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Paper 9 - Numerical investigation of tensile strain capacity of gas pipeline under girth weld strength undermatching condition

Contents

Introduction

1. North America: Unexpected failures in the vicinity of girth welds observed.

First wave

- *Occurred in 2007-2009*
- *Not published in the major pipeline conferences (IPC, JTM and PTC).*
- *Information only available in a PRCI report by Bruce et al..*

Second wave

- *Occurred in 2015-2019.*
- *Published in the major pipeline conferences and presented in API meetings since 2016.*
- *Motivated the establishments of several on-going research projects (PRCI, JIP and more recently FFCRC)*

Introduction

2. Common features of the two waves.

- X70 pipelines;
- Newly constructed pipelines;
- SMAW welding with E6010/E8010 consumables;
- No failed weld made by GMAW;
- No pre-existing defect;
- Necking around the weld observed.

3. Major differentiating factors (as reported)

- First wave: HACC and high stress around weld.
- Second wave: Weld metal strength undermatching and HAZ softening

Introduction

6. Australian context

- Shares similarities with NA counterparts
  - *Material specifications*
  - *girth welding procedures.*

- Mechanical properties ranges of a recently constructed X70 Australian pipeline
  - *Yield strength:* ***520-590*** *MPa → upper portion of X70 YS distribution*
  - *UTS: 620-680 MPa*

- According to reported conclusions,
  Most newly constructed Australian pipelines would have a high risk of girth weld failure

Introduction

7. Future Fuels CRC research project:

- Tensile strain capacity (TSC) of pipeline with strength undermatching girth weld.
- Literature review,
- Full-scale pipe tensile tests (FSPTT) and curved wide plate tensile tests (CWP) on pipes sourced from two recent Australian pipeline projects
- Extensive Finite Element Analysis (FEA) studies.

Objectives:

- Assessment of level of risk for Australian pipelines relative to what was experienced in North America
- "Validated" and "standardised" testing method to determine properties of weld, HAZ and base metal

FEA simulation models of tensile strain capacity

FEA simulation models of tensile strain capacity

FEA models

- Purpose: predict tensile strain capacity (TSC).

- Major work published (PRCI, JFE, EWI, ExxonMobil, UGhent)
  - *Weld metal strength mismatch*
  - *HAZ softening*
  - *Pressure*
  - *Notch size / geometry*
  - *Pipe geometry & properties*
  - *Weld metal / HAZ profiles*

- Less reported
  - *Post-necking hardening*
  - *Variation of mechanical properties over circumference (e.g. Denys reported Ys_{min} @ ~5 o'clock, Ys_{max} @ ~1 o'clock)*
  - *Defect location (inner/outer surface)*

FEA simulation models of tensile strain capacity
Simulation parameters

Parameters	Values	Parameters	Values
Pipe diameter	457 mm	YS of pipe	518 MPa
Pipe wall thickness	9.1 mm	UTS of pipe	575 MPa
Bevel angle	30°	Notch depth	3 mm
Root height	1.6 mm	Notch length	25 mm
Root gap	1.6 mm	Internal pressure	15.3 MPa
Weld cap (h_c)	0-1.6 mm	Misalignment	0.0 mm
HAZ width	2 mm	Strength matching ratio of weld and HAZ (λ)	0.8, 0.9 and 1.0
Pipe length	1143 mm	Mechanical properties in HAZ	Uniform

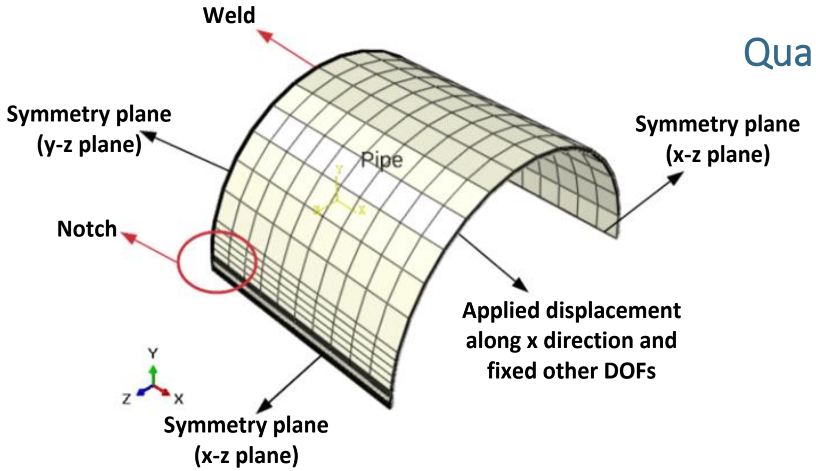
FEA simulation models of tensile strain capacity

FEA models

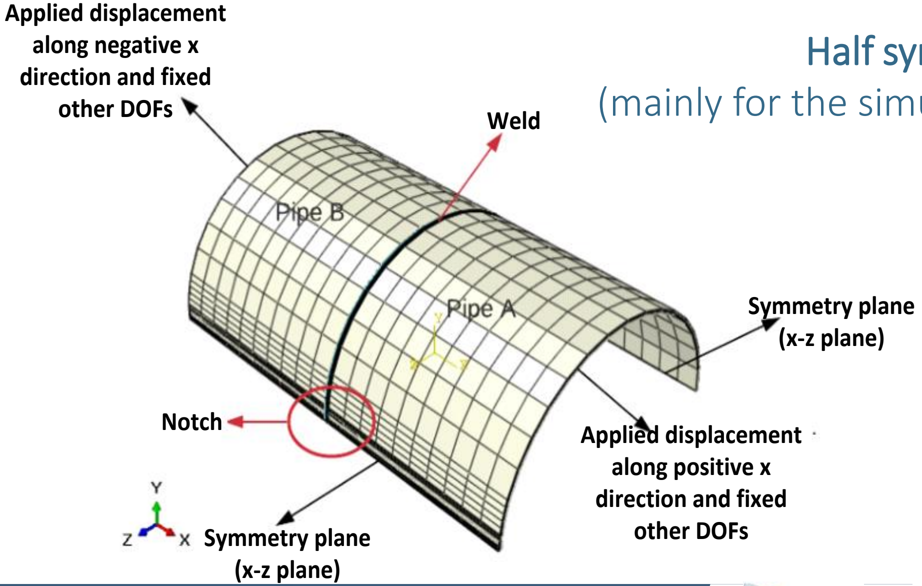
- Simulation matrix: significant number of cases.
- Resource intensive if pre/post-processing carried out manually.
- Application developed to streamline the process.
  - Allows setting up & run multiple simulations in batch mode on a HPC.

FEA simulation models of tensile strain capacity Major features of developed Matlab-based program

- Ability to create two FEA models
  - Quarter / half symmetry model
- Automatic
  - Generation of Abaqus input file,
  - Execution of the simulation in Abaqus
  - Post-processing of the results;



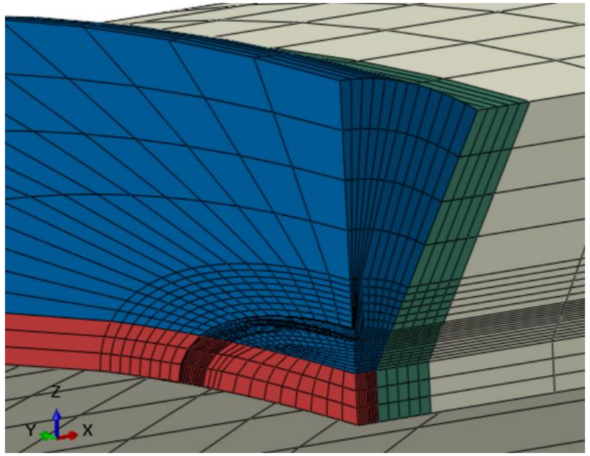
Quarter symmetry model

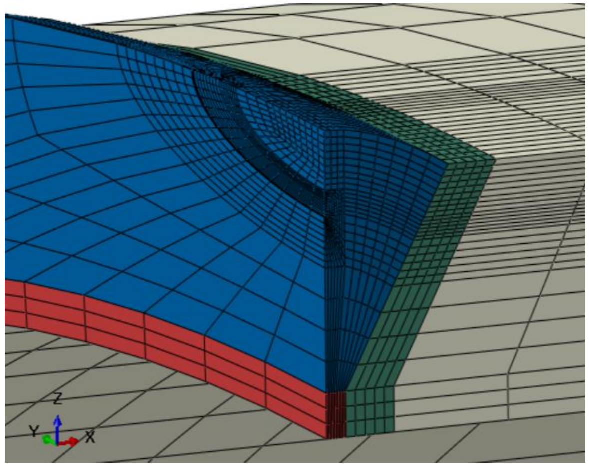


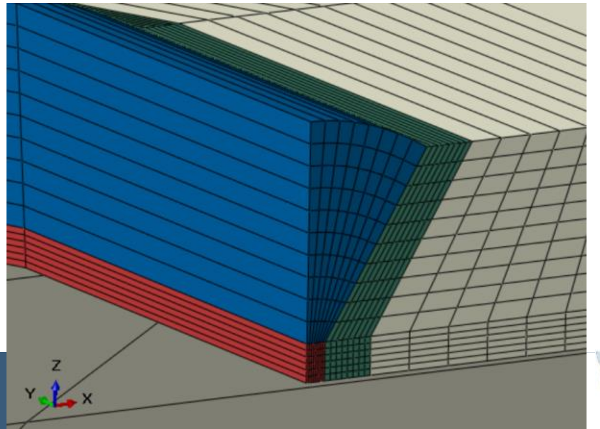
Half symmetry model
(mainly for the simulation with misalignment)

FEA simulation models of tensile strain capacity
Major features of developed Matlab-based program

- Semi-elliptical notch at WCL
  - Inner/outer pipe surface or without notch;
- Automatic mesh generation
  - Any given geometries of pipe, weld and HAZ
  - Spider-web meshing around the notch;
- Meshing control
  - User-controlled mesh density
  - Gradual mesh refinement;


Inner surface notch

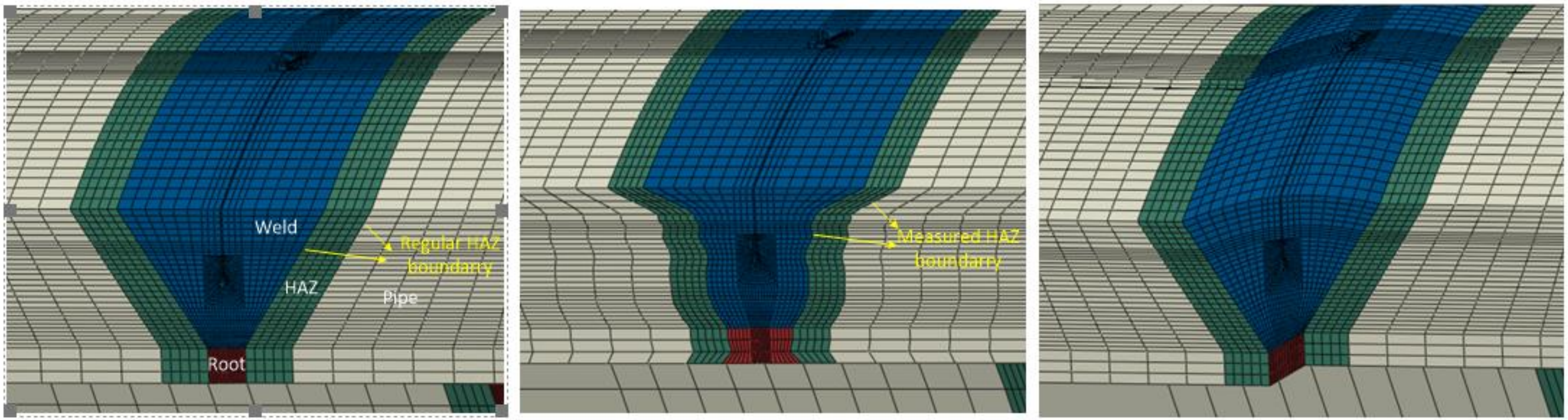

Outer surface notch


Without notch

FEA simulation models of tensile strain capacity
Major features of developed Matlab-based program

- Regular or "as measured" HAZ boundary profile

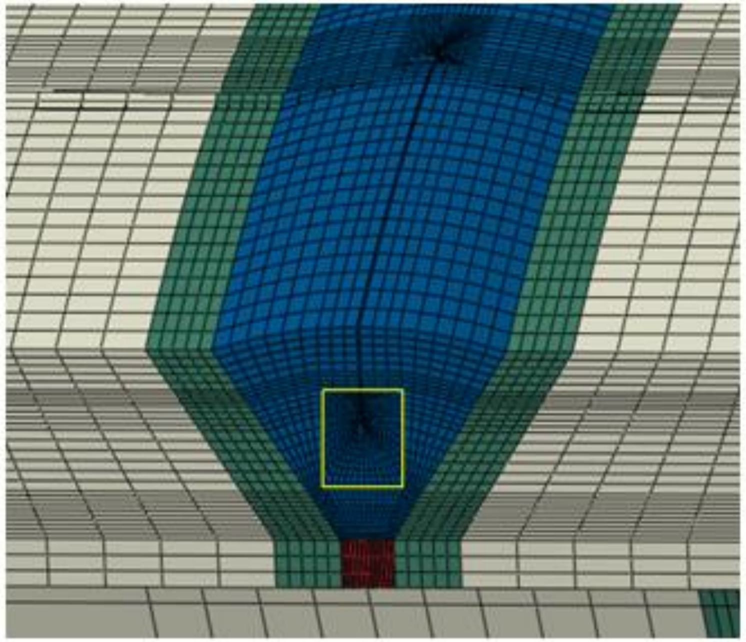
- Handling of
  - Excess weld cap (overfill);
  - Surface misalignments
    - *Pipe centre offset*
    - *Differences in pipe diameters, wall thicknesses;*

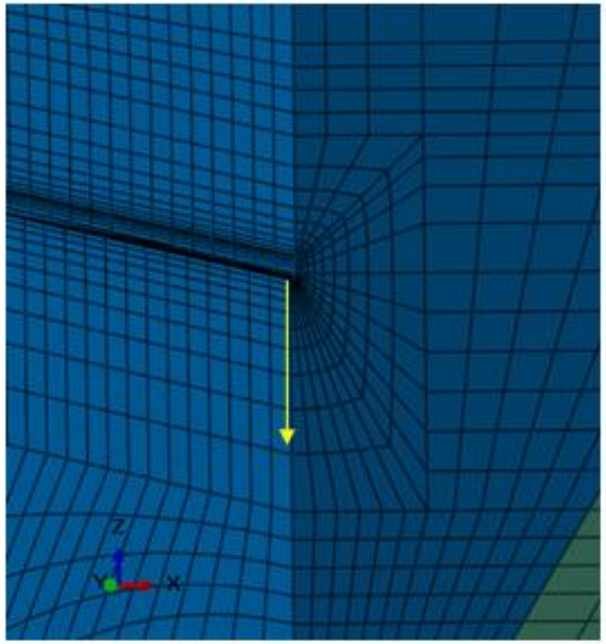


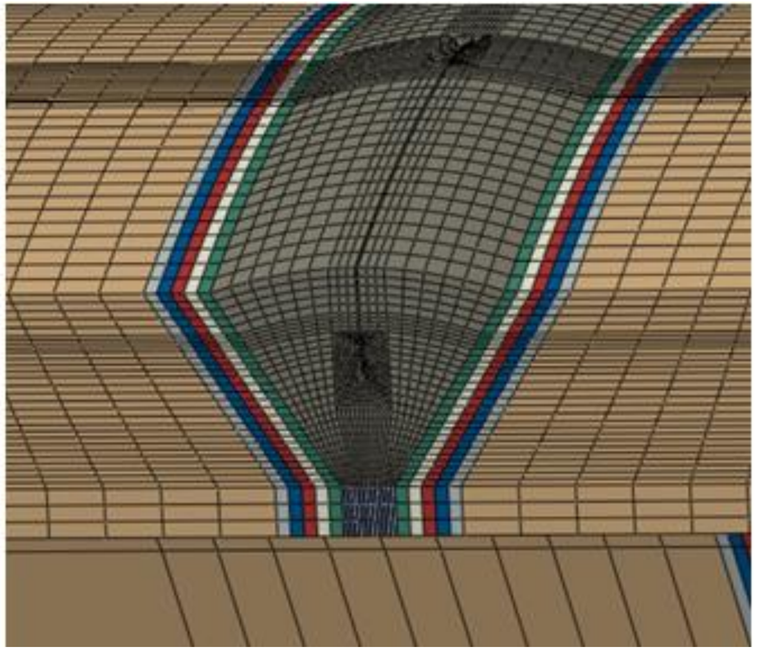
FEA simulation models of tensile strain capacity
Major features of developed Matlab-based program

Material properties

- Specific for pipe, HAZ, root pass and remainder of the weld;
- PRCI models used to generate the engineering stress-strain curve;
- Gradients of mechanical properties in HAZ.

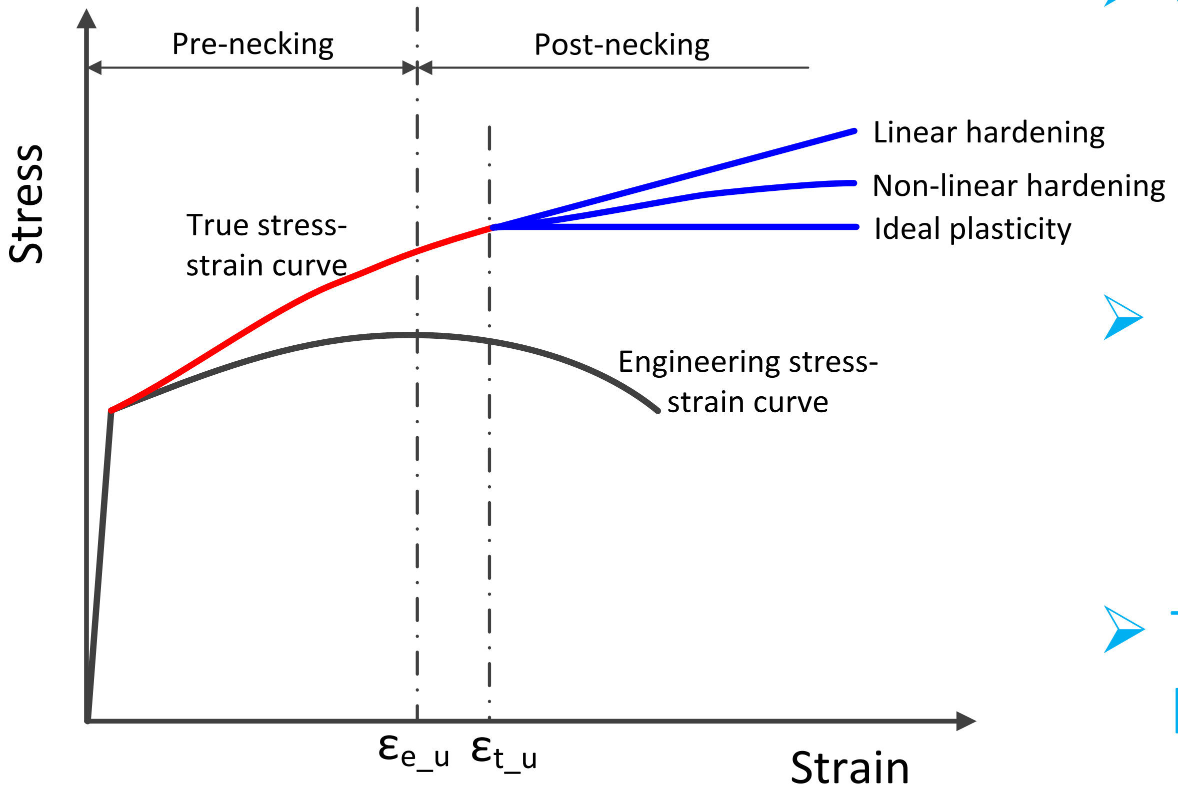






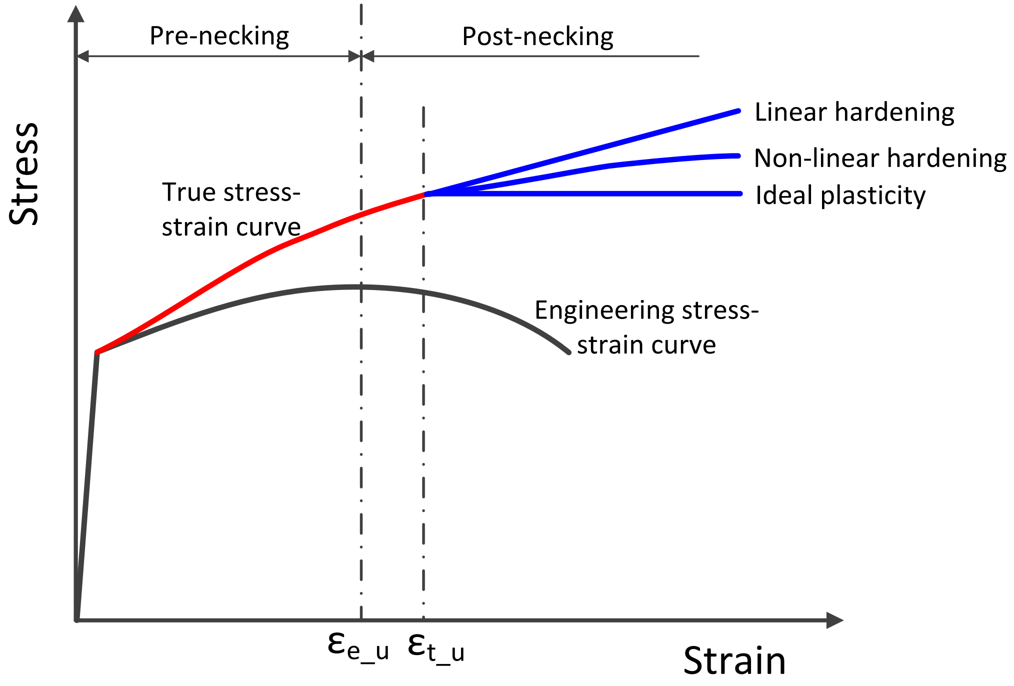
Post-necking hardening

FEA simulation models of tensile strain capacity
Post-necking hardening models



- Ccl of past experimental and numerical studies:
  - Equivalent plastic strain could reach 0.7 when fracture is initiated at the notch tip,
  - Much higher than true strain of line pipe steels at necking…
- Suggests post-necking equivalent stress-strain relation plays a very important role in determining the TSC.
- Three post-necking hardening models are used here.

FEA simulation models of tensile strain capacity
Post-necking hardening models



1. Ideal plasticity model
   Equivalent stress remains constant after necking;

2. Linear hardening model
   Equivalent stress-strain curve linearly extrapolated;

3. Non-linear model (Davidenkov-Siebel)
   Equivalent stress-strain curve is non-linear past necking point

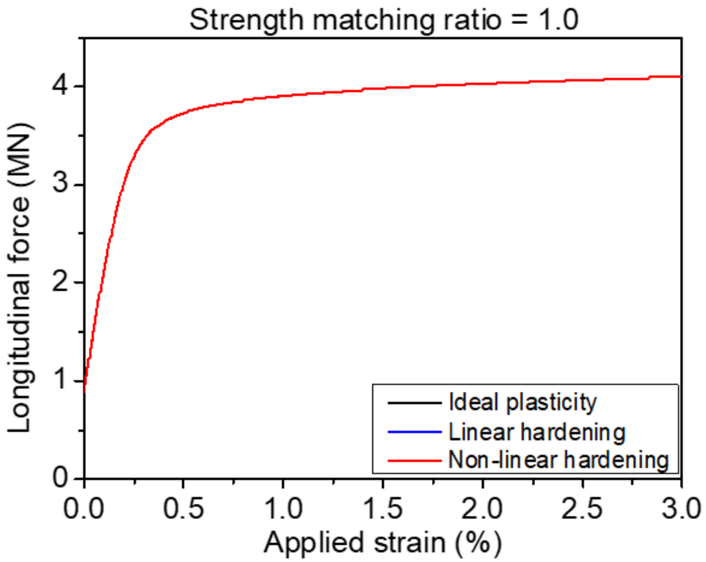
$$\sigma_{eq} = \frac{\sigma_t}{\zeta} \qquad \zeta = 1 + \frac{a}{4R} \qquad \frac{a}{R} = 1.1\left(\varepsilon_{eq} - \varepsilon_{t\_u}\right)$$

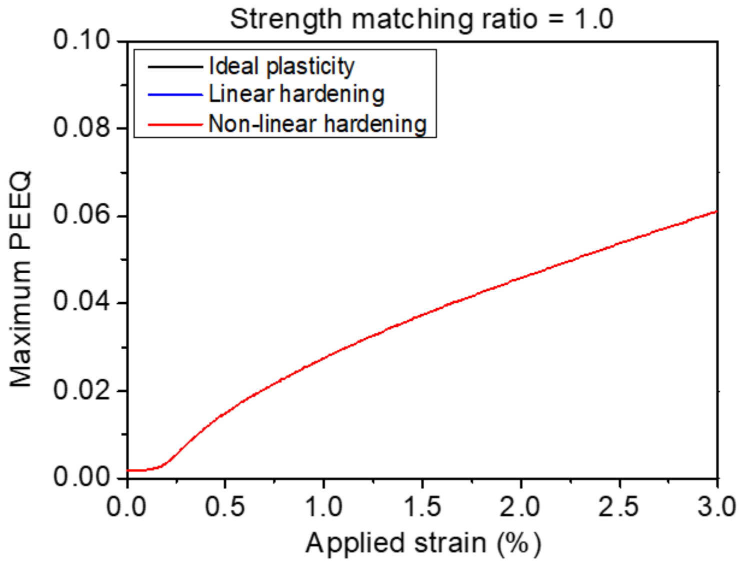
- Ideal plasticity and linear hardening models
  Lower bound and upper bound of the post-necking behaviour respectively.

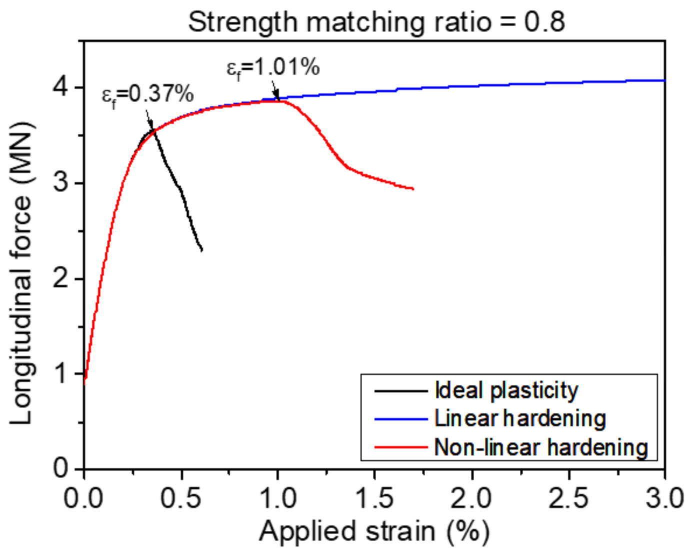
- Observations from experimental and numerical investigations
  Demonstrated that the real post-necking equivalent stress-strain curve is non-linear.

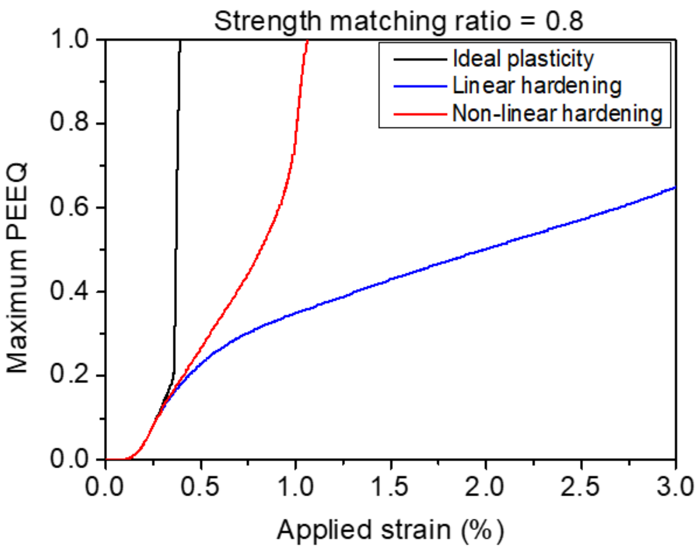
Results and discussion

Simulations without notch
Post-necking hardening





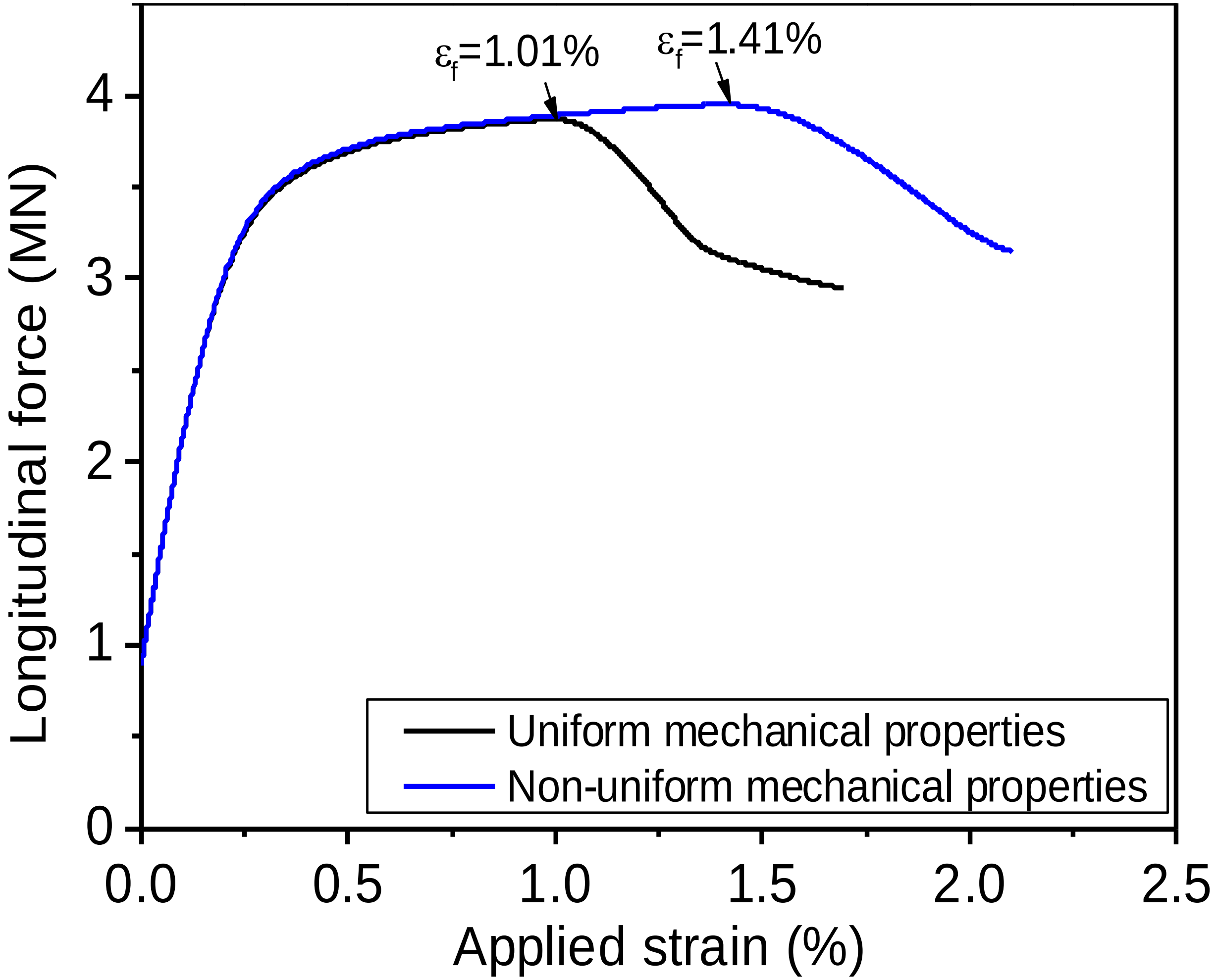




Ccl:

Post-necking hardening law significantly influences TSC for cases with weld strength undermatching.

Simulations without notch
Non-uniform mechanical properties



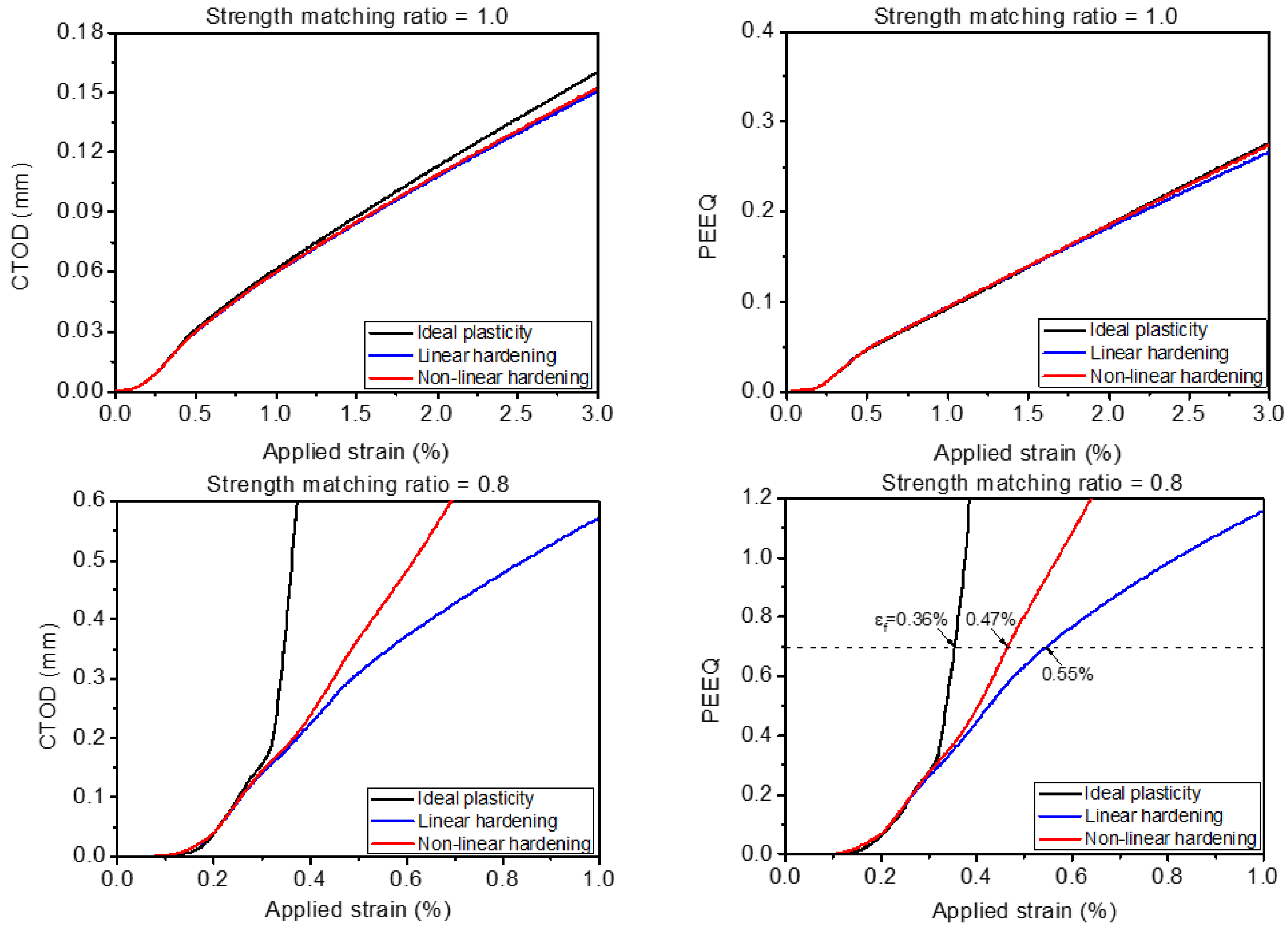
Conditions:

- With strength undermatching girth weld, Strength matching ratio = 0.8
- Without defect
- Non-linear post-hardening curve

Ccl:

Failure strain of pipe affected by variation of mechanical properties along the pipe circumferential direction.

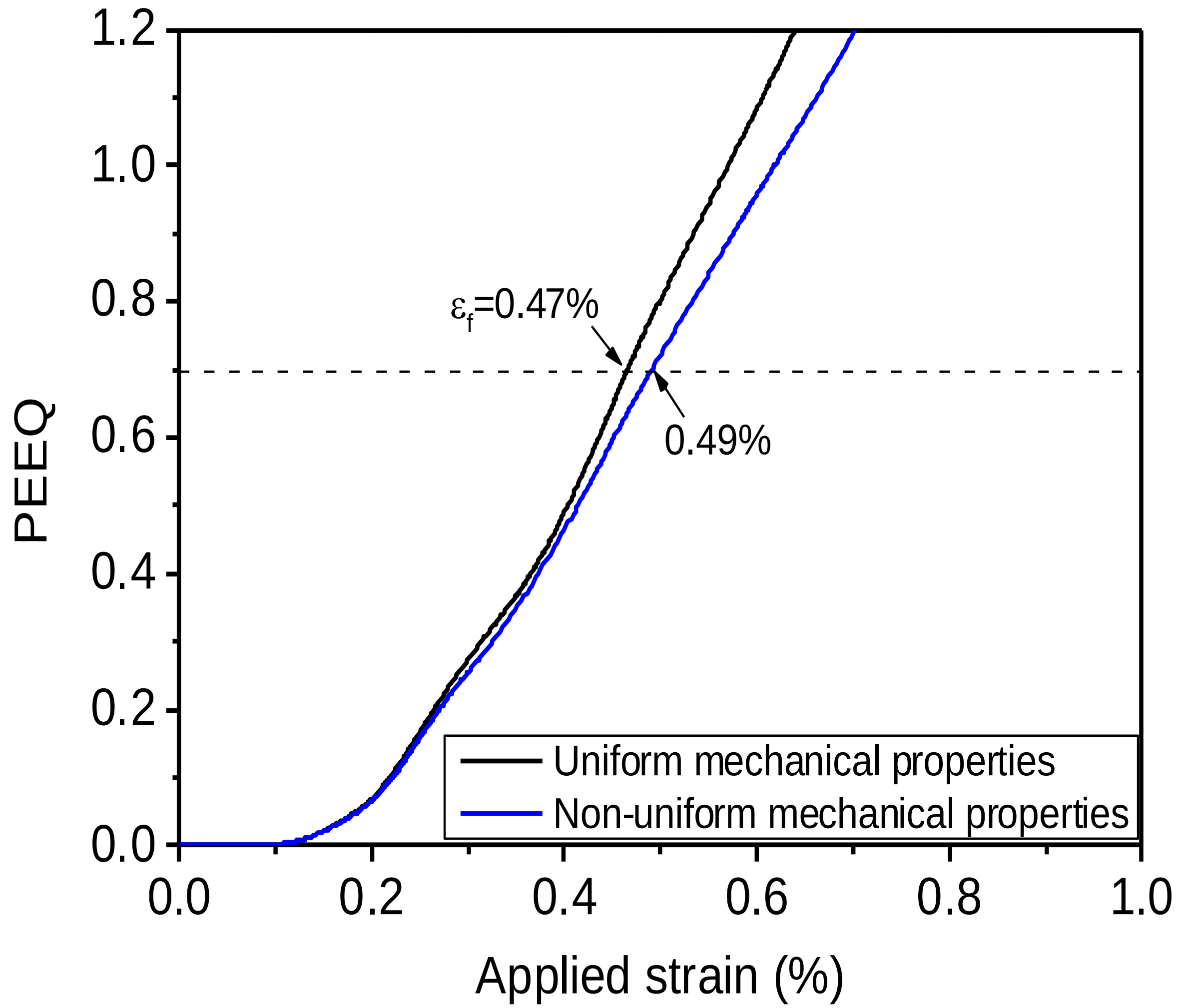
Simulations with outer surface notch
Post-necking hardening



Ccl:

Post-necking hardening significantly affects CTOD and PEEQ at the notch tip for strength undermatching cases.

Simulations with outer surface notch
Non-uniform mechanical properties



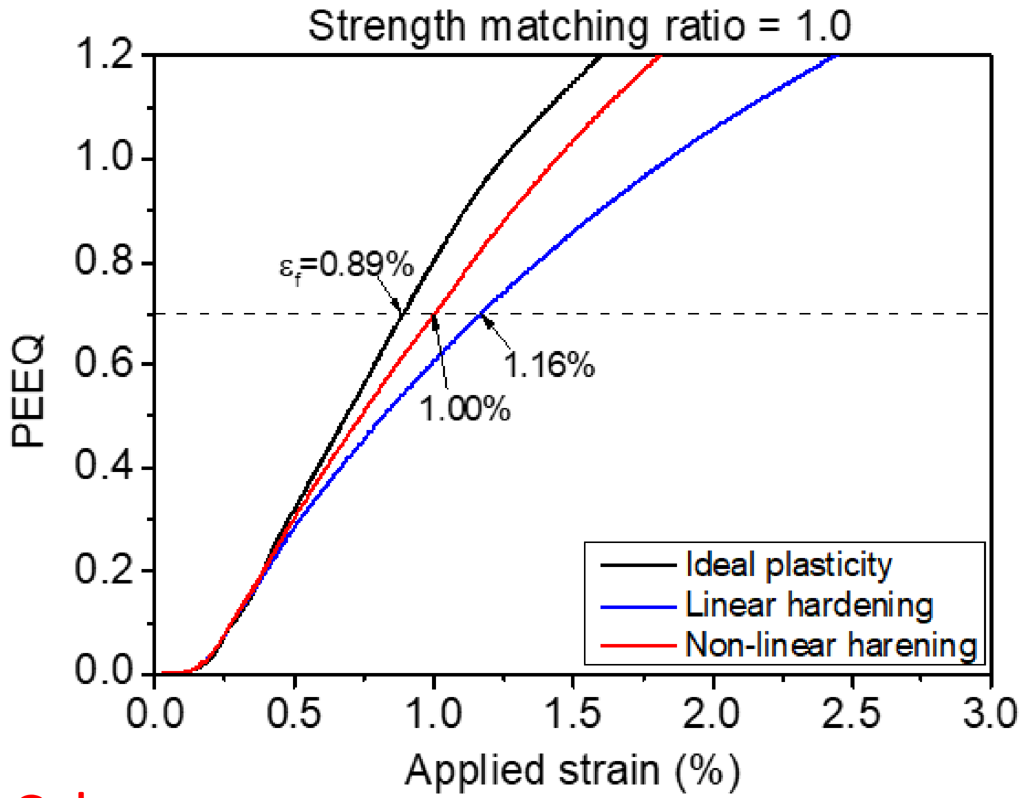
Conditions:

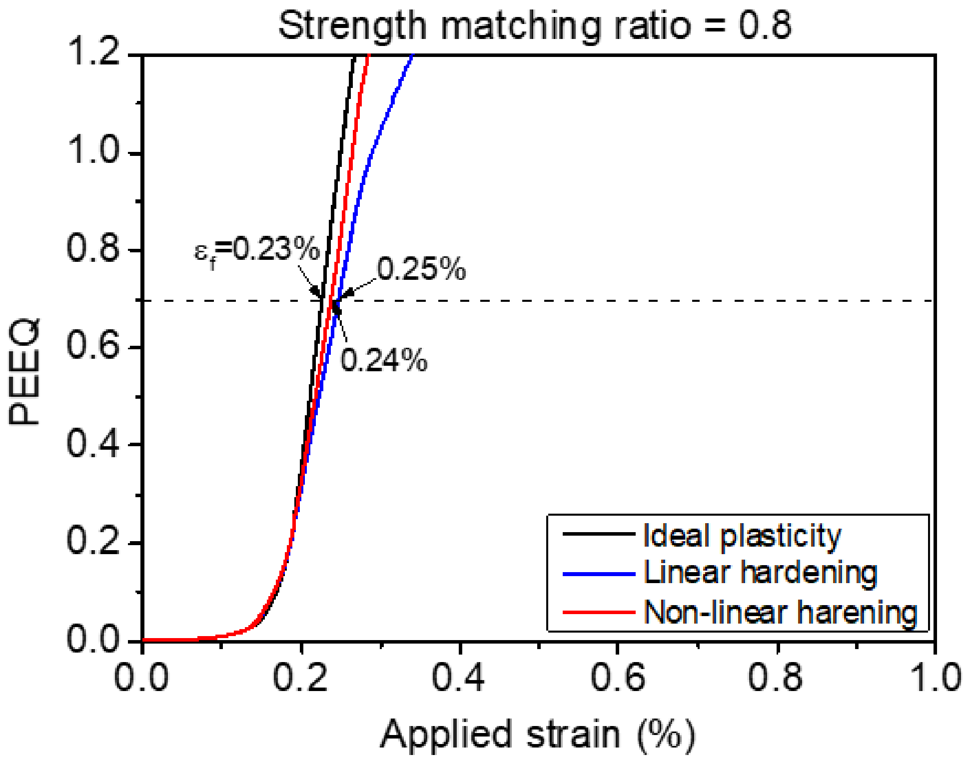
- With strength undermatching girth weld, Strength matching ratio = 0.8
- With outer defect
- Non-linear post-hardening curve

Ccl:

The variation of mechanical properties along the pipe circumferential direction has a small influence on PEEQ at the notch tip.

Simulations with inner surface notch
Post-necking hardening



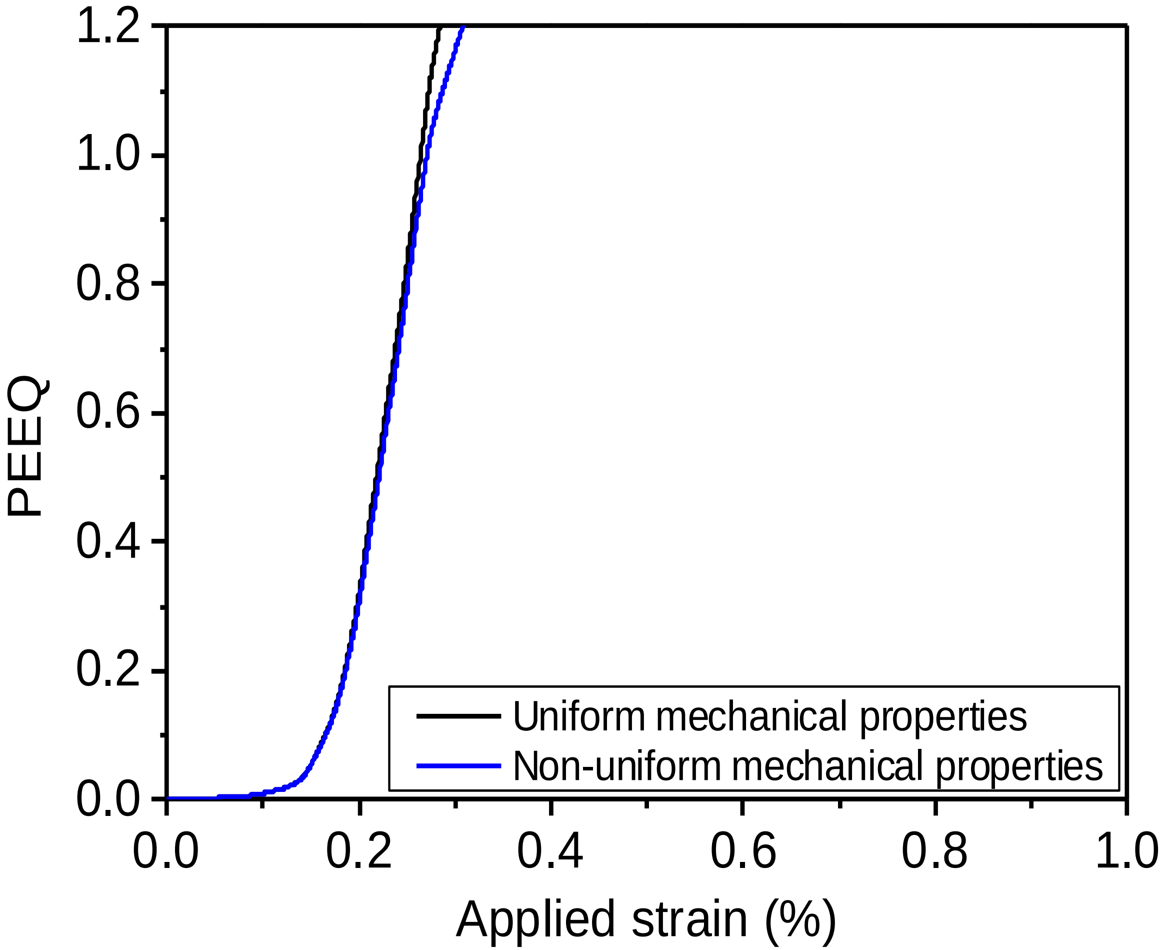


Ccl:

Influence of post-hardening on the PEEQ

- Larger for strength even-matching (λ=1.0)
- Smaller for strength undermatching (λ=0.8).

Simulations with inner surface notch
Non-uniform mechanical properties



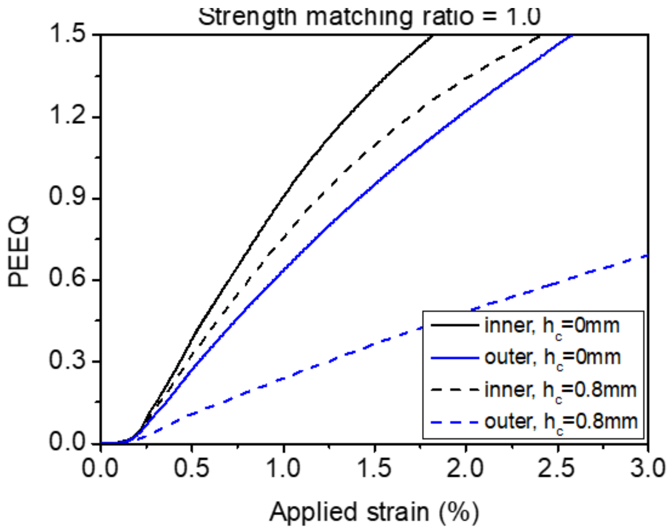
Conditions:

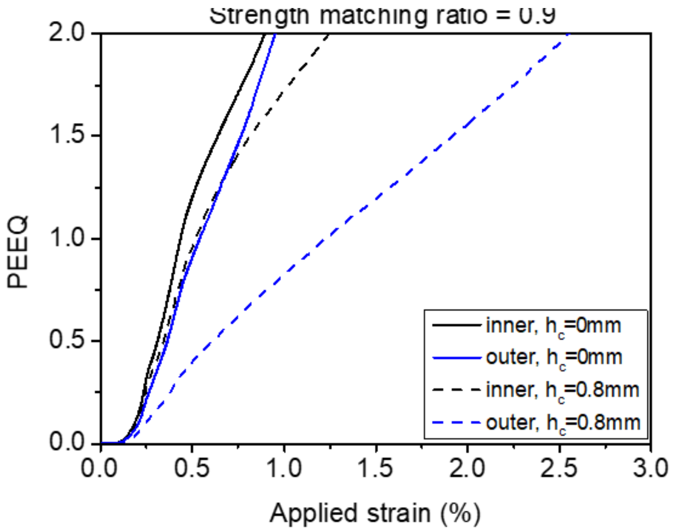
- With strength undermatching girth weld, Strength matching ratio = 0.8
- With inner defect
- Non-linear post-hardening curve

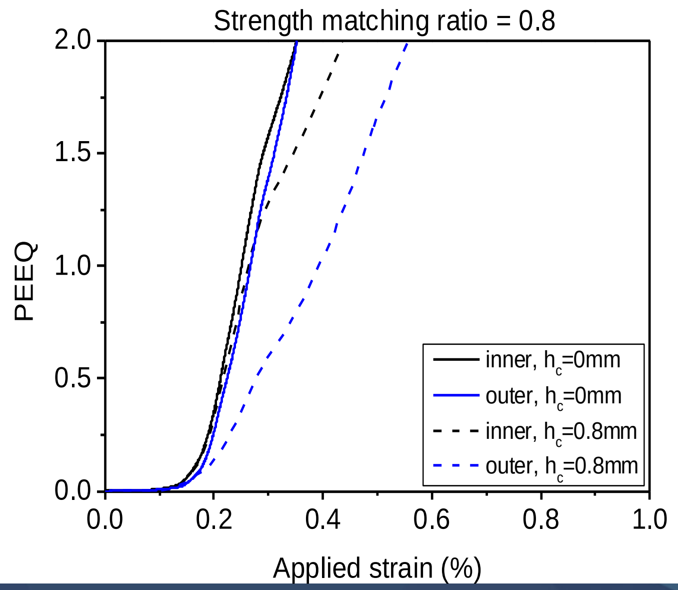
Ccl:

The variation of mechanical properties along the pipe circumferential direction has a negligible influence on PEEQ at the notch tip.

Comparison inner/outer notch locations







- PEEQ
  - Generally larger at tip of inner surface notch @ same applied strain;
- Difference in PEEQ strongly depends on
  - **Weld cap height**
    - *Larger weld cap height causes a larger difference in PEEQ;*
  - **Strength matching ratio;**
    - *Difference reduces with decrease in strength undermatching ratio.*

Implications for future work

Implications for future works

1. Post-necking hardening plays an important role in TSC prediction
   - Project to conduct NRBT tests with inverse method to determine post-necking hardening curves for full-scale pipe tensile tests (FSPTT) and CWP tensile tests.
2. Tendency to fracture at notch tip depends on local mechanical properties
   - Specimens for lab tensile tests should be machined at the same location as the notch.
3. Notch normally machined at outer surface of full-scale pipe tensile specimens.
   - But... Fracture initiates at the inner surface in most girth weld failure accidents.
4. Reported simulations show CTOD and PEEQ larger at the tip of the inner surface notch.
   - TSC measured in FSPTT may not be conservative.

Implications for future works

5. The weld cap around the notch location is normally ground flush in the full-scale test.
    - May minimise the influence of the notch location.

6. Influence of notch location can still be significant for some conditions.
    - TSC measured in FSPTT may need to be corrected.

Conclusions

Conclusions

1. FEA simulations to investigate tensile strain capacity with strength undermatching girth weld.
   - Matlab-based program developed to facilitate the simulation process.

2. Reports simulation results relevant to:
   - Post-necking hardening,
   - Variation of mechanical properties along the pipe circumferential direction,
   - Location of the notch.

Conclusions

3. Post-necking hardening behaviour significantly influences the failure strain
   - Irrespective of whether with or without notch.

4. Variation of mechanical properties along the pipe circumferential direction can influences the failure strain
   - Important for cases without a notch
   - Small / negligeable for cases with a notch.

5. CTOD and PEEQ
   - Larger at the tip of the inner surface notch.
   - Difference between the fracture metrics at the two notch locations depends on the weld cap height and strength matching ratio.

FUTURE FUELS CRC

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Thank you