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Supplement of

Structural integrity investigations of spent nuclear fuel with finite element modeling

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Structural Integrity Investigations of Spent Nuclear Fuel with Finite Element Modeling

S. Pudollek

Interdisciplinary research symposium: On the safety of nuclear disposal practices, Berlin, 10-12 November 2021

safeND Interdisciplinary research symposium on the safety of nuclear disposal practices

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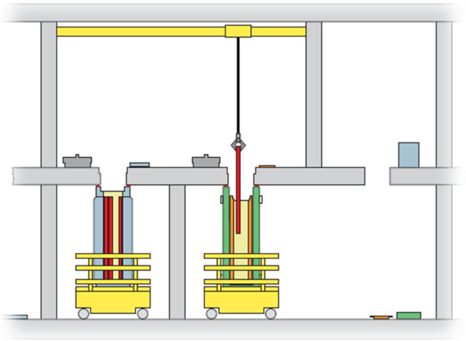
Introduction

- Swiss waste management includes various back-end activities before SNF final disposal
  - wet/dry interim storage, transport, handling and re-packaging for final disposal
- SNF is subjected to various temperature and loading conditions
- Pre-disposal requirements:
  - ensure **safety** of SNF handling and encapsulation operations
  - investigate **fuel ageing** mechanisms during long-term dry interim storage

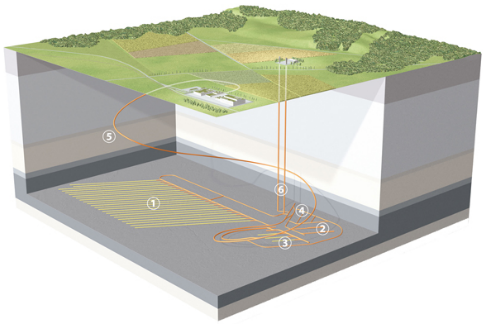
Swiss waste management concept: SNF flow to final disposal

Dry Interim Storage

Cask Transport



Encapsulation Plant



Deep geological Repository

Final Disposal Canister

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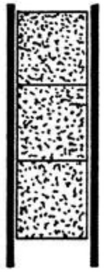
Motivation

- Mechanical response of SNF depends on:
  - cladding properties being of highest importance and
  - fuel/cladding interaction and composite SNF material properties

- The mechanical properties of nuclear fuel rods change:
  - During irradiation (pellet cracking, cladding embrittlement, PCMI, etc.)
  - After irradiation (hydride formation and/or re-orientation, radioactive decay damage, etc.)

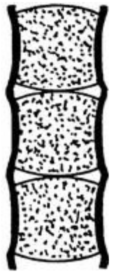
- Challenge…
  - Predicting **mechanical response** of SNF in different loading types
  - Evaluate **consequences** in case of SNF rod integrity loss

before irradiation



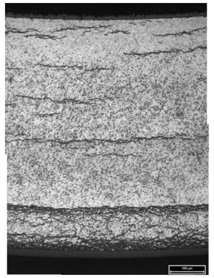
Known geometrical and mechanical prop.

after irradiation

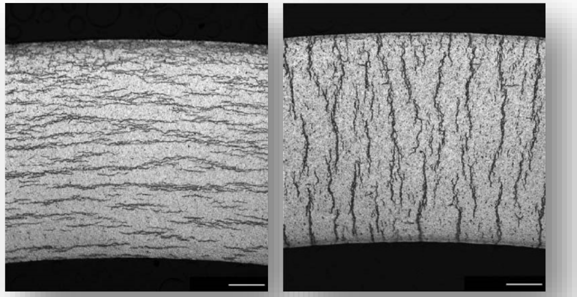


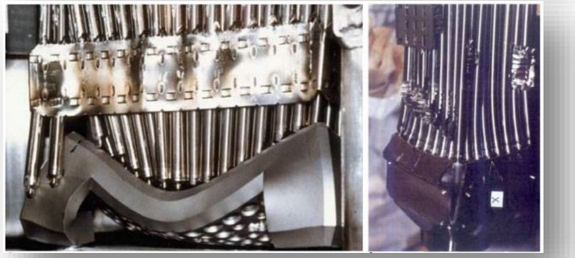
Hydrogen absorption and **change** of mech. & geom. prop.

after **dry-storage**



Hydride reorientation and **ageing** effects → mech. prop. **?**

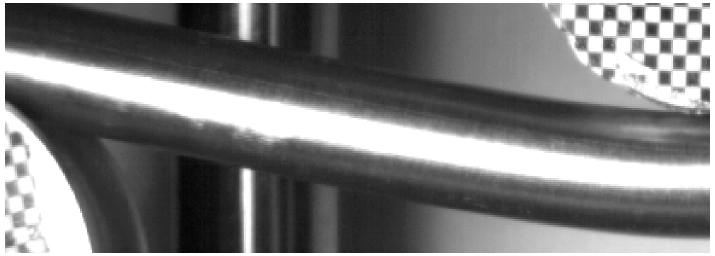


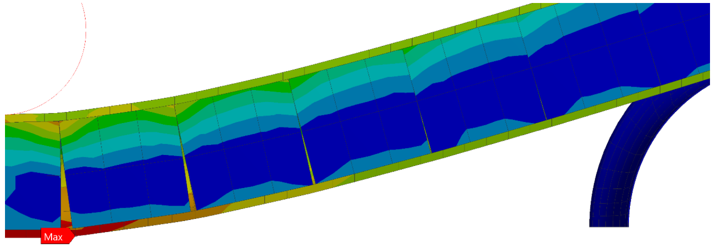


Nagra - SNF Integrity Investigations

- **Objective**:
  - Assess the mechanical response of SNF rods in quasi-static & dynamic loads

- **Approach, i.e. experimental / numerical** :
  - Investigate **mechanical properties** of SNF rod: empirical laws: $\sigma_f = f(BU, \varepsilon)$
  - Study rod **failure** processes and consequences
  - Develop Finite Element Models (**FEM**) validated against experimental data





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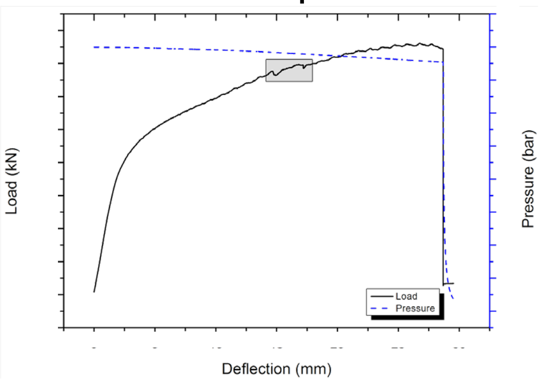
3-point bending test

Force vs. displacement



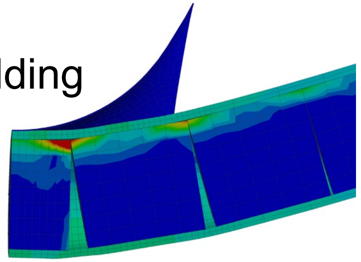
$\sigma_f = f(BU, \varepsilon)$

Post-test examinations:
1. H_2 measurement
2. Metallography
3. Fuel mass release
4. Particle size distribution

3D FEM

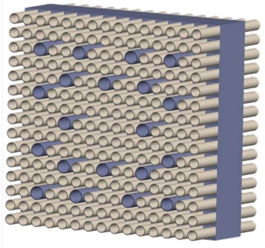
Effective mechanical properties

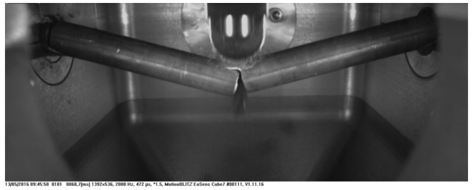
Pellet/Cladding



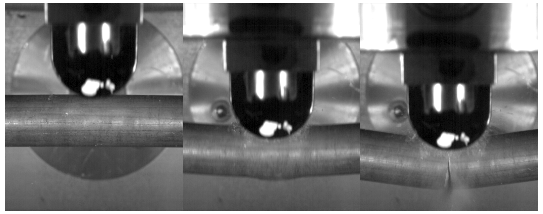
1D FEM

1. SFA integrity investigations
2. Failure criteria



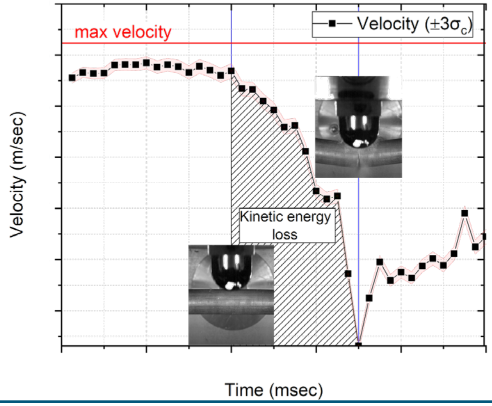


Impact test



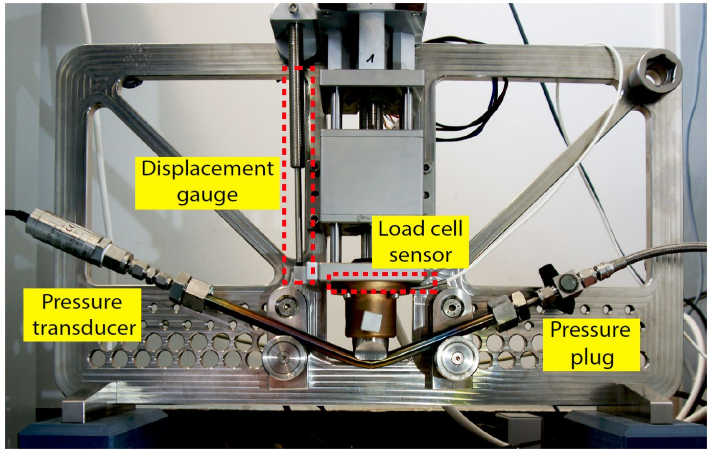
Impact sequence

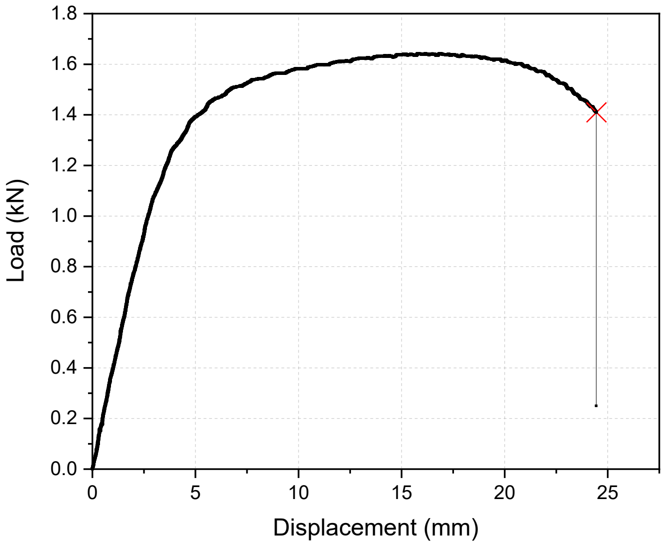
High-speed imaging

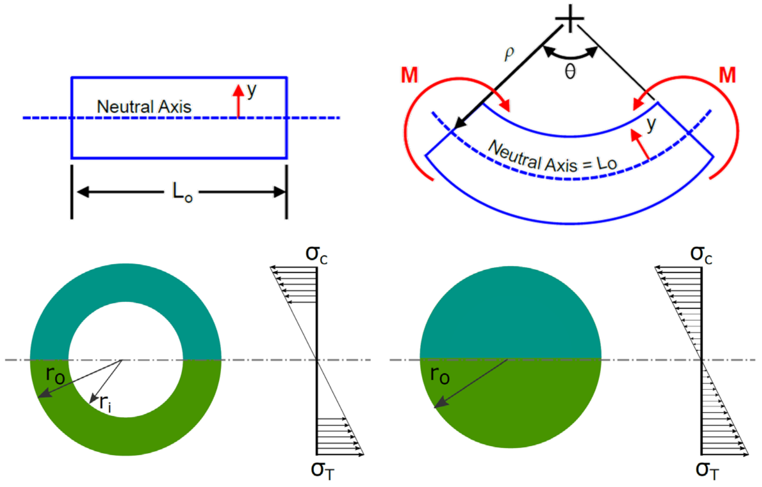


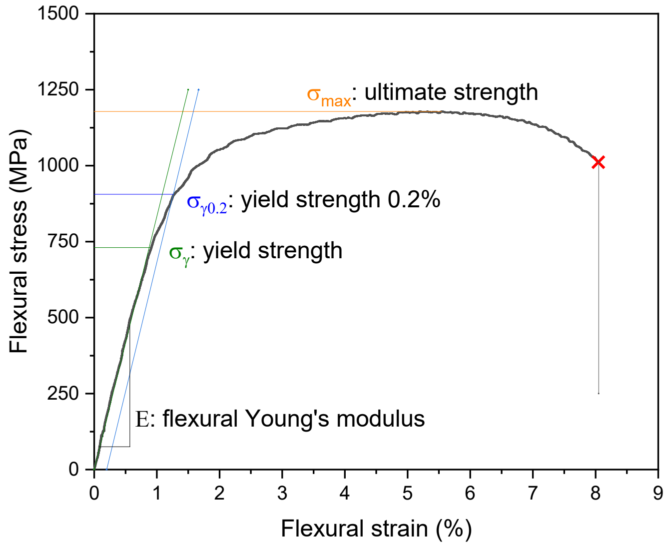
3-Point Bending Tests – Setup and Method

- **Quasi-static** loads: 1 mm/min applied with step-motor
- **Sensors**: pressure, displacement and applied loads
- Use of **simple beam theory** for flexural properties derivation
  - Properties derived as function of:
    - Burnup
    - Cladding hydrogen content







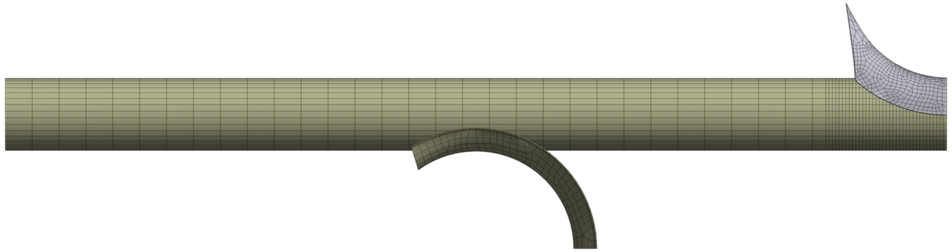


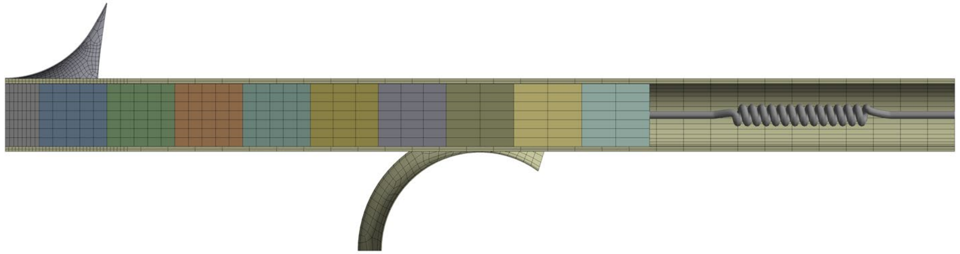
Numerical Investigations of SNF Mechanical Properties

- Objective:
  - Derive **effective mechanical properties** of SNF rod that reflect the mechanical response of the composite spent fuel/cladding system

- **Finite Element Modeling** (FEM) in ANSYS Mechanical with implicit static structural analysis for the 3-point bending case

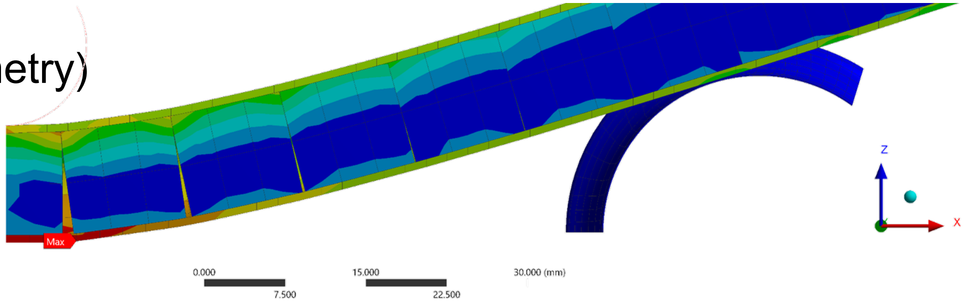
- Modeling **approach**:
  1. Explicit modeling of fuel and pellets (3D FEM) to simulate experimental tests
  2. Sensitivity analysis of the model and calibration against experimental results
  3. Simplification of modeling approach (1D FEM)





3D Finite Element Modeling

- **Development** approach:
  - Based on 3-point bending tests on surrogate rods
  - Uncertainties elimination (known mechanical properties & fixed geometry)



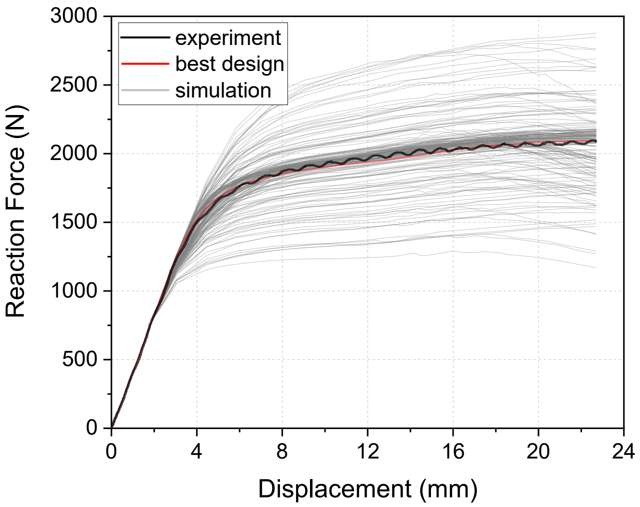
- **Sensitivity** analysis:
  1. Material model for pellets/cladding
  2. Numerical parameters
  3. Physical parameters

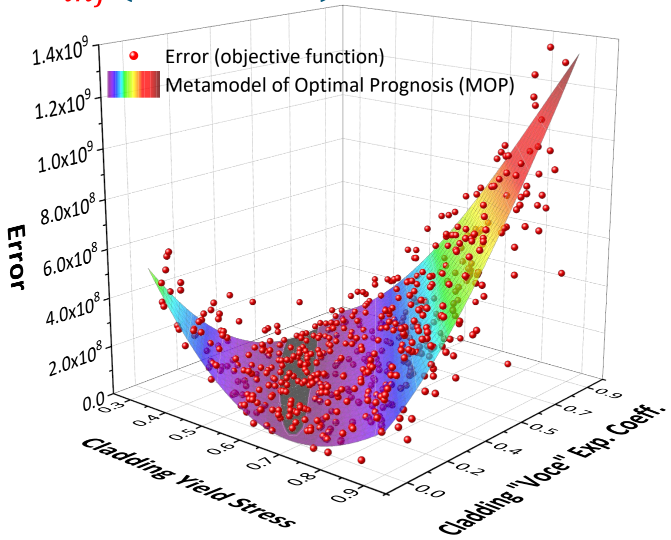
- Final model as:
  - Best compromise between **solution quality** and **computational time**

Voce plasticity model used for cladding

$$\sigma = \sigma_0 + R_0\varepsilon_{pl} + R_{inf}(1 - e^{-b\varepsilon_{pl}})$$

- SNF rod effective **properties derivation**
  - **Optimization** process minimizing difference between experimental and numerical results
    - Evaluate parameters relative importance
    - Best model provides material parameters



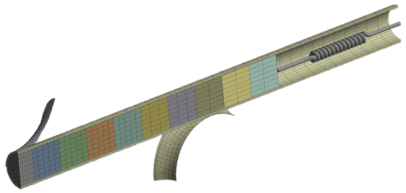


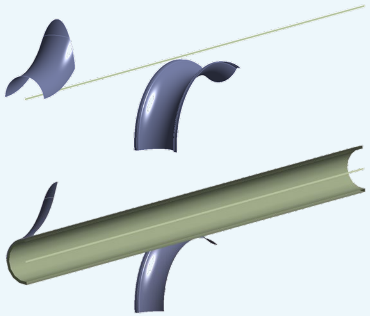
Towards 1D Beam Modeling

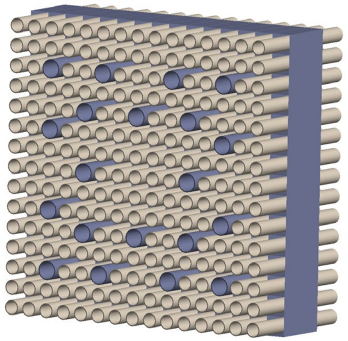
- 3D FE model can **accurately** predict bending behavior
  - However, **too slow** to be used for a large scale SFA design

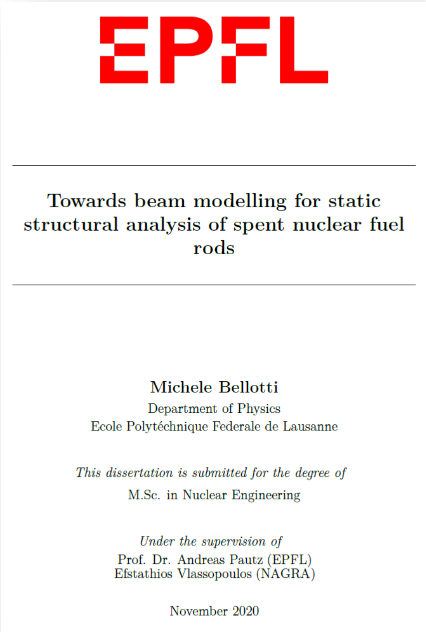
- A 1D beam model was created and optimized to fit experimental data
  - Faster convergence compared to the 3D model
  - Optimized to predict bending behavior as accurately as the 3D model

3D detailed modeling on small fuel segments → **1D beam modeling at small-scale** → **1D beam modeling at full-scale**





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Towards beam modelling for static structural analysis of spent nuclear fuel rods

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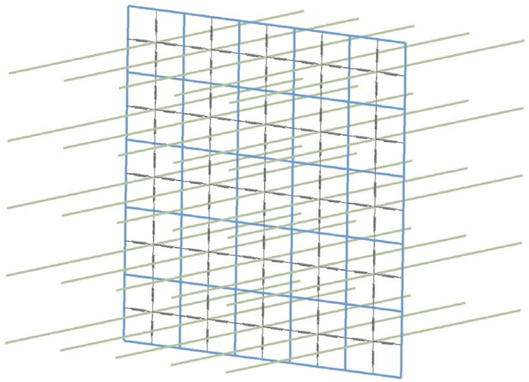
This dissertation is submitted for the degree of
M.Sc. in Nuclear Engineering

Under the supervision of
Prof. Dr. Andreas Pautz (EPFL)
Efstathios Vlassopoulos (NAGRA)

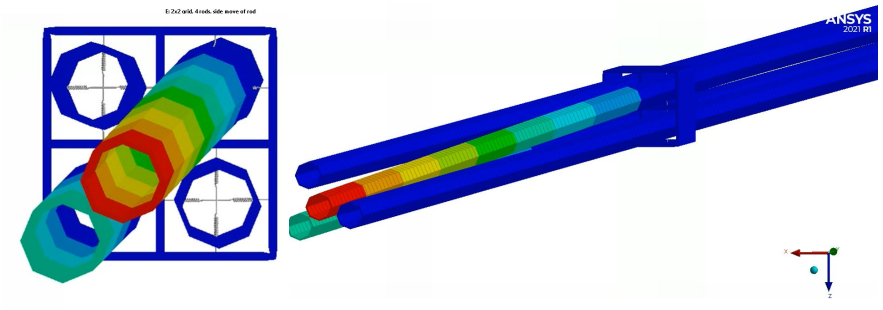
November 2020

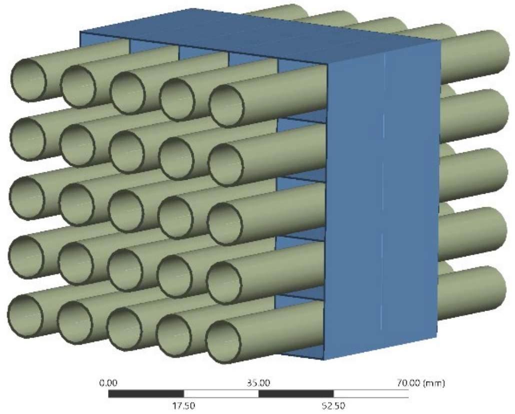
Towards Full-Scale Model – Single Spacer Grid Models

- **Step-wise** development of full-scale PWR SFA model
  - Spacer grid, rods and guide tubes modeling (from 2x2 to 5x5 and 15x15)
    - Fuel rods modeled using beam elements
    - Spacer grid modeled using either beam or shell elements
    - ANSYS spring elements are used to model spacer grid springs and dimples

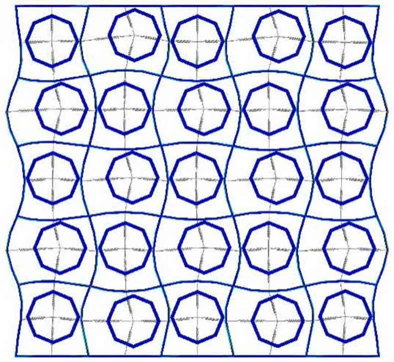


- In each step the model convergence was optimized
  - Contacts/interactions between beam-to-beam and beam-to-spacer grid
  - Faster convergence

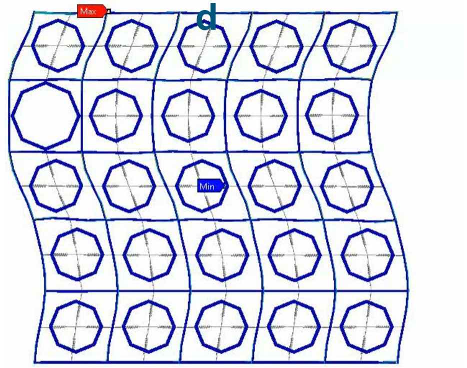




No guide tubes implemented



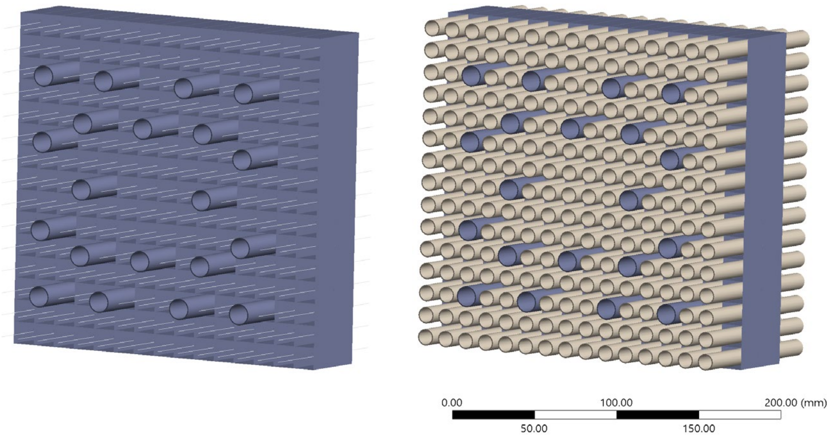
1 guide tube implemente d

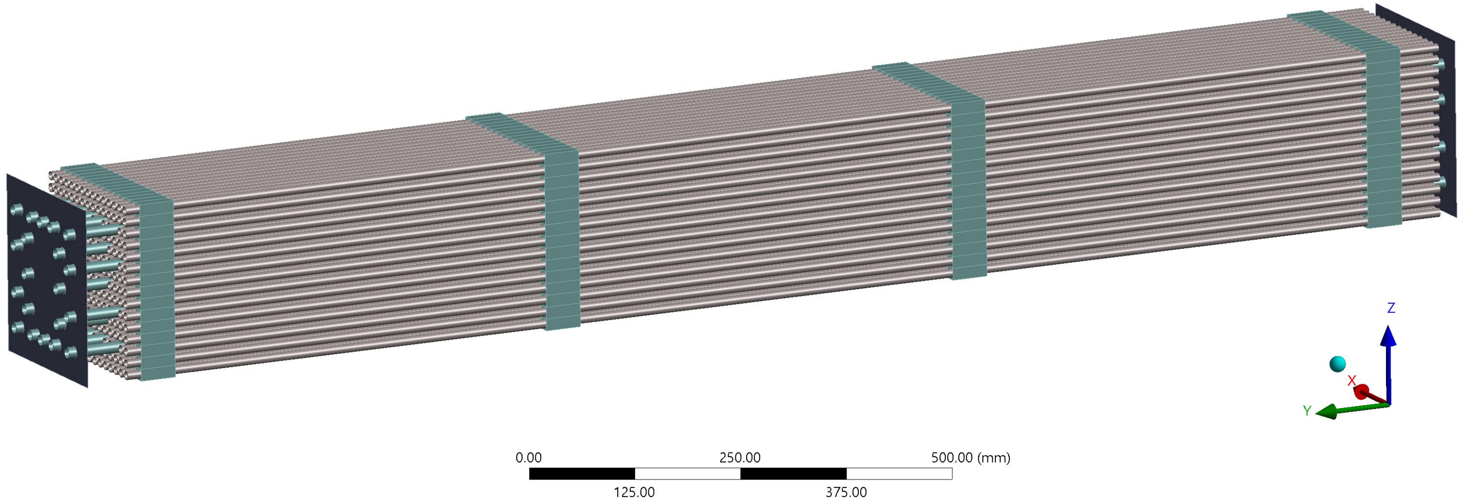


Towards Full-Scale Model – SFA Sub-Model

- Extension of sub-model to include 4 spacer grids in 15x15 grid
  - Top and bottom end pieces (simplified design – perforated shell element plates)

- Simulation of various loading configurations
  - Used to determine model stability and evaluate simulation time



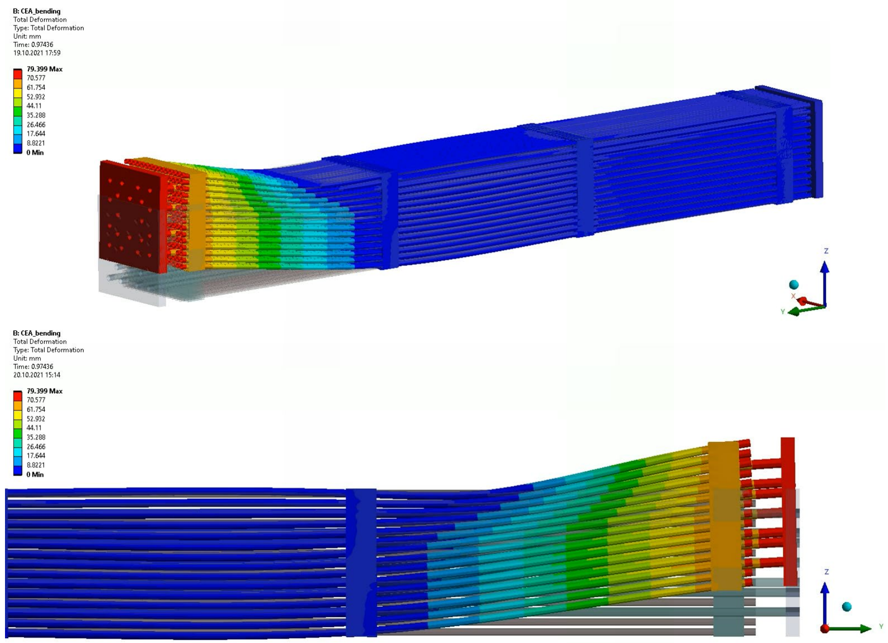


Loading Scenarios Tested

- Two different loading conditions have been tested simulating postulated accident scenarios:
  1. Spacer grid deformation
  2. Bending of SFA

SG deformation:
12 mm compressive load

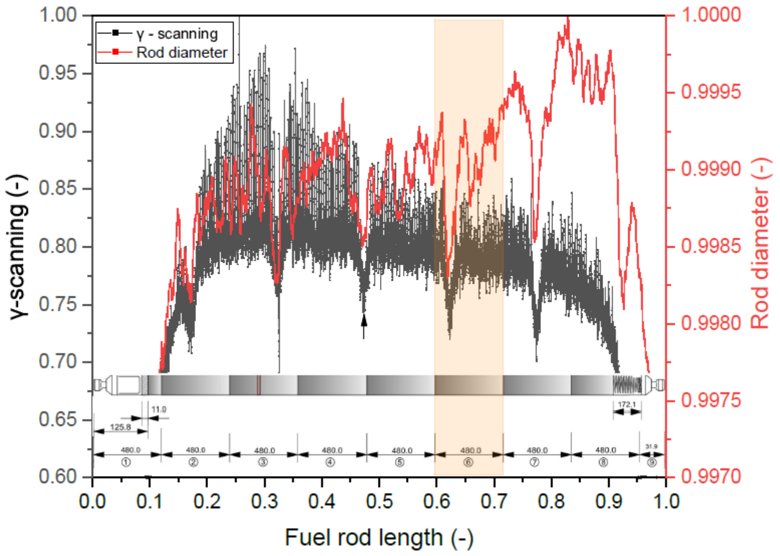
Bending:
Obstacle btw 1st and 2nd spacer grids



Future Goals

- Development of full-scale 15x15 PWR SFA model

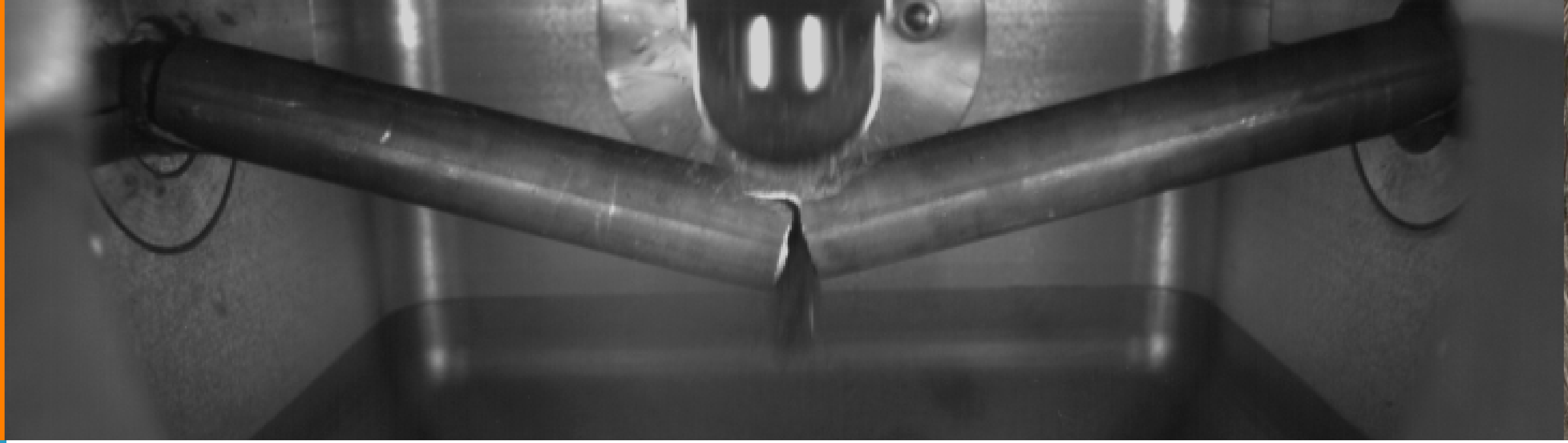
- Mechanical **properties variation** based on axial positions
  - Burnup profile



- **Failure criteria** based on rods plastic strain
  - Derived from calibration process against experimental results

- **Investigation** of **SFA structural integrity** under different loading scenarios
  - Current data can be used for static analysis under bending loads

- Further optimization of existing and future models to reduce simulation time



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- **Kernkraftwerk Gösgen**
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- **Nagra**:
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thank you for your attention

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