Gwise®-TSC

Introduction

Center for Reliable Energy Systems

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Webinar

9/14/2023

Overview

- Logistics
- High-level introduction of Gwise®-TSC
- Relevance of Gwise®-TSC to real-world issues
- Fundamental concepts of tensile strain failure and strain-based assessment
- Generations of tensile strain models/approaches
- Development and utilization of Gwise®-TSC
  - Features and software interface
  - Single run and batch mode
- Focus of this presentation
  - Background and application scenarios
  - Brief overview of software interface
  - Details of the software capability and interface can be discussed in separate follow-up meetings.

Part 1

Logistics

Logistics

- Time allocation
  - Presentation 45 minutes
  - QA 15 minutes
  - “Bonus” QA 30 minutes
- All attendees are muted during presentation other than the speaker(s).
- The presentation is recorded.
  - The recorded presentation may be posted publicly at CRES’ discretion.
- The QA will not be posted.

Speakers

- Yong-Yi Wang, Ph.D.
  - S.M. and Ph.D., MIT, mechanics and materials, focusing on fracture mechanics
  - Founded CRES in 2007
  - Led the development of strain-based design and assessment from ~2000
  - Chair of Fracture Mechanics subcommittee of API 1104
  - Track lead, strain-based design and assessment, IPC
  - Recent events
    - API RP 1176, work group lead of a new Annex N, management of circumferential cracks
    - One of the lead authors of INGAA JIP on the management of geohazards
- Banglin Liu
  - B.S. and M.S. in mechanical engineering from University of Illinois Urbana-Champaign
  - Led the development of Gwise®-TSC
  - Leading projects on the applications of strain-based assessment, most in geohazards environment

Part 2

High Level Introduction of Gwise®-TSC

Gwise® and TSC

- Gwise® is a registered trademark of CRES.
- TSC, tensile strain capacity
  - Maximum level of longitudinal/axial tensile strain that a pipeline can sustain without negative consequences, such as a leak or rupture
- Gwise®-TSC is a tool that provides relations between TSC and major factors affecting TSC.
- Members of Gwise® family
  - Gwise®-TSC
  - Gwise®-SBA Version 1.0
    - A tool to assist mitigation decisions with identified landslide impacting a pipeline
    - Level 1 strain demand assessment + lower bound TSC for pipeline groups
    - Mitigation decisions are made based on the concept of safety margin, i.e., different between strain capacity and strain demand

Possible Applications of Gwise®-TSC

- Existing assets
  - ILI sentencing criteria for circumferential features
  - Systematic ranking of TSC for different pipelines or different segments of a pipeline
  - Site- or girth weld-specific TSC, as a part of strain-based FFS assessment
  - Strain action threshold
- New construction
  - Making balanced decisions between mitigating hazards and building resilient pipelines
  - Achieving a target TSC through setting of
    - Pipe spec
    - Girth welding procedures
    - Flaw acceptance criteria
  - Set future intervention criteria, e.g., IMU strain action threshold

Applicable Conditions of Gwise®-TSC

- Vintage / year of construction
  - 1930's – present day
- Pipe grade: Grade B – X70/X80
- OD: 8.625" – 48"
- WT: 0.181" – 1.25"
- Linepipe steels: vintage normalized and modern TMCP
- Girth welds joining pipes of nominally equal wall thickness

- Girth welding processes
  - Vintage
    - Standard bevel
      - Manual SMAW
  - Modern
    - Standard bevel
      - Manual SMAW (cellulosic or low hydrogen electrodes)
      - Semi-automatic FCAW-S
      - Mechanized FCAW-G and FCAW-S
    - Narrow groove
      - Mechanized GMAW

Acceptance by the Industry

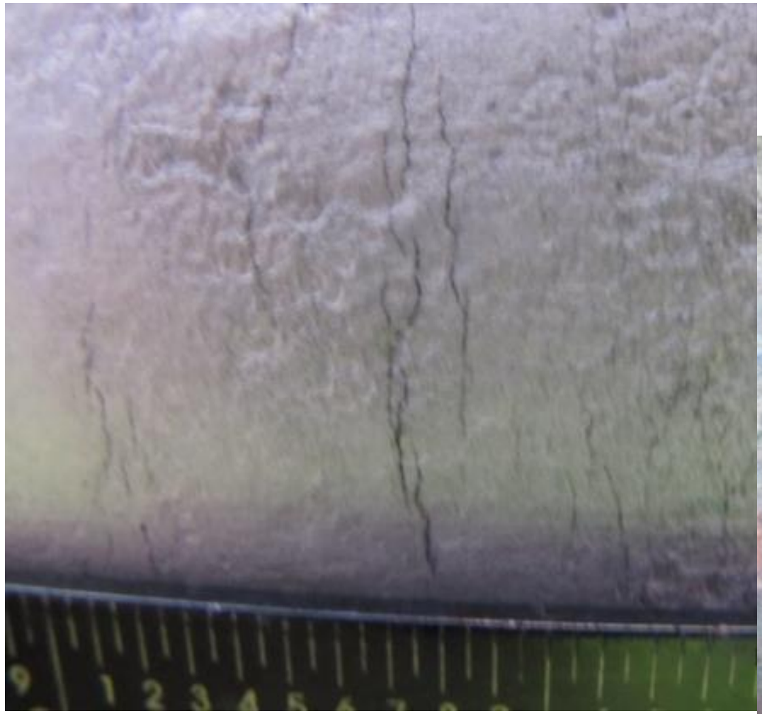
- Strain-based assessment (SBA), including procedures/processes in Gwise®-TSC, falls under the general category of FFS assessment, ECA, or EA.
- Guidance on SBA is being incorporated into industry-wide documents
  - API RP 1176, management of cracks
  - API RP 1187, management of geohazards
  - API 579, general FFS assessment

Threats and Limit States

- Tensile leak/rupture at girth welds

Threats and Limit States

- Tensile leak/rupture from SCC with major circumferential orientation



Part 3

Relevance of Gwise®-TSC to Real World Issues

Safety Advisories

- PHMSA Advisories
  - Pipeline Safety: Potential for Damage to Pipeline Facilities Caused by Earth Movement and Other Geological Hazards, 87 Fed. Reg. 33,576 (June 2, 2022).
  - Pipeline Safety: Potential for Damage to Pipeline Facilities Caused by Earth Movement and Other Geological Hazards, 84 Fed. Reg. 18,919 (May 2, 2019).
  - Pipeline Safety: Potential for Damage to Pipeline Facilities Caused by Flooding, River Scour, and River Channel Migration, 84 Fed. Reg. 14,715 (April 11, 2019).
  - Pipeline Safety: Potential for Damage to Pipeline Facilities Caused by Flooding, River Scour, and River Channel Migration, 81 Fed. Reg. 2,943 (January 19,2016).
- CER Safety Advisory SA 2020-01 – Girth Weld Area Strain-Induced Failures: Pipeline Design, Construction, and Operation Considerations
  - https://www.cer-rec.gc.ca/sftnvrnmnt/sft/dvsr/sftdvsr/2020/2020-01-eng.html

Pipeline Incident – A New Pipeline

- On February 22, 2020, a CO_2 pipeline ruptured near Satartia, Mississippi.
- The rupture followed heavy rains that resulted in a landslide, creating excessive axial strain on a pipeline weld.

- Delhi Pipeline
  - Installed in 2009
  - 24” OD X80 ERW pipes
  - 77 miles
  - CO_2 was used for enhanced oil recovery (EOR)

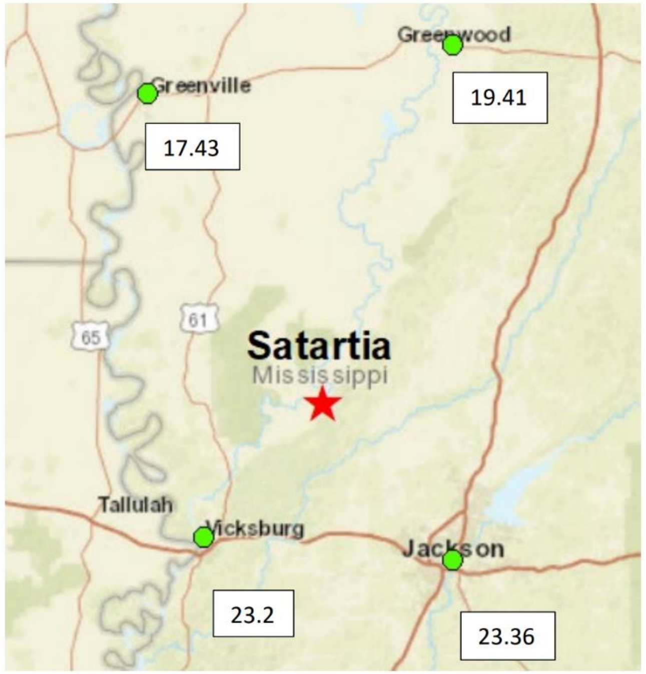
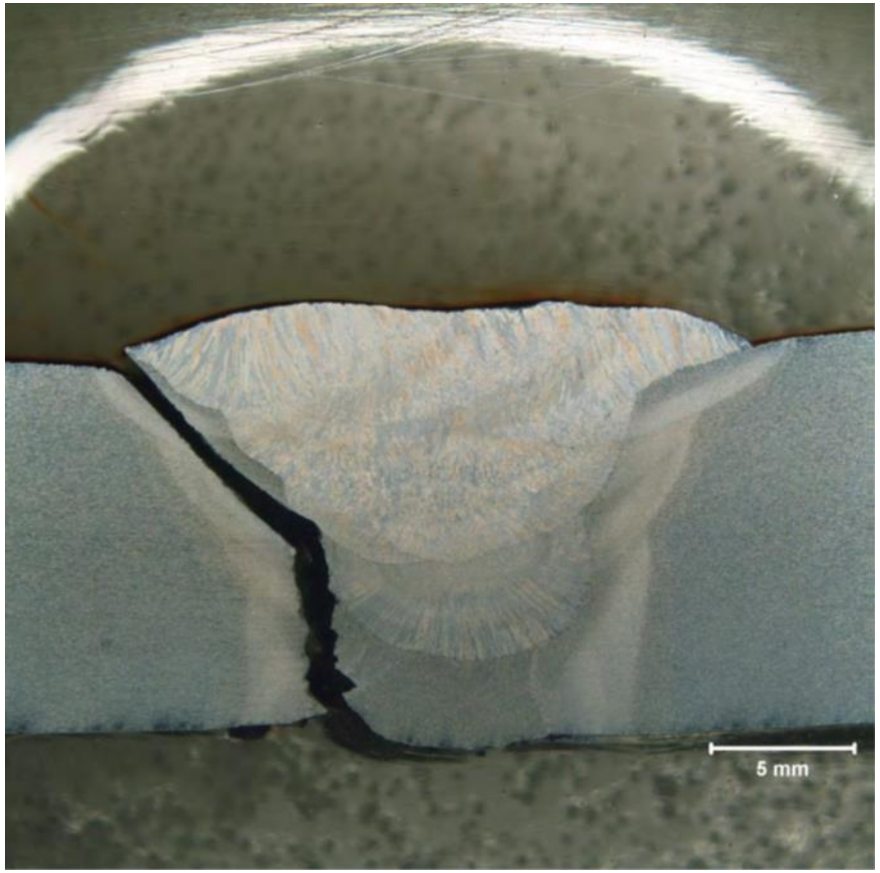


Figure 2: Vehicle is Parked on HWY 433 - The White is Ice Generated by the Release of CO_2 - The Blue Arrow Points North (Aerial Drone Photograph Courtesy of the Mississippi Emergency Management Agency)

Wesley Mathews, “Failure investigation report – Denbury Gulf Coast Pipelines, LLC – Pipeline Rupture / Natural Force Damage,” US DOT PHMSA OPS, May 26, 2022.

Pipeline Incident – A New Pipeline

- CO2 pipeline rupture near Satartia, Mississippi, February 22, 2020



Wesley Mathews, “Failure investigation report – Denbury Gulf Coast Pipelines, LLC – Pipeline Rupture / Natural Force Damage,” US DOT PHMSA OPS, May 26, 2022.

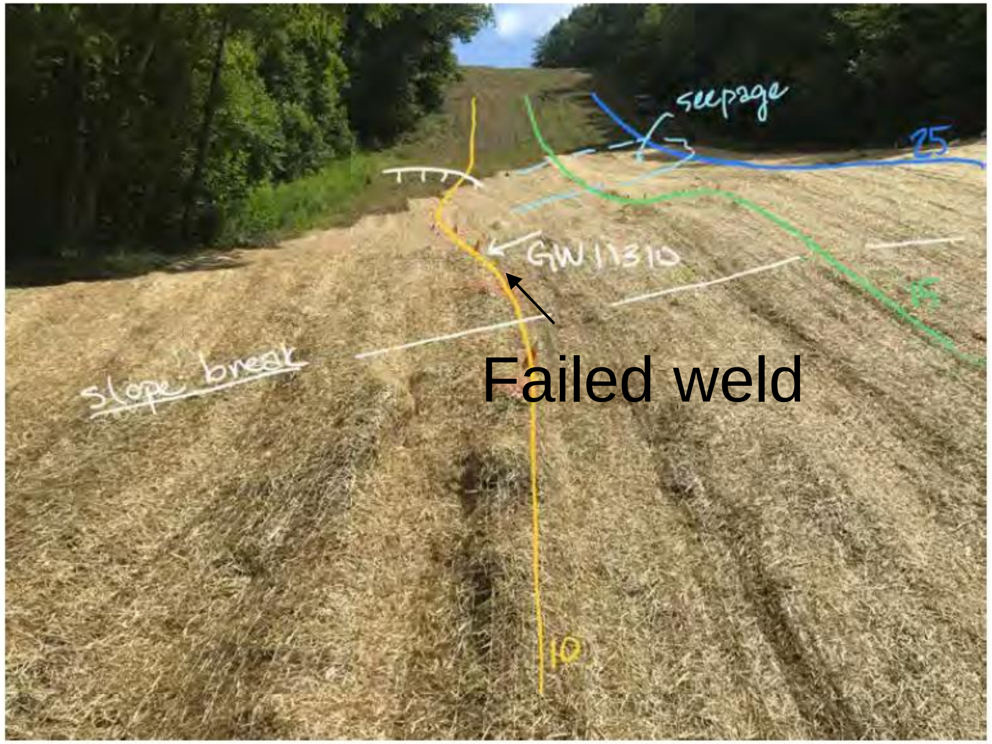
Pipeline Incident – A Vintage Pipeline

- ❑ Rupture: March 11, 2022 at about 8:15 a.m. local time, near Edwardsville, Illinois.
- ❑ The rupture resulted in the release of about 3,900 barrels of crude oil, some of which entered Cahokia Creek, a tributary of the Mississippi River.
- ❑ Woodpat pipeline
  - ❖ Constructed in 1949
  - ❖ 22” OD
  - ❖ A complete circumferential separation at a girth weld at the rupture origin
- ❑ Previous in-line inspections and field studies had identified movement of the pipeline, erosion, and soil subsidence in the area near the rupture site.

NTSB Docket PLD22FR002, March 11, 2022, Accident No. PLD22FR002.

Pipeline Incident – A Vintage Pipeline

- Fleming County, Kentucky, May 4, 2020
- Rupture, fire, no injuries or fatalities
- Texas Eastern Line 10
  - Constructed 1952
  - 30” OD
  - 0.375” WT
  - X52 DSAW straight seam

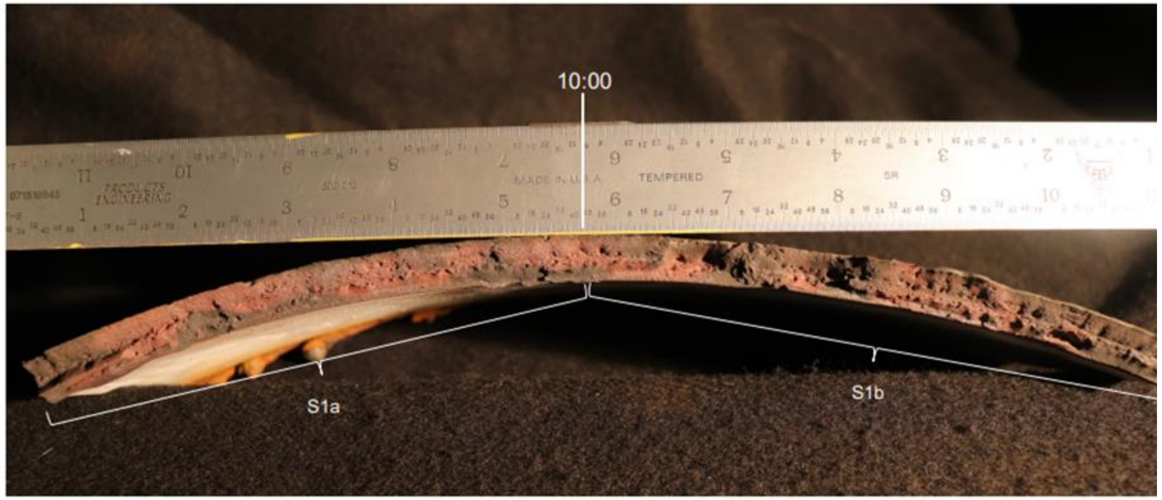


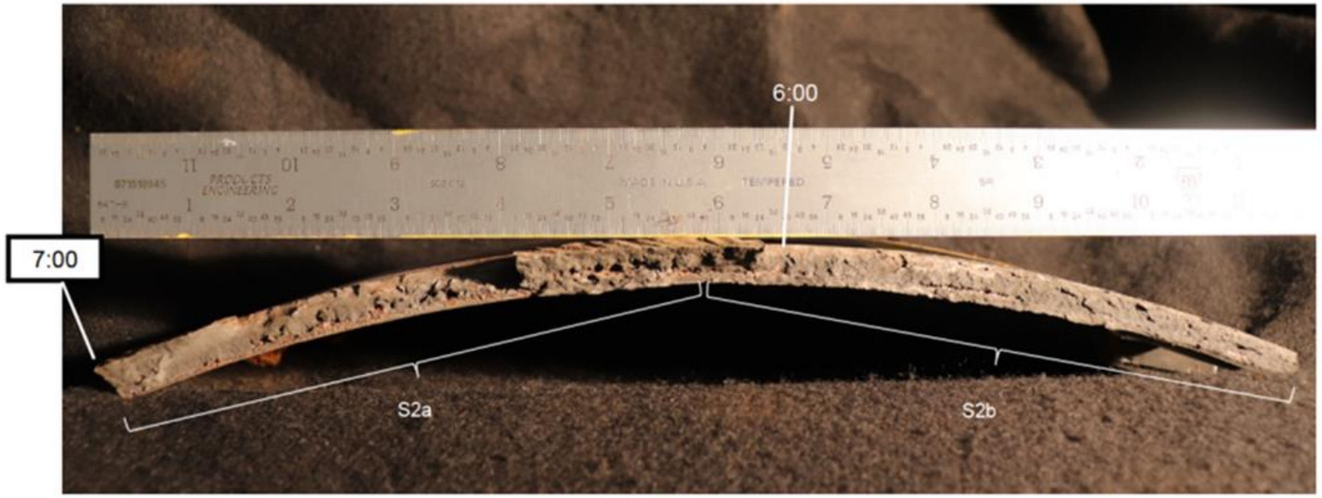
Standing on ROW, looking upslope (NE) at deflected Lines 10 and 15.

Figure 1. Ruptured pipeline.
Source: BGC Engineering USA, Inc.)

Pipeline Incident – A Vintage Pipeline

- Texas Eastern Line 10 rupture, May 4, 2020
  - Tensile failure at girth weld followed by weld separation
  - Two large flaws (IP/LORF) on the fracture surface of the failed weld
    - ►7” x 0.13” (~ 10:00 orientation)
    - ►4.9” x 0.1” (~ 6:30 orientation)





Girth Weld Failures of Newly Constructed Pipelines

- Girth weld incidents on newly constructed pipelined
  - 30+ incidents.
    - ►US
    - ►Asia
    - ►South America
  - Grade: X52 to X80
  - Manual or semi-automatic welds
- Major drivers
  - Weld strength undermatching
  - HAZ softening
  - Elevated longitudinal/axial stress

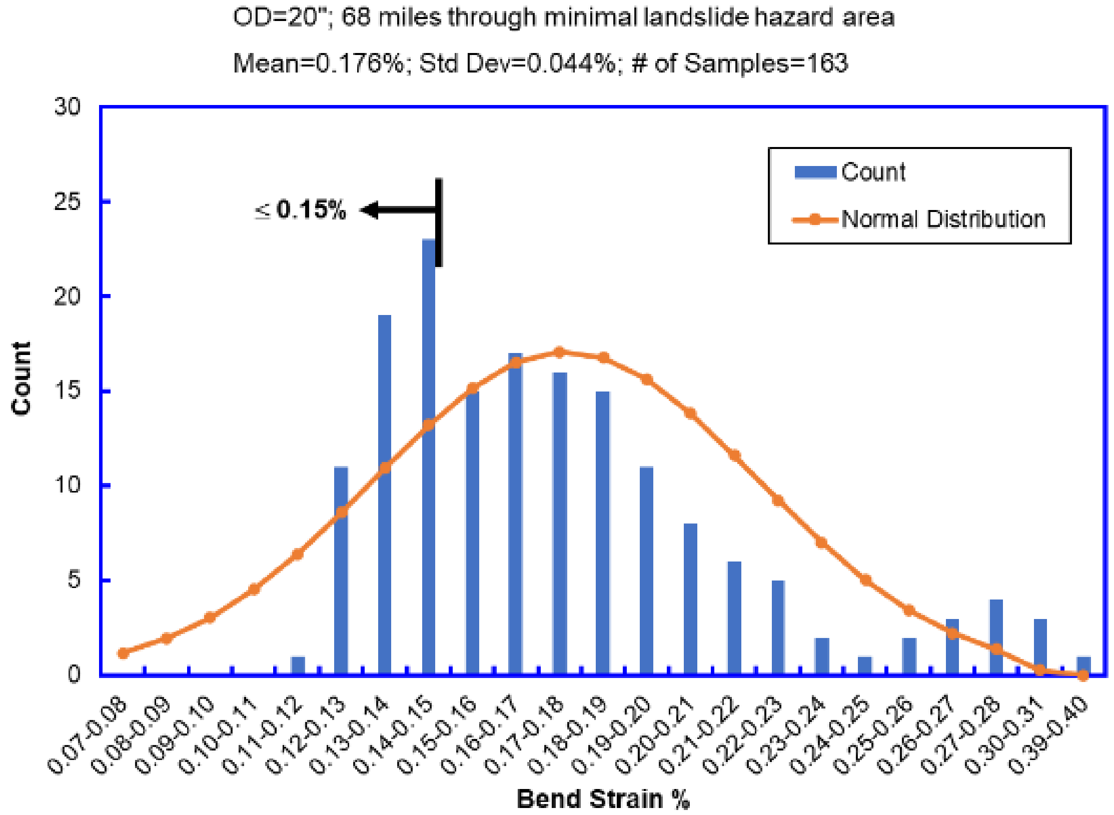
Incident No.	OD (inch)	Grade	Nature of Incident	Approximate Elapsed Time for Start of Service
1	20"	X70 PSL2	In-Service Rupture	1 Year
2	30"+	X80/X70	In-Service Rupture	6 years
3	12.75"	X52	In-Service Leak	14 years
4	30"	X70M	Hydrostatic Leak	N/A
5	30"	X70	Hydrostatic Leak	N/A
6	42"	X70 PSL2	In-Service Rupture	3 years
7	12.75"	X52/X65	In-Service Rupture	4-5 years
8	24"	X70	In-Service Rupture	3.5 years
9	36"	X70	Hydrostatic Leak	N/A
10	Information can't be released	X70	In-Service Rupture	Less than 1 year

Common Features of Incidents

- Cause of incidents
  - High longitudinal/axial stress/strain
  - Low strain tolerance
- Drivers of high longitudinal/axial stress/strain
  - Geohazards
  - Differential settlements
  - Construction stress
- Primary drivers of low strain tolerance
  - Vintage girth welds
    - Large weld flaws
  - Modern girth welds
    - Weld strength undermatching and/or HAZ softening
    - Unfavorable weld profiles, such as unmitigated high-level of high-low misalignment
- These factors have been considered in the development of Gwise®-TSC.

Longitudinal/Axial Stress vs. Hoop Stress

- The level of hoop stress, being primarily driven by internal pressure, is generally known.
- By controlling the internal pressure, the magnitude of hoop stress is reliably managed in the operation of a pipeline.
- The magnitude of longitudinal stress is not precisely managed, nor is it known in most cases.
- Longitudinal/axial stress can be high in certain locations even in the absence of geohazards.

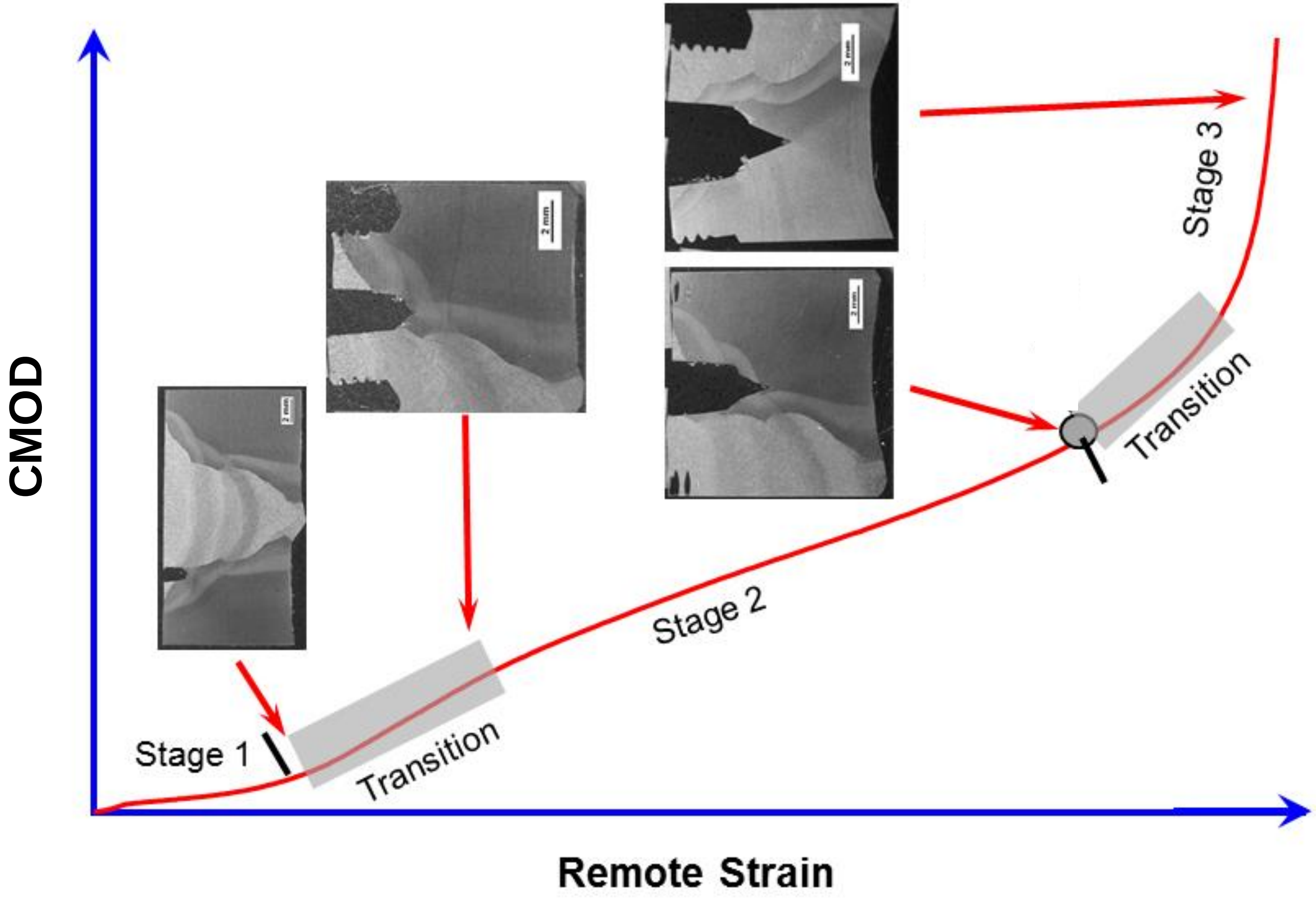


Part 4

Fundamentals of Tensile Strain Failure and SBDA

Physical Process of Tensile Failure

- Flaw blunting →Flaw growth initiation →Stable growth → Unstable growth



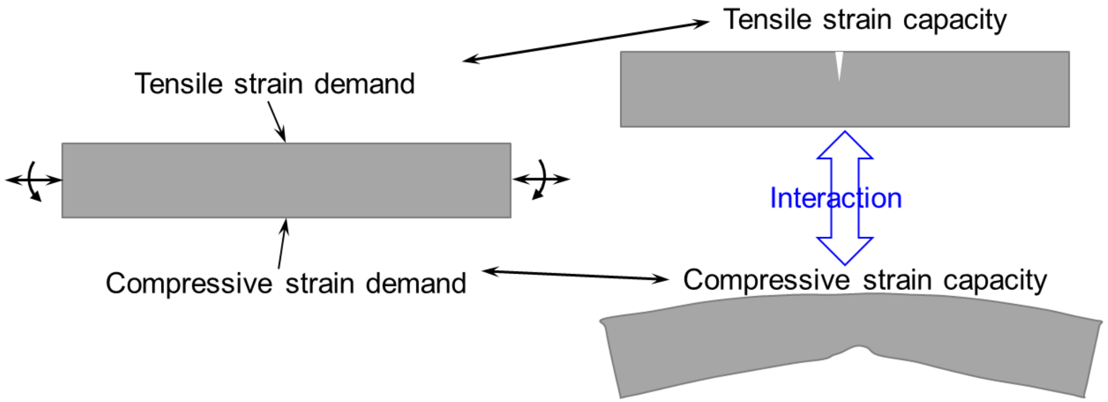
Strain-Based Design and Assessment (SBDA)

- Using longitudinal/axial strain as a measure of driving force and resistance
- Safe condition

  ε_d (strain demand) ≤ ε_d^L (strain demand limit)

  $\varepsilon_d^L = \varepsilon_c$ (strain capacity) / f (safety factor)

- Factors affecting the outcome of an integrity assessment
  - Strain demand
  - Strain capacity
  - Safety factor



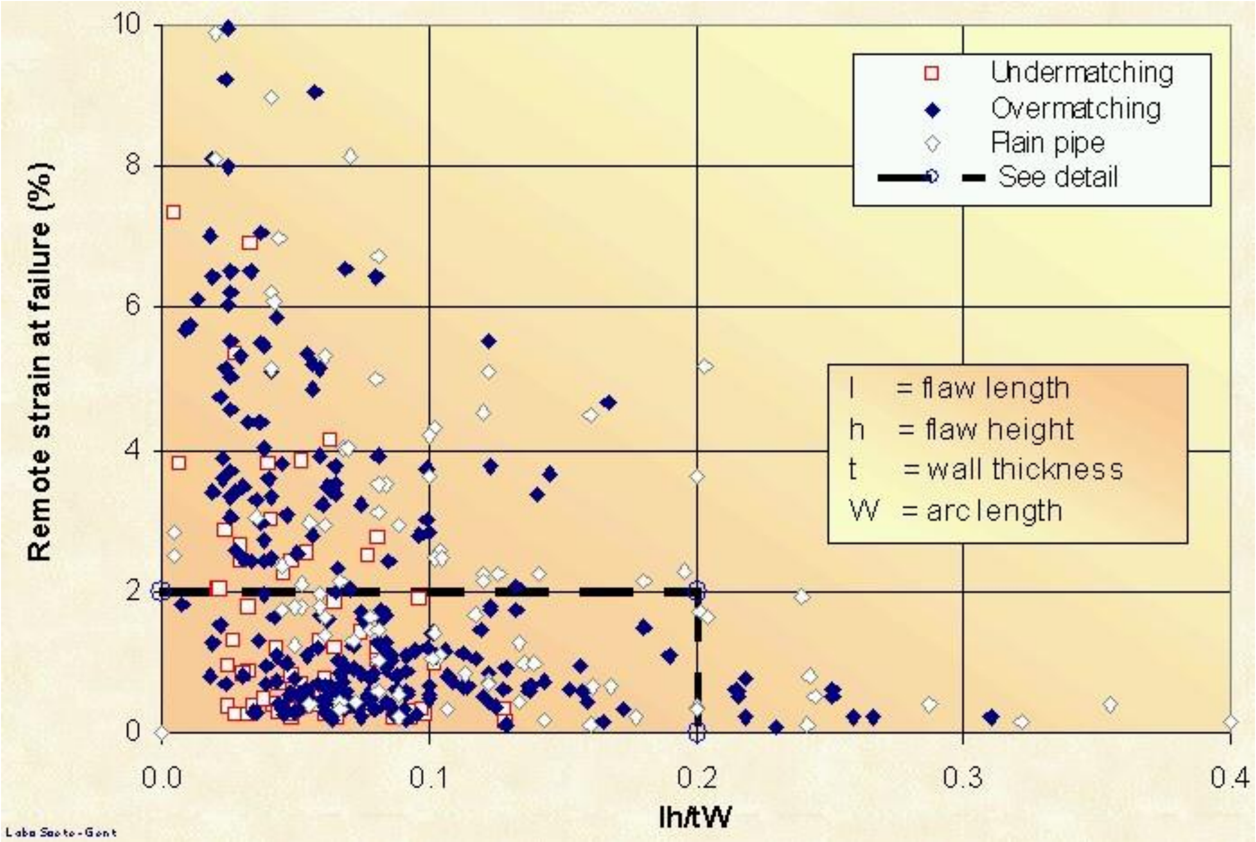
Why Strain-Based Assessment is Advantageous?

- Stress or strain likely to have integrity consequences for most girth welds would be
  - Stress > 90% SMYS
  - Strain > 0.2%
- The state of loading can be more precisely measured in strains than stresses at this stress/strain level.
- Stress-based assessment procedures tend to
  - Become less accurate when resolving strains
  - Produce overly conservative outcomes, leading to unnecessary mitigations
- Most stress-based procedures don't take certain factors that can have strong effects on TSC, such as
  - Weld profiles (high-low misalignment, cap reinforcement, etc.)
  - Weld strength mismatch and HAZ softening

Generations of Tensile Strain Models

TSC Models – Generation 0

- Largely derived from tests: e.g., curved-wide plate tests
- Example project application: early phase Imperial Oil’s Mackenzie Gas Pipeline

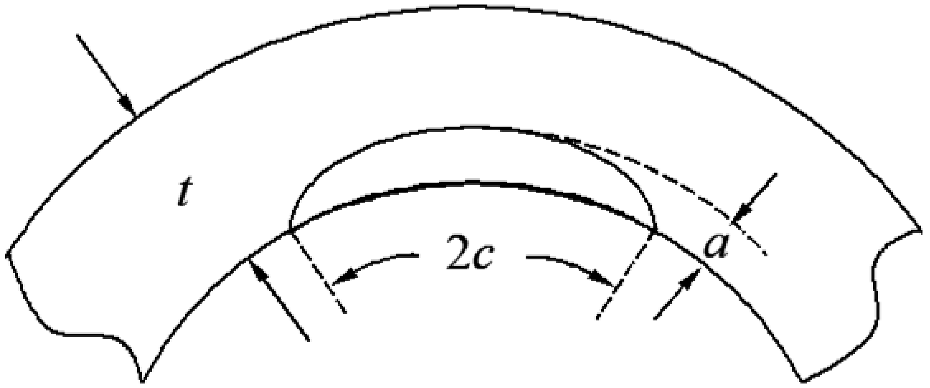


TSC Models – Generation 1

- CSA Z662 Annex C Equation
  - Wang, Y.-Y., Liu, M., Horsley, D., and Zhou, J. “A Quantitative Approach to Tensile Strain Capacity of Pipelines,” IPC2006-10474.
- Surface-breaking defects

$$\varepsilon_t^{crit} = \delta^{2.36-1.58\lambda-0.101\xi\eta}(1 + 16.1\lambda^{-4.45})(-0.157 + 0.239\xi^{-0.241}\eta^{-0.315})$$

- Input parameters:
  - Apparent toughness, δ
  - Yield to tensile ratio, $\lambda \equiv \mathrm{Y/T}$
  - Defect length ratio, $\xi \equiv 2c/t$
  - Defect height ratio, $\eta \equiv a/t$



- There is a TSC equation for buried defects

TSC Models – Generation 2

- Development started around 2006
- Long-distance large diameter high-grade pipelines were expected to be built in Northern environment.
- Key technologies
  - Strain-based design
  - Ultra high-strength linepipes, mostly X100
    - Pipe manufacturing
    - Crack arrest
    - Girth welding
- Efforts were jointly funded by the industry and US DOT PHMSA
- Representative Generation 2 models
  - PRCI-CRES models (ABD-1 models)
  - ExxonMobil models

Structure of PRCI-CRES Tensile Strain Models

Level of PRCI-CRES Models	Limit State	Format of the Model	Toughness Option	Intended Use	Range of Applicability				
					Intended Application	Target Strain Demand	Linepipe	Girth Welding Process	Wall Thickness (inch)
1	Initiation	Tables	Upper shelf Charpy energy	Initial screening	New pipeline construction (strain-based design)	≥ 0.5%	Modern	GMAW/FCAW/ SMAW	≥ 0.5
2	Initiation	Equations	Upper shelf Charpy energy, CTOD or J from SENB (high-constraint)	Nominal analysis for most applications					
3a	Initiation	Equations	Initiation toughness from low-constraint test specimens (e.g., shallow-notched SENB, SENT, or CWP) or equivalent from conversion	Advanced analysis with low-constraint toughness tests or equivalent from conversion					
3b	Ductile instability	Equations	CTOD or J resistance curves from low-constraint test specimens (e.g., shallow-notched SENB, SENT, or CWP) or equivalent from conversion						
4a	Initiation	Case-specific FEA and/or toughness testing	Initiation toughness from low-constraint test specimens (e.g., shallow-notched SENB, SENT, or CWP) or equivalent from conversion	Expert analysis using first principles of driving force and toughness	New pipeline construction (strain-based design) and existing pipelines (strain-based assessment)	≥ 0.15%	Modern and vintage	All	All
4b	Ductile instability	Case-specific FEA and/or toughness testing	CTOD or J resistance curves from low-constraint test specimens (e.g., shallow-notched SENB, SENT, or CWP) or equivalent from conversion						

- Gwise®-TSC is an application of Level 4a of the PRCI-CRES models.

Factors Affecting TSC and Incorporation in PRCI-CRES Models

- Pipe wall thickness
- Weld profiles
  - Weld cap reinforcement
  - High-low misalignment
  - Bevel geometry
- Pipe and weld tensile properties
  - Strain hardening
  - Weld strength mismatch
- HAZ softening
- Flaw type and dimensions
- Pressure factor (internal pressure)
  - Diameter
  - Wall thickness
  - Grade

→ Driving force relations

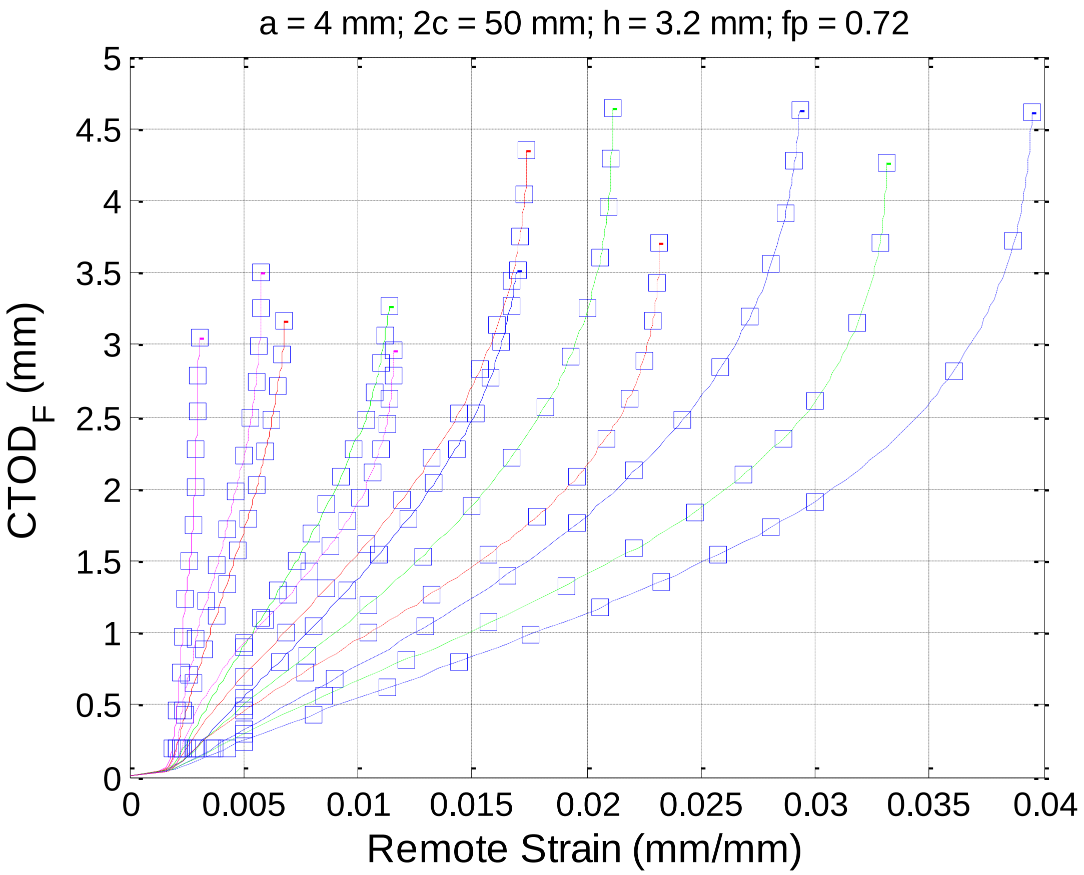
- Toughness → Tied to the selected limit state

  initiation → initiation toughness

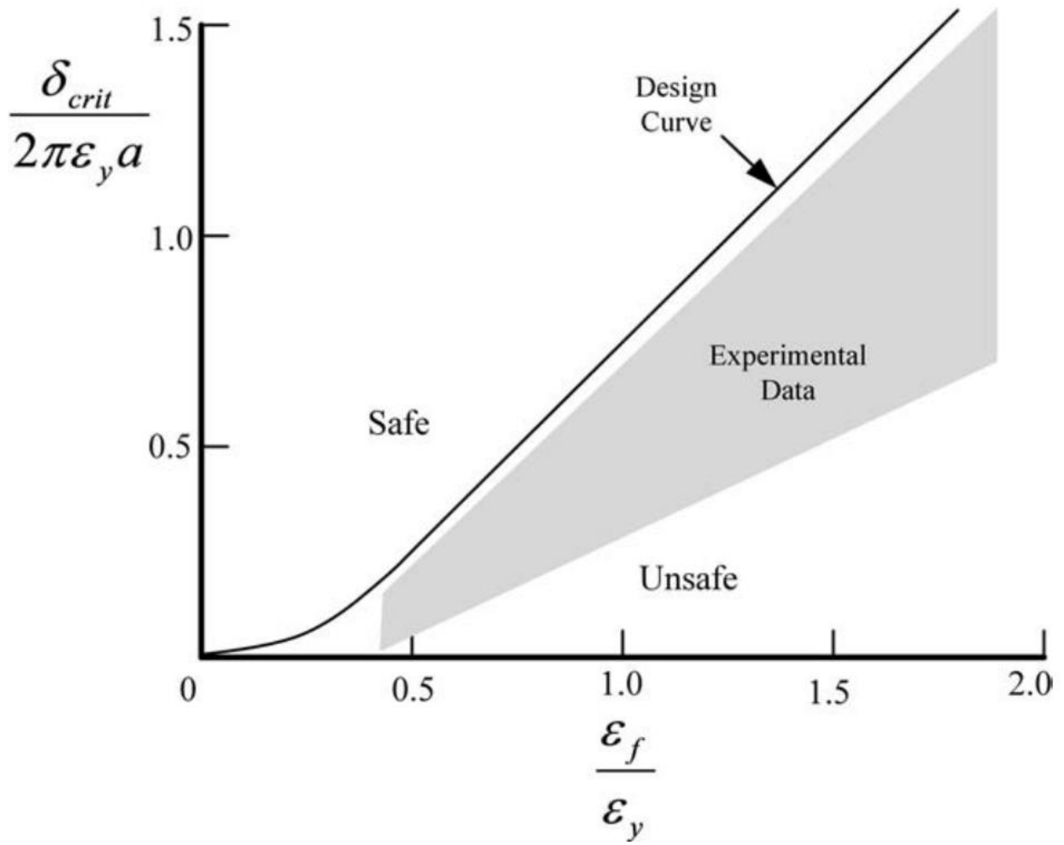
  ductile instability → R-curves

Implementation of Concept

Driving force curve of PRCI-CRES models

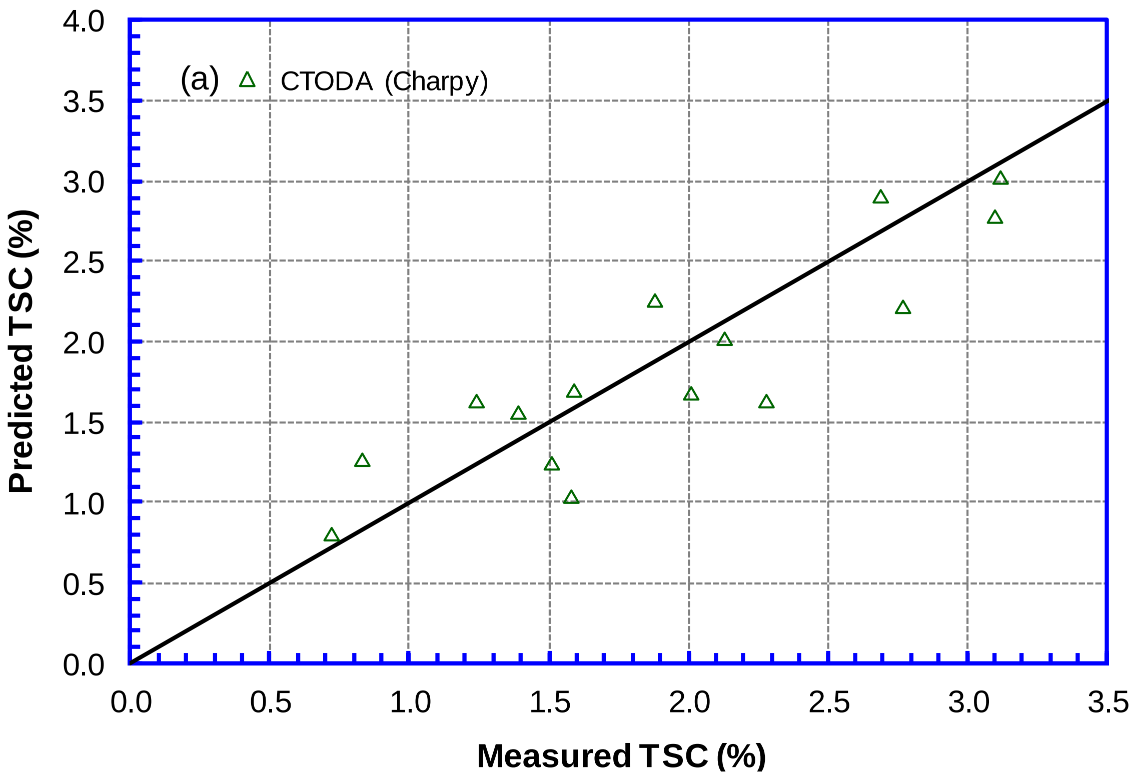


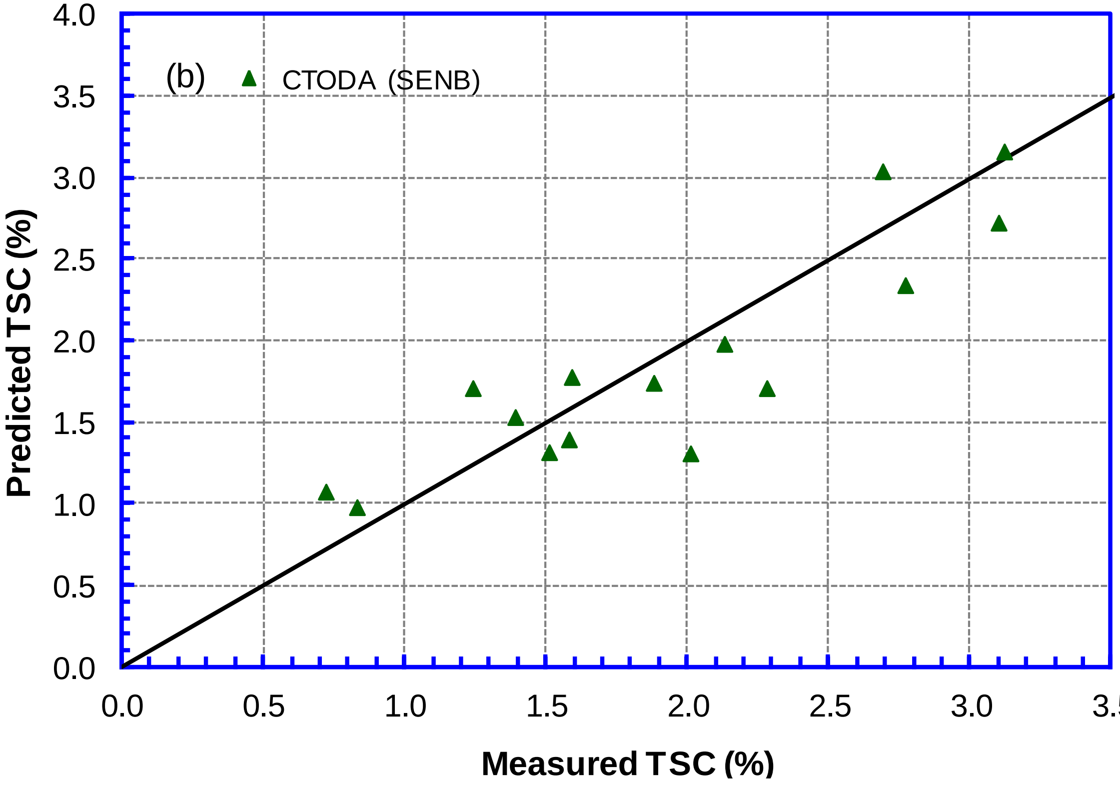
CTOD Design Curve of PD 6394 (1980)



PRCI-CRES Level 2 TSC Prediction vs. Test Results

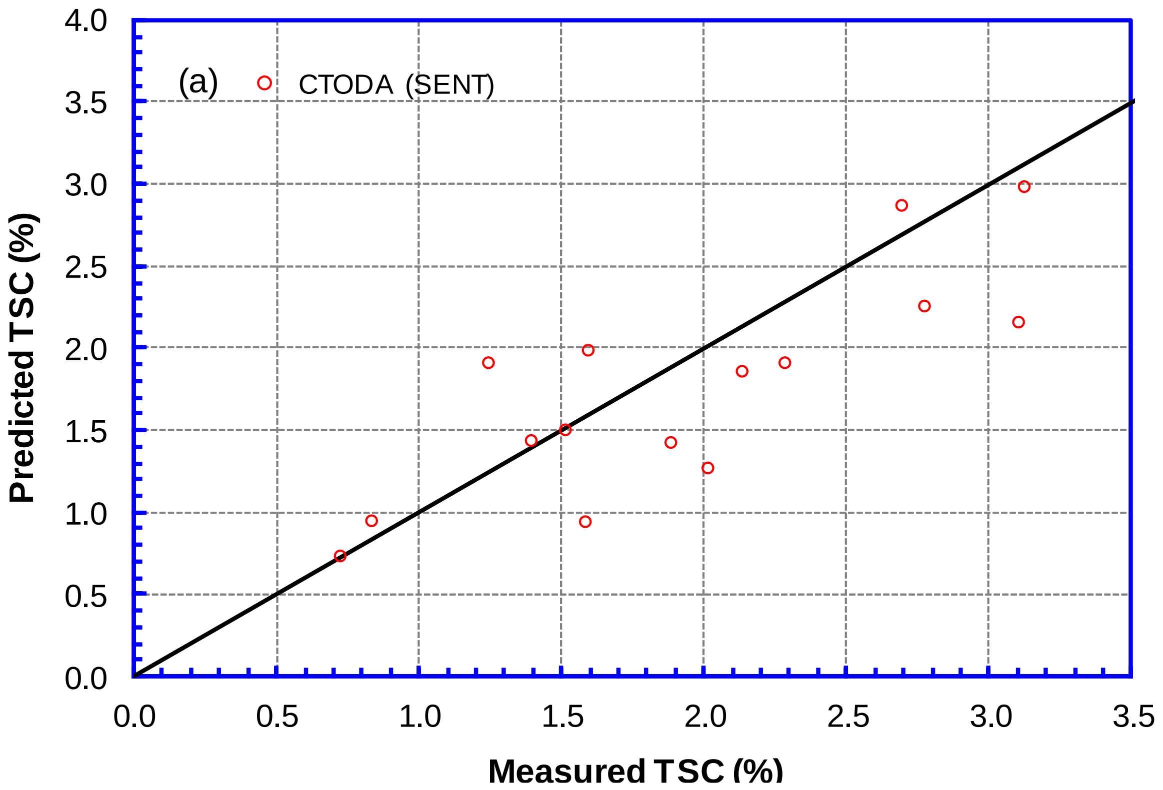
- Full-scale pressurized tensile tests
- Two toughness options provide similar outcome.

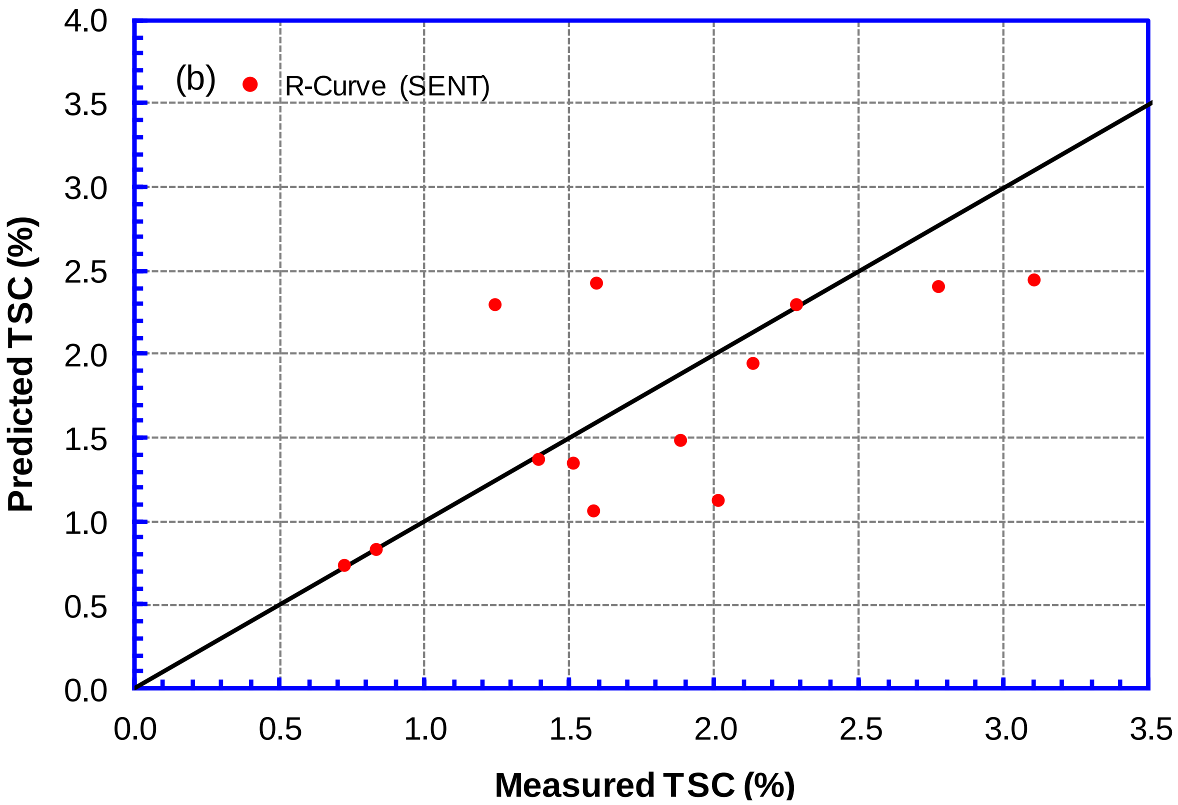




PRCI-CRES Level 3 TSC Prediction vs. Test Results

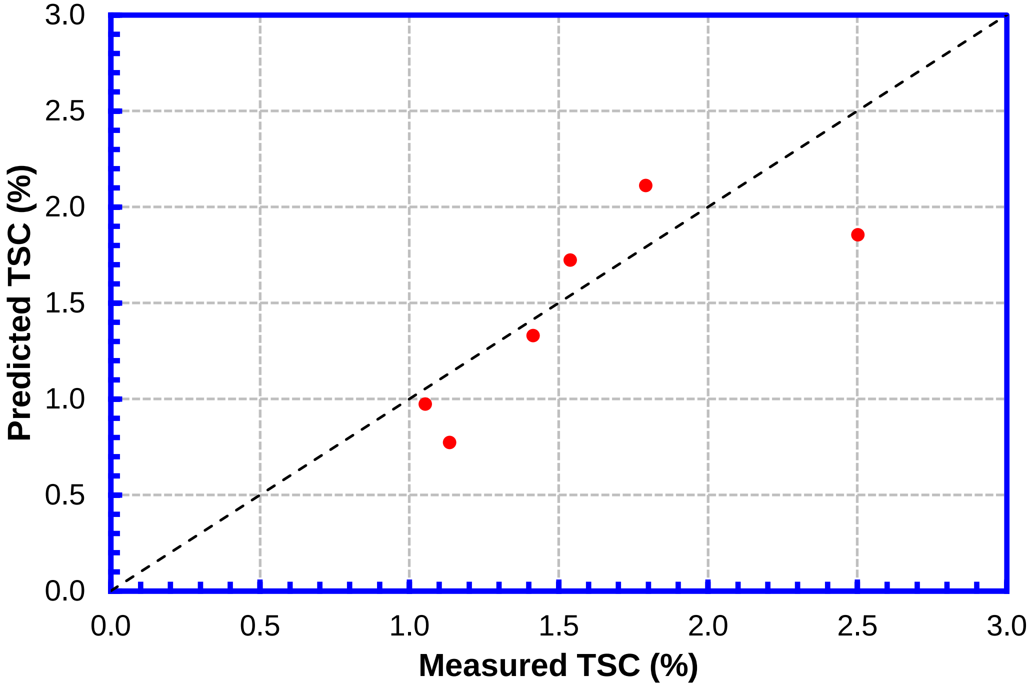
- Full-scale pressurized tensile tests
- Two limit states provide similar outcome.





PRCI-CRES Level 4a TSC Prediction vs. Test Results

- Full-scale pressurized bending tests
  - Test procedures and results as reported by [1]
  - Predictions by Gwise®-TSC



[1] Agbo, S., Lin, M., Ameli, I, Imanpour, A, Duan, D.M., Cheng, J.J.R., and Adeeb, S., "Experimental evaluation of the effect of the internal pressure and flaw size on the tensile strain capacity of welded X42 vintage pipelines," *International journal of Pressure Vessels and Piping* 173 (2019) 55-67.

Two data points were removed due to unmeasured pre-existing flaws.

Part 6

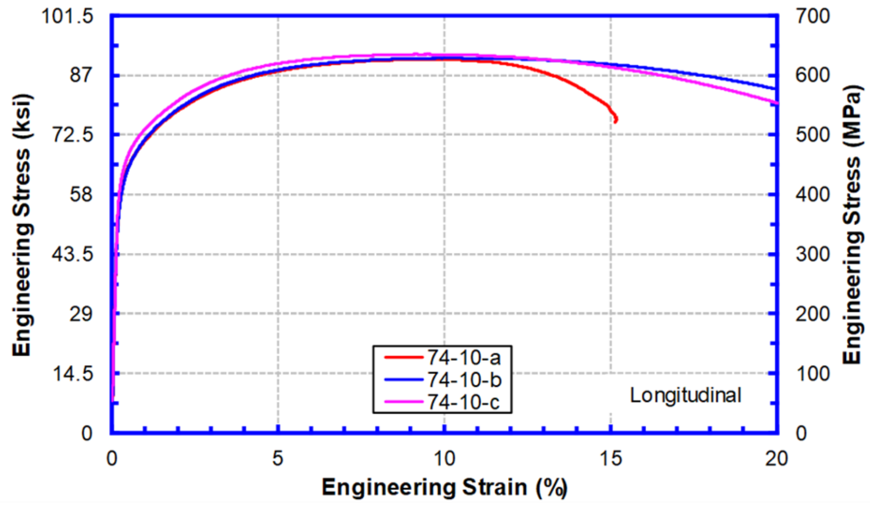
Development and Utilization of Gwise®-TSC

Development Framework and Process

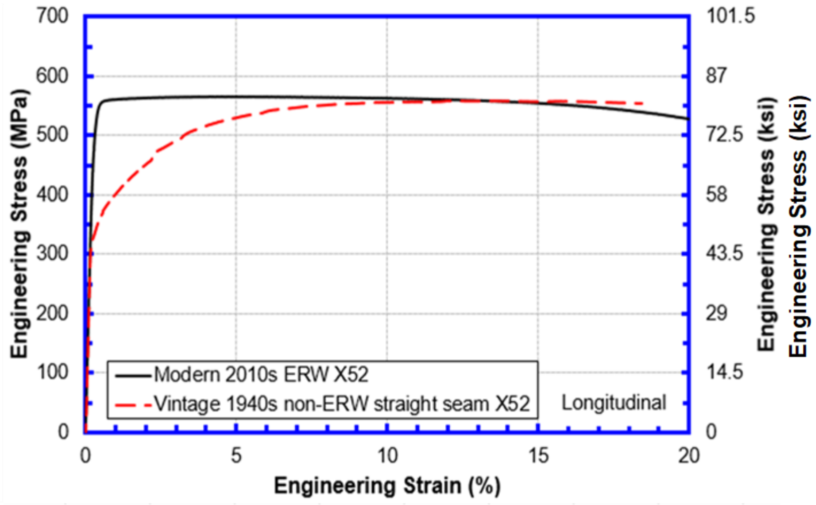
- Follows Level 4a procedures of the PRCI-CRES tensile strain models.
- Input characterization
  - Key TSC-influencing material and geometry parameters were characterized from historical data.
  - Linepipe and girth weld features of different vintages were incorporated.
- Crack-driving force generation
- Implementation
  - TSC model was developed using parametrized driving force relations and toughness.
  - Model was packaged into a standalone executable with an optional graphical user interface.

Example Consideration – Linepipe Properties

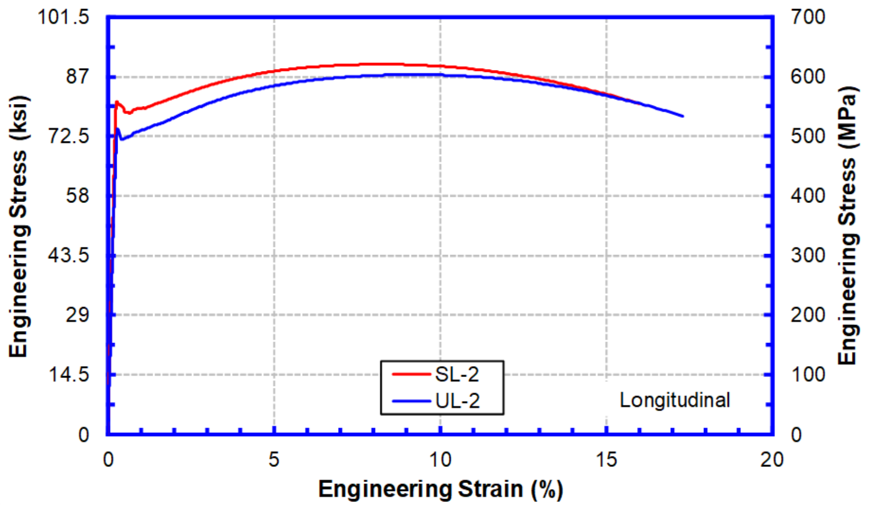
- Material stress-strain curves are influenced by linepipe vintage.



Longitudinal, X52, 1964



Longitudinal, X52, 1940s vs. 2010s

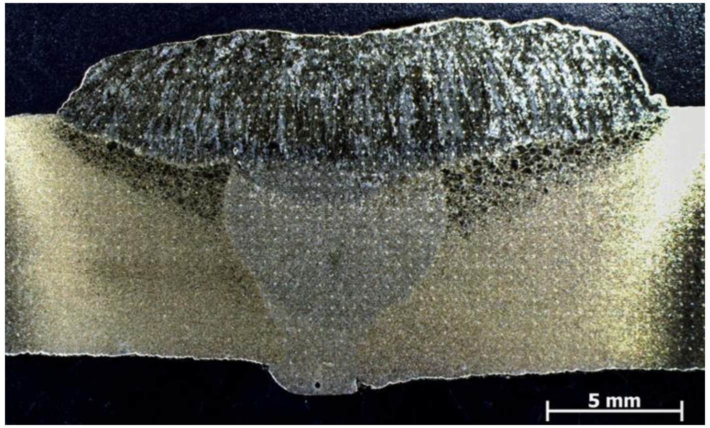


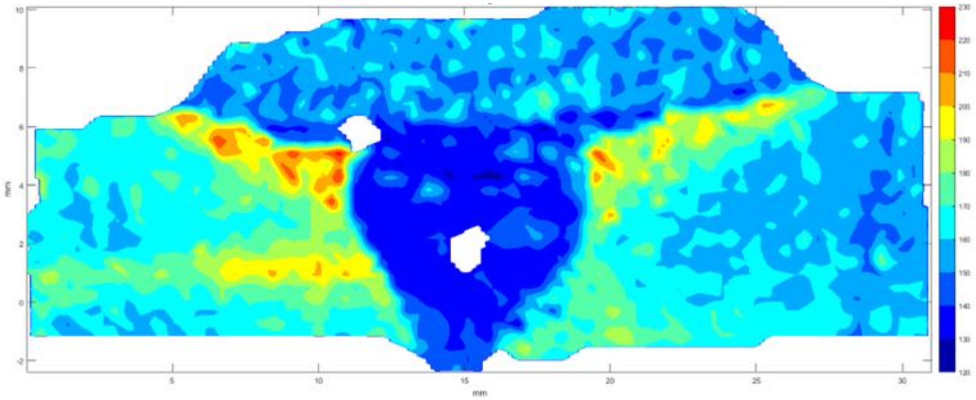
Longitudinal, X70, 2000s

Example Consideration – Girth Weld Profiles

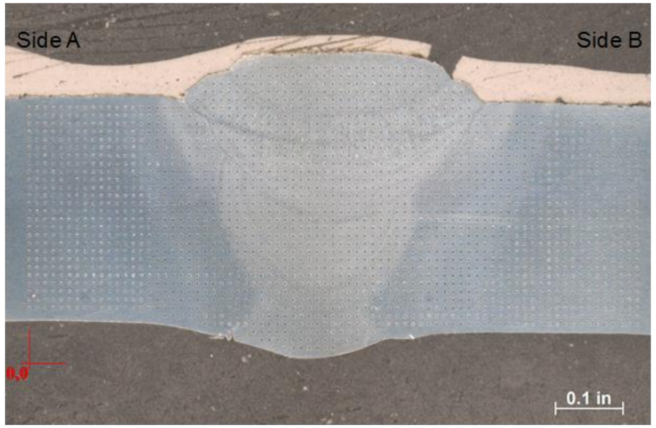
- Girth weld profiles differ by vintage and welding processes

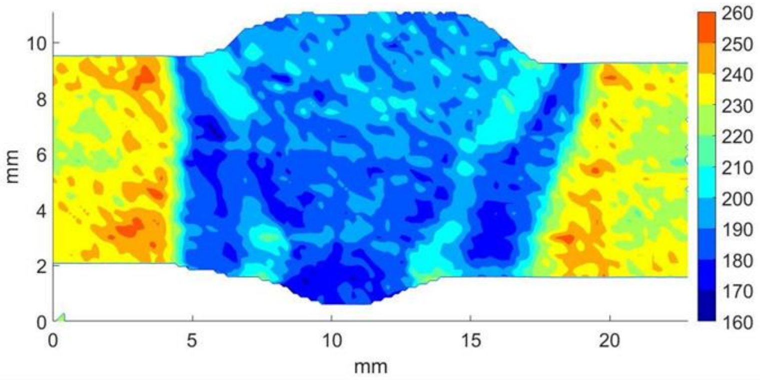
Pipe: X37, 24” OD, 0.375” WT
Weld: manual SMAW
Mid 1940s



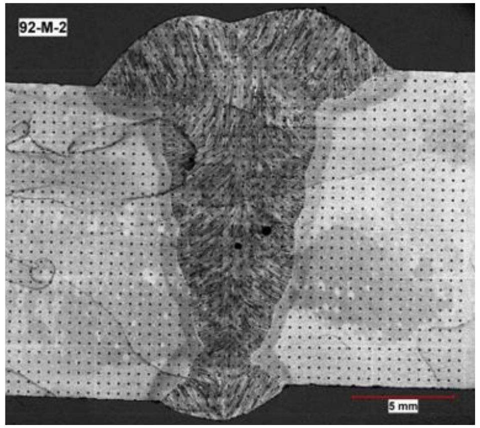


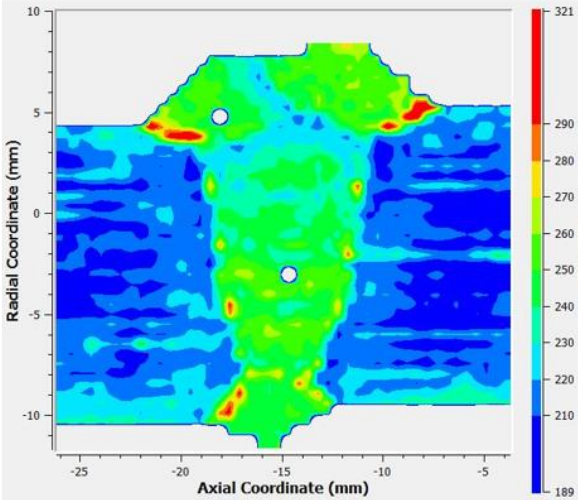
Pipe: X70, 24” OD, 0.344” WT
Weld: manual SMAW
Mid 2010s





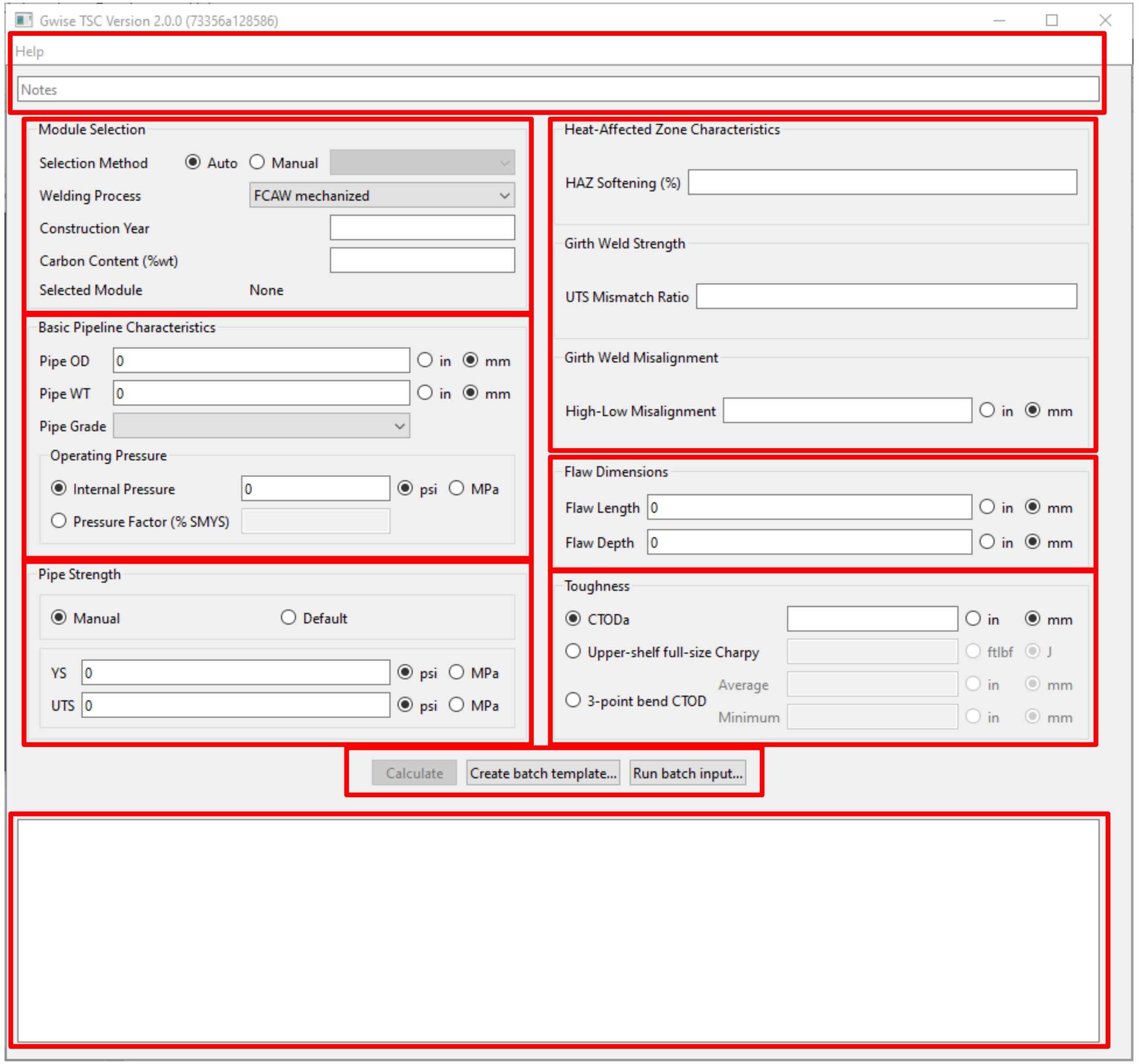
Pipe: X70, 30” OD, 0.625” WT
Weld: mechanized GMAW
Mid 2010s





Gwise®-TSC – Graphical User Interface

- Interactive input collection and output display
- Supports single-case and batch analysis.



Gwise®-TSC – Components Beyond GUI

- Command line utilities
  - Single-case and batch analysis through csv templates and Windows® command line
  - Designed for task automation

- Application programming interface
  - C++ function library for input check, TSC calculation, and error handling
  - Designed for in-depth customization, e.g., Monte Carlo simulation in support of risk-based assessment, integration into existing sentencing process

- Software and API documentation

Licensing, Tech Support, and Maintenance

- Gwise®-TSC license is renewed annually.
- An active license grants the following:
  - Technical support to ensure Gwise®-TSC operates as stated under supported hardware and software environments
  - Training sessions and support hours, up to stated limits in license agreement
  - Access to updates and new features to Gwise®-TSC

Long Term Support and Outlook

- Support users in accessing correct inputs
  - Updates to the software
  - Interactions with users
- Facilitate integration with existing internal systems
  - Integrity management
  - Geohazards management
  - ILI programs
- Maintenance and extension
  - Usability updates and bug fixes
  - Scope extensions to address existing limitations
  - Added functionalities

Applying Gwise®-TSC

- Gwise®-TSC covers an extensive range of pipe and girth weld characteristics and corresponding TSC performance.
  - Applying appropriate input parameters is key to minimize misuse or misinterpretation of the results.
- Features are built in to reduce but not eliminate misuses.
  - Default values are provided where sufficient historical data is available.
  - Sensible range checks are performed on user inputs.
- Sound understanding of the principles and key assumptions is the most reliable assurance of correct use.
  - Influencing factors and their dependency on vintage and associated practices
  - Applicable ranges and limitations
- Users are strongly encouraged to leverage the training and support accommodations.

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Q&A

- Thank you

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