Benchmark on Cast Austenitic Stainless Steel Probabilistic Fracture Mechanics Modeling

Overview and Summary of Current Status

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Background

- Probabilistic fracture mechanics (PFM) codes have been used to perform analyses of cast austenitic stainless steel (CASS) components, which face technical challenges in achieving reliable volumetric nondestructive examination (NDE)
  - MRP-479 (EPRI Report 3002023893)

- A previous benchmark organized by OECD/NEA evaluated differences in modeling of an Alloy 182 dissimilar metal weld in straight piping by subject PFM codes
  - NEA report to be published in 2026 (tentative)
  - Interim results provided in PVP2022-84724 and PVP2023-105733

- This EPRI CASS PFM benchmark builds upon the learnings of the OECD/NEA benchmarking effort to investigate differences specific to the modeling of CASS material
  - Focus on crack propagation by fatigue instead of stress corrosion cracking (SCC)
  - Focus on stability of cracks in low toughness material (thermally aged CASS)

Objectives

- Understand the effects of modeling differences among CASS PFM codes under a set of controlled problems
- Understand the differences in CASS PFM software design
- Understand the differences in underlying deterministic models used in CASS PFM codes
- Evaluate the importance of key input parameters for CASS PFM codes
- Understand how differences in analyst input choices affect results

Project Overview

Phase 1: Capabilities Survey

- Information collection on participant codes via a survey
- Key information areas:
  - General information
  - Models and Inputs
  - Outputs
- Leverage results to develop widely applicable benchmark problems

Phase 2: Deterministic Benchmark

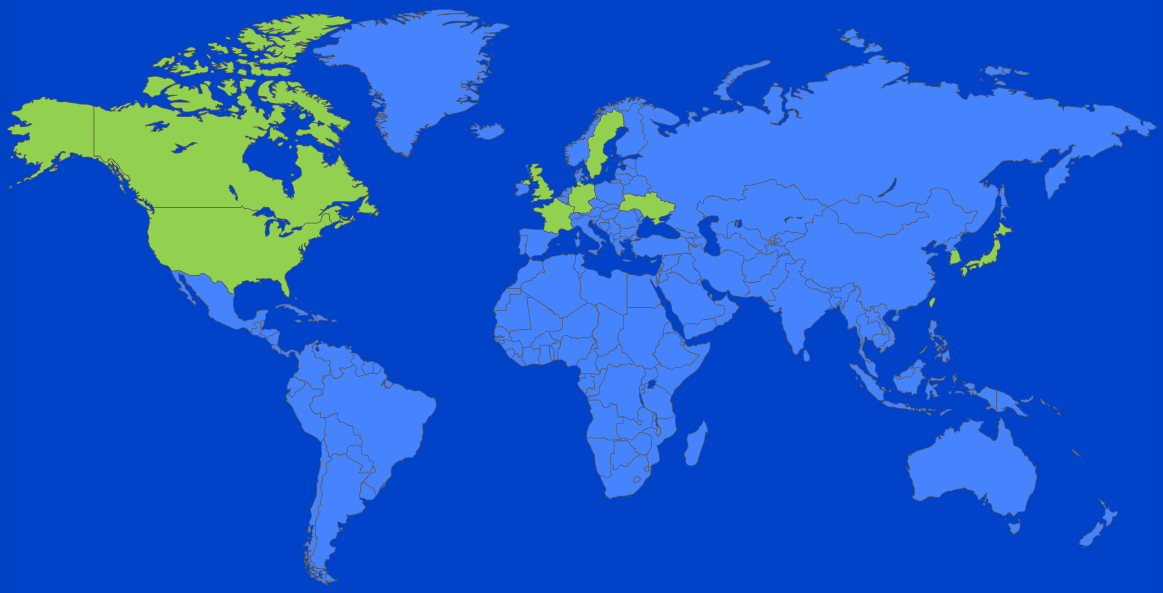
- Develop deterministic problems that each participant evaluates using their code
- Consolidate results for all evaluations and compare key results
- Identify differences in deterministic models between the codes

Phase 3: Probabilistic Benchmark

- Develop probabilistic problems that each participant evaluates using their code
- Consolidate results for all evaluations and compare key results
- Identify differences in probabilistic modelling approaches between the codes

Participants and Codes

Country	Organization	Codes
USA	EPRI / DEI	xLPR
		PIPER-CASS
USA	SIA	CASSPAR / pc-CRACK
Japan	JAEA	PASCAL-SP2
Japan	CRIEPI	PEDESTRIAN
Korea	KAERI	PROFAS-PIPE
Korea	KHNP/SNUST	xLPR
Germany	GRS	PROST
Canada	Atkins Realis	PRAISE-CANDU
UK	Amentum	PROBLBB
Taiwan	NARI	PRO-LOCA
Ukraine	IPP-Centre	SIF-Master
France	EDF	OpenTURNS / OAR
Sweden	KIWA	ISAAC / NURBIT



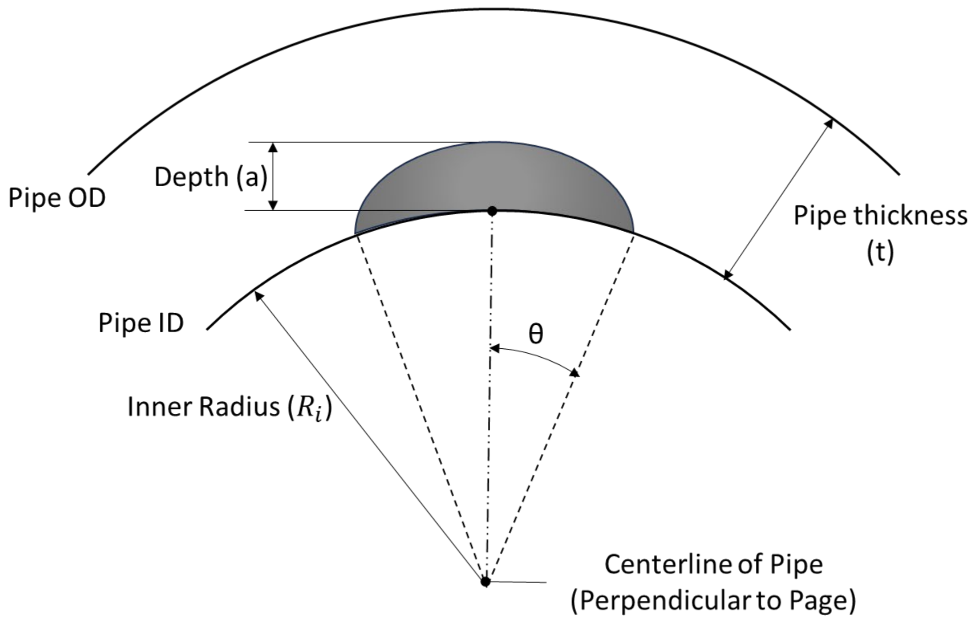
- 10 Countries
- 13 Organizations
- 13 Codes

Current Status of Benchmark

- Initial deterministic benchmark results have been analyzed
  - Summary of results presented to participants in October 2025
- Notable differences among the initial deterministic results submissions necessitated additional investigation into differences among deterministic models and analyst approaches
- Additional (“Add-on”) fatigue crack growth and stability evaluations were developed to further investigate source of observed differences
  - 11 of the 13 participants have submitted results to the add-on deterministic problems
- Currently in the process of analyzing the add-on problem submissions and developing conclusions
  - Developing the probabilistic problem statement concurrently

Fatigue Crack Growth (FCG) Problem Overview

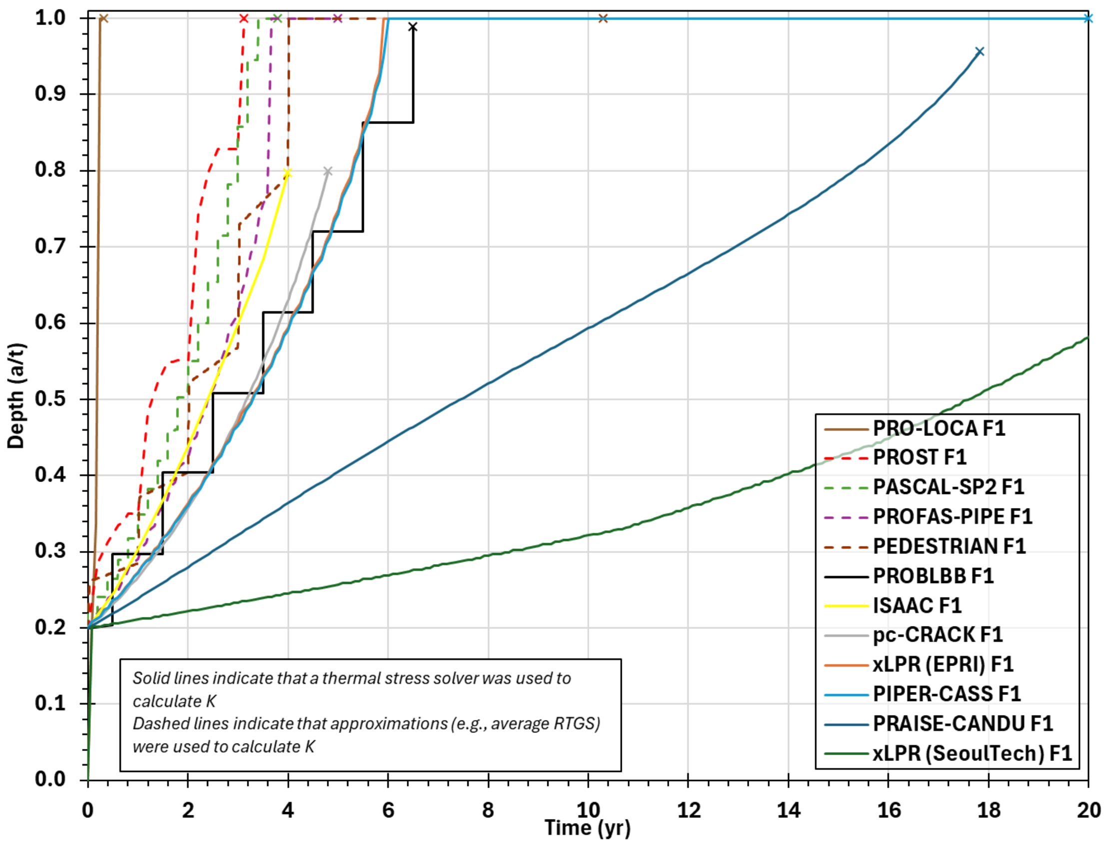
- Model a single circumferential crack in CASS piping
- Applies a modified (accelerated) FCG equation, derived from Code Case N-809
- For many inputs, one set of values applied for all deterministic problems
  - Representative geometry, loading, weld residual stress, and transients
- Material properties and initial flaw sizes varied:
  - Material property sensitivities include high toughness/low strength (Case F1) and low toughness/high strength CASS materials (Case F2)
  - Case F4 allows participants to apply their own material aging model
  - Flaw size sensitivity Case F3 evaluates a narrower initial flaw aspect ratio
- Optional axial fatigue crack growth: Case F5



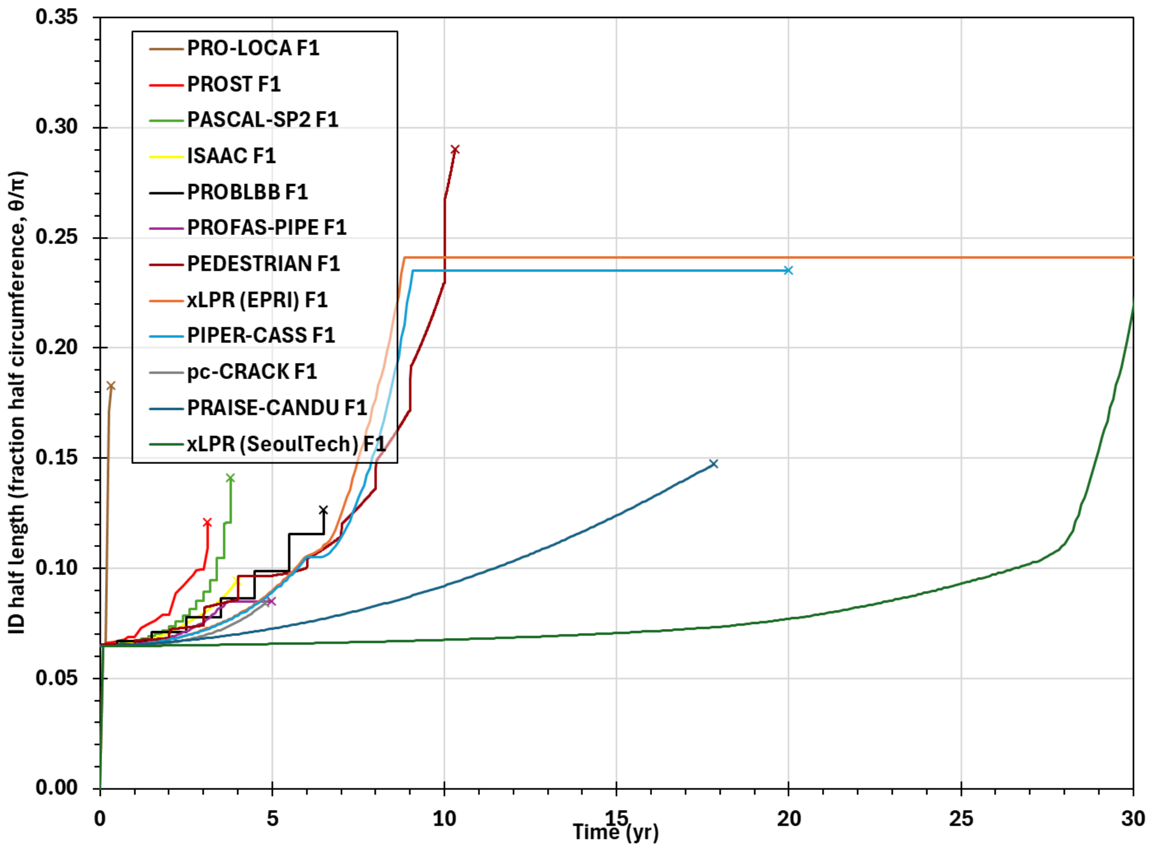
Case ID	Description
F1	Baseline fatigue crack growth case (CF8)
F2	CF8M material properties
F3	Reduced initial crack aspect ratio
F4	Custom material aging model
F5 **(optional)**	Axial cracking

Case F1: High Toughness Circ. Crack Growth Results

Depth Time History



Length Time History



Notes:

1. PROBLBB results not reported with time data. Plotted time history assumes growth occurs instantaneously at mid-year.
2. xLPR results provided assuming a transient uncertainty multiplier of 1. SeoulTech results applied a factor of 0.5, resulting in slower growth.

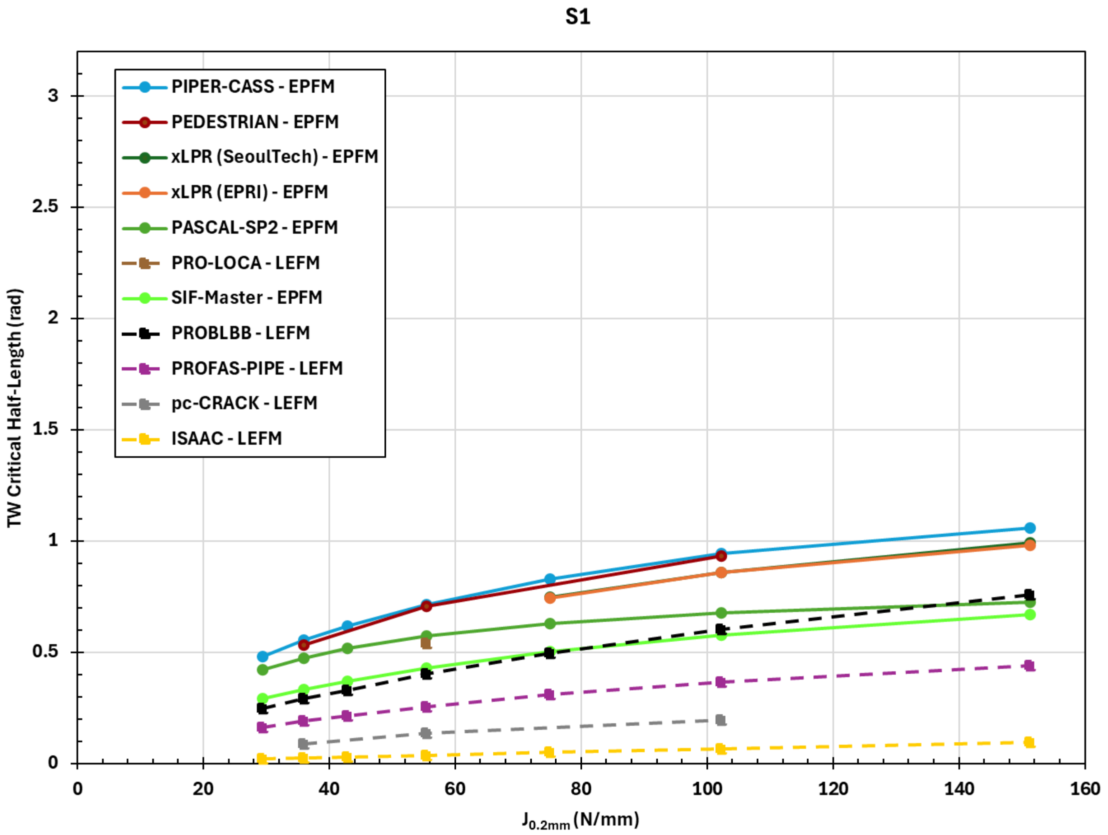
Stability Evaluation Problem Overview

- Determine the critical size for EPFM instability of a circumferential flaw, both for a through-wall flaw and for a surface flaw with depth of 75% through-wall
  - Evaluate for varying material toughness inputs (J-R curves) given a constant yield and ultimate strength (Case S1)
  - Evaluate for varying yield and ultimate strengths given a constant material toughness (J-R curve) (Case S2)
- Optional evaluations of EPFM critical size of axial flaws applying the same material property sets (Cases S3 and S4)

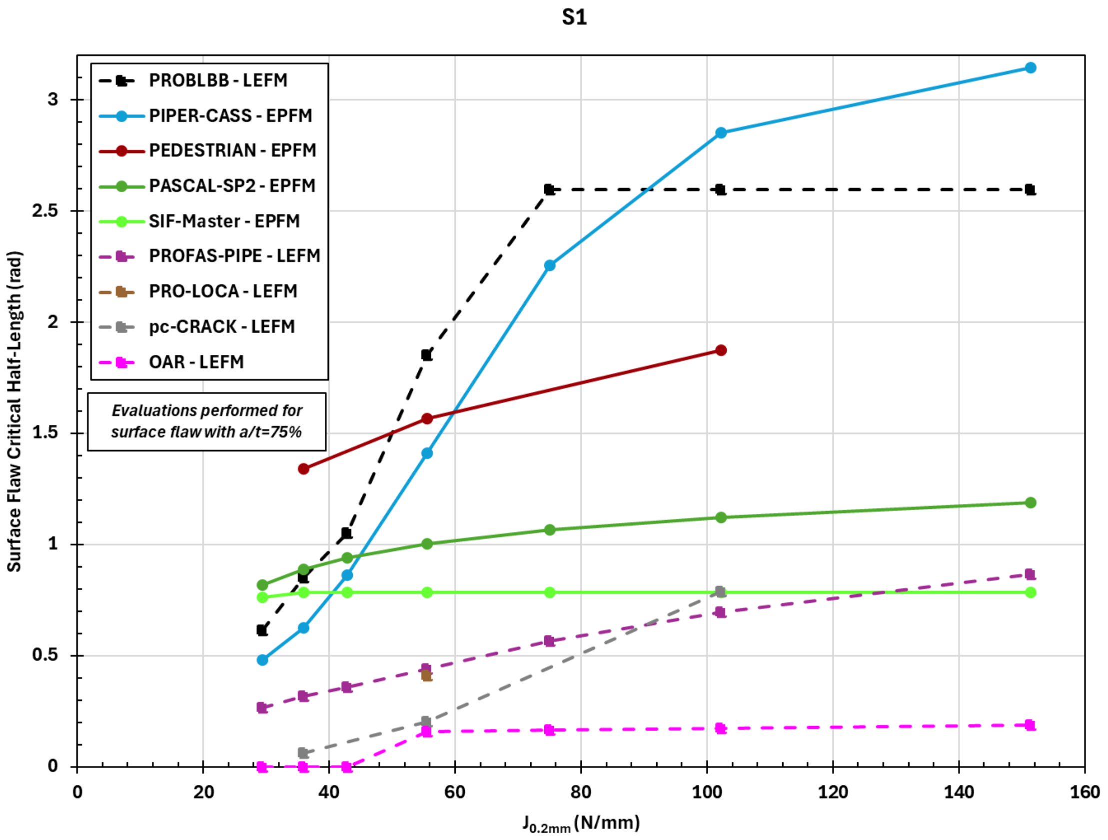
Case ID	Description
S1	Evaluate circ crack stability as function of toughness
S2	Evaluate circ crack stability as function of **strength**
S3 **(optional)**	Evaluate **axial** crack stability as function of toughness
S4 **(optional)**	Evaluate **axial** crack stability as function of **strength**

Case S1: Circ. Stability vs. Toughness Results

Idealized Through-Wall Crack



Part-Through-Wall Crack



Notes:

1. Dashed lines indicate that an LEFM-based approach was utilized to calculate critical sizes. Solid lines indicate that an EPFM approach was utilized to calculate critical sizes.
2. xLPR results included only for cases in which a converged solution is found

Initial Deterministic Benchmark Findings

- Notable differences among the initial deterministic results submissions
- Common sources of differences in fatigue crack growth results include:
  - Calculation and/or application of fatigue crack growth rate coefficients (e.g., not all codes model load ratio, R, dependence)
  - Method of determining time of occurrence of transients given input transient event frequencies
  - Calculation of transient stress intensity factors, including identifying minimum and maximum stresses
- Common sources of differences in stability evaluation results include:
  - Type of EPFM model (J-integral, FAD, etc.)
  - Selection of Ramberg-Osgood parameters, for EPFM models based on J-integral methods
  - Application of input loads (e.g., inclusion/exclusion of residual stress for stability)
- Supplemental "add-on" deterministic problems proposed to further investigate the differences in approach and to assess whether better agreement among the results could be obtained by simplifying the problem statement

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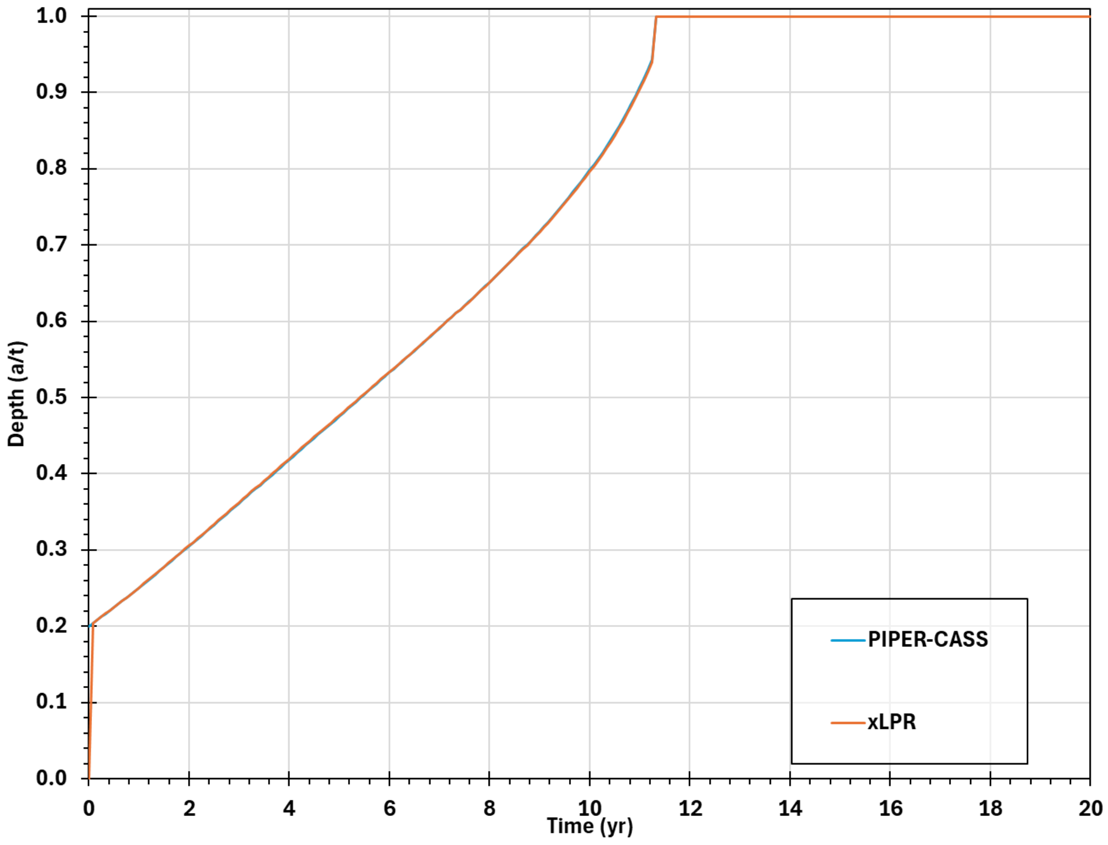
Add-on Deterministic Problem Overview

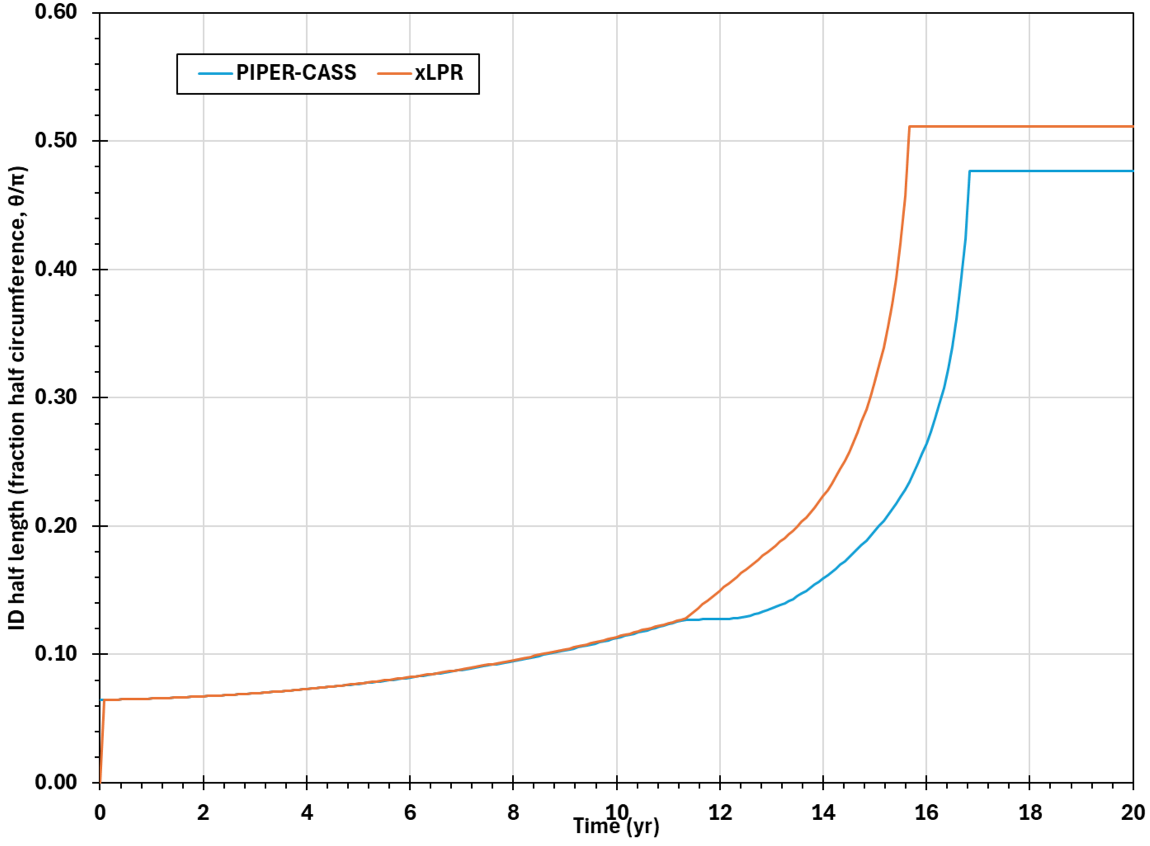
- Fatigue crack growth evaluation using a simplified set of inputs and models relative to the baseline cases (Case F6)
  - Consideration of a single transient, with frequency modified such that one cycle per timestep is modeled
  - Normal operating stresses (except pressure stress) and weld residual stress eliminated
  - Fatigue crack growth coefficient (C in ${}^{da}/_{dN} = C(\Delta K)^n$) set to a constant
    - Eliminated dependencies on temperature, load ratio, and loading rise time in modified N-809 equation in original cases
- Evaluation of J and dJ/dθ as a function of flaw length for both TW and 75% depth flaws under a specified pressure + bending load (Case S5)

Case F6: Sample Add-on FCG Results

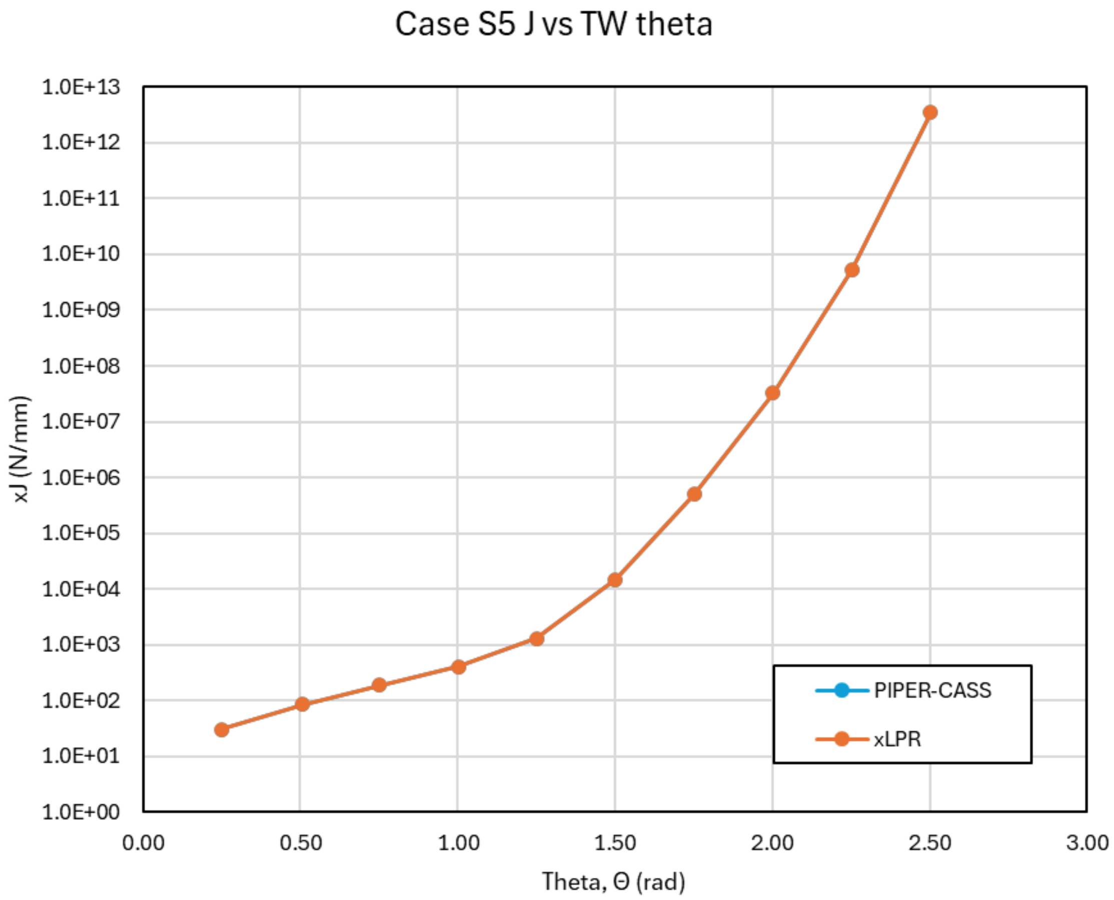
Depth Time History

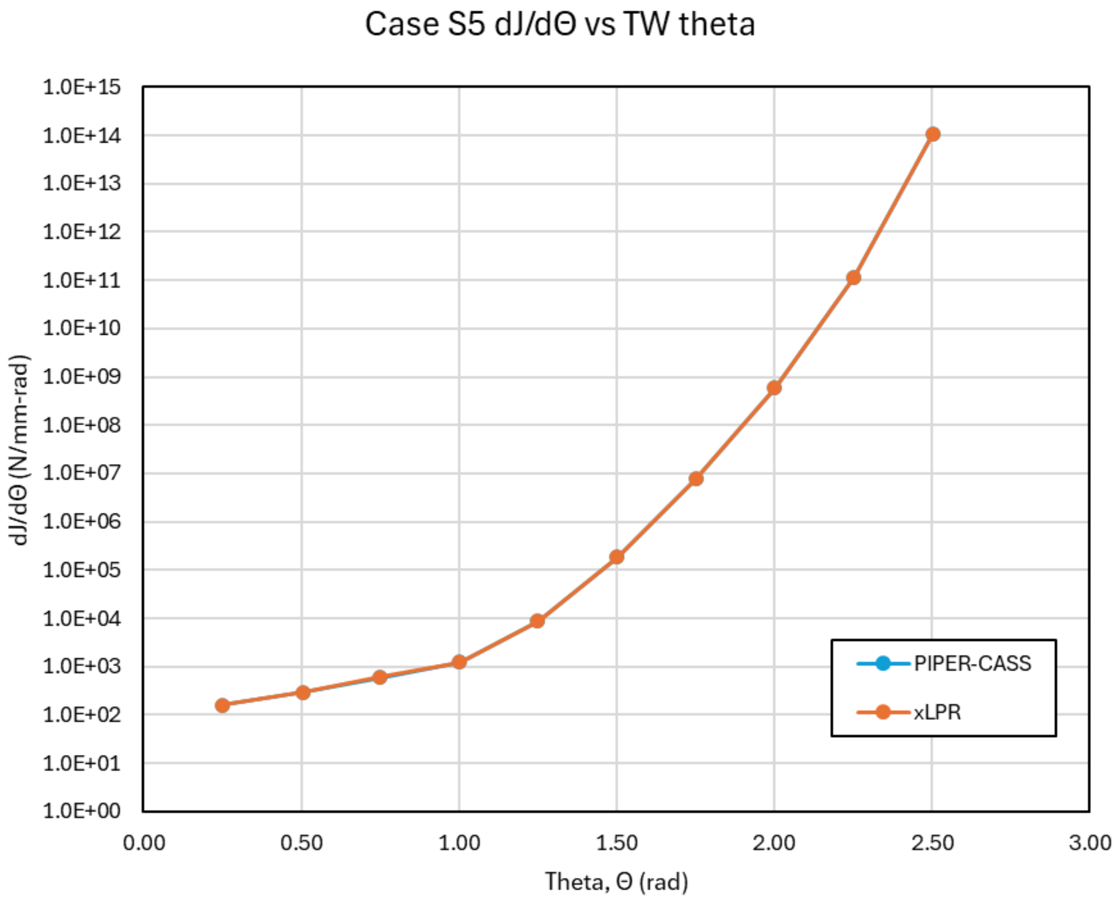


Length Time History



Case S5: Sample Add-on Stability Evaluation Results





Results shown are for through-wall flaws

Conclusions

- Analysis of add-on submissions and investigation of differences in results is ongoing
- Findings from both the initial and add-on deterministic problems will be leveraged to develop the probabilistic problem statement

Overall Project Schedule

Phase	Schedule Item	Date
1	Release survey to participants	November 14th, 2024
	Survey responses due	January 10th, 2025
	Hold virtual meetings to discuss survey responses	March 6th/7th, 2025
2	Release deterministic benchmark problem to participants	April-May 2025
	Execute deterministic benchmark problems	May-September 2025
	Hold virtual meetings to discuss deterministic benchmark results	September 2025
	Share summary of deterministic benchmark results	October 2025
	Release add-on deterministic benchmark problem to participants	November 2025
	Execute add-on deterministic benchmark problems	November 2025-February 2026
	Share summary of additional deterministic benchmark results	March 2026
3	Release probabilistic benchmark problem to participants	March 2026 - April 2026
	Execute probabilistic benchmark problems	April 2026 - July 2026
	Hold virtual meetings to discuss probabilistic benchmark results	July 2026
	Share summary of probabilistic benchmark results	August 2026
	Provide draft report for participant comments	September 2026

Final report will be publicly available on EPRI.com

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