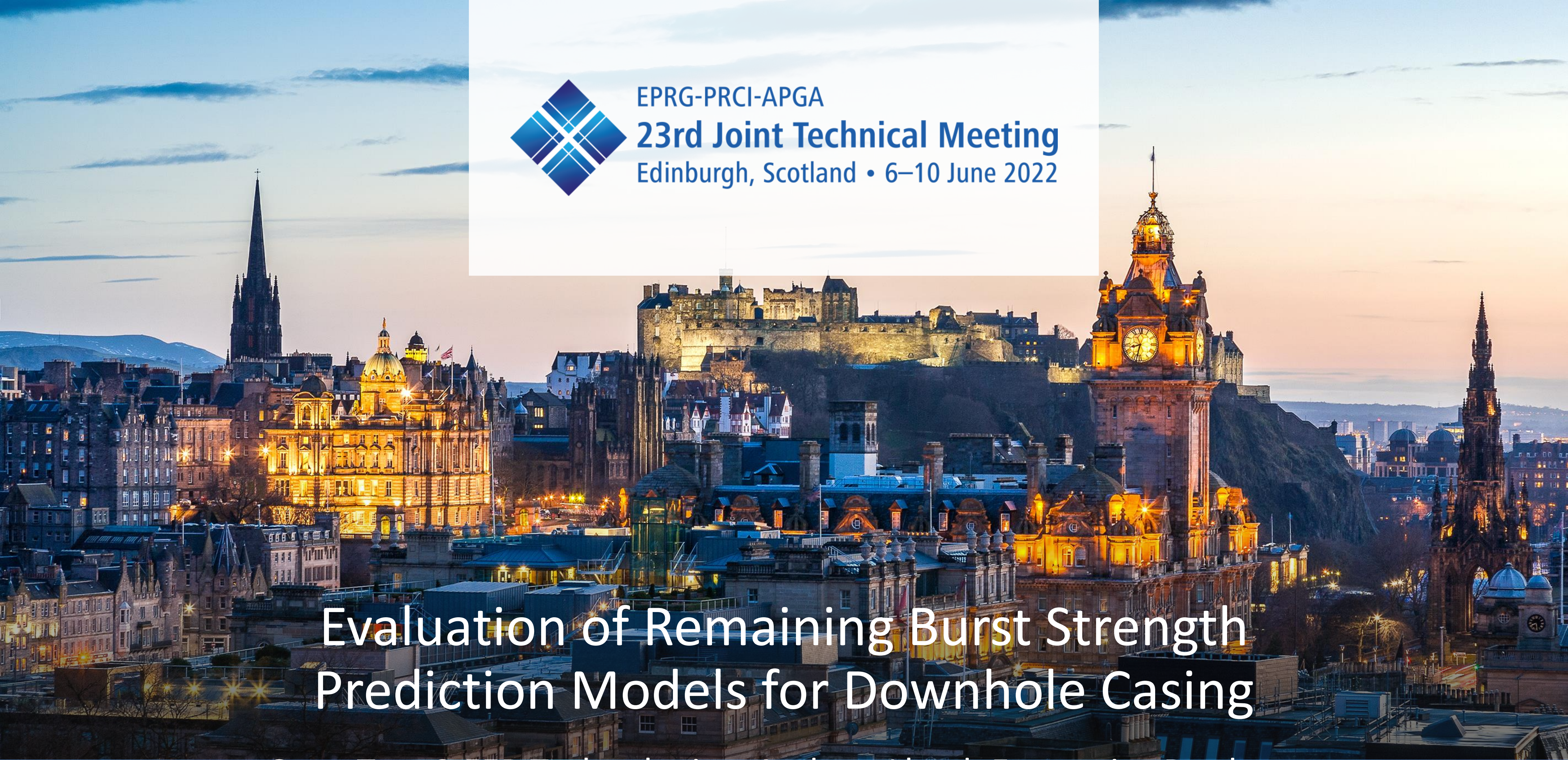

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Edinburgh, Scotland • 6–10 June 2022

Evaluation of Remaining Burst Strength Prediction Models for Downhole Casing

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09 June 2022

Disclaimer

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Content

- Introduction
- Physical Tests
- Finite Element Analysis
- Prediction Model Evaluation
- Conclusions
- Recommendations for Future Research

Introduction

- Address technical gaps and improve the efficiency in casing corrosion management
- A comprehensive research program co-funded by PRCI and PHMSA
  - Corrosion Inspection: logging tool test evaluation
  - Remaining Burst Strength Assessment: full-scale testing, FEA and model evaluation
  - Integrity Management: development of a reliability-based casing integrity assessment framework
- Final report is available for public download at

  https://primis.phmsa.dot.gov/matrix/PrjHome.rdm?prj=747

PRCI
LEADING PIPELINE RESEARCH

Catalog No. PR-244-18702-R01

Evaluation of Casing Integrity for Underground Storage Wells

US-3J

PRCI Contract No. PR-244-18702

PHMSA Contract 693JK31810014 - Project #747

C-FER Project No. C430

Prepared for the

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Reviewers: Brian Wagg, MSc, PEng

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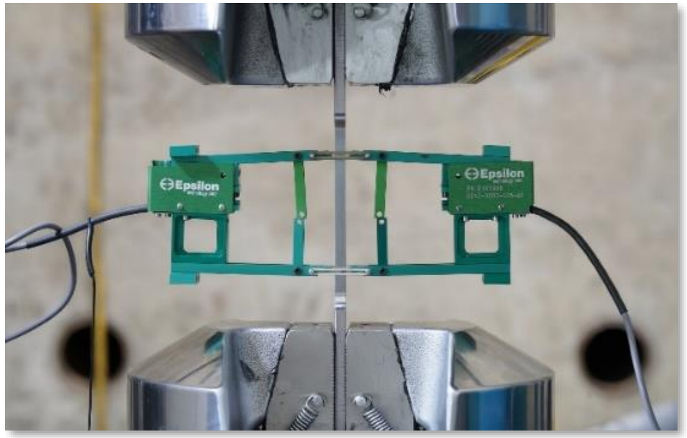
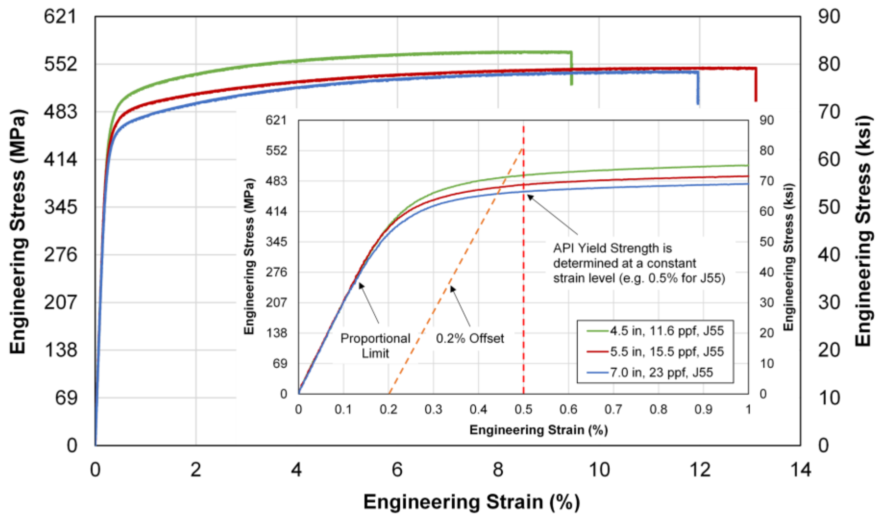
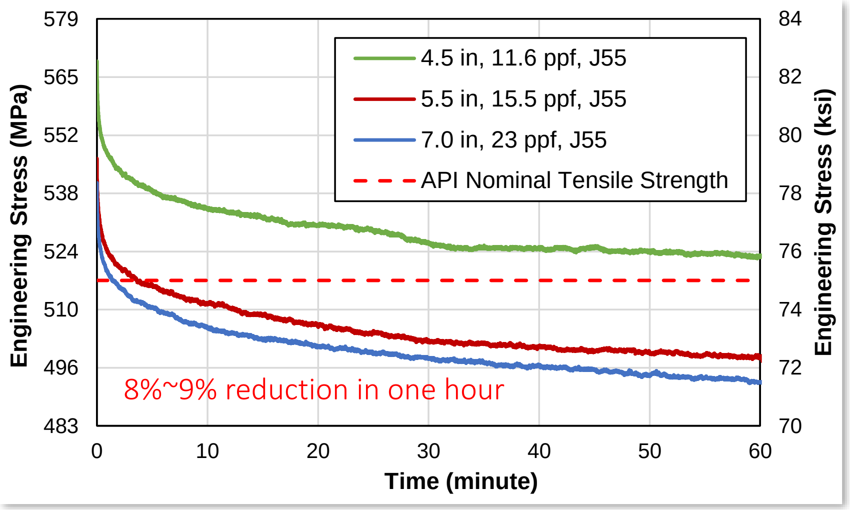
Draft 01	March 10, 2021	March 11, 2021	Initial draft
Final	May 26, 2021	May 26, 2021	Final

Physical Tests – Coupon Tensile Test







Test Specifications

- ASTM E111
- Strain-controlled (0.3%/min)

Test Results

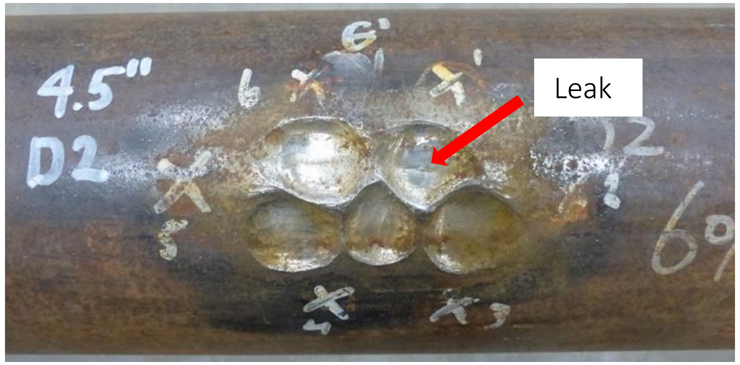
- Accurate stress-strain curves for FEA
- Key mechanical properties for prediction models (YS, UTS)

Stress Relaxation

- Viscoplastic behavior at room temperature
- Ductile burst pressure is strain rate dependent and lab test can be unconservative*

* *Tao G, Matthews C, Adams A. 2020. Special considerations for well tubular design at elevated temperatures. SPE Drill & Comp (2020). SPE-199570-PA.*

Physical Tests – Burst Test



20 Capped-end Tests

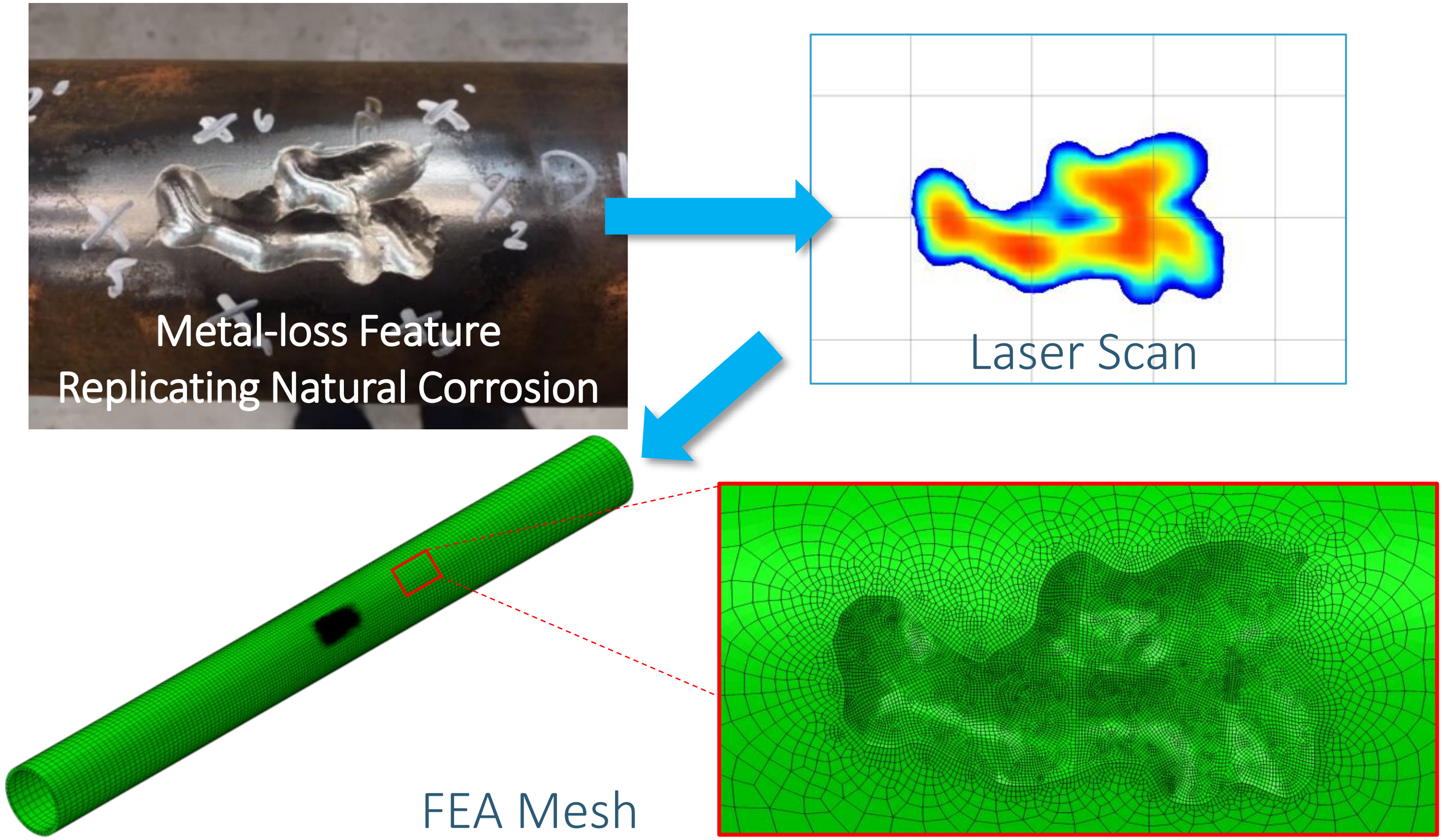
- OD: 4.5”, 5.5”, 7.0”
- D/t: 18.0 ~ 22.1
- Grade: J55

Test Results

- Burst pressure in the range of 5,000~10,000 psi
- Extensive wall thinning and tearing indicating ductile failure
- Failure as ductile rupture or leak

Finite Element Analysis

- FEA using Abaqus
- Material response from coupon tests
- Geometry model based on nominal casing size and actual metal-loss profile
- Load conditions
  - Capped-end (lab test condition)
  - Axially constrained (in-situ condition)

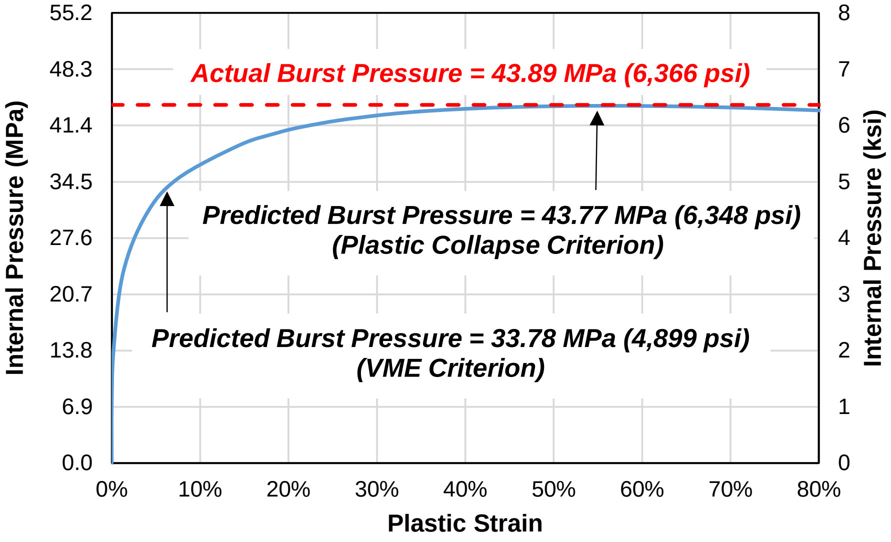


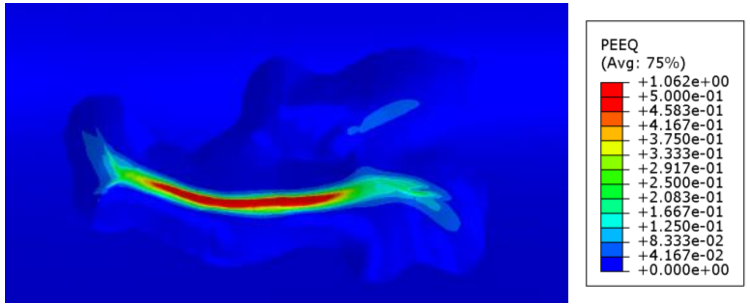
Finite Element Analysis

Failure Criteria

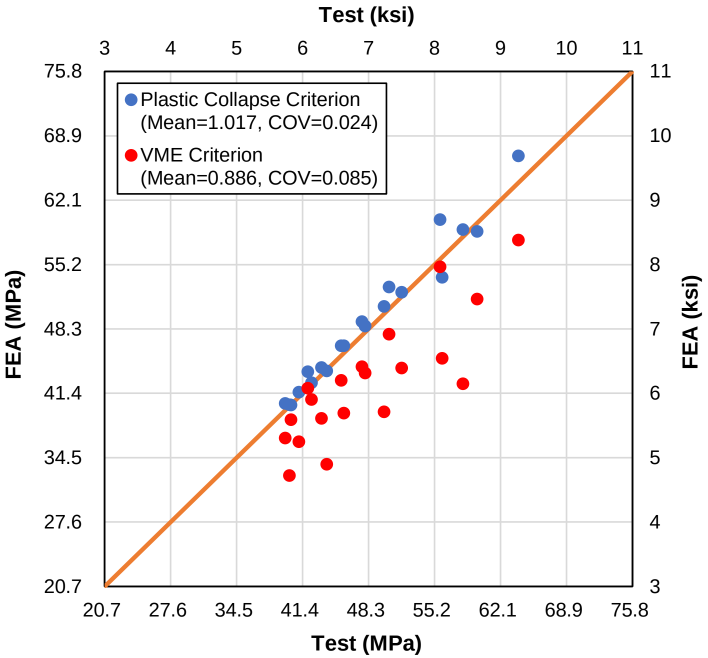
- von Mises stress (VME) based
  - compare VME value with UTS
  - extensively used for corroded pipe
  - larger bias error and scatter
- Plastic collapse (instability) based
  - Includes both strain hardening & local geometry change
  - well studied and used for uncorroded pipe
  - less bias error and scatter

UTS is the plastic instability limit under uniaxial tension and cannot be directly related to pipe ductile burst.





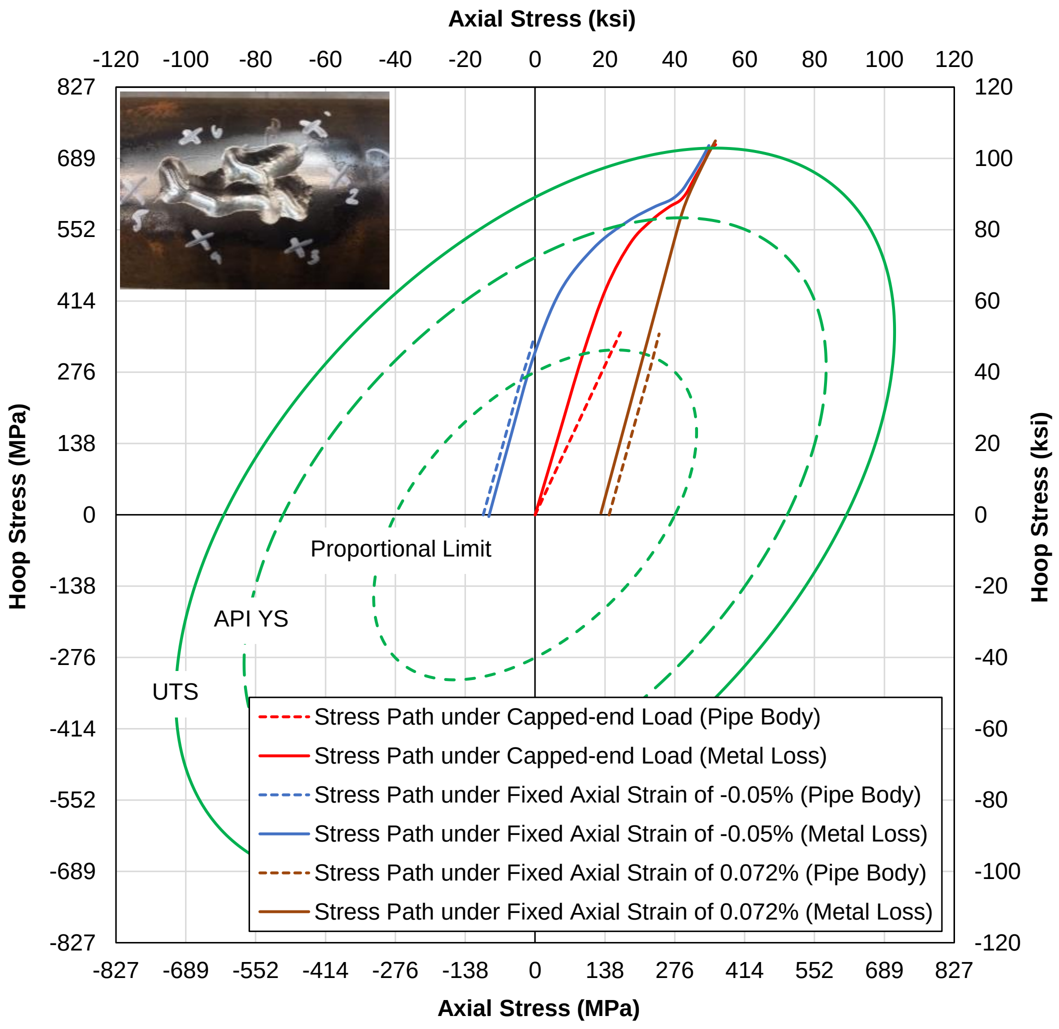
Plastic Strain Distribution at Peak Pressure



Failed Specimen

Finite Element Analysis

- Axial constraints (e.g. cemented casing) showed minimal impact on remaining burst strength in FEA.
    - Well bottom (compression): 1.7% burst pressure reduction
    - Well Top (tension): almost no impact
- Different stress ratio (axial vs. hoop) in pipe body vs metal-loss region
    - Pipe Body: typically remains in elastic range
        - Capped-end: 0.5
        - Axially Constrained: 0.3 (Poisson's ratio)
    - Metal-loss: gradual transition to 0.5 after yielding
- Plastic flow within the metal-loss region is nearly independent from the stress in the surrounding uncorroded pipe body.



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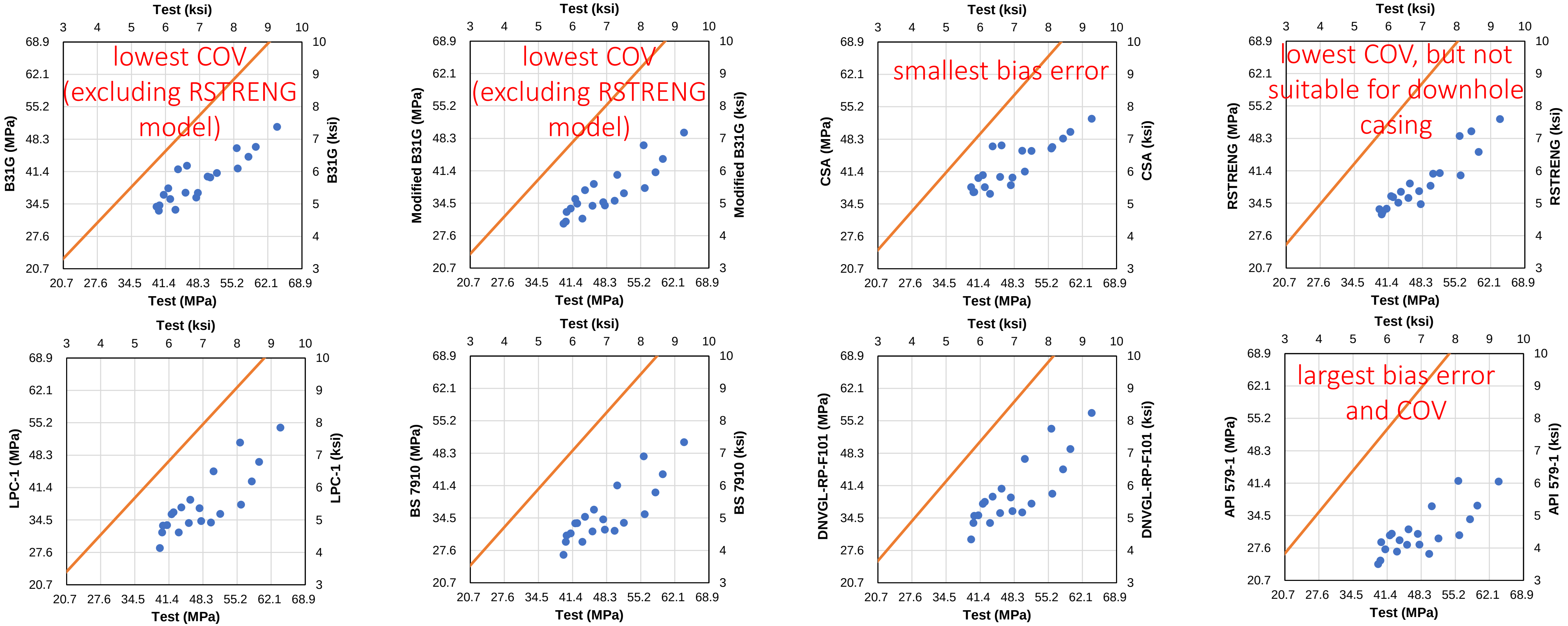
Prediction Model Evaluation



- Actual YS and UTS used instead of SMYS and SMTS in the calculation
- All analytical models underestimate burst capacity by between 10% and 36% (mean value).
- Bias error can be corrected with a multiplicative factor, and COV (coefficient of variance) is a critical measure of model prediction capability.

Prediction Model Evaluation

Effect of D/t Ratio

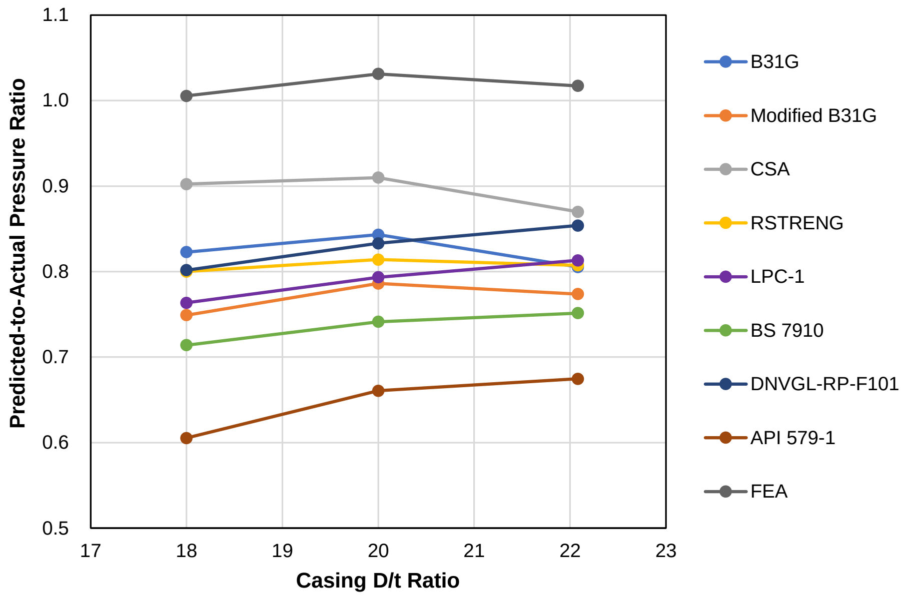
- D/t is implicitly included in the Folias factor

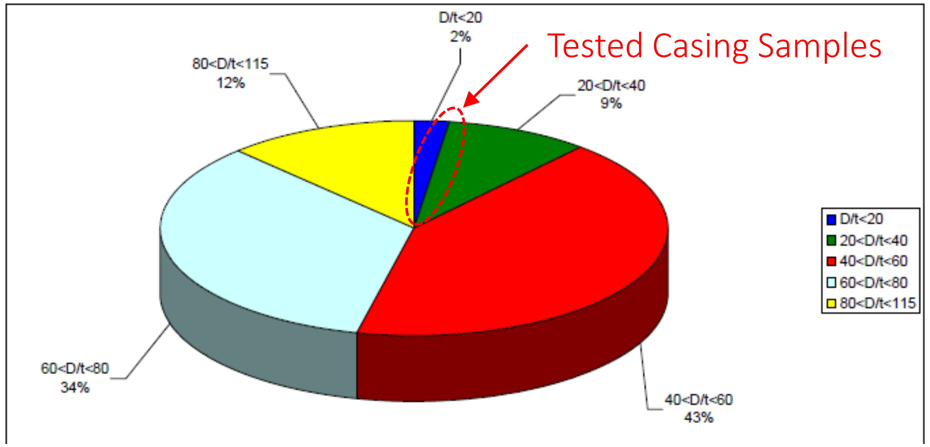
Metal-loss Geometric Factor

$$M = f\left(\frac{L}{\sqrt{Dt}}\right) = f\left(\frac{L/t}{\sqrt{D/t}}\right)$$

D/t Ratio

- Models calibrated based on tests with larger D/t line pipe samples are likely to have bias error for casing application.





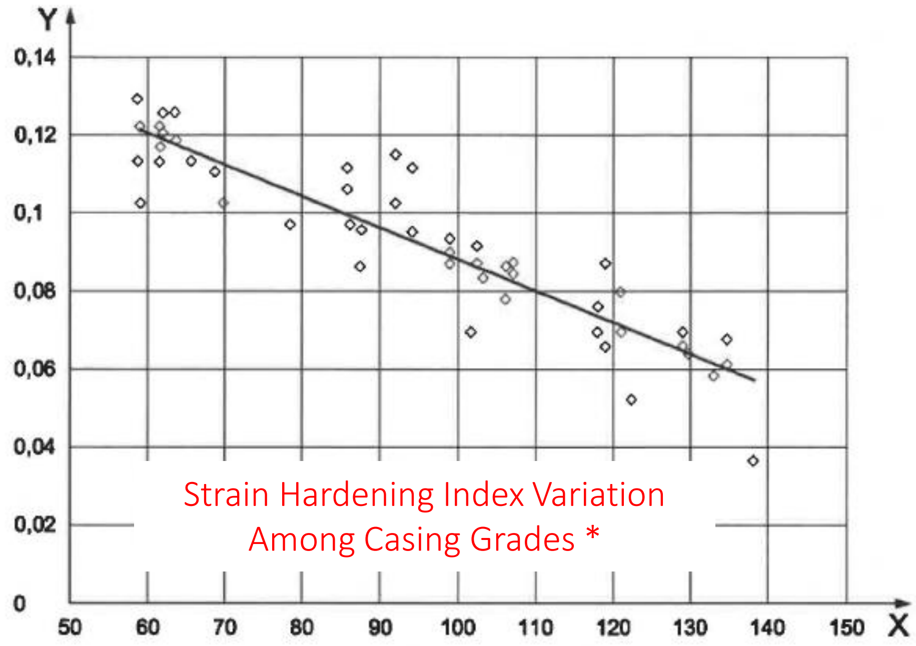
D/t of Line Pipe Samples *

* CHAUHAN, V. and J. BRISTER. A Review of Methods for Assessing the Remaining Strength of Corroded Pipelines. Loughborough, UK: GL Industrial Services UK, Nov. 2009. Report No. 6781, US DOT Contract No. DTPH56-05-T0003 – Project 153.

Prediction Model Evaluation

Effect of Strain Hardening Property

- Comparison of FEA to burst tests confirms ductile rupture failure mechanism.
- Ductile rupture is a plastic instability problem that depends on both local pipe geometry and post-yield stress-strain relationship.
- Ductile rupture of corroded pipe shares the same fundamental physics as uncorroded pipe.
- Therefore, burst strength prediction models in both cases need to consider post-yield stress-strain response (i.e., often represented by the UTS and a strain hardening index).



Grade	n
H40	0.14
J55	0.12
K55	0.12
M65	0.12
N80	0.10
L80 Type 1	0.10
L80 Chrome	0.10
C90	0.10
R95	0.09
T95	0.09
P110	0.08
Q125	0.07

Key
X measured yield strength, ksi
Y n

NOTE Least squares fit of data results in $n = 0.1693 - 0.000812 \times$ measured yield strength; coefficient of variance = 0.10.

Figure B.1—Correlations for Hardening Index from Typical Experimental Data for Steel Grades Listed in Table B.2

** API Technical Report 5C3, Calculating Performance Properties of Pipe Used as Casing or Tubing, seventh edition. 2018. Washington, DC: API.*

Conclusions

- Every model evaluated under-estimates the burst capacity of corroded casing.
  - D/t parameter implicitly included in the Folias factors is likely the cause.
  - Models calibrated based on large D/t line pipe samples are not readily suitable for smaller D/t casing samples.
- Comparison between FEA and full-scale tests confirms the plastic instability failure mechanism.
  - FEA prediction should use plastic instability based criterion rather than VME based criterion.
  - Consideration of the strain hardening property is expected to improve the model prediction.
- Some existing methods to account for axial load effects (e.g., in-situ load condition) on casing burst strength are questionable, and further investigation is needed.
- Further development of remaining burst strength prediction models for downhole casing is warranted.
  - Eliminate excessive conservatism in burst strength calculations (correct D/t ratio effect)
  - Develop advanced models considering strain hardening property of casing materials
  - Consider additional safety factor for reduced burst strength under sustained pressure (strain rate dependency)

Recommendations for Future Research

- Expand the burst test dataset to support model improvement
  - Metal-loss features covering a broad range of casing corrosion conditions
  - Additional casing sizes and weights to investigate the D/t ratio effect
  - Additional casing grades (e.g., K55, N80, L80, P110) to support development of advanced models considering strain hardening property
  - FEA can be used to supplement test data with reduced cost (excellent prediction capability as demonstrated)
- Further investigation of in-situ locked-in axial load effects
  - Full-scale burst testing with locked-in axial load/strain
  - FEA to supplement test data to develop method to account for axial constraint effects
- Investigate remaining burst strength of vintage casing (80% of UGS wells drilled before 1980)
- Investigate strain rate impact on casing remaining burst strength
- Confirm model performance for line pipes (i.e. strain rate effect, axial load effect)

Thank you for your attention.