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UNIVERSITY OF ICELAND
FACULTY OF INDUSTRIAL ENGINEERING, MECHANICAL ENGINEERING AND COMPUTER SCIENCE

Structural Analysis of the Casings in High-Temperature Geothermal Wells

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Doctoral committee:
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University of Iceland

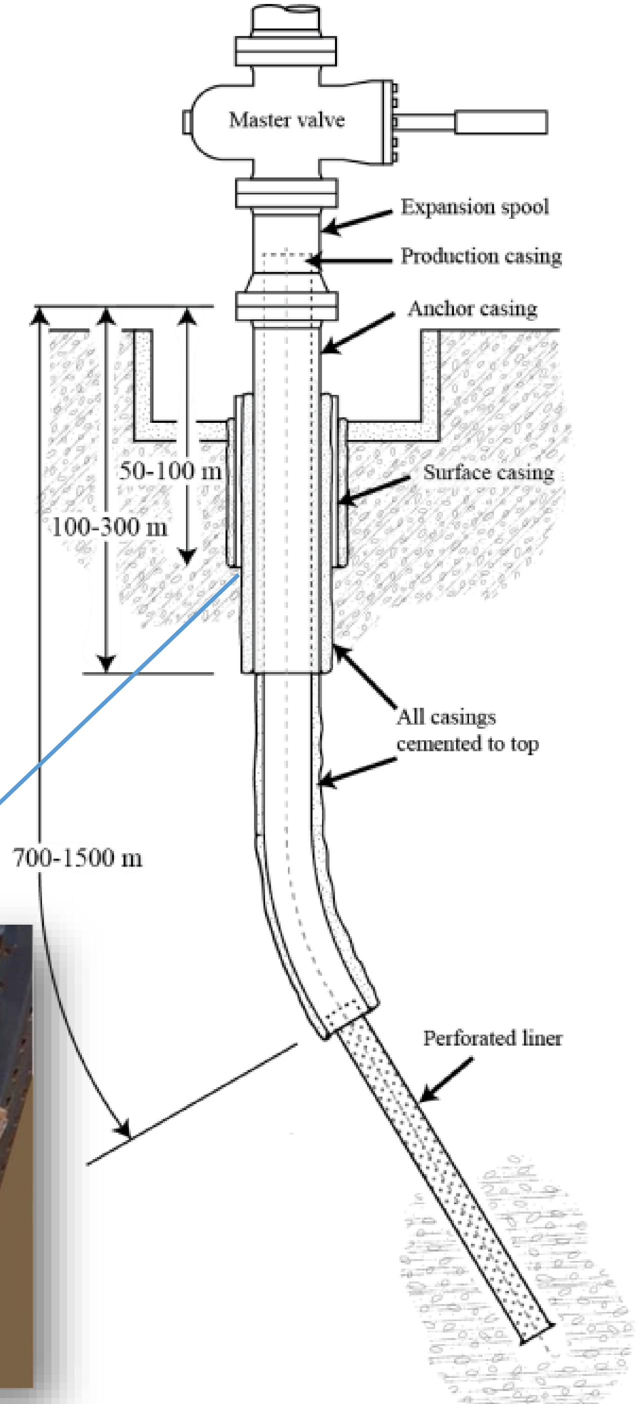
Introduction

- PhD project at University of Iceland
- Objective:
  - To analyze casing failures in high-temperature geothermal wells
  - To develop structural models of casings for evaluating well integrity and casing failure modes with the nonlinear finite-element method (FEM)
- Outline today:
  - Introduction to challenges and failure modes in high-temperature geothermal wells
  - FEM modeling and analyses of casings
  - Main results
  - Current design considerations/limitations
  - Further work (other projects)

High temperature geothermal wells

- Typical casing program includes 3-4 casings (API grades)
- Casings are constrained by cement over their full length from the casing shoe to the surface
- Perforated liner supports the wellbore in the production section of the well
- Expansion spool is used to allow thermal expansion of the production casing at the wellhead
- Design procedure for typical high temperature geothermal wells is good and failures are not very common in conventional wells with moderate temperatures ~200°C
- Initial survey suggest that at higher temperatures >250°C the failure rate is higher


Fig: Sigrún Nanna Karlsdóttir



Design challenges of high enthalpy wells

- Thermal expansion of casings in typical high-temperature wells generate stresses that surpass their yield strength
- Therefore plastic (permanent) strains are formed in the material
- Most casing failures that occur in wells are directly related to large temperature changes
- Typical wellhead temperature in high temperature geothermal wells is **200-250°C** (~20-40 bar-g)
- In IDDP-1, the hottest recorded producing well to date, superheated steam was produced at the wellhead with temperatures of **450°C** (140 bar-g)
- Future aim is to produce from deep supercritical sources where temperatures could reach as high as **550°C**
- This provides “new” challenges in casing design
- Current design standards do not account for these high temperatures

Failure modes

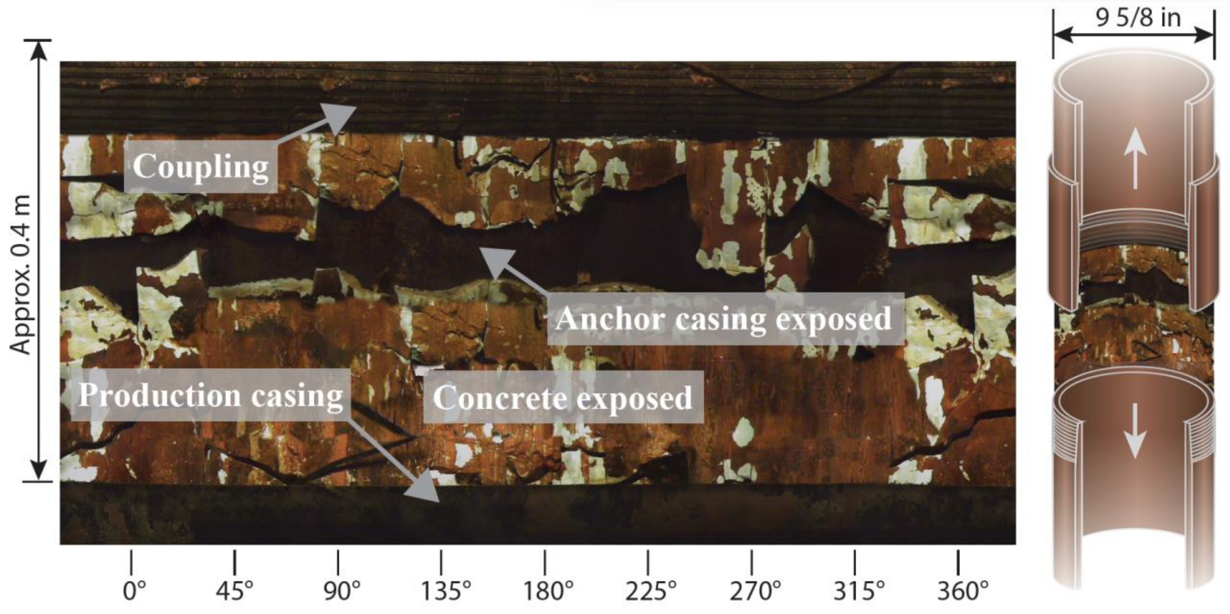
Casing failures can occur due to multiple reasons, and a mix of loads

Axial compression loads are generated when wells warm up after drilling

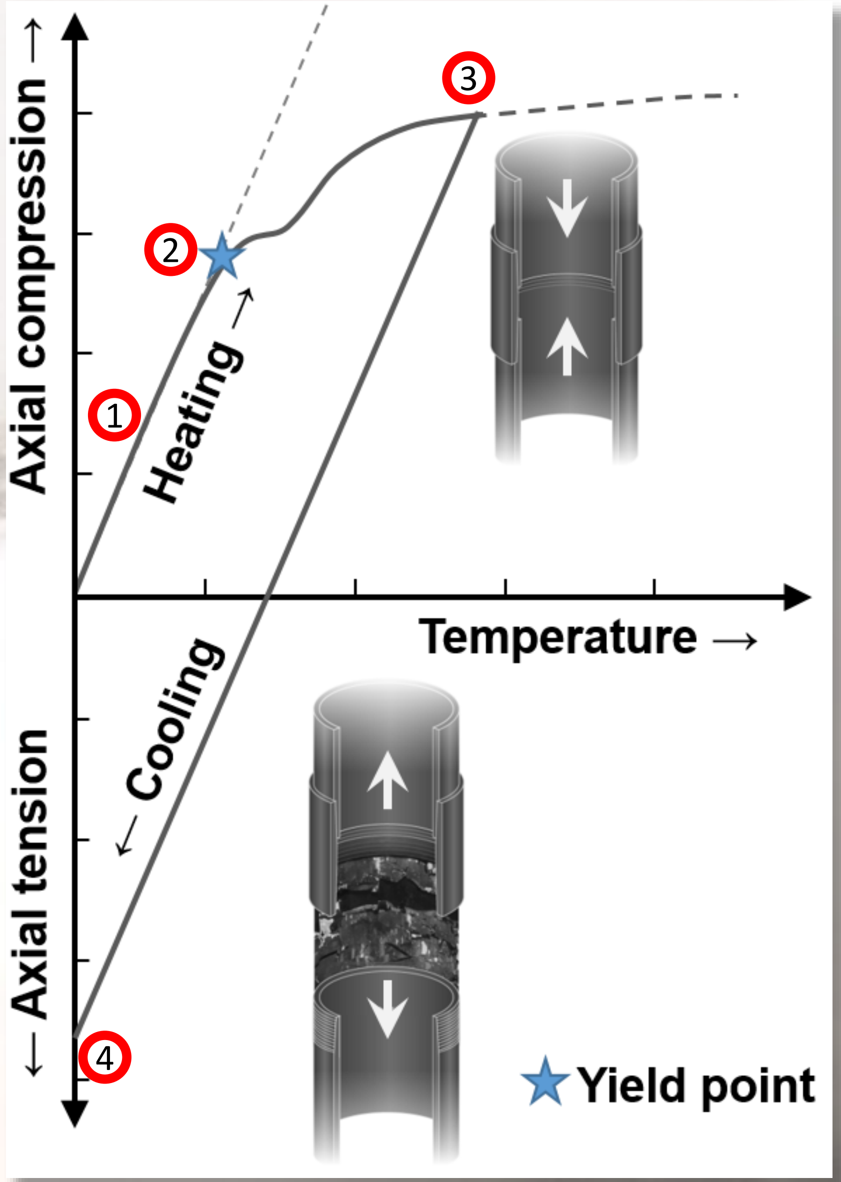
- Material yields and plastic (permanent) strains are formed
- Can induce collapse (bulging/puckers) – collapse resistance reduced
- Such collapse can occur if the cement behind casing includes water

If wells are allowed to cool again, axial tension can lead to tensile rupture in the:

- Casing body
- Casing body near connections (at the location where the first threads begin)
- Threads of the casing/threads of the coupling



Failure modes

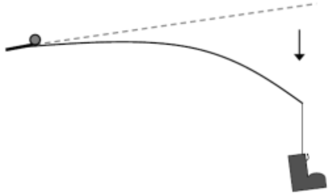


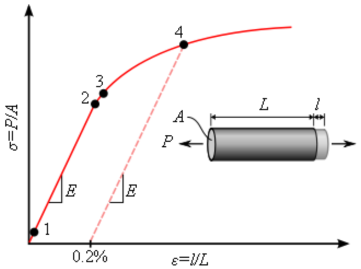
Adopted from a diagram by Rahman & Chilingarian, 1995

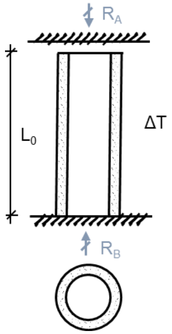
FEM Modeling

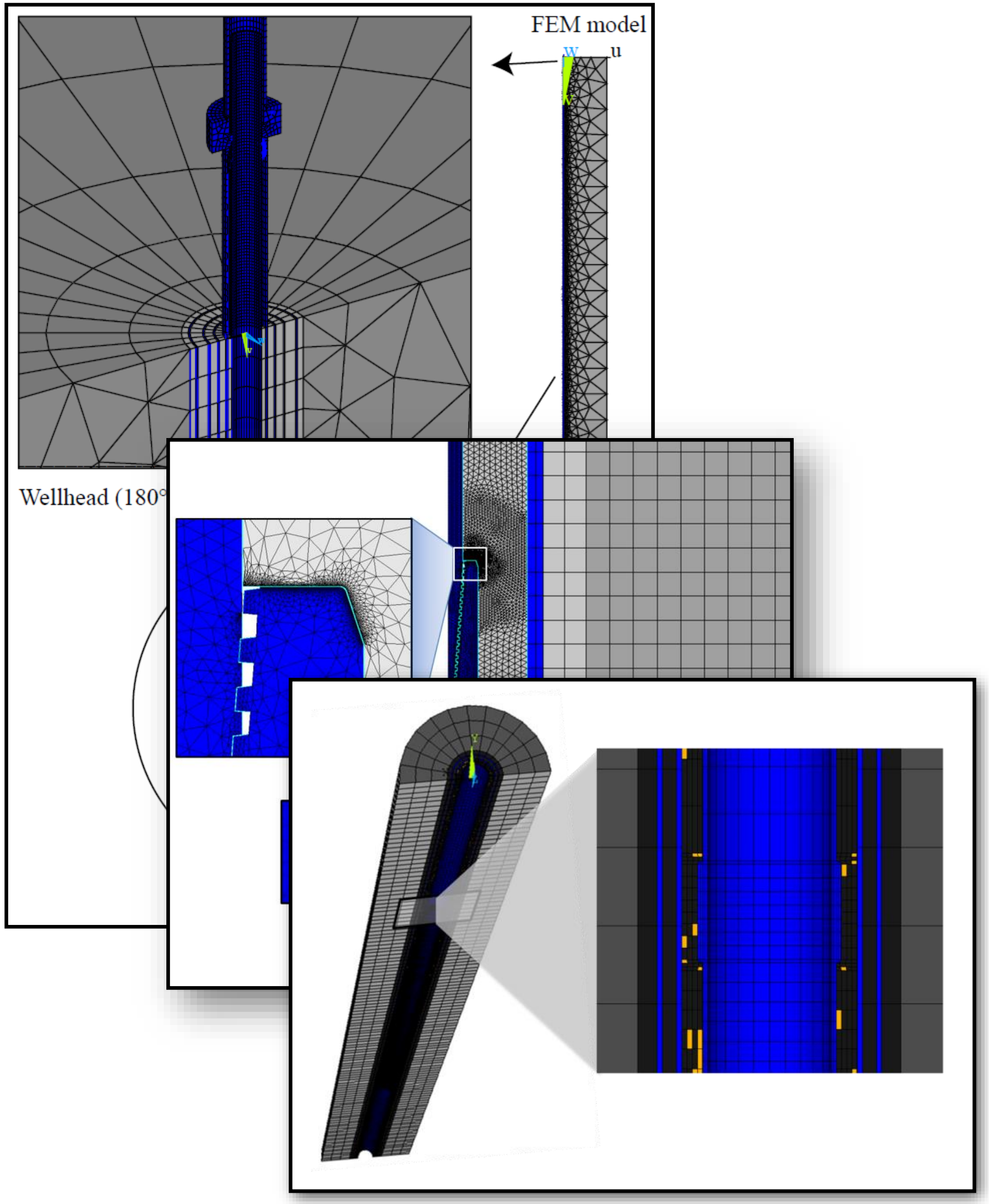
- Thermal and structural models of the cased section of the well
- The (nonlinear) finite-element method is used to capture nonlinear behavior of materials, displacements and friction between contacting surfaces
- The models are used to evaluate the structural integrity of the casings when subjected to transient thermo-mechanical loads
- Three models presented:
  - – Cased section of the well (2D axi-symmetric)
  - – Connection in cement (2D axi-symmetric)
  - – Section of the well (3D collapse analysis)

Nonlinearities:





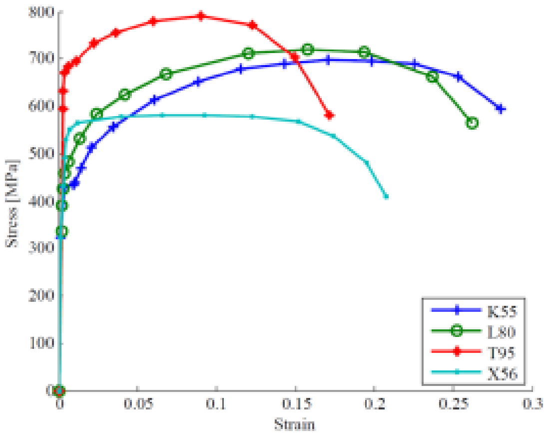




FEM Modeling

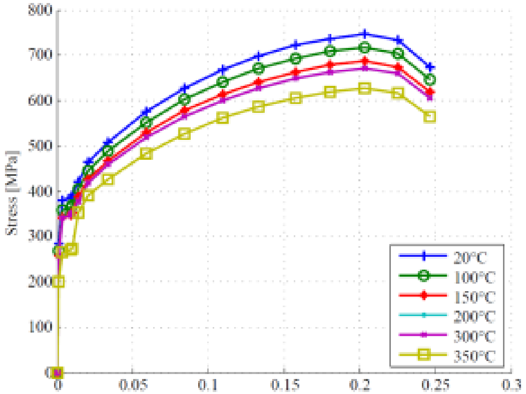
Nonlinear material properties and friction

Stress-strain curves:



Karlsdottir, S.N. and Thorbjornsson, I.O., 2009

Strength reduction at elevated temperatures:

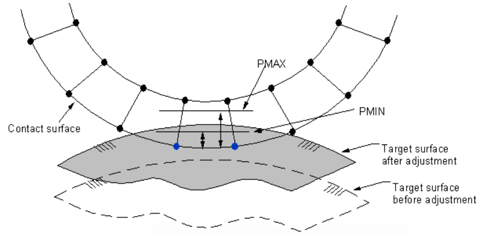


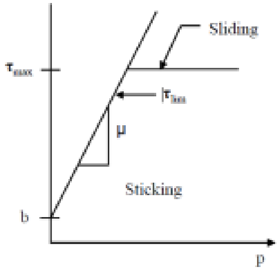
Friction between surfaces (contact elements):

$$\tau = \begin{cases} \mu P + b & \text{if } \tau < \tau_{max} \\ \tau_{max} & \text{if } \tau \geq \tau_{max} \end{cases}$$

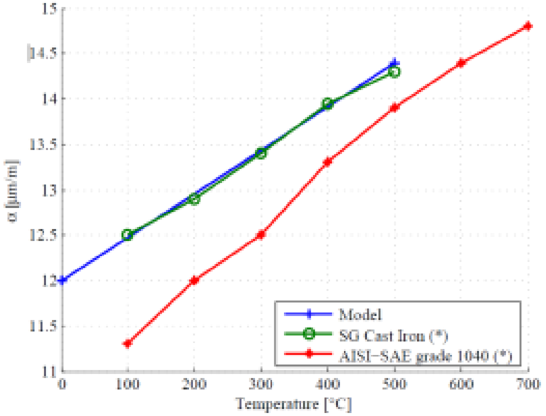
τ: equivalent shear stress

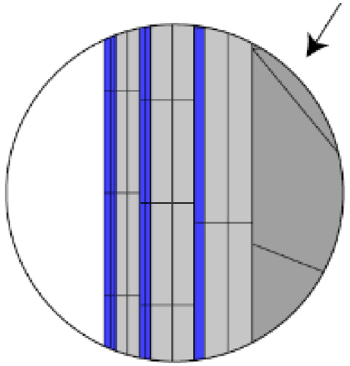
μ: isotropic coefficient of friction
P: contact normal pressure
b: is the contact cohesion
τ_{max}: maximum shear stress





Temperature dependency:

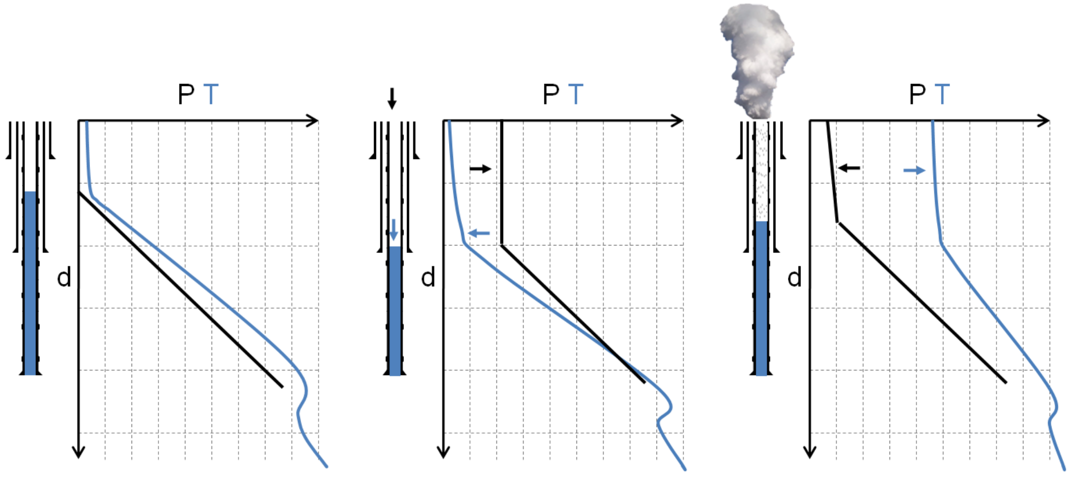


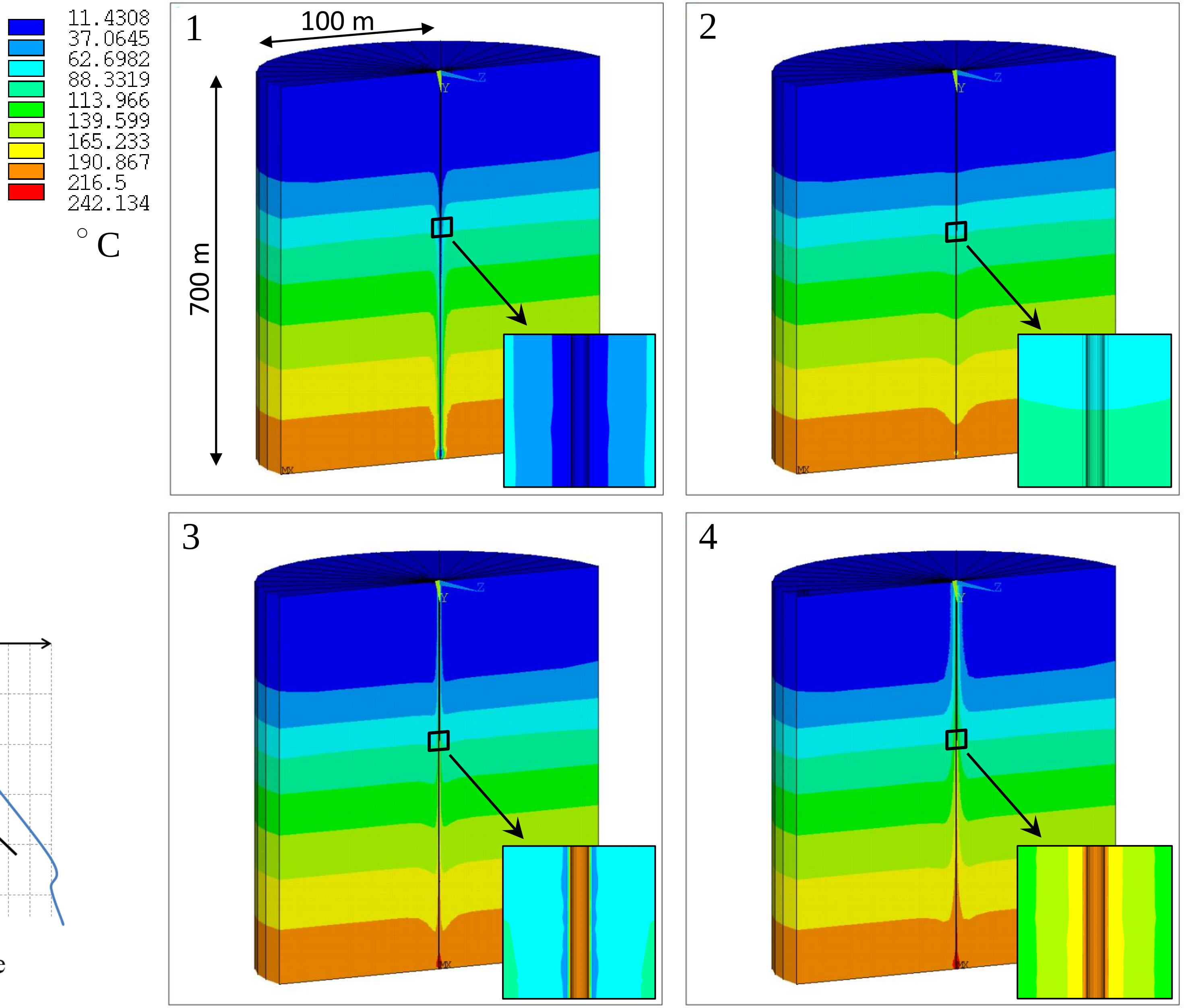


Friction defined between contacting surfaces

FEM results

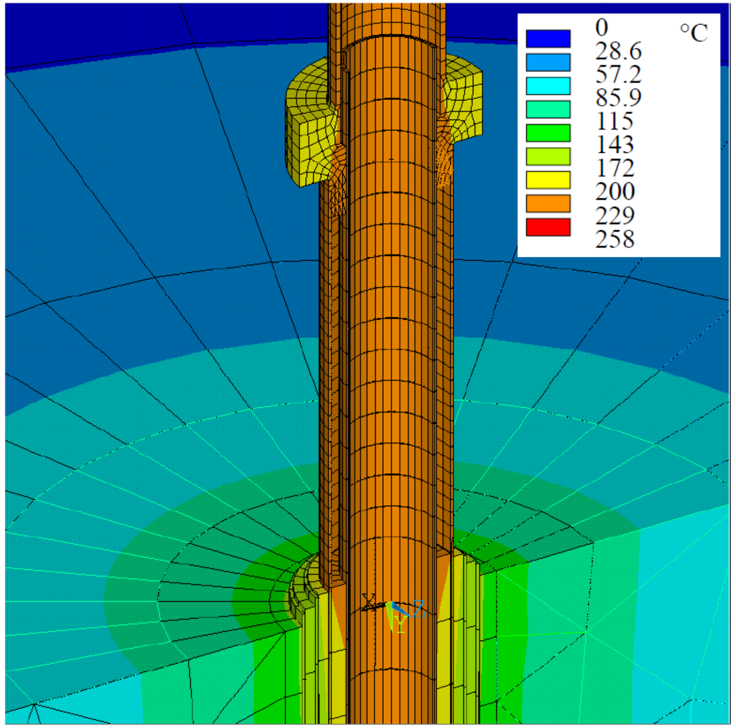
- Production history modeled.
- T-P logs and wellhead data are used as load.
- Transient thermal analysis is performed and the results used as load in the structural analysis.
    1. Cooling due to drilling.
    2. Thermal recovery.
    3. Flow-test (12 min).
    4. Flow-test (3 months).





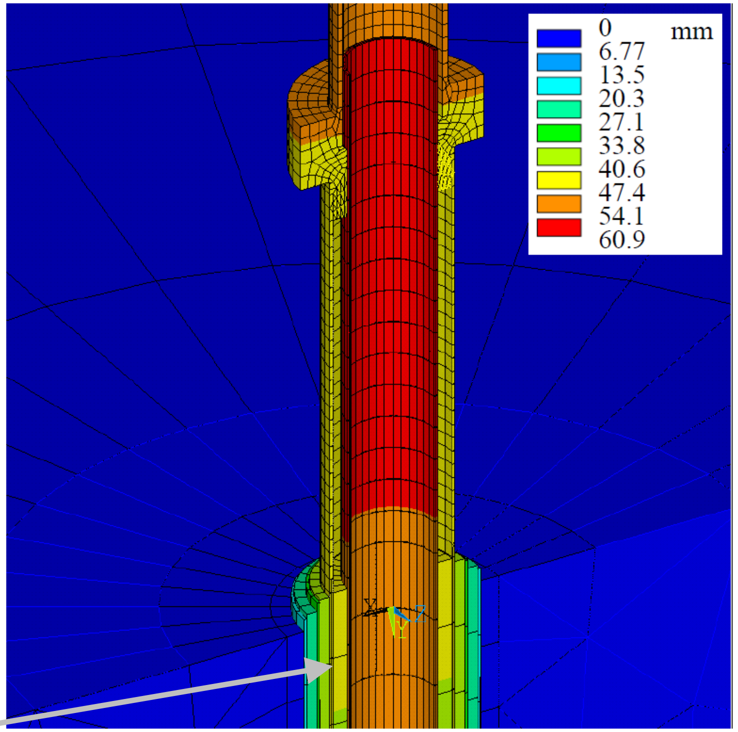
FEM results

- Wellhead rise as the casing warms up
- The production casing expands and slides inside the wellhead (expansion spool)



Temperature distribution after 9 days of discharge.

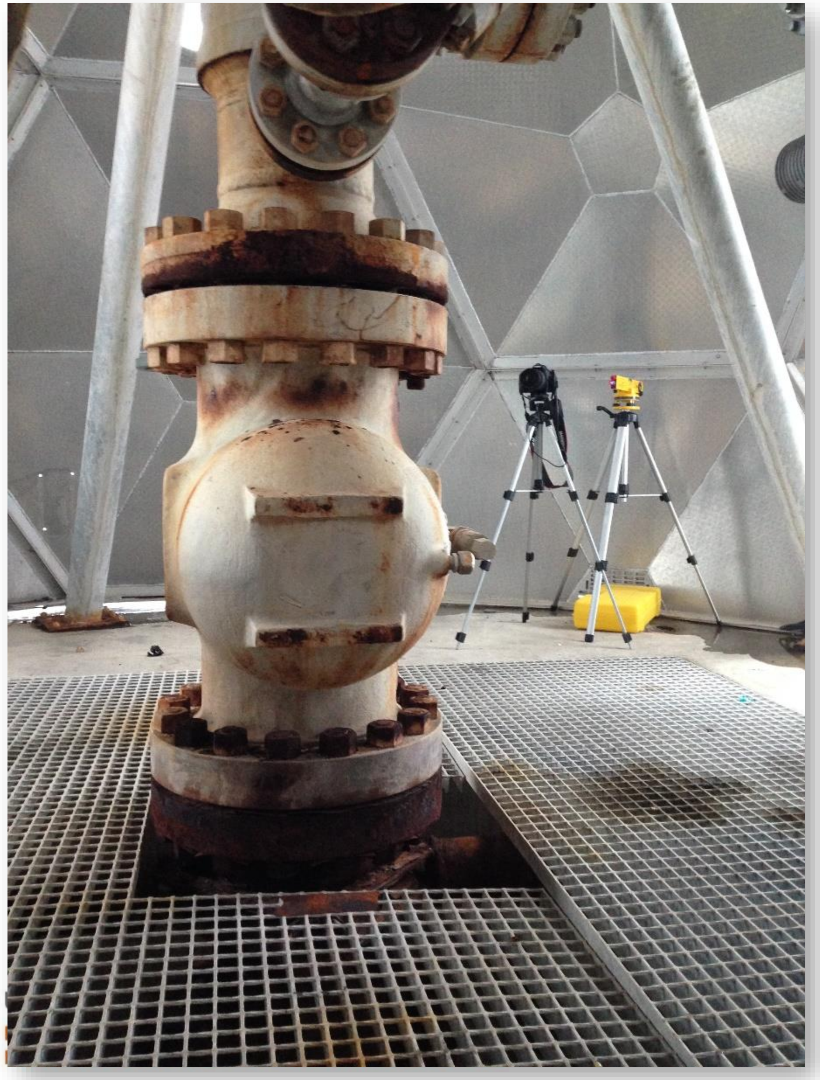
Wellhead displacement.



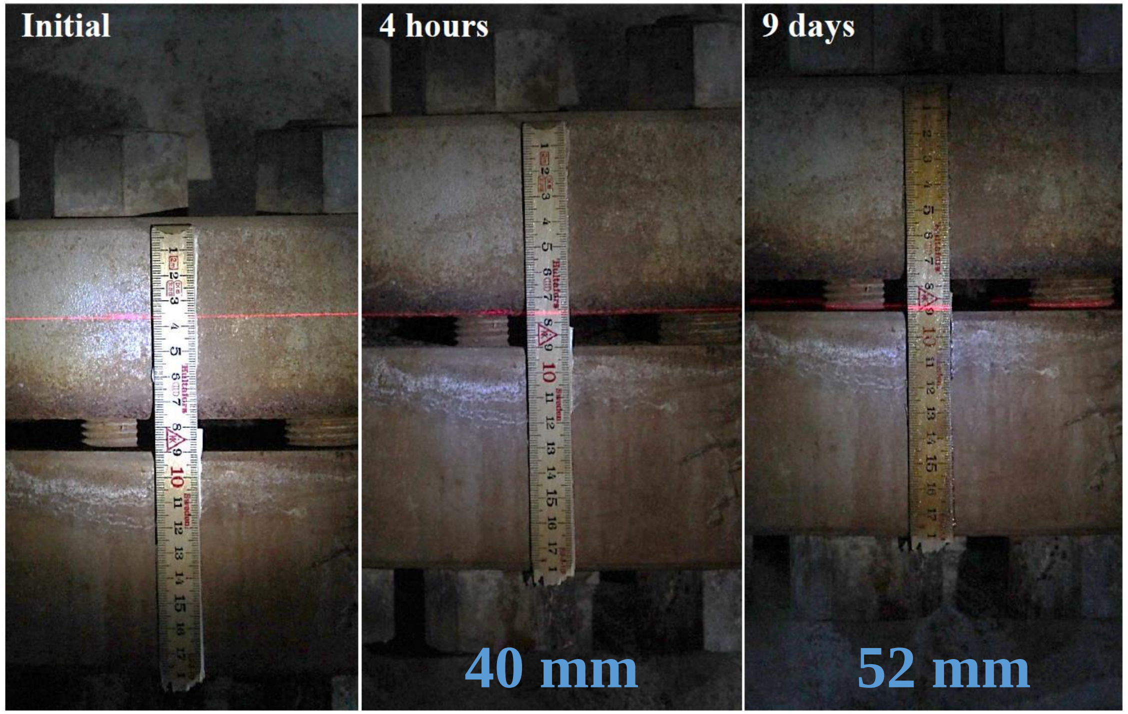
Friction is defined between casings and cement

Wellhead displacement survey

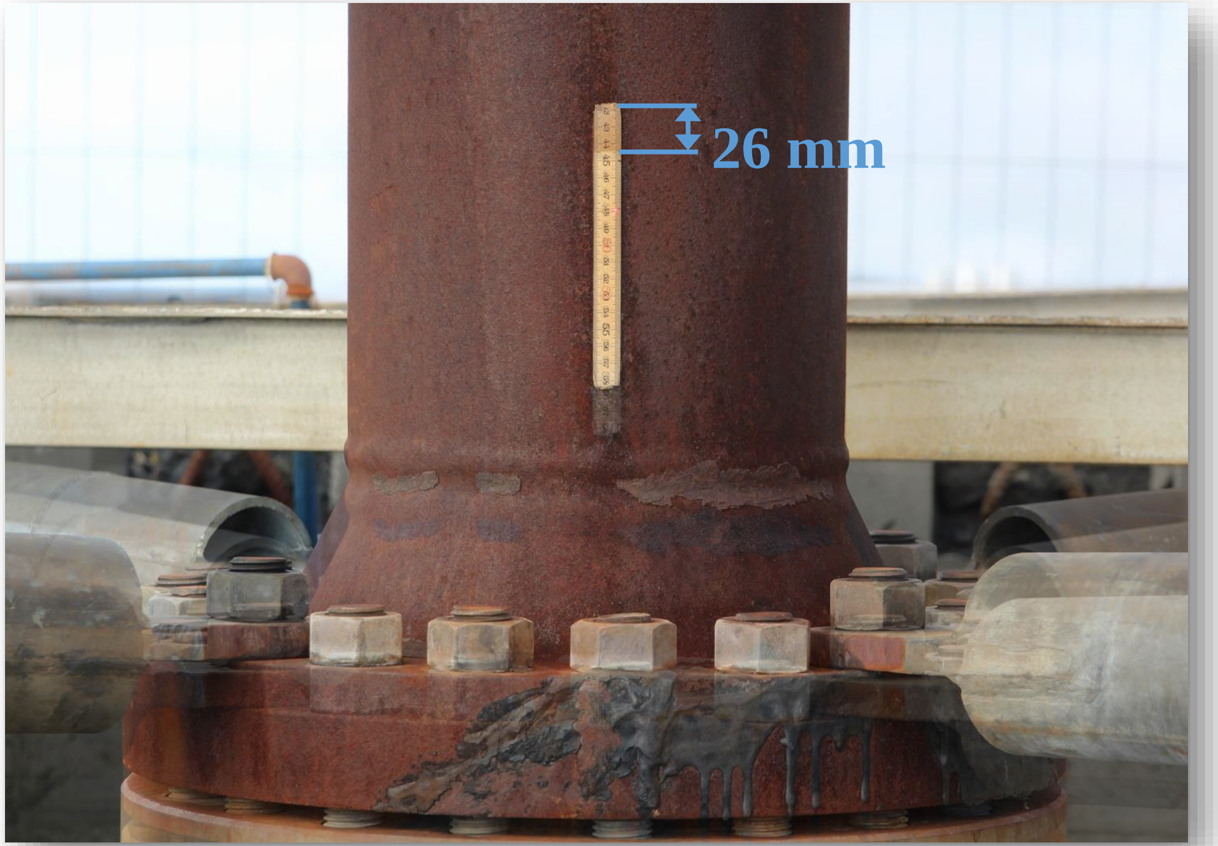
- Wellhead displacement measured during flow-test



Wellhead displacement survey



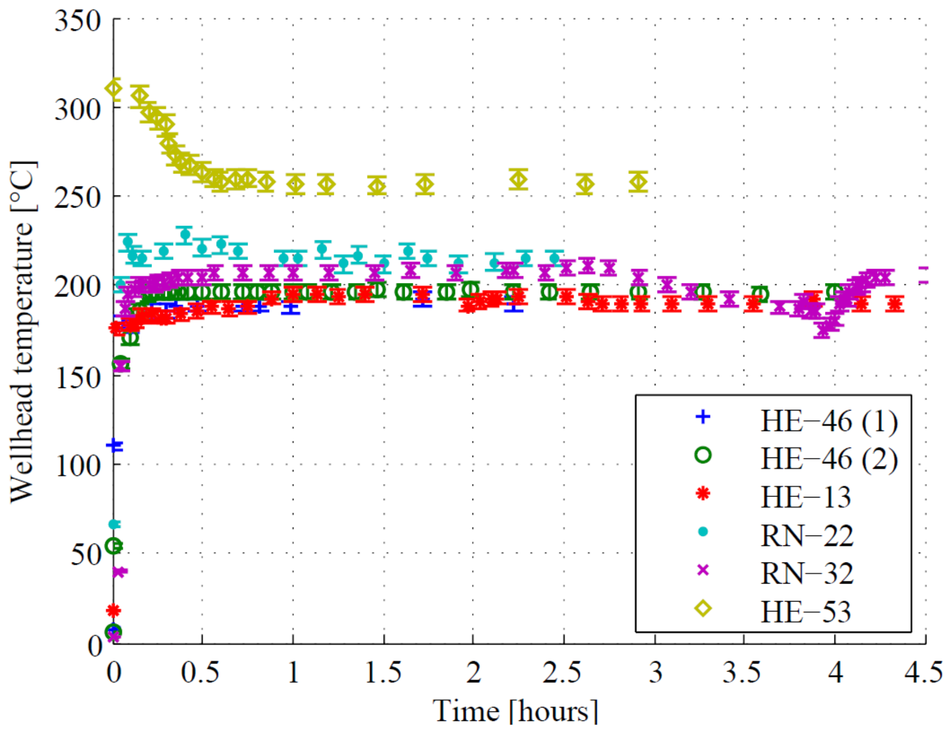
Photographic series of the wellhead of HE-46 during flow-test.

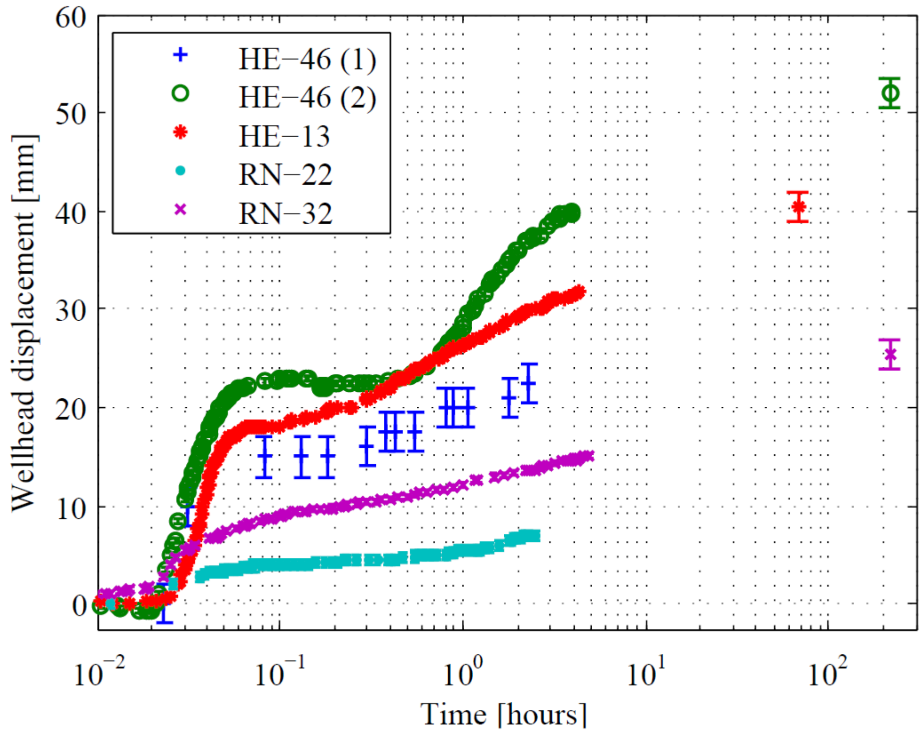


Merged photographs of the wellhead of RN-32 after 9 days of flow-testing.

Wellhead displacement survey

- Wellhead displacement measured during flow-test

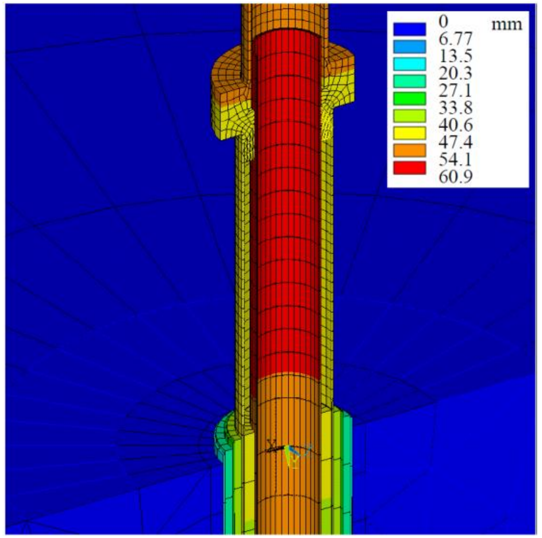


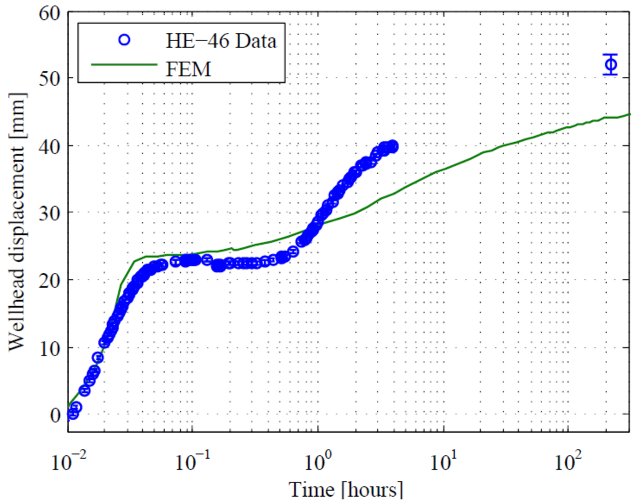


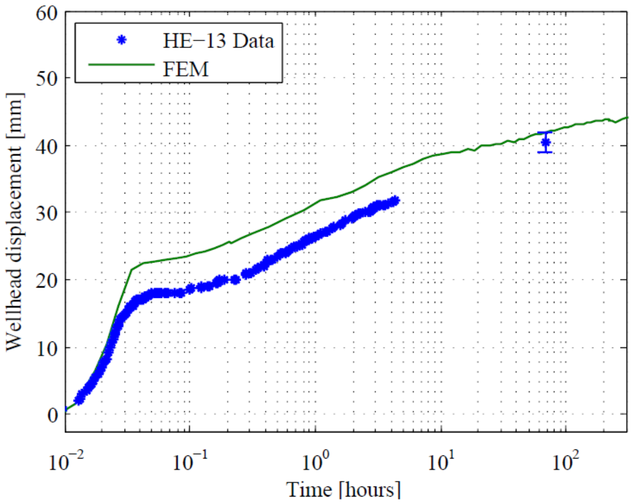
Kaldal, G.S., Jonsson, M.T., Palsson, H., Karlsdottir, S.N., 2015. Structural modeling of the casings in high temperature geothermal wells. Geothermics 55, 126 – 137.

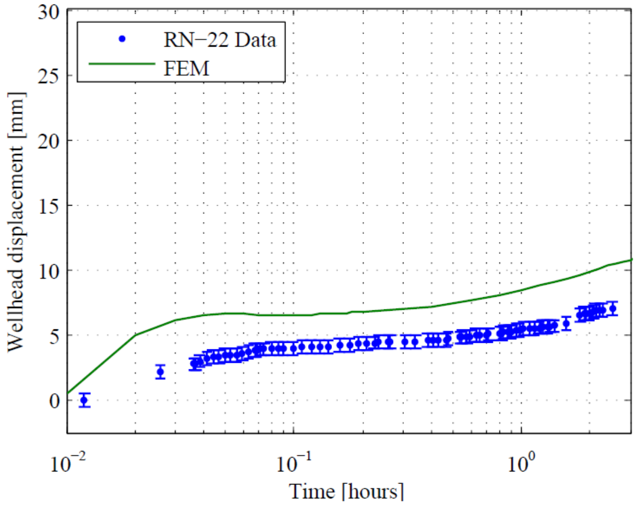
Model results

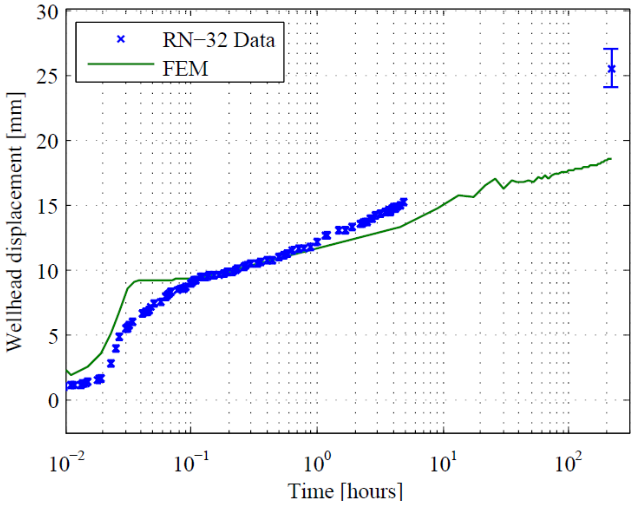
- T and P logs for each well used to build load cases
- Modeled wellhead displacement compared to data





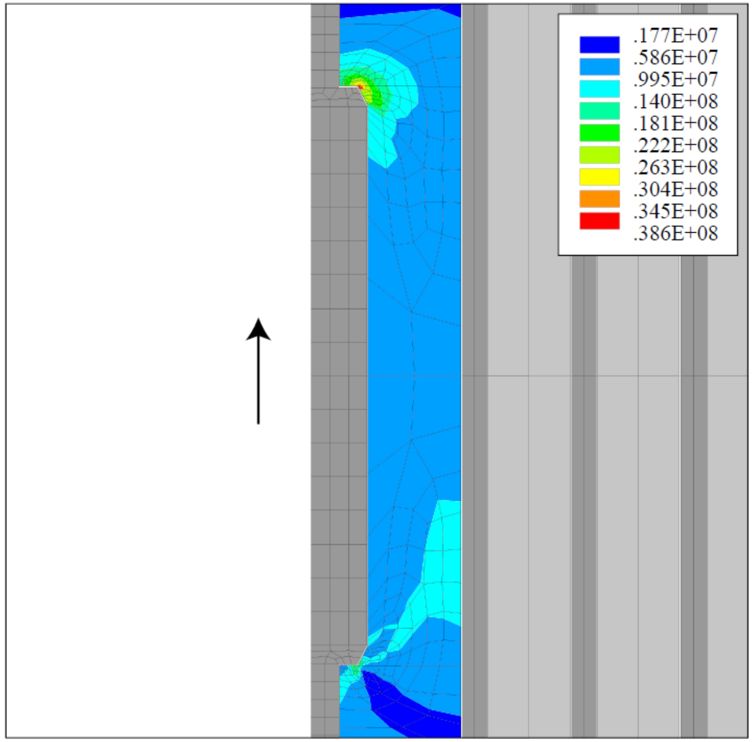




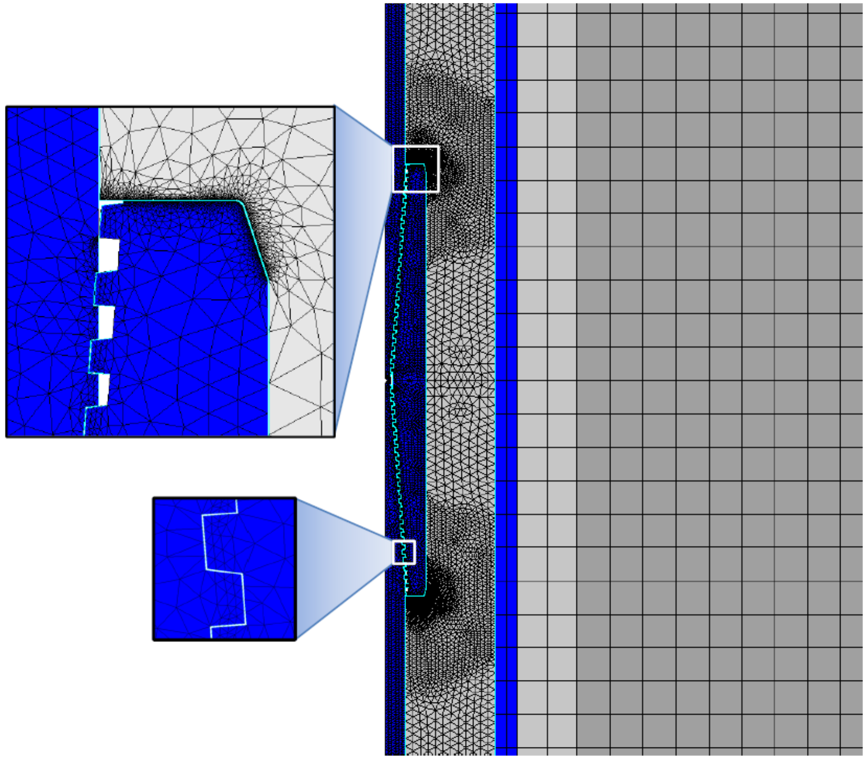


Cement integrity

- Nature of the modeled geometry is that models become large quickly
- Anchoring of couplings in cement
- Large stresses are produced near couplings, that anchor the casing in the cement



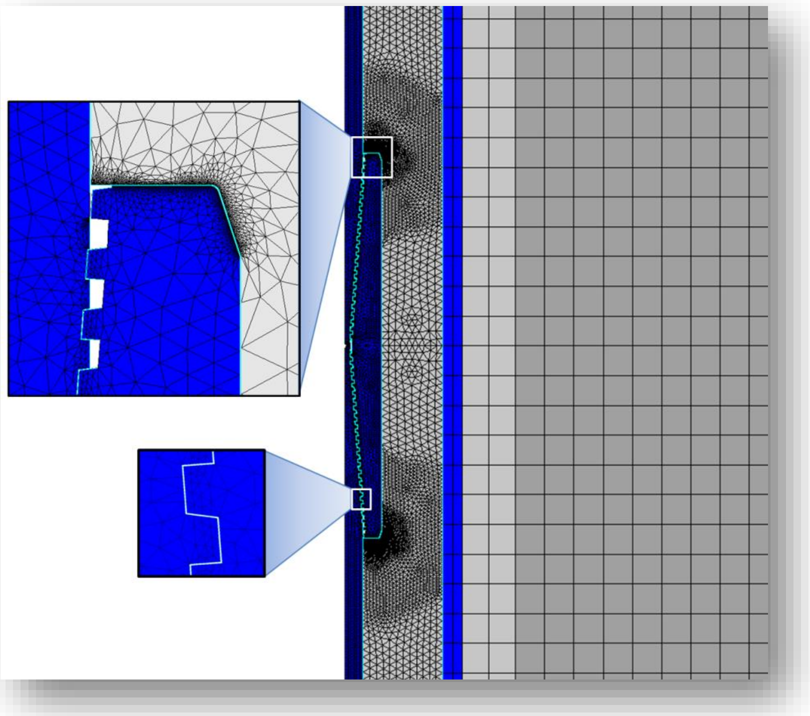
Model i. Cased section of the well

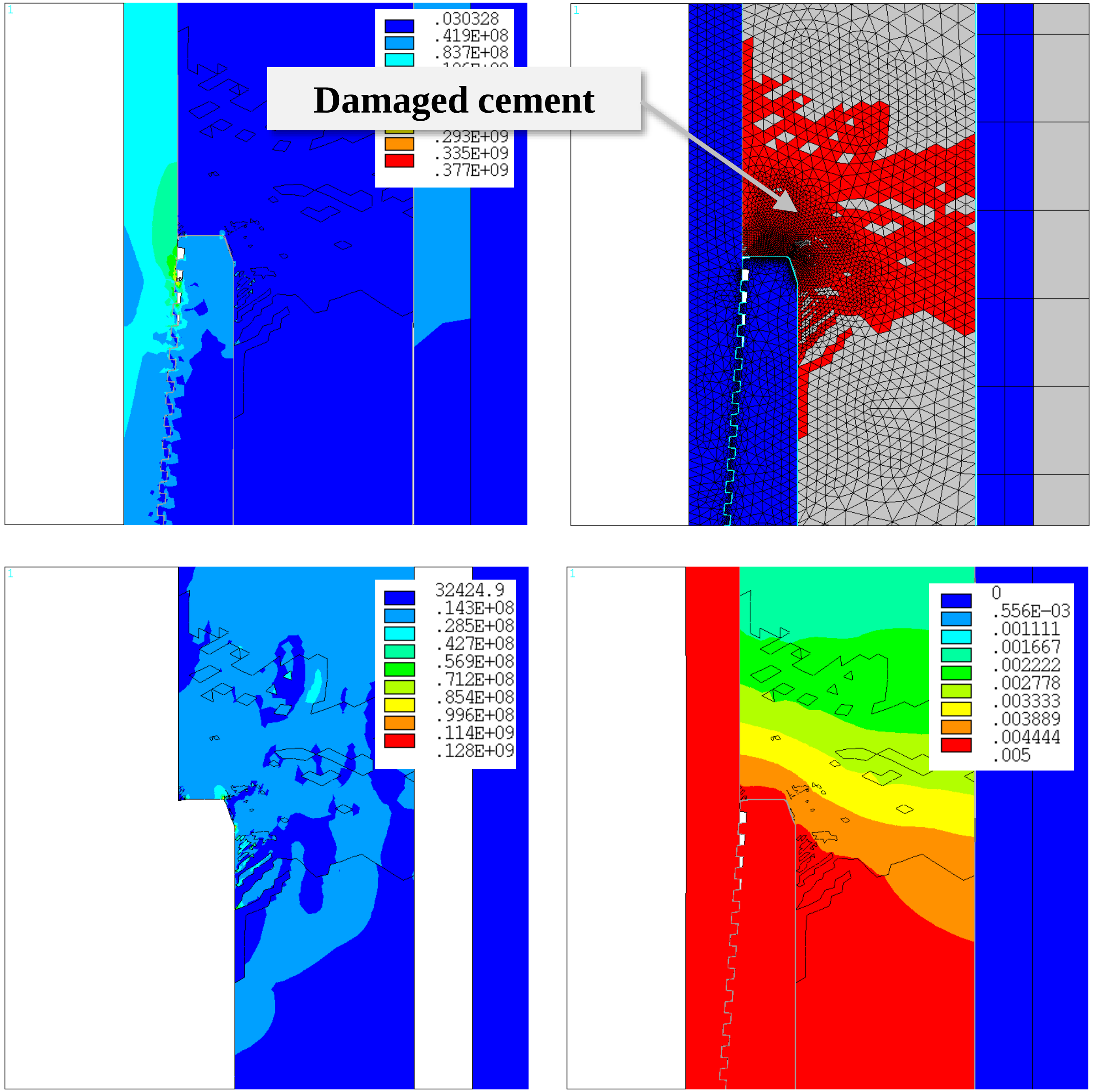


Model ii. Coupling in cement

Cement integrity

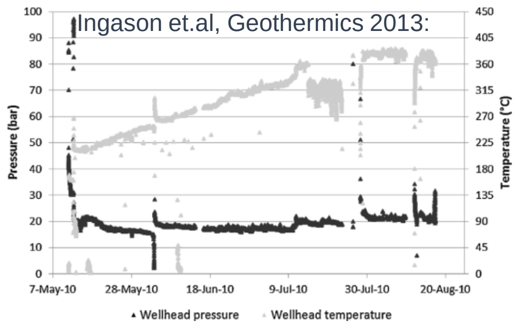
- Connection displacement in cement
- Upward displacement of 5 mm

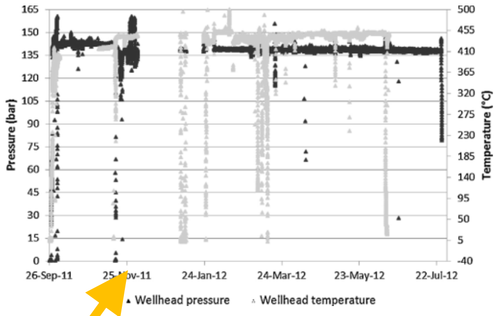




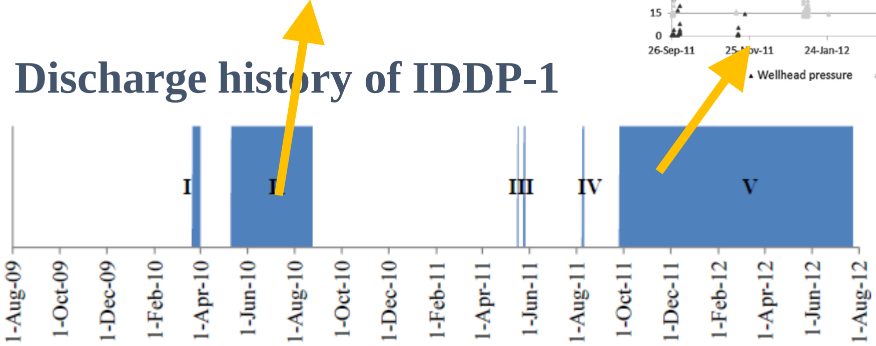
FEM results

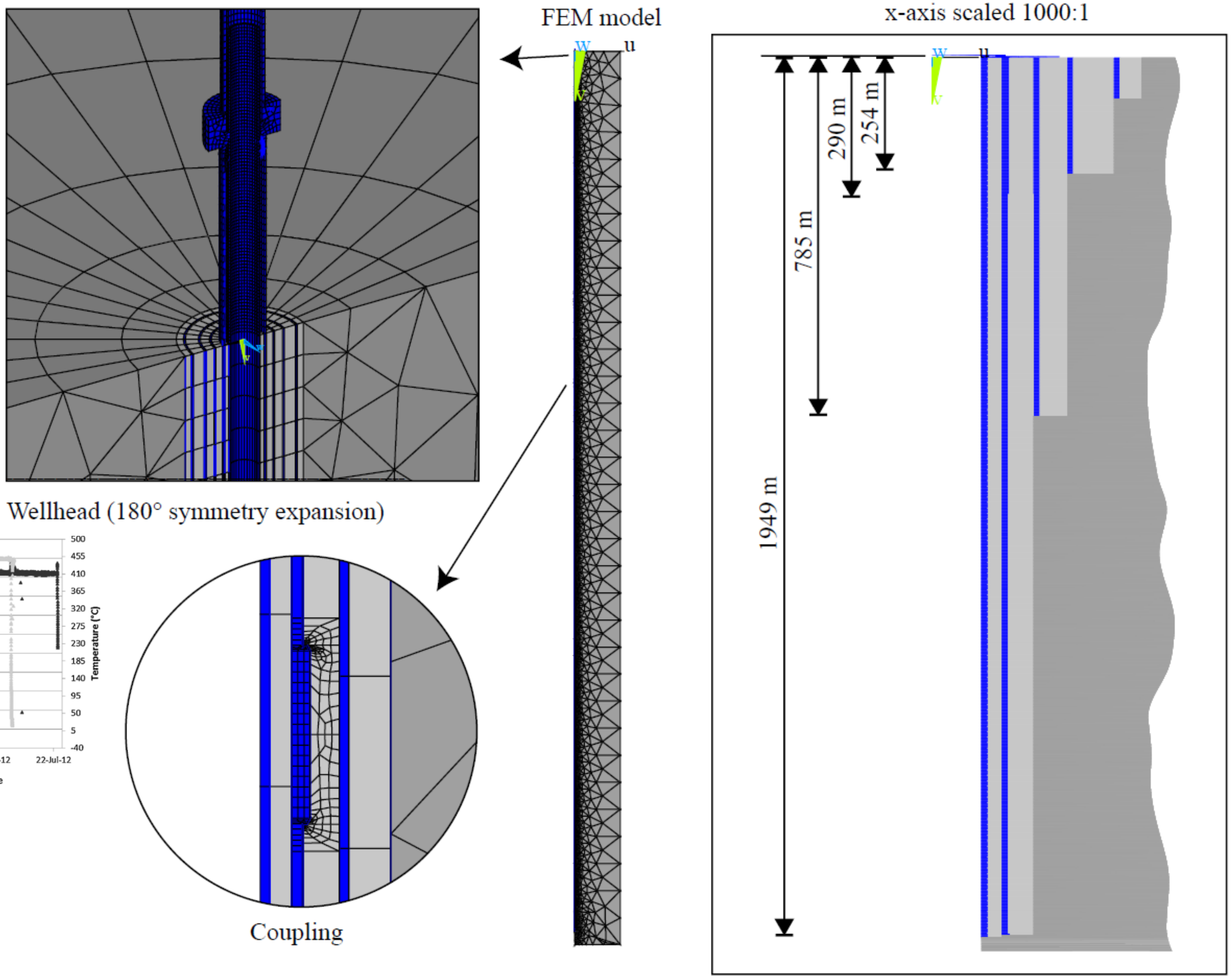
- Case study: structural analysis of IDDP-1.
- Operation history modeled.
  - Initial conditions
  - Warm-up
  - Multiple flow-tests and shut-in periods
  - Quenching with water





Discharge history of IDDP-1

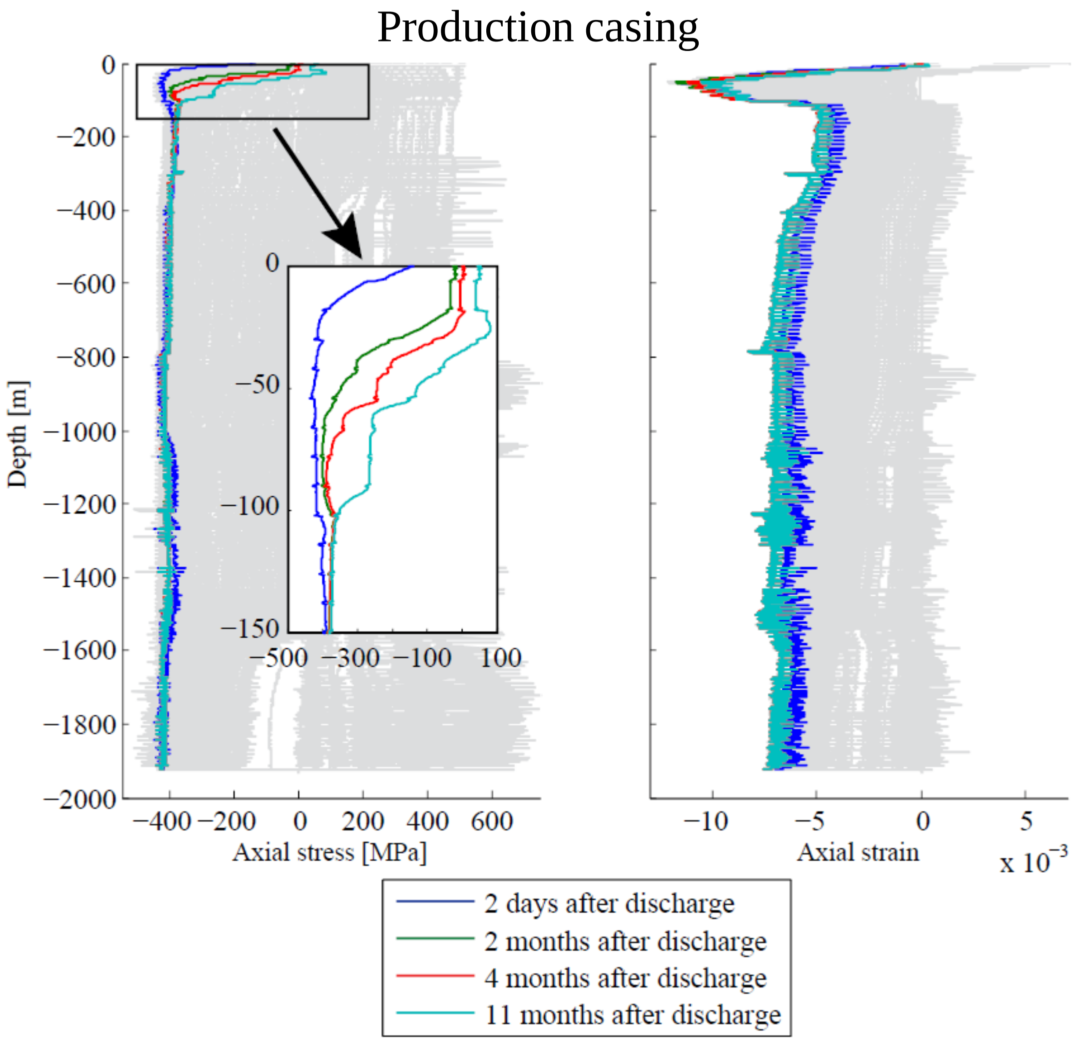


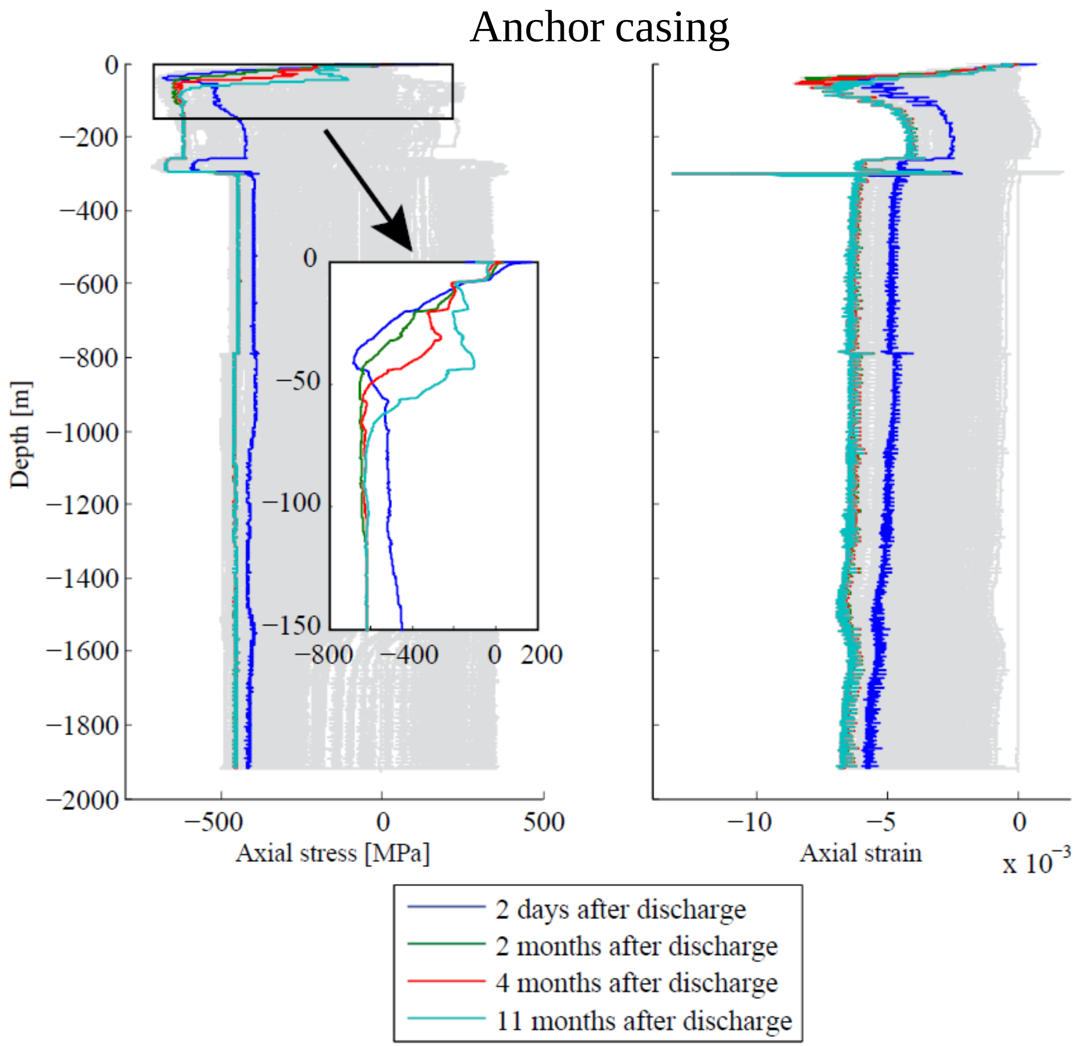


FEM results

- Stress and strain analysis.

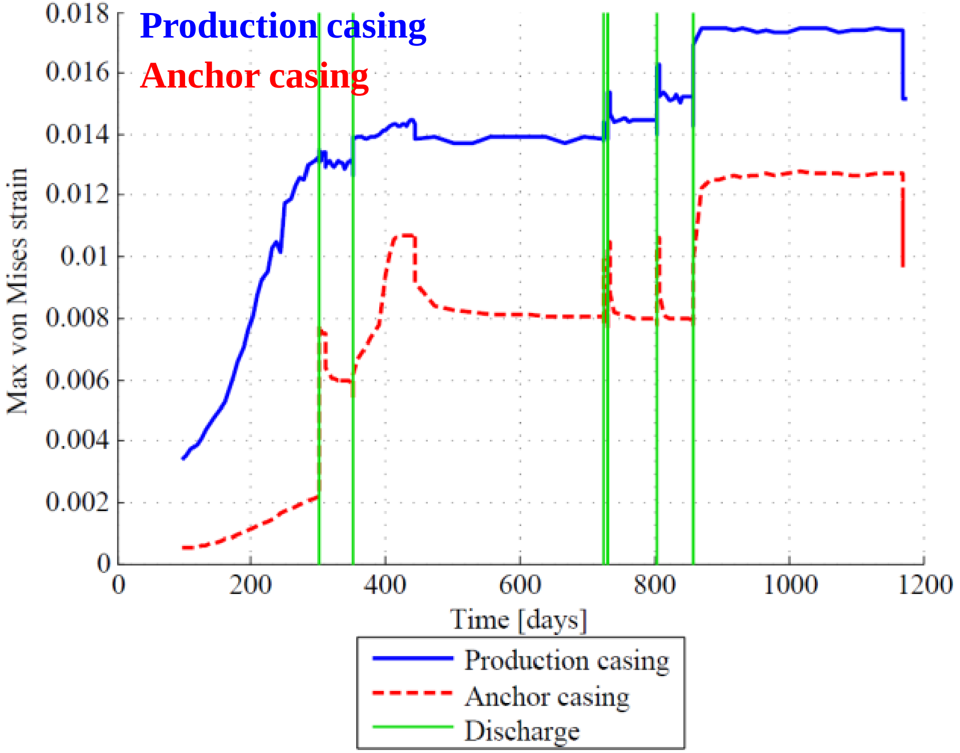
Discharge phase V of IDDP-1



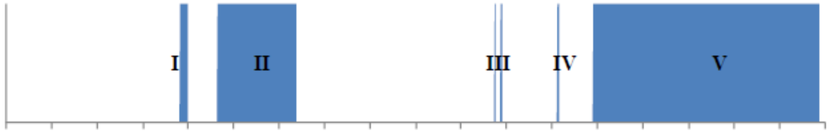


FEM results

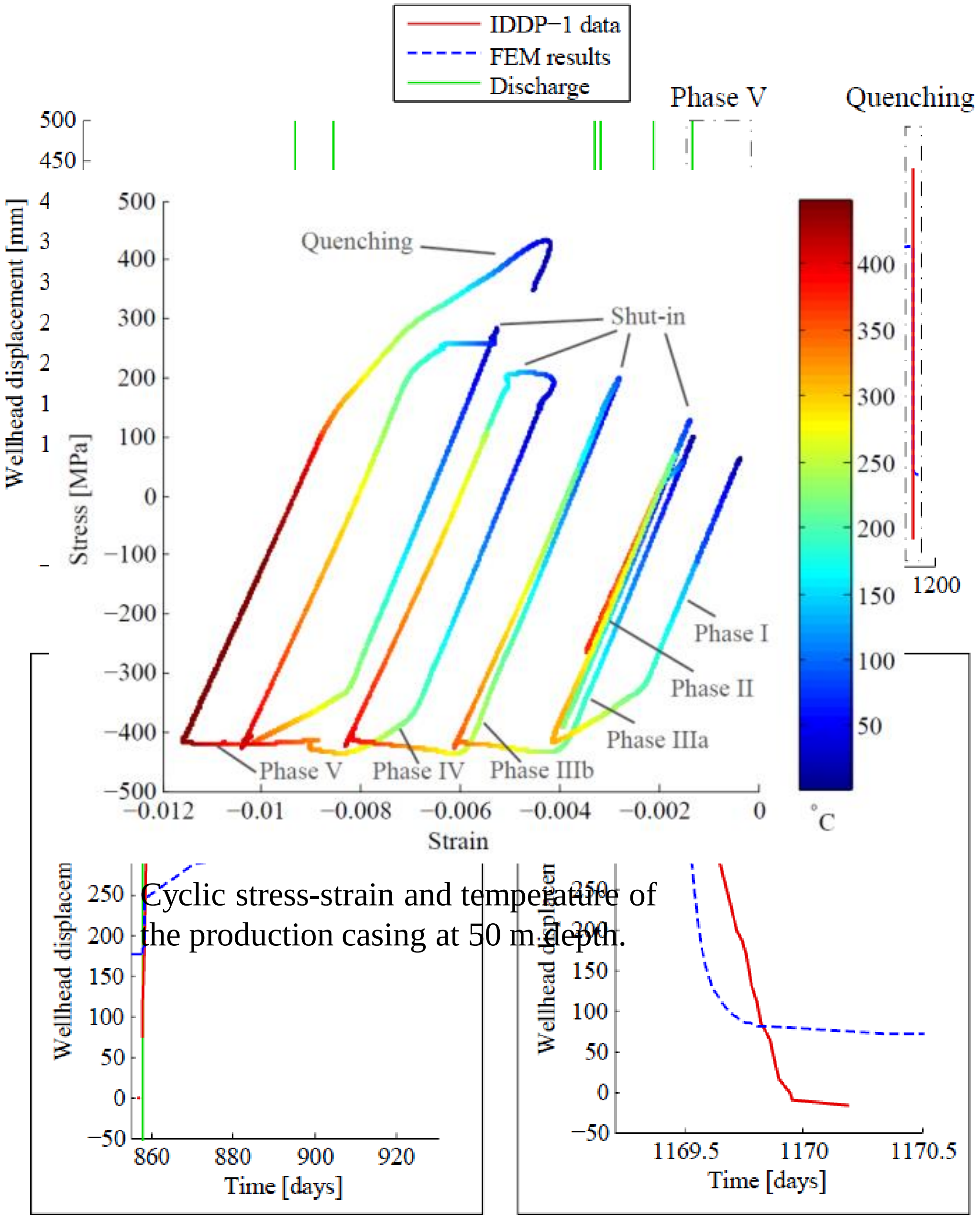
- Permanent strain is generated in the casings during the operation history.



Discharges:



Wellhead displacement:

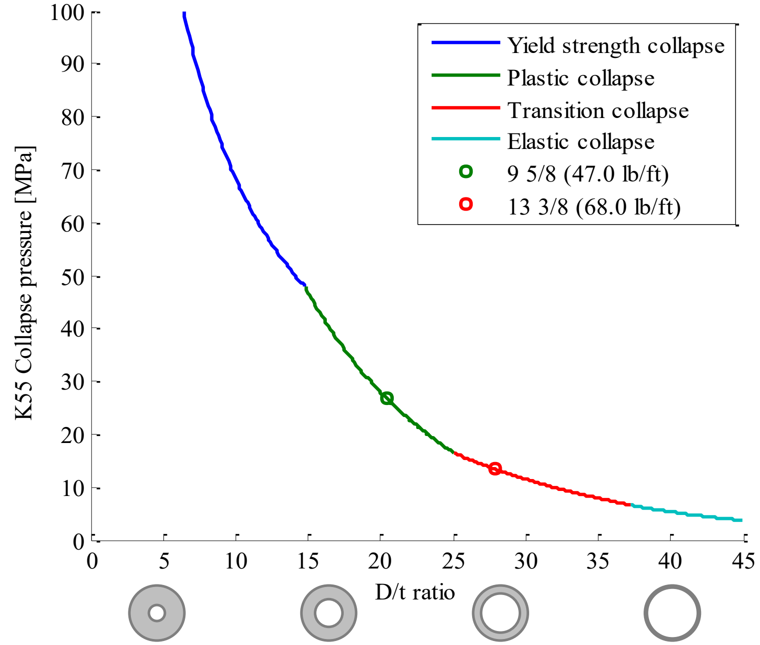


Cyclic stress-strain and temperature of the production casing at 50 m depth.

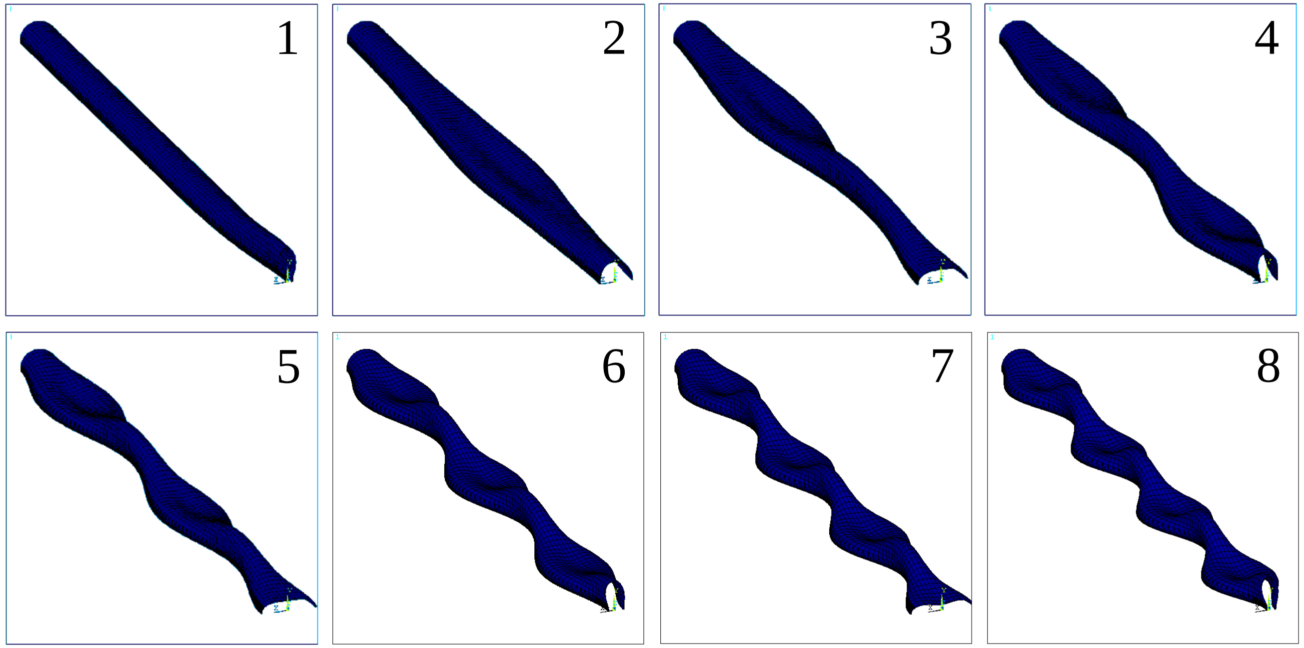
Collapse analysis

- Collapse analysis of the production casing.
  - ➢ Eigenvalue buckling analysis (theoretical collapse strength).
  - ➢ Nonlinear buckling analysis (includes nonlinearities)
  - ➢ Effect of initial geometry
  - ➢ Effect of cement support

API collapse resistance (standard ISO/TR 10400):



Eigenvalue buckling analysis (theoretical collapse strength).



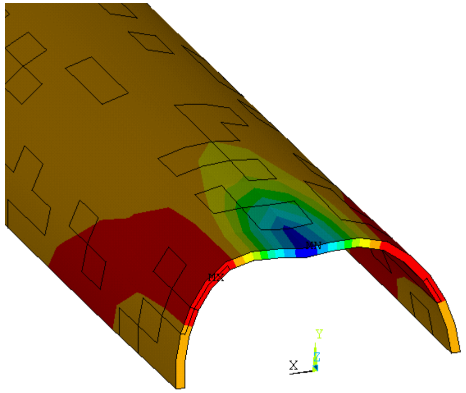
Mode shape nr.	Theoretical collapse strength [MPa]	% of API collapse resistance
1	14.4	107.1
2	14.5	107.9
3	14.5	108.4
4	14.7	109.6
5	15.1	112.4
6	15.7	117.1
7	16.7	124.9
8	18.1	135.3

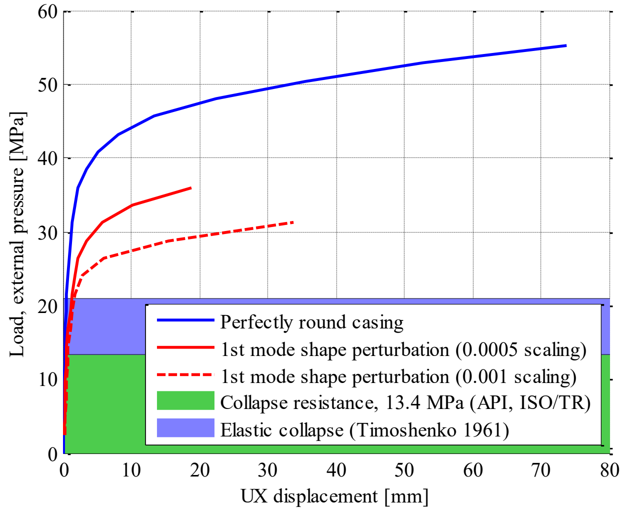
Casing: OD = 13 3/8 in, t = 12.2 mm
API collapse resistance: 13.4 MPa

Collapse analysis

- Nonlinear buckling analysis.
- Initial geometry and defects:
  - Mode shape perturbation
  - Ovality
  - External defect
  - Water pocket in concrete

Mode shape perturbation

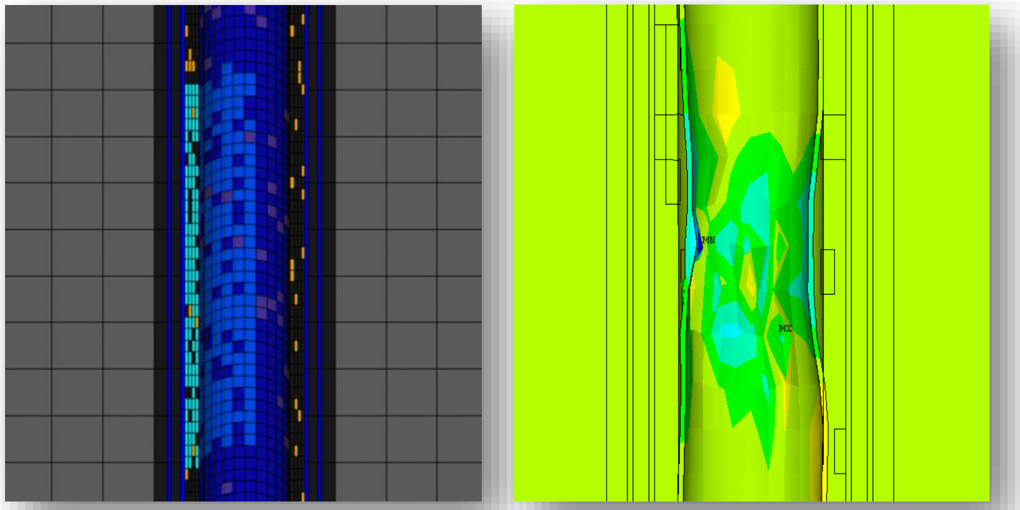




- Limit load for a perfectly round casing: 38.4 MPa
- Limit load using mode shape perturbation: 21.6 MPa
- API collapse resistance: 13.4 MPa

Casing: OD = 13 3/8 in, t = 12.2 mm
API collapse resistance: 13.4 MPa

Water pocket in concrete

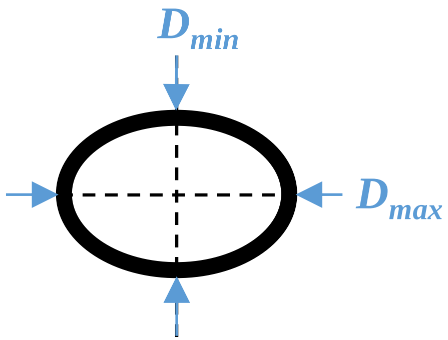


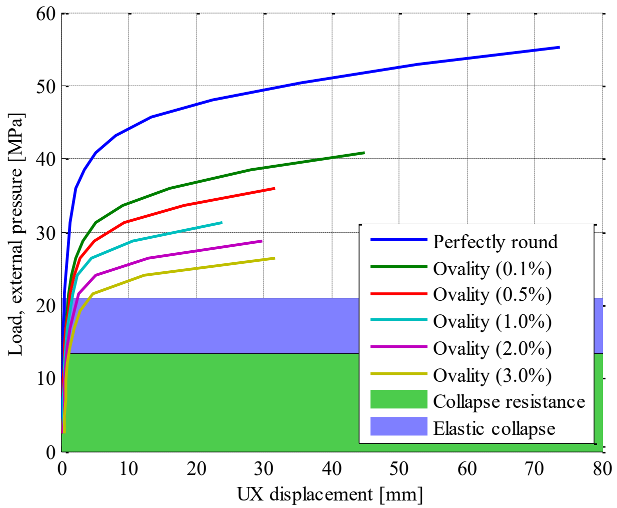
Von Mises stress at collapse: 440 MPa

Collapse at 300°C and 20 bar external net pressure

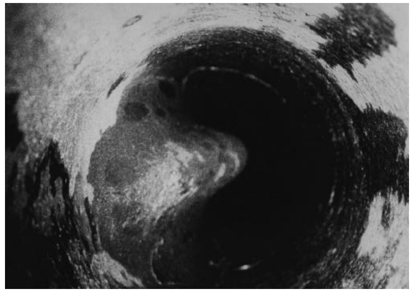
Effect of ovality

$$\text{Ovality} = \frac{D_{max} - D_{min}}{D}$$



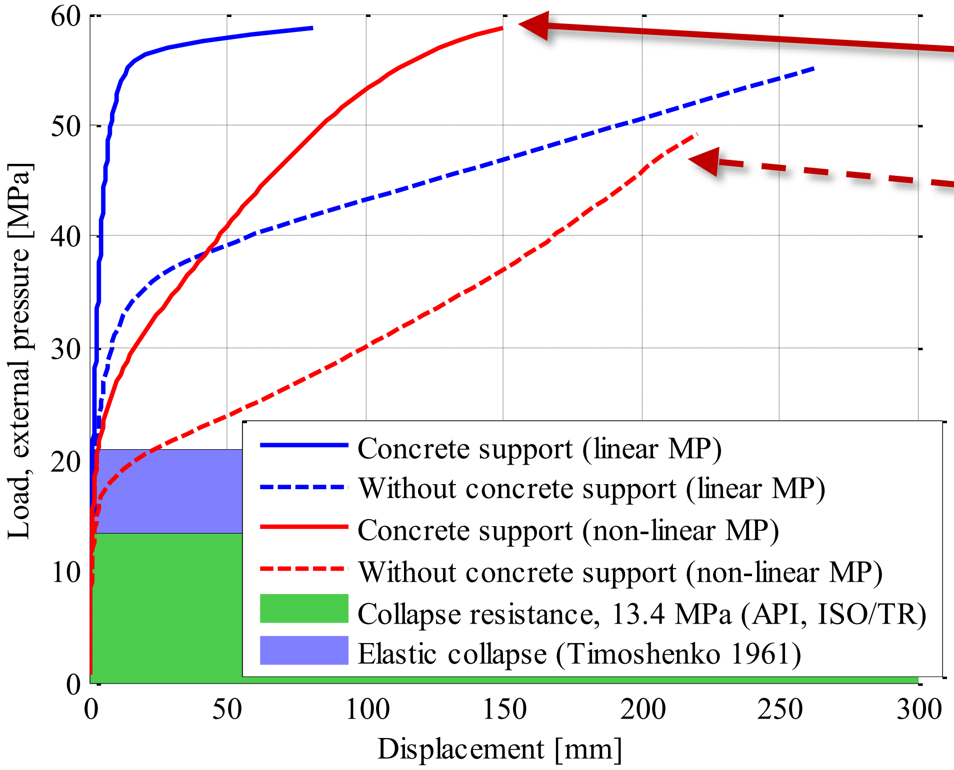


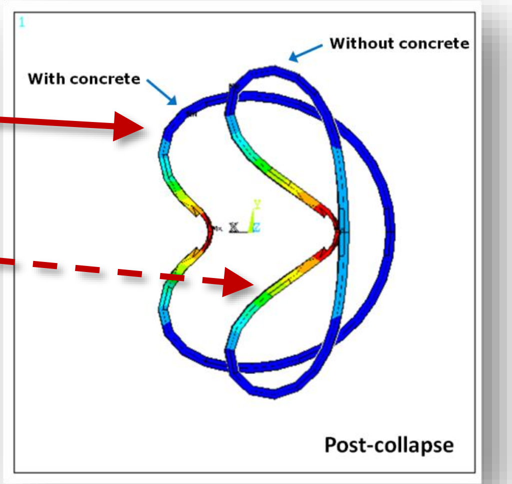
Collapse analysis

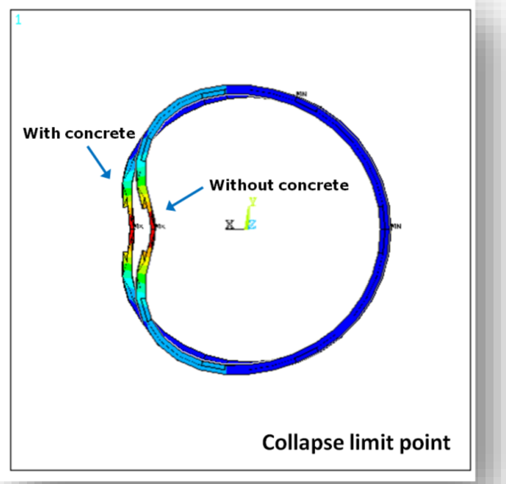


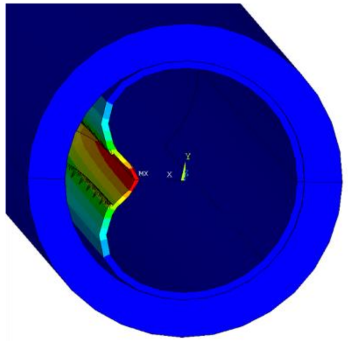
- Nonlinear buckling analysis

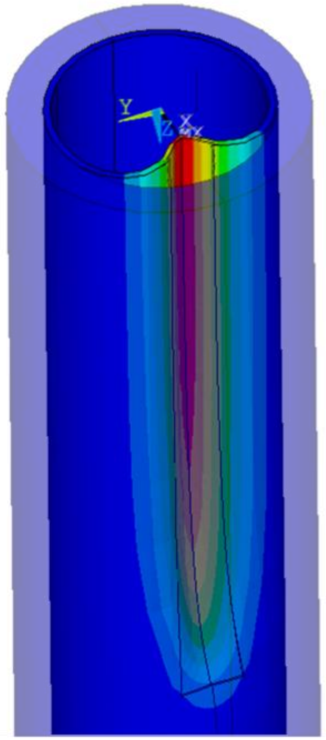
Effect of external defect and concrete support











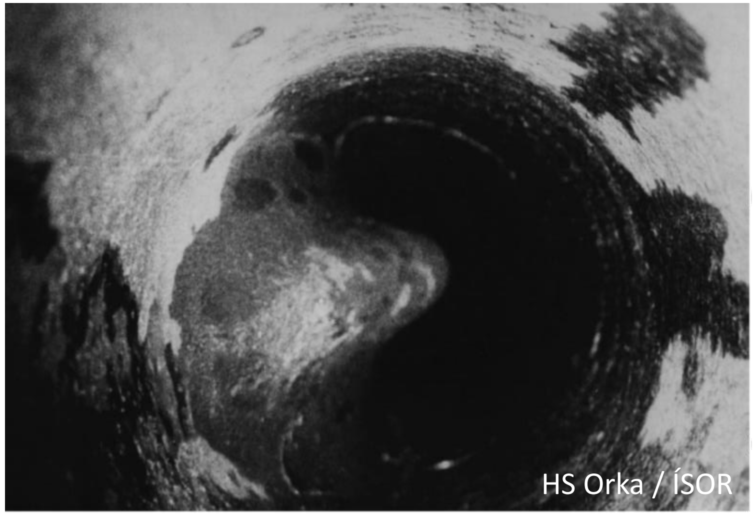
Casing: OD = 13 3/8 in, t = 12.2 mm
API collapse resistance: 13.4 MPa

Summary and conclusions

- Thermal expansion is one of the major cause of casing failures
- Current design standards have their limit in well design in terms of temperature
- Analyses of the casings in high-temperature geothermal wells were presented
- The models are used to evaluate the structural integrity and failures of casings
- Can be used to analyze various load scenarios and material selections
- Conclusions…
- Further work “sidetrack” coming up

Conclusions - Collapse

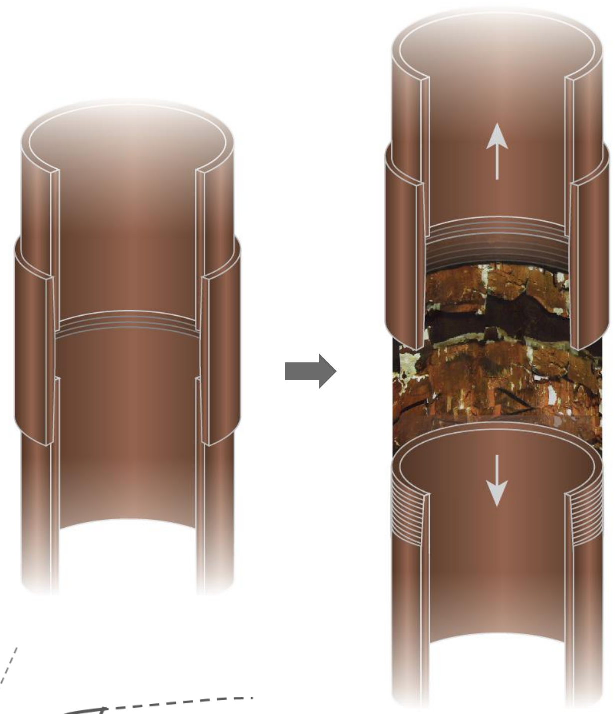
- Caused by excessive net external pressure and induced by axial compression (biaxial loading)
- Collapse strength reduction due to axial tension is incorporated into API standards (compression is not)
- Cement integrity and casing roundness (and other defects) have great effect on collapse resistance
- Cement is very important for lateral and radial support – increases collapse resistance
- Collapse resistance can also be increased by selecting better materials (HC) under strict quality control (casing roundness important)

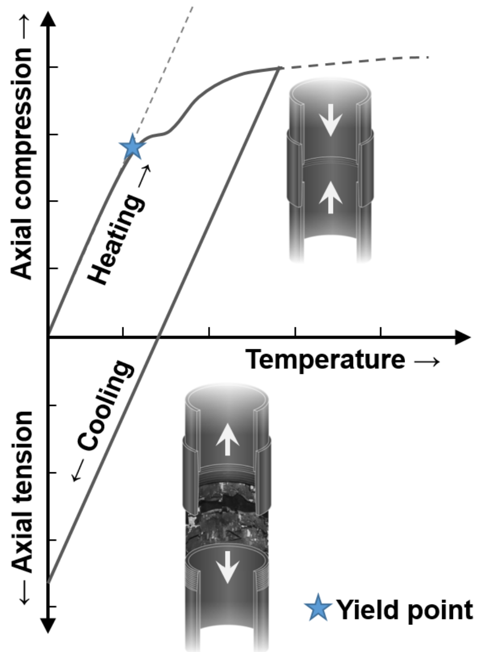


HS Orka / ÍSOR

Conclusions – Tensile rupture

- Caused by excessive axial tensile stress when casings cool down after production, shut-in or maintenance (killing with water)
- The failure mode is well understood, but control cooling rate or limit in temperature variations (ΔT) remains unresolved
- The failure mode has occurred in a number of wells in Iceland in connection to fast cooling while pumping cold water into a hot well
- FEM analyses indicate that:
  - Failures are more likely to form near changes in outer casings, e.g. at material grade changes (T95-K55) and near casing shoes
  - Thermal gradient between casing layers leads to thermal expansion mismatch which generates (higher) stresses/strains
  - Slow temperature changes have less consequences than fast ones
  - The thermal load is more severe for the innermost casing which is in direct contact to the geothermal fluid than external casings



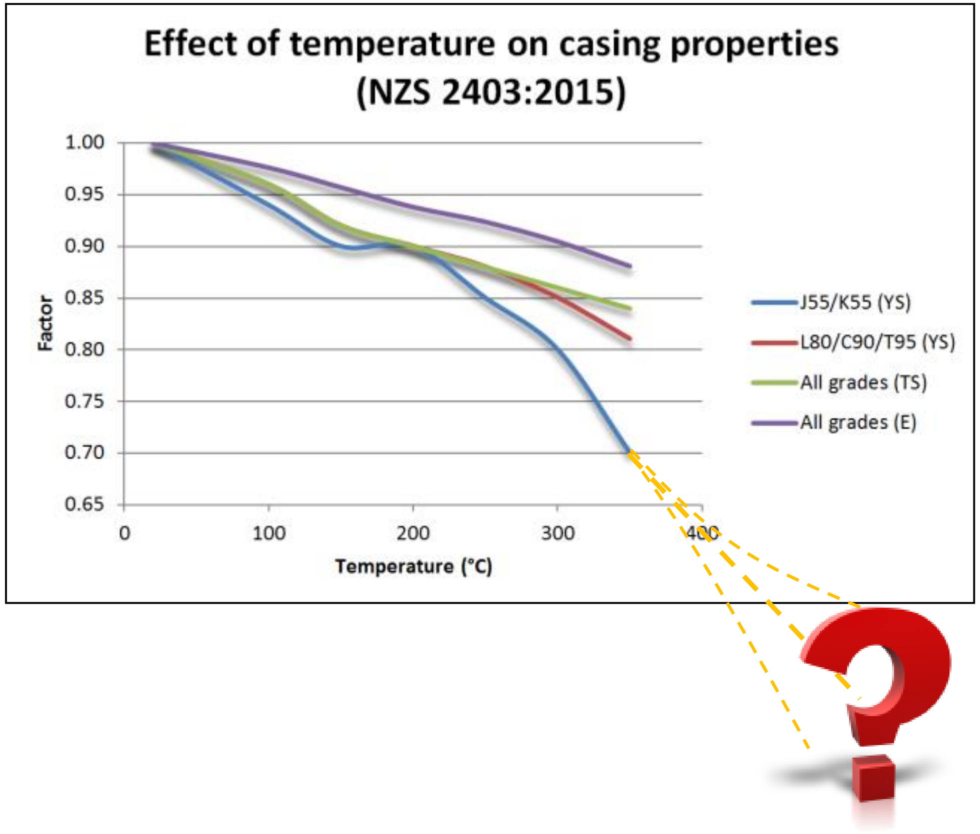


Adopted from a diagram by Rahman & Chilingarian, 1995

Conclusions – Looking ahead

What further information is needed?

- Material integrity at high temperatures >350°C
  - Knowledge of strength reduction
  - Solution to corrosion effects
  - Creep and stress relaxation effects not well known
- Can wells for 300°C+ be designed within the elastic region of materials?
- Is it possible to
  - Flow-test a >550°C hot well without causing casing failures?
  - Or cool such hot wells without causing failures?



Further work – "sidetrack"

Introduction to work at ÍSOR – Iceland GeoSurvey related to the topic of the PhD study

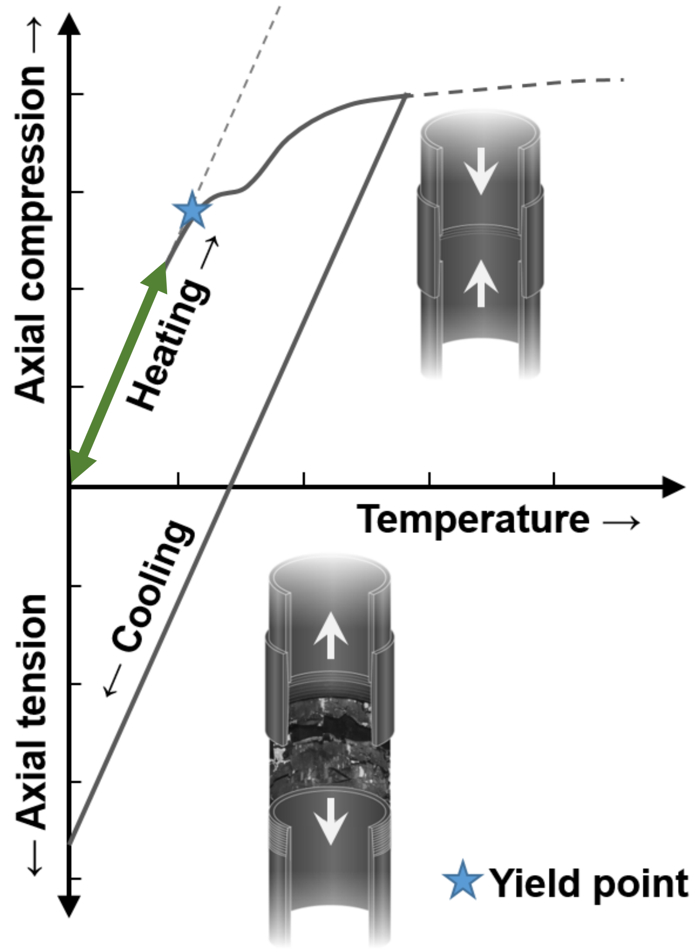
- Since year 2015, a number of projects focused on improving well design and completion for high-enthalpy wells have been ongoing
- Including H2020 GeoWell, GeMEX and DEEPEGS with international cooperation
- Further projects are being planned

- Current objectives and work includes (GeoWell/DEEPEGS):
  - Improved material selection for geothermal wells to mitigate corrosion effects – corrosion studies (ÍSOR/Statoil)
  - Tensile testing at elevated temperatures to extend design curves (ÍSOR/TNO)
  - Development of Flexible Couplings to allow thermal expansion of casing segments (ÍSOR)
  - Cement analysis and development of cement blends for (TNO)
  - Monitoring techniques using fiber optic sensing (GFZ)
  - Risk evaluation, including gathering data of casing failures in Iceland (IRIS/ISOR)

Mitigation

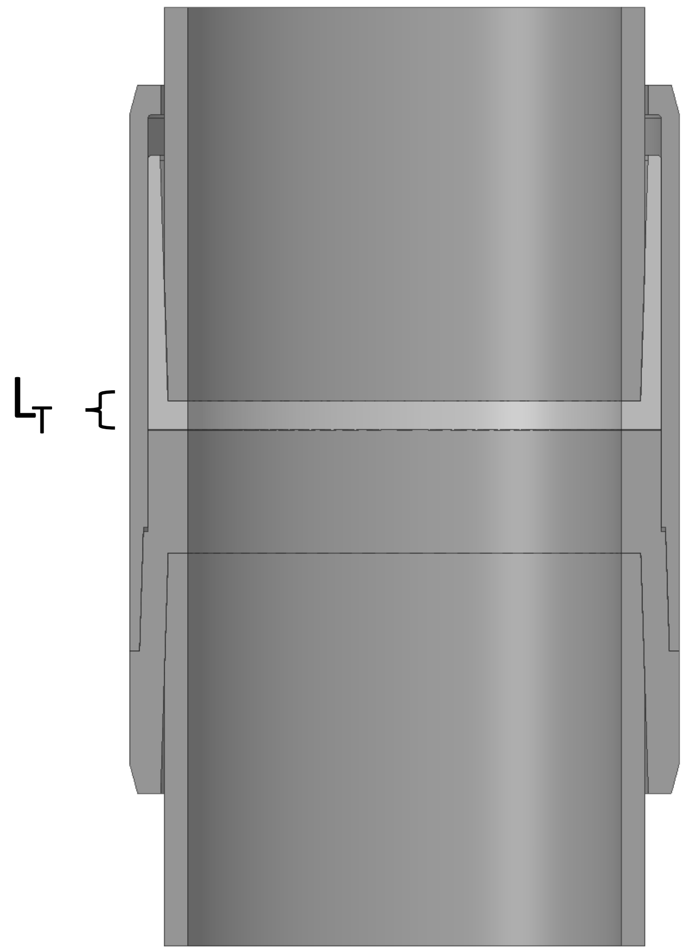
Flexible couplings

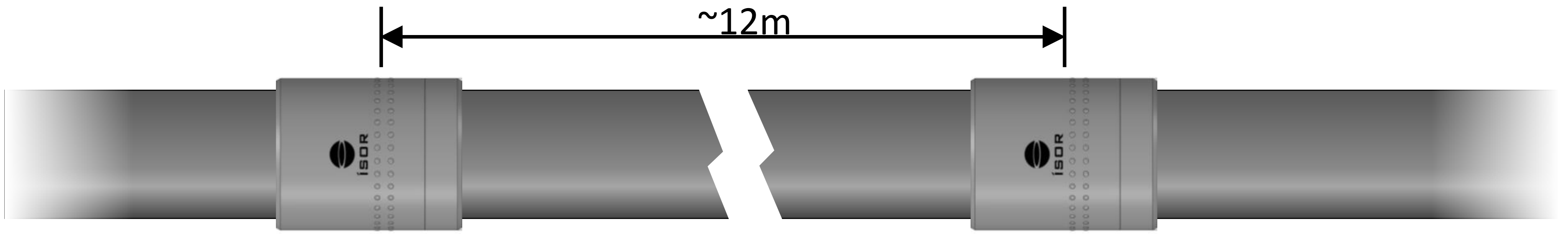
- Allow displacement that compensate for thermal expansion of the casing
- Stress in the casings will be within the elastic range
- No plastic strains are therefore generated
- As wells are warm-up the coupling takes up the expansion
- And if wells need to be shut-in or quenched with cold water for maintenance, no axial tension is generated if the well cools down again



Flexible couplings – function

- Casings with Flexible coupling are run in hole with same procedure as normally done
- The couplings remain in their open position during casing installation
- The gap length L_T is fixed for design temperatures in each case
- When the casing warms up it expands and the Flexible couplings close without generating plastic strains in the casing





Flexible couplings – function

Main load cases of couplings

- Installation:
  - make-up torque
  - axial tension (self weight)
- Operational:
  - axial compression due to thermal expansion
  - axial tension due to cooling
  - burst and collapse pressures (radial and hoop loads)
  - and additionally bending
- The Flexible Coupling is designed so that when the casing expands thermally it reaches 70-80% of its yield strength without generating plastic deformations

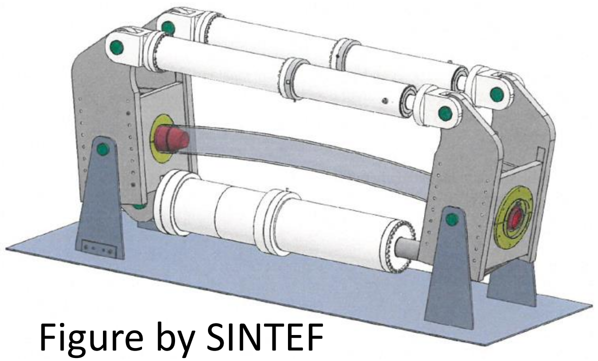
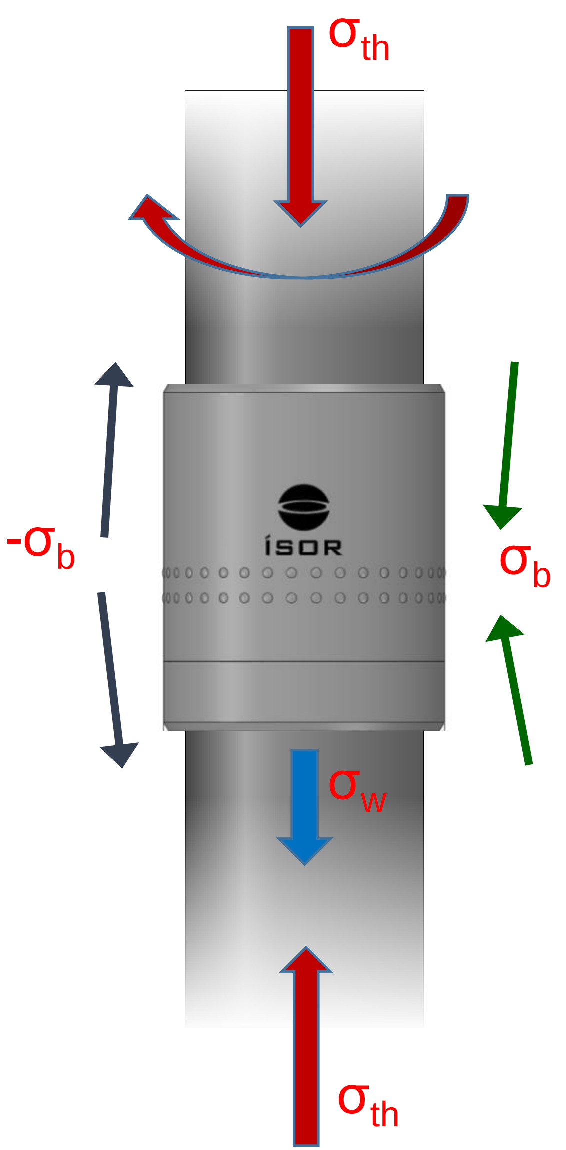
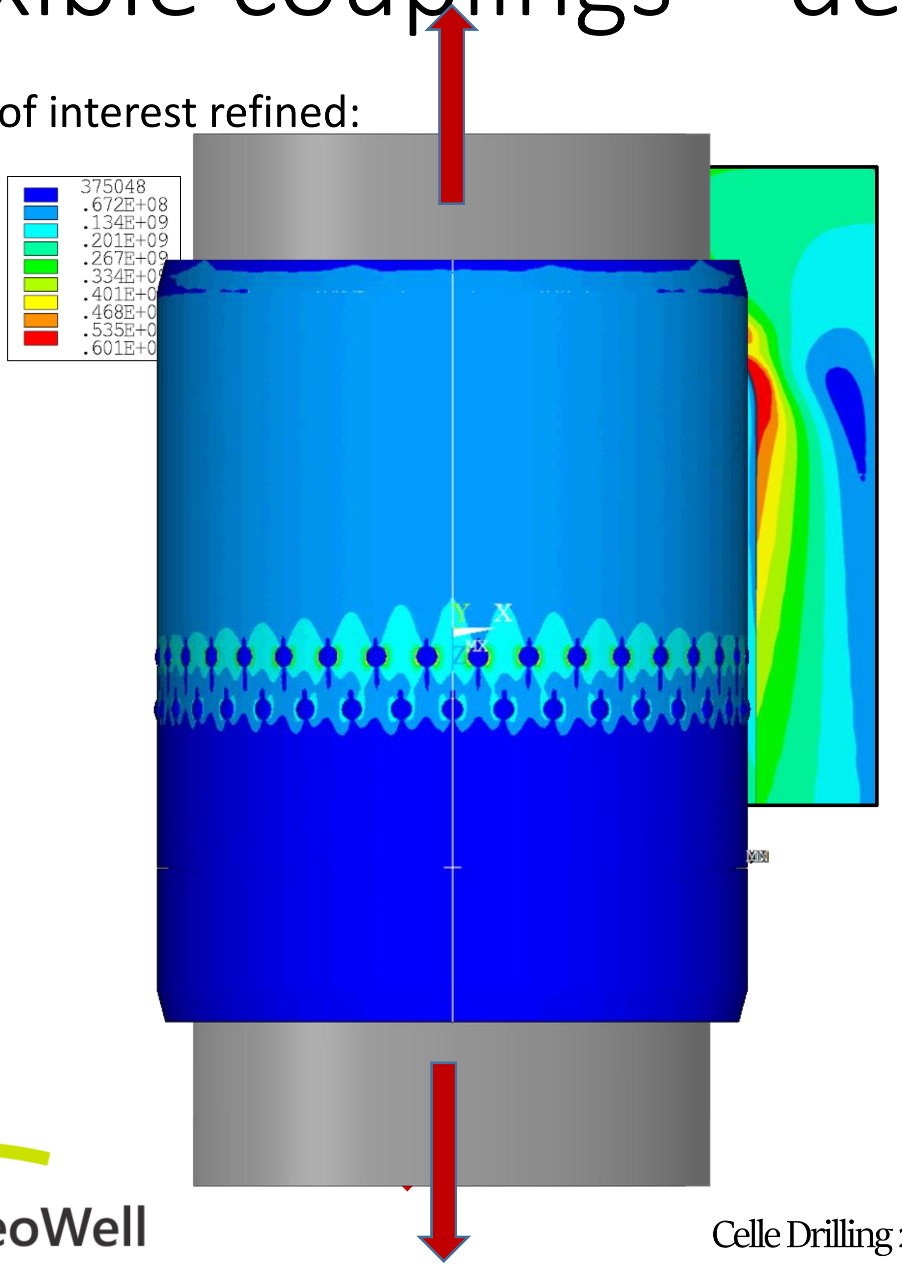


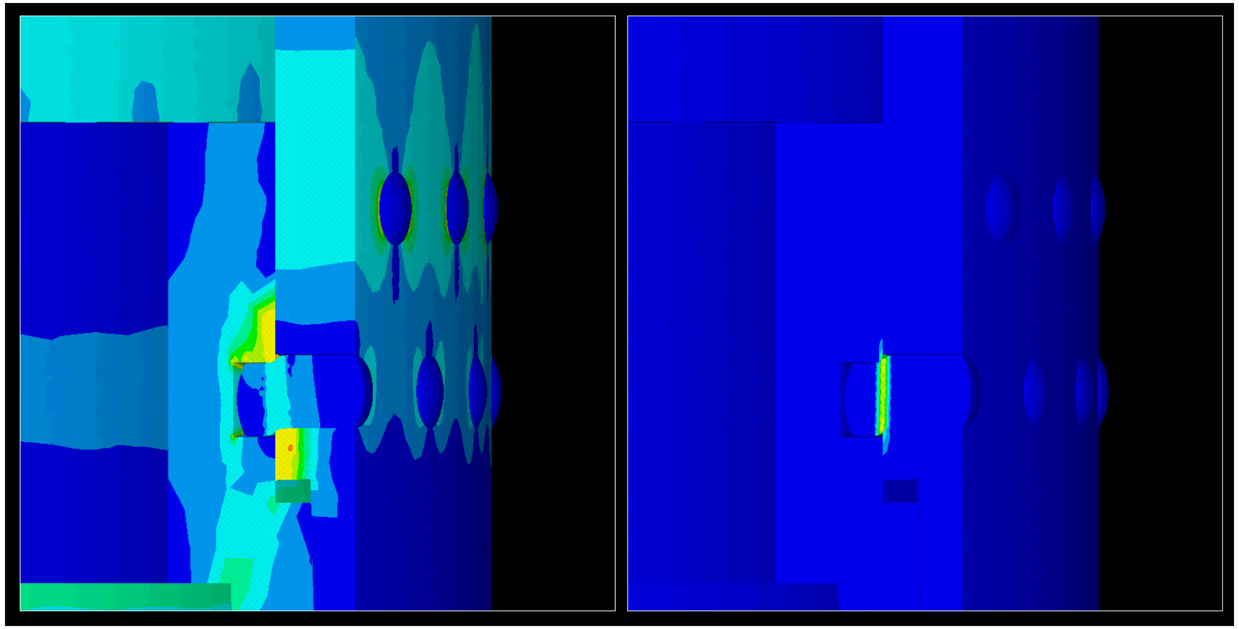
Figure by SINTEF

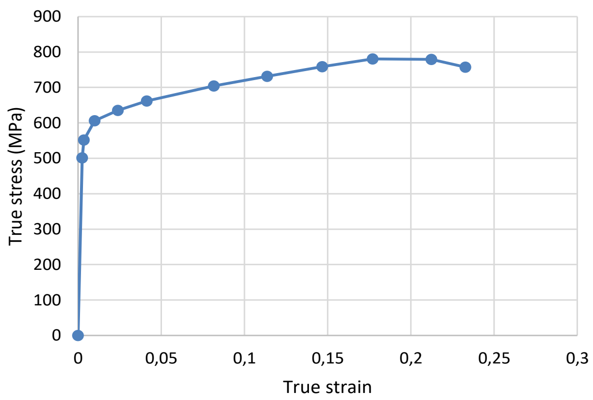


Flexible couplings – design with FEM

Points of interest refined:

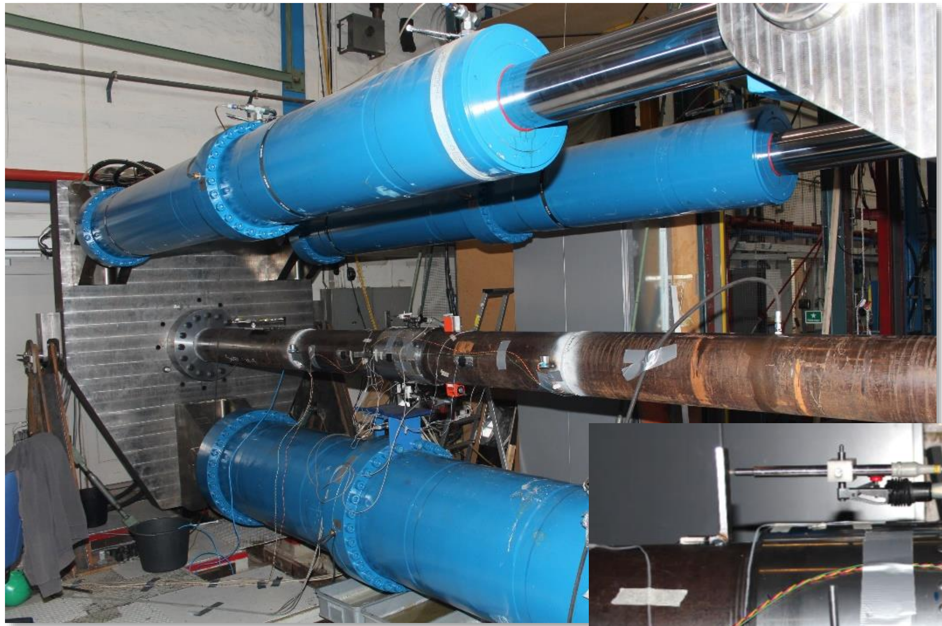


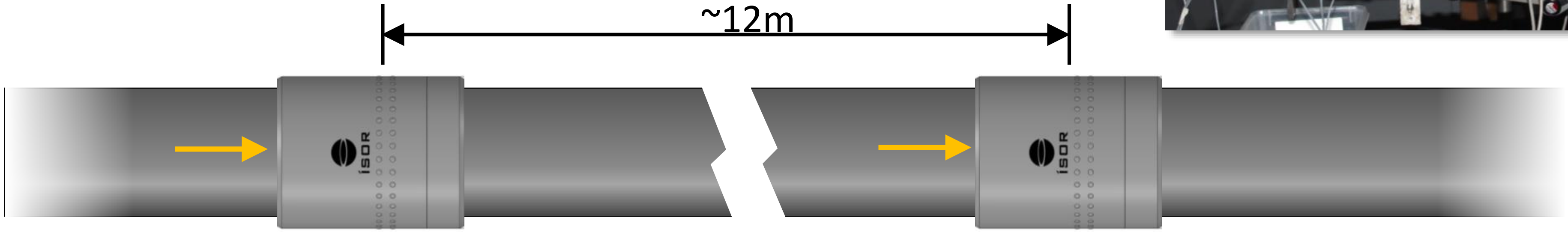




Flexible couplings - prototype

Prototypes of Flexible Couplings for 9 5/8" casings





GeoWell

ÍSOR

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Thank you