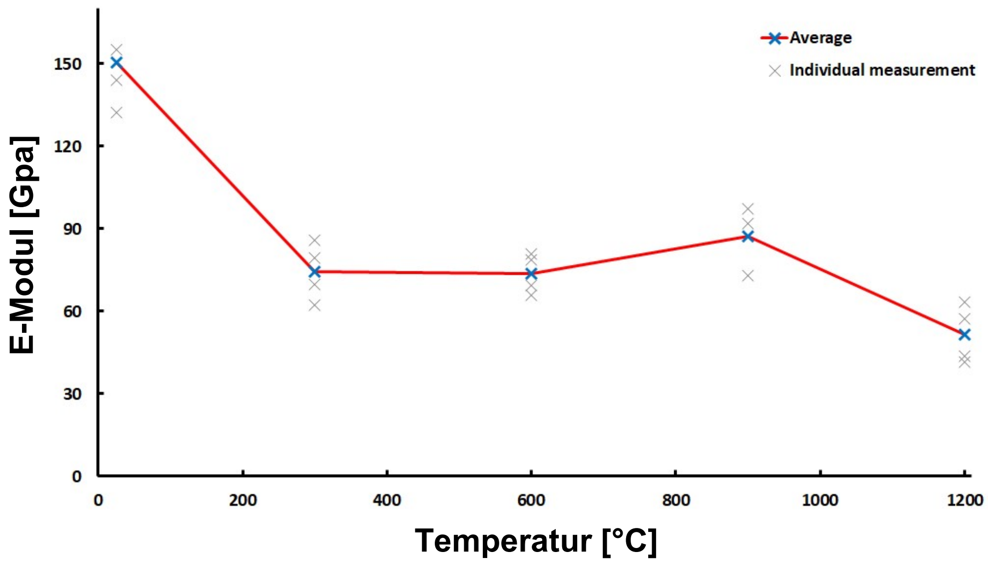
Apparent displacement correction at high temperature







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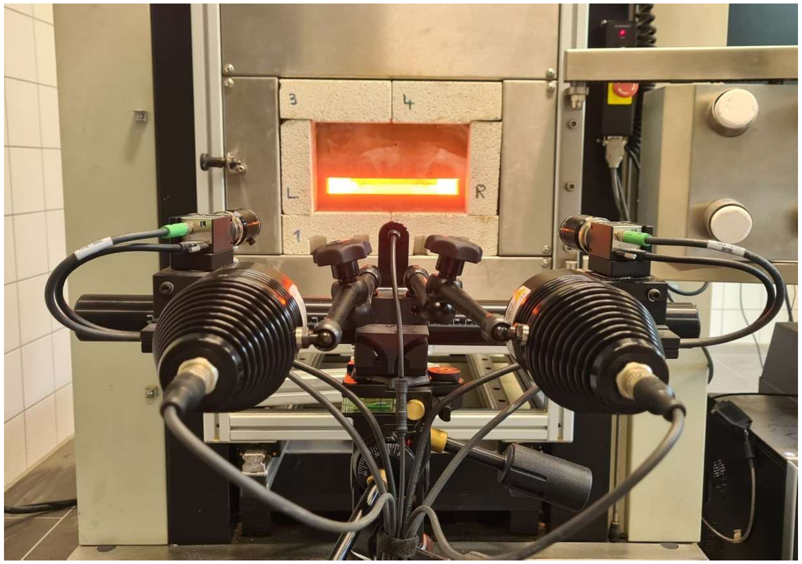
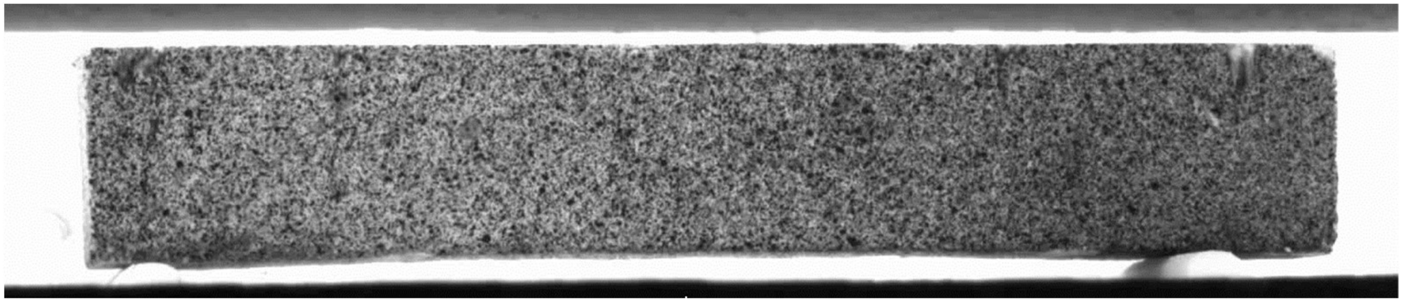
3-Point bending test – Digital Image correlation – high temperature



- The quality decreases with increasing temperature and yielding no usable results



Air turbulence between hot and cold air (different refractive indices) resulted in poor measurements

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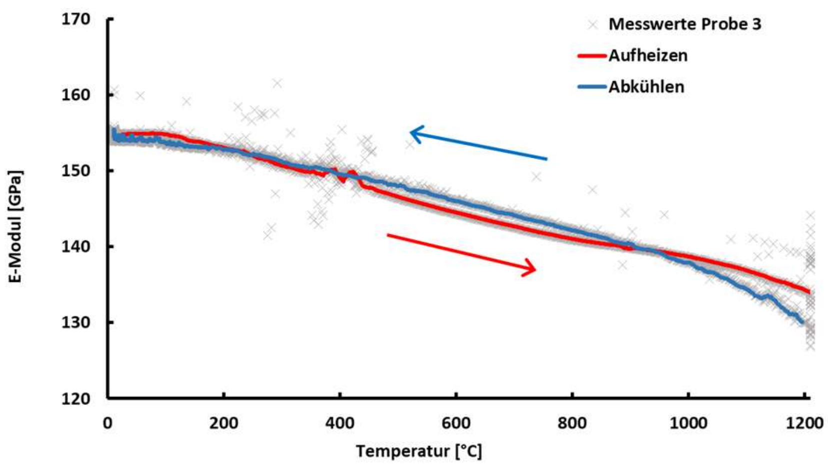
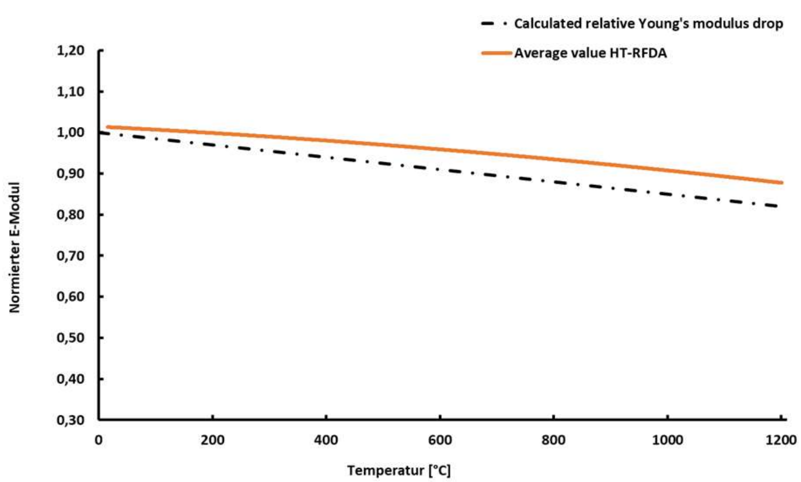
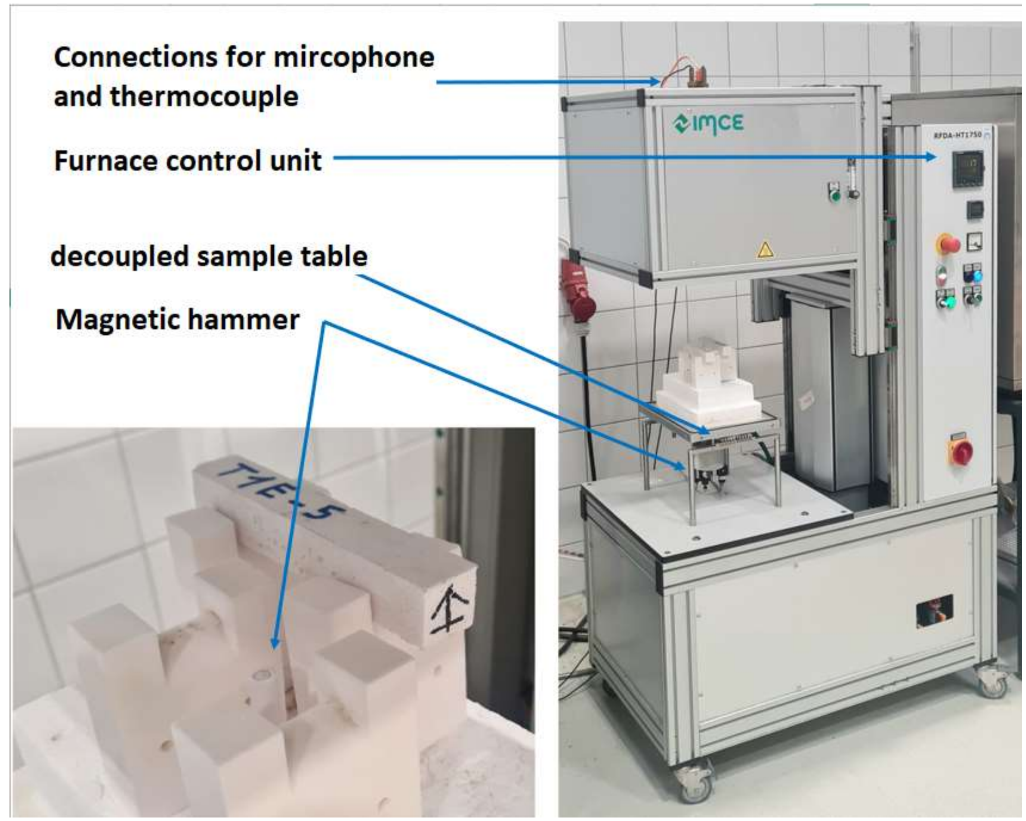
High-Temperature Dynamic E-Modulus Measurement via RFDA







Tests conducted with IMCE's HT1750 testing system, using the Sonelastic-RFDA software

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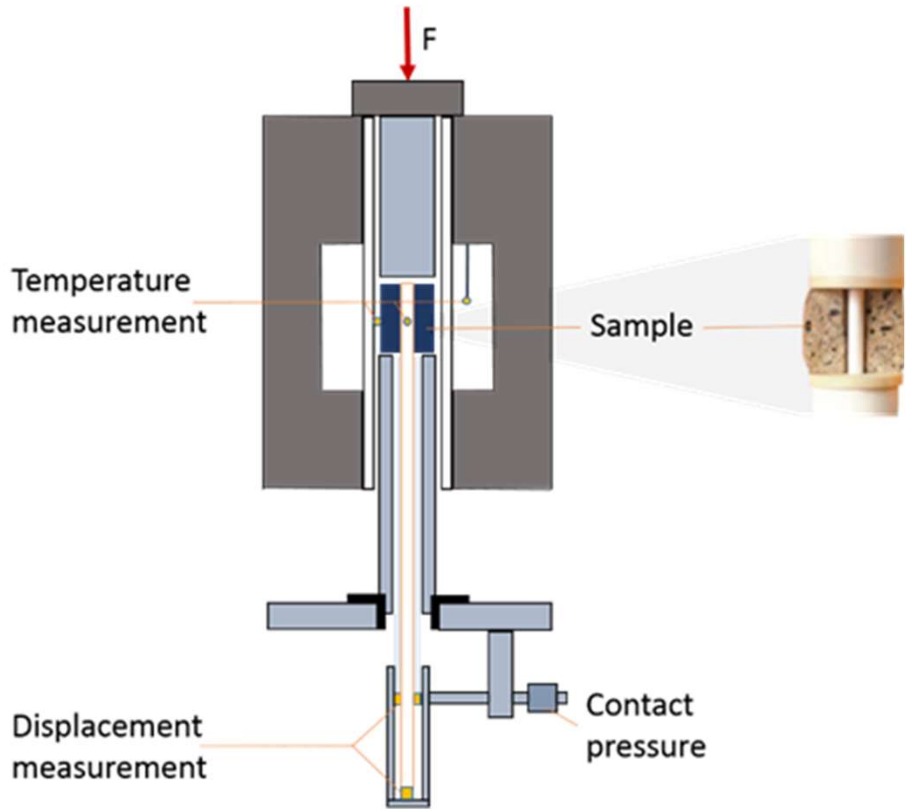
State of the Art

- RUL: static test method, used to determine pressure softening point
- Commonly used for refractories
- Cylindrical specimen with inner drilling loaded and heated
- Standardized load of 0.2 MPa (ISO 1893)
- Change in length measured directly on specimen
- Also used to measure thermal expansion using a neglectable load of 0.01 MPa



RUL test schematic

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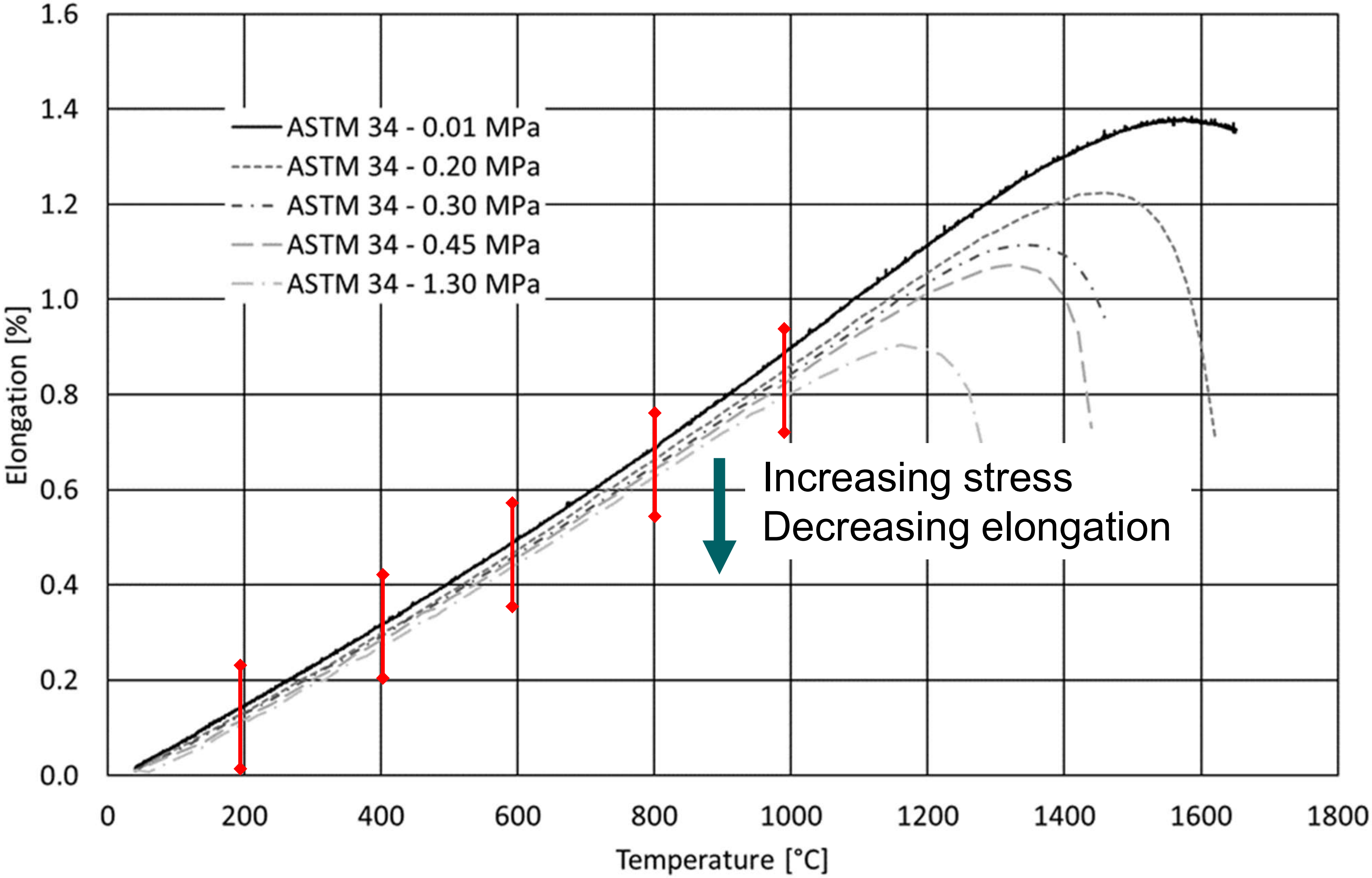
Experimental Results – RUL Lightweight Brick



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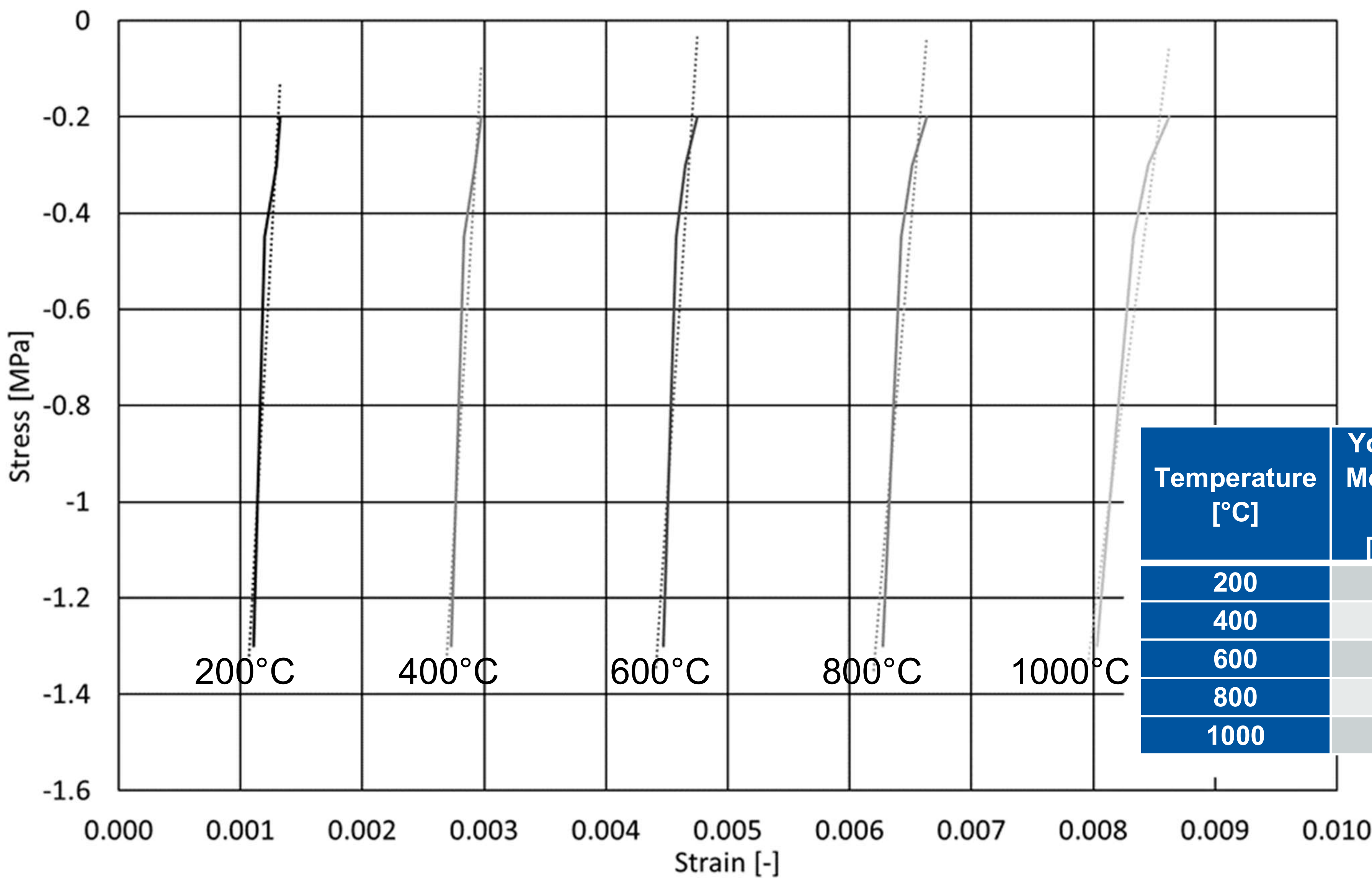

Temperature [°C]	Young's Modulus RUL [GPa]
200	4.7
400	4.3
600	3.9
800	3.0
1000	1.9

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Experimental Results - RFDA

- RFDA measurement as comparison
- $E_{dynamic}$ (RFDA) constant, increase at 1000 °C
  → High porosity of ASTM 34 may lead so sintering
- $E_{dynamic}$ several GPa higher, than E_{static} (RUL)
- Deviation between static and dynamic Young's modulus in a plausible range

Temperature [°C]	Young's Modulus RUL [GPa]	Young's Modulus RFDA [GPa]
200	4.7	11.8
400	4.3	11.4
600	3.9	11.6
800	3.0	11.6
1000	1.9	12.5

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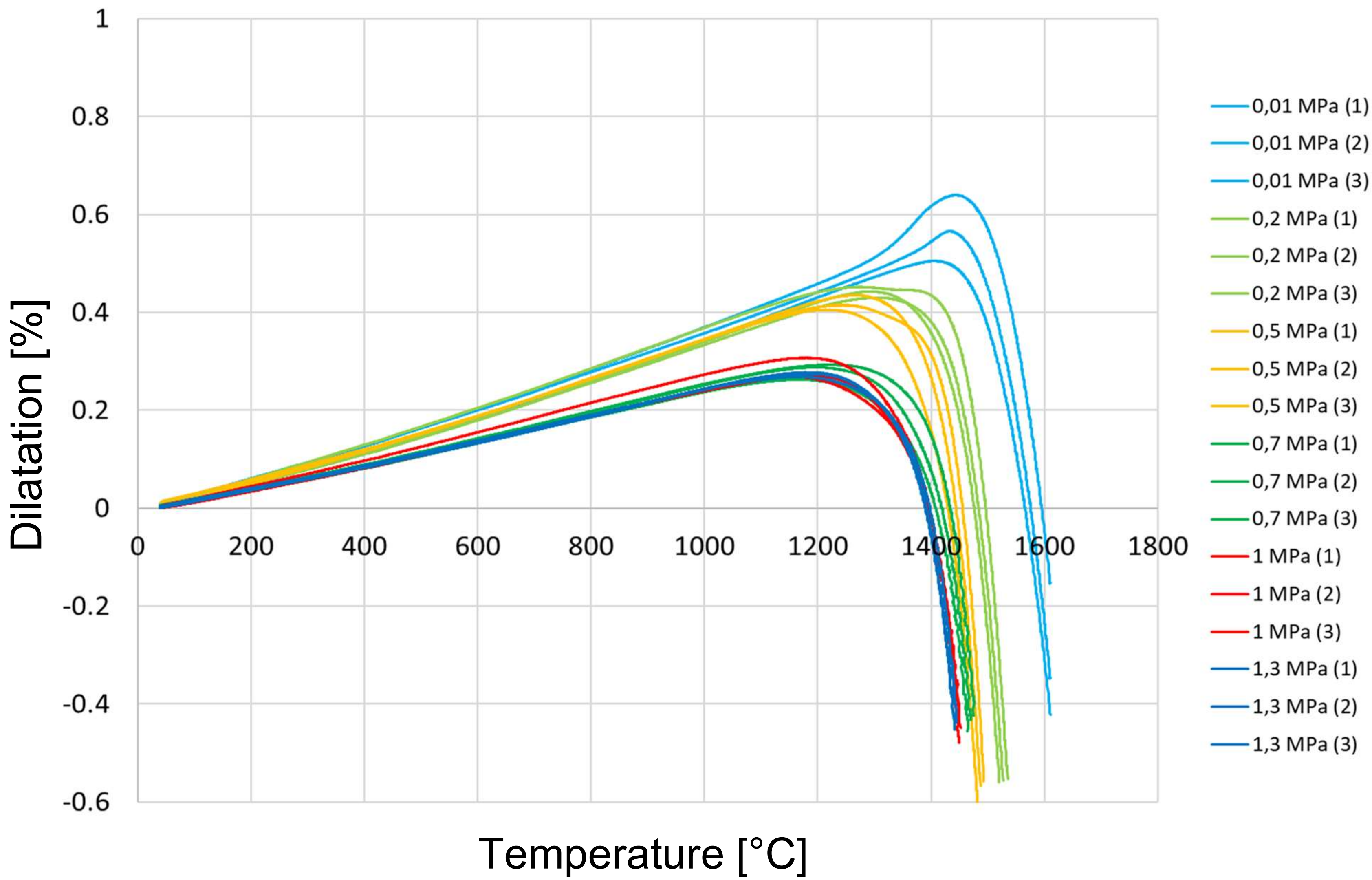
Experimental Results – RUL Bauxite Brick



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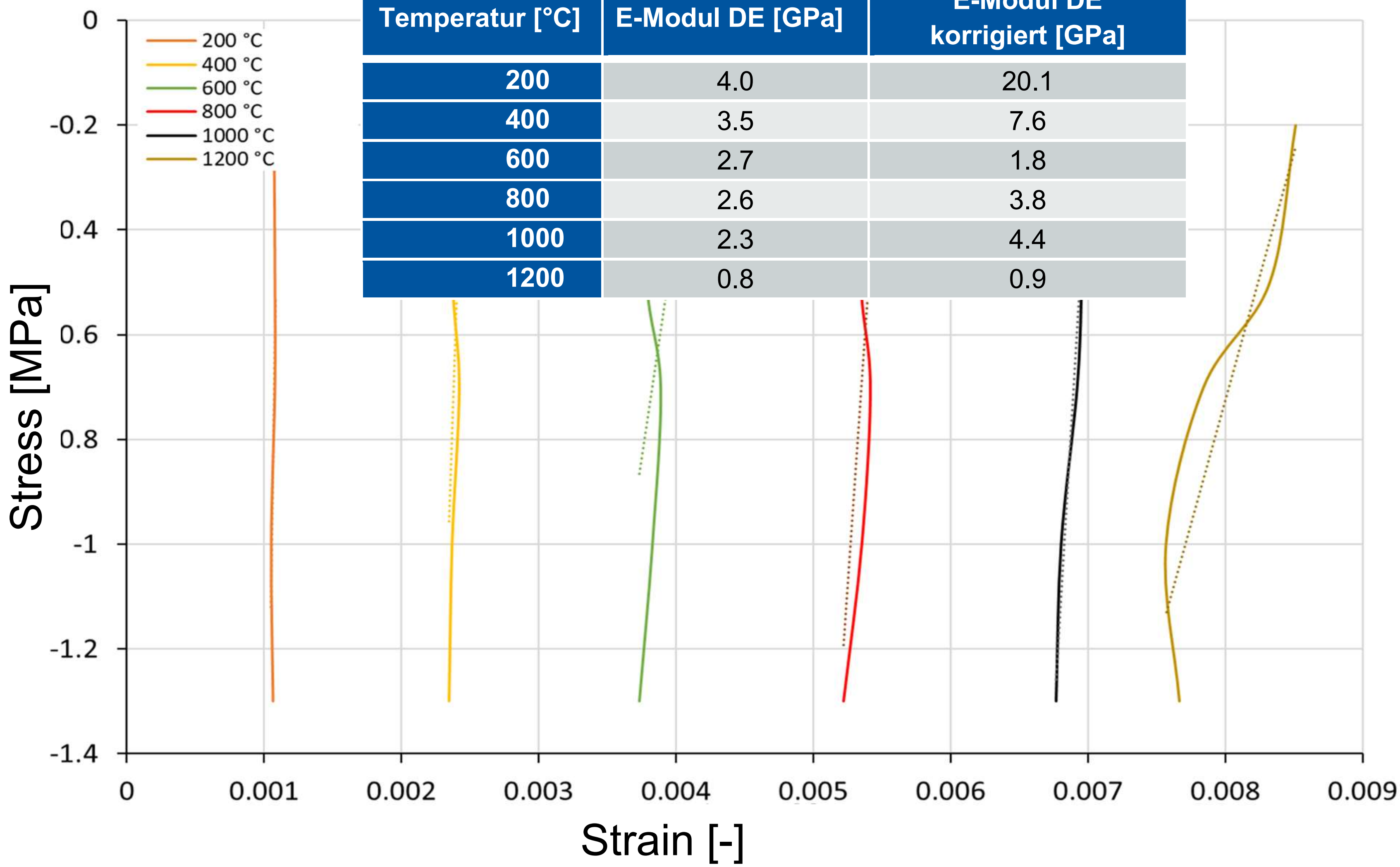
Experimental Results – RUL Bauxite Brick

Temperatur [°C]	E-Modul DE [GPa]	E-Modul DE korrigiert [GPa]
200	4.0	20.1
400	3.5	7.6
600	2.7	1.8
800	2.6	3.8
1000	2.3	4.4
1200	0.8	0.9



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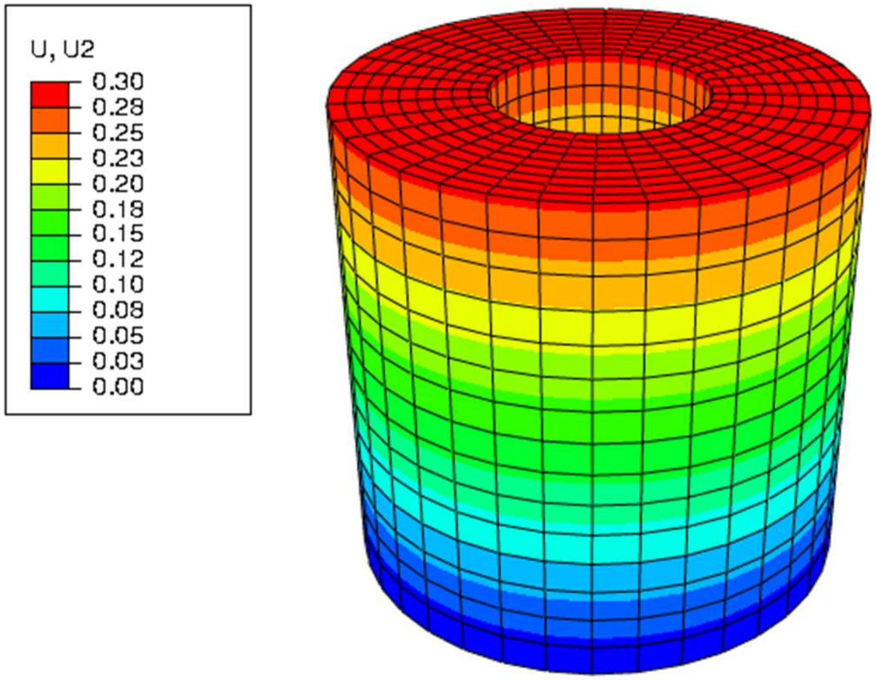
FEM Validation - Model

- Validation of determined Young‘s modulus using FEM model of RUL test
- Abaqus/CAE 2019
- 2D axisymmetric model
- Approx. 500 Elements mesh
- Load of 1.3 MPa, since influence of E increases with stress
- Thermal expansion from RUL test with 0.01 MPa (temp.-dependent)
- Simulation with temperature-dependent:
  - E_{static} (RUL)
  - $E_{dynamic}$ (RFDA)



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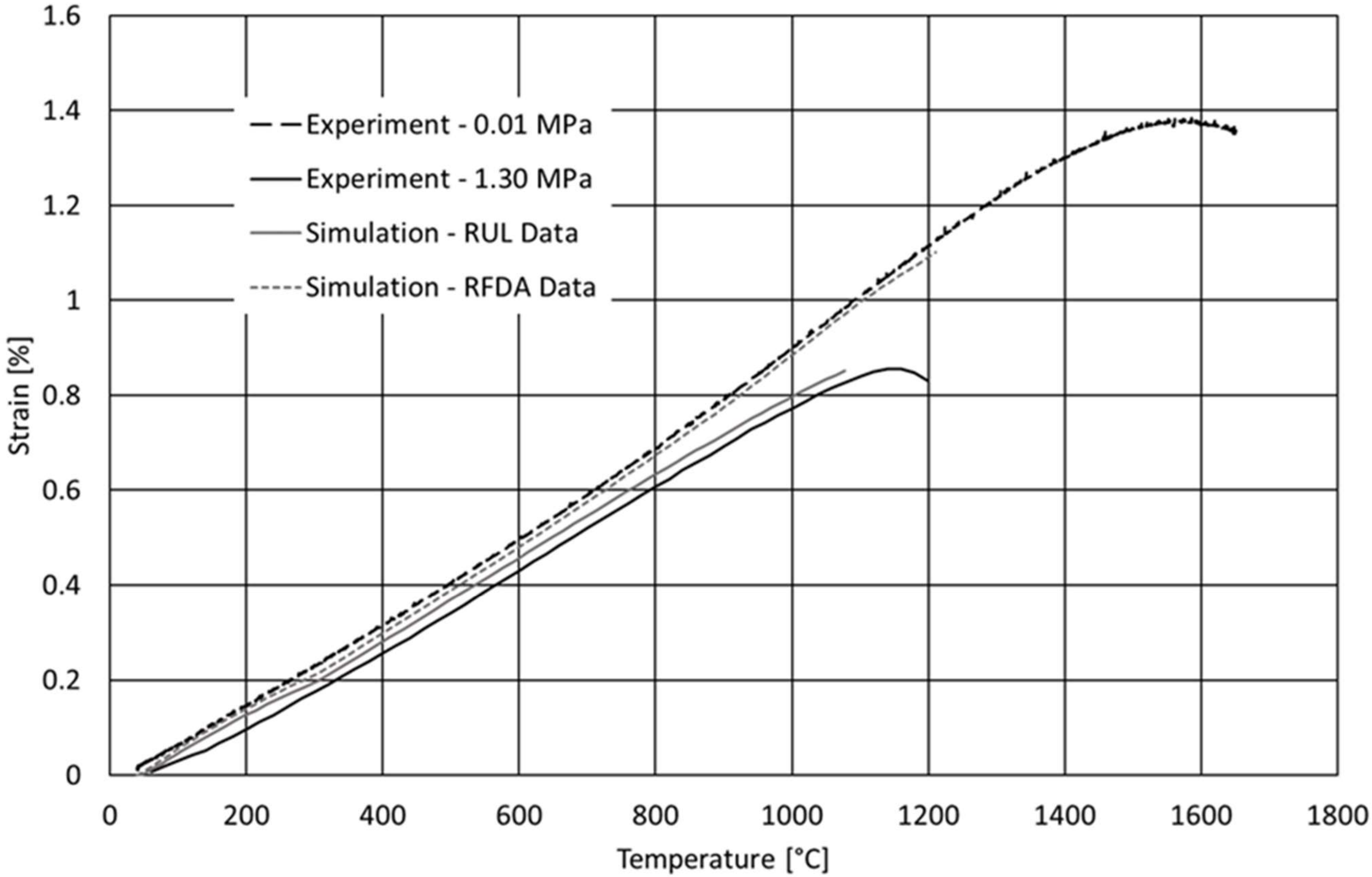
FEM Validation - Results



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Summary

- New method investigated:
  Determination of E_{static} (T), using RUL tests

- RUL tests carried out at several stresses on ASTM Brick 34 and Bauxite brick, determination of E_{static} using isothermal lines

- Comparison with $E_{dynamic}$ from RFDA shows reasonable deviations

- FEM validation using model of RUL test shows good agreement for determined E_{static}

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Thanks you for for your attention!

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