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CASS PFM Benchmark

Add-On Phase 2 Result Summary and Phase 3 Introduction

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Current Status of CASS PFM Benchmark

- Initial results for deterministic problems demonstrated substantial differences among the results
- Additional deterministic problems to further investigate observed differences in results were released in November 2025
- Iterated with participants to fully understand results during Q1 2026
- Finalized results and findings from the deterministic phase have been prepared
- The probabilistic problem statement is being drafted with the goal of releasing the probabilistic problem statement in May 2026

Case ID	PIPER-CASS	xLPR (EPRI)	xLPR (SeoulTech)	PASCAL-SP2	PROFAS-PIPE	PEDESTRIAN	PRO-LOCA	pc-CRACK	PROST	PRAISE-CANDU	PROBLBB	SIF-Master	OAR	ISAAC
F6	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	No	Yes
S5	Yes	Yes	Yes*	No	Yes	Yes	Yes**	Yes	No	Yes	Yes	Subset	No	Yes

* FEA results provided instead of xLPR results

** Still working to understand Case S5 results, which are not currently presented

Add-On Deterministic Problem Objectives

Fatigue Crack Growth

- Determine whether better agreement among the fatigue crack growth predictions could be obtained when evaluating a simpler case
- Identify differences in fatigue crack growth evaluation approaches leading to differences in predictions to inform case selection for probabilistic phase

Stability Evaluation

- Further investigate differences in stability models and critical crack size results by comparing J-estimation results directly
- Characterize the impact of differences in J-estimation procedures on the critical crack size predictions

Add-On Fatigue Crack Growth Evaluation

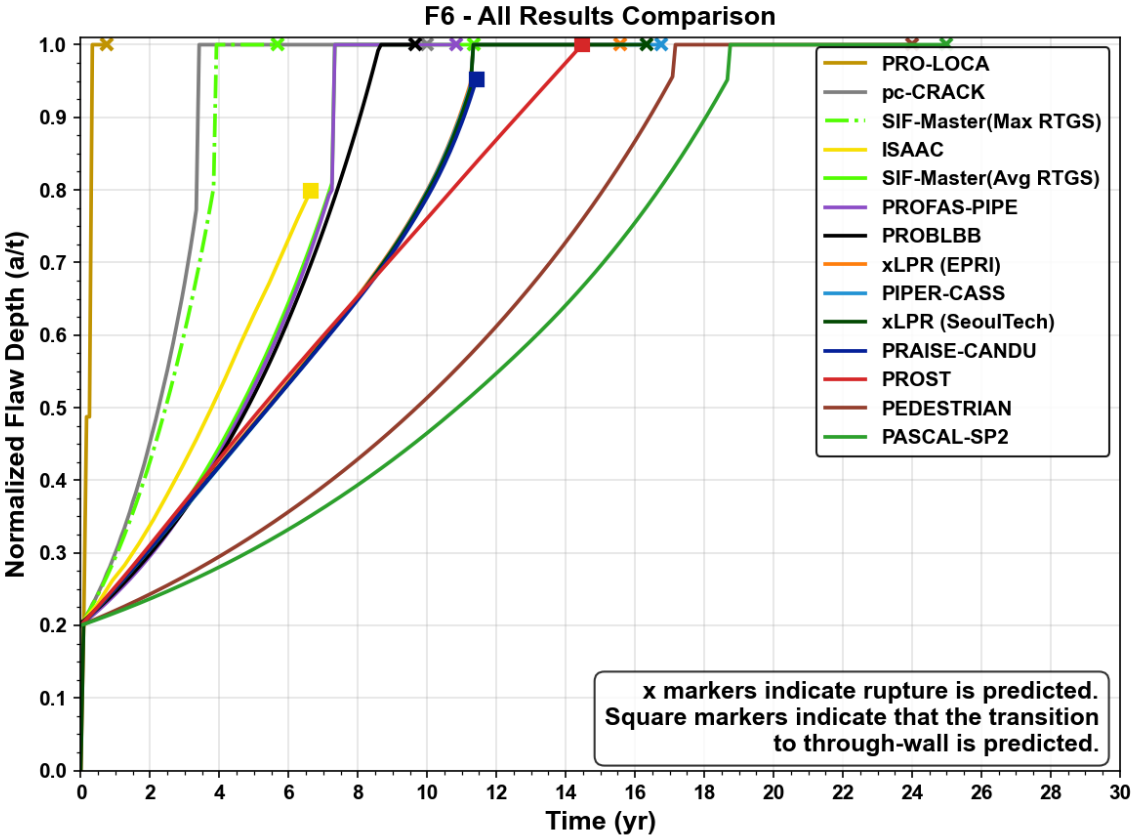
Add-On Deterministic FCG Problem Overview

- Fatigue crack growth evaluation using a simplified set of inputs and models relative to the baseline cases (Case F6)

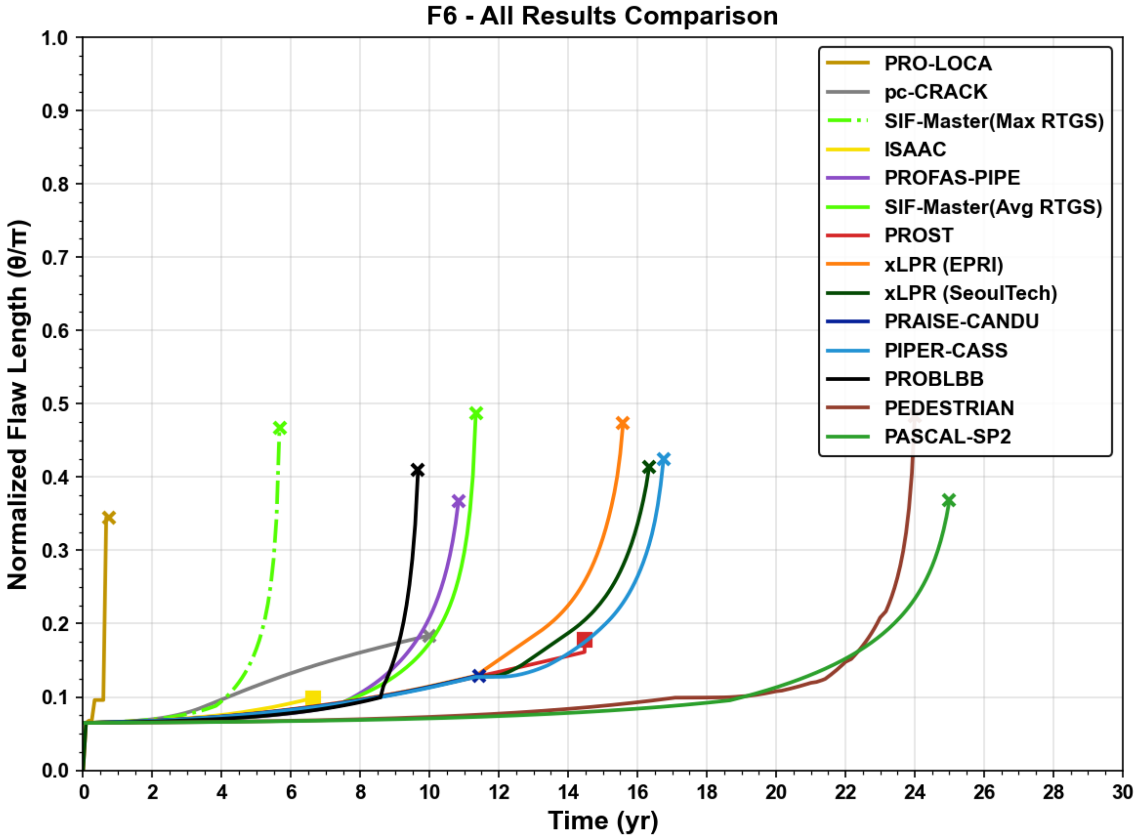
Component	Initial Evaluations (Cases F1-F5)	Add-On Evaluation (Case F6)
Transient modeling	7 unique transients with varying frequencies	Single transient with frequency equivalent to 1 occurrence in each 1-month timestep
Fatigue crack growth coefficient	Modified Code Case N-809 approach, with factors dependent on fluid temperature during the transient, load ratio (R), and threshold ΔK	Constant Coefficient
Pipe bending loads	Net thermal expansion bending stress (modeled to vary as function of transient time) and deadweight bending stress (modeled as time-invariant, global bending stress)	Not Included (set to 0)
Axial piping loads (excluding pressure)	Membrane stress due to deadweight	Not Included (set to 0)
Welding residual stress	Included (constant)	Not Included (set to 0)

Case F6 Crack Size Time History

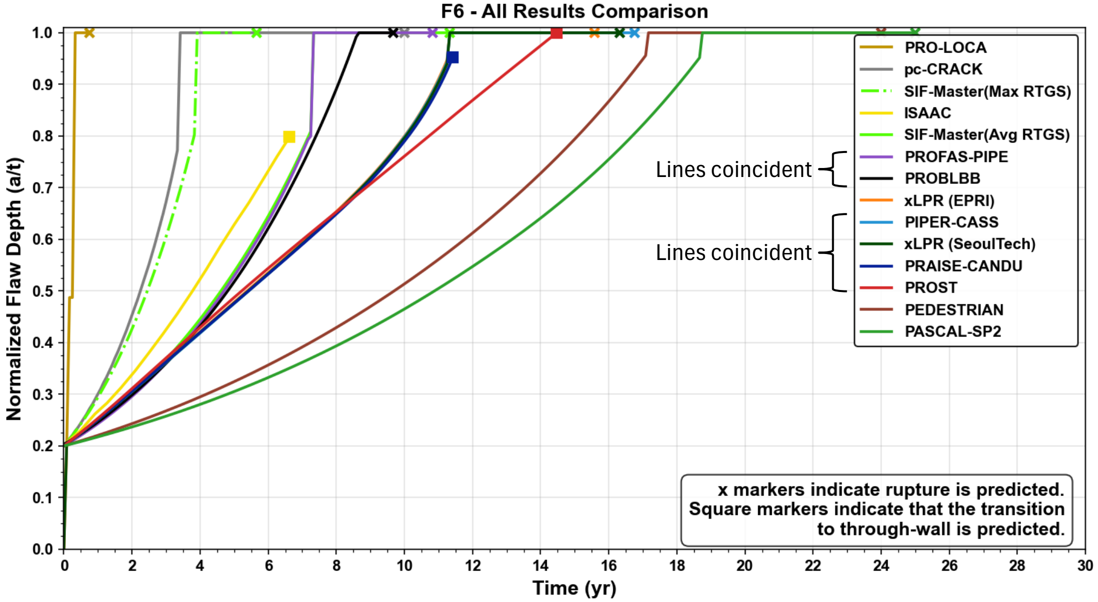
Depth



Length



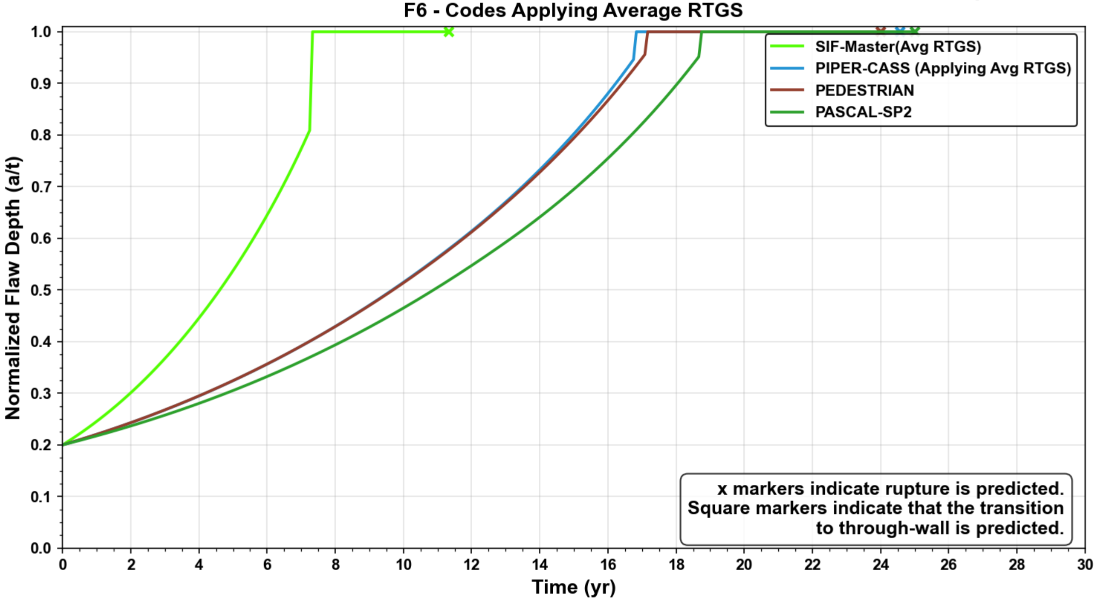
Depth Comparison by Stress Application Methodology


F6 - All Results Comparison

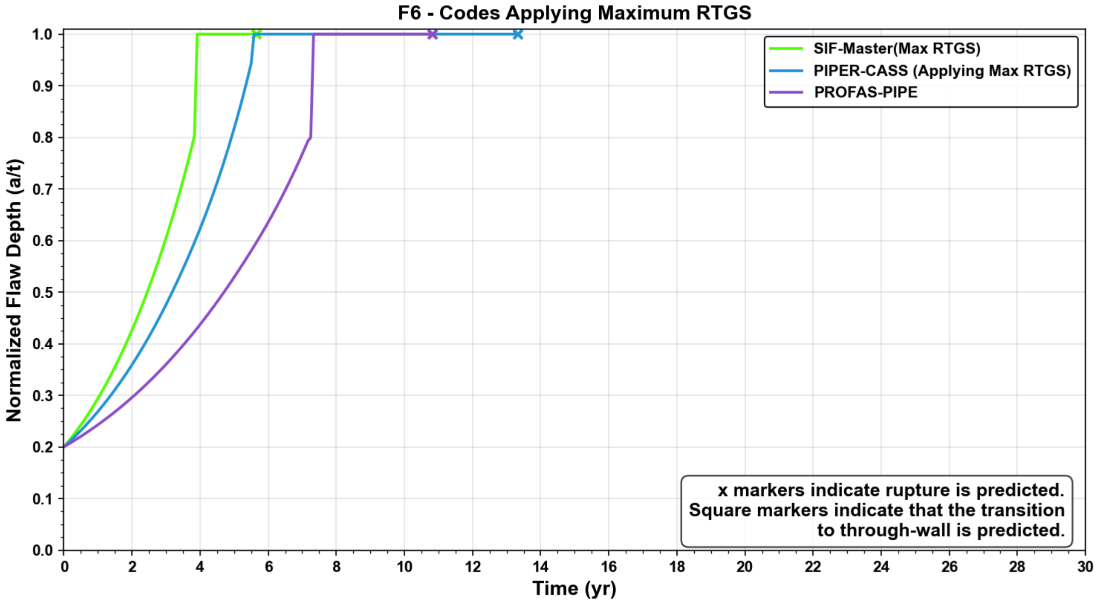
Lines coincident

Lines coincident

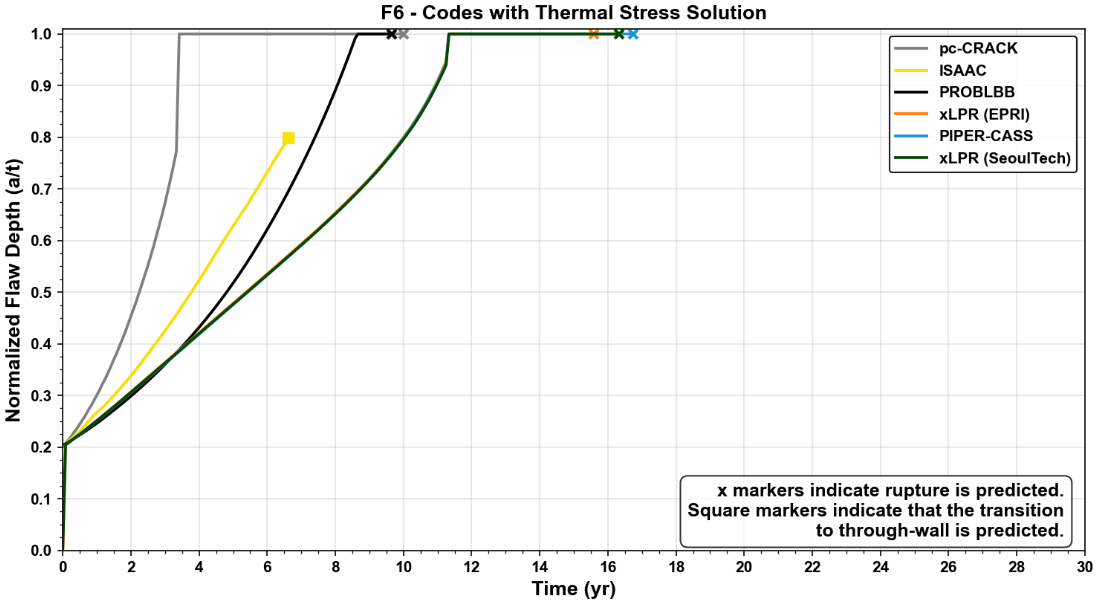
x markers indicate rupture is predicted. Square markers indicate that the transition to through-wall is predicted.


F6 - Codes Applying Average RTGS

x markers indicate rupture is predicted. Square markers indicate that the transition to through-wall is predicted.


F6 - Codes Applying Maximum RTGS

x markers indicate rupture is predicted. Square markers indicate that the transition to through-wall is predicted.


F6 - Codes with Thermal Stress Solution

x markers indicate rupture is predicted. Square markers indicate that the transition to through-wall is predicted.

Findings and Discussion

- Differences between codes with dedicated thermal stress solvers attributed to a variety of factors
  - ISAAC results consider the maximum and minimum crack face pressure which increases the maximum delta K
  - pc-CRACK also fixed $K_{min} = 0$, resulting in faster growth relative to ISAAC, xLPR, PIPER-CASS
- Much of the differences versus codes that could not directly model RTGS stress profiles are attributable to the treatment of RTGS
  - PIPER-CASS modified to implement alternative treatments of RTGS for benchmarking
  - Good agreement obtained with codes utilizing the average RTGS
  - Differences still present for codes utilizing maximum RTGS value
    - SIF-Master predicts substantially faster growth due to fixing $K_{min} = 0$
- PRAISE-CANDU results in near perfect agreement with xLPR, PIPER-CASS
- Expecting to continue working with participants to answer any remaining open questions before report is published

Application of stresses drives differences in Case F6 results

Add-On Stability Evaluation

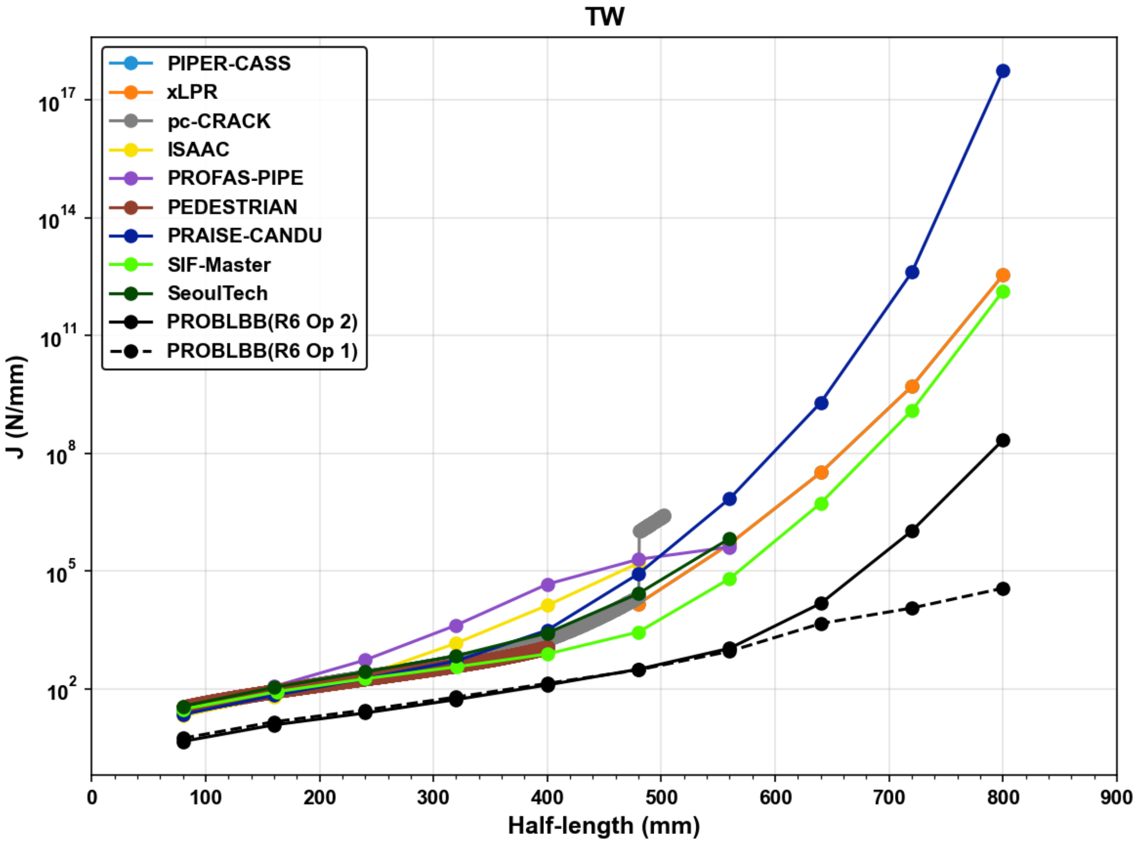
Add-On Stability Evaluation Problem Overview

- Determine the applied J and dJ/dc of a through-wall flaw as function of length
- Determine the applied J and dJ/da of a surface flaw with a/t=0.75 as a function of length
- Loadings include axial stress to due internal pressure and global bending stress
- Material properties, J-R curve, and Ramberg-Osgood parameters provided as inputs

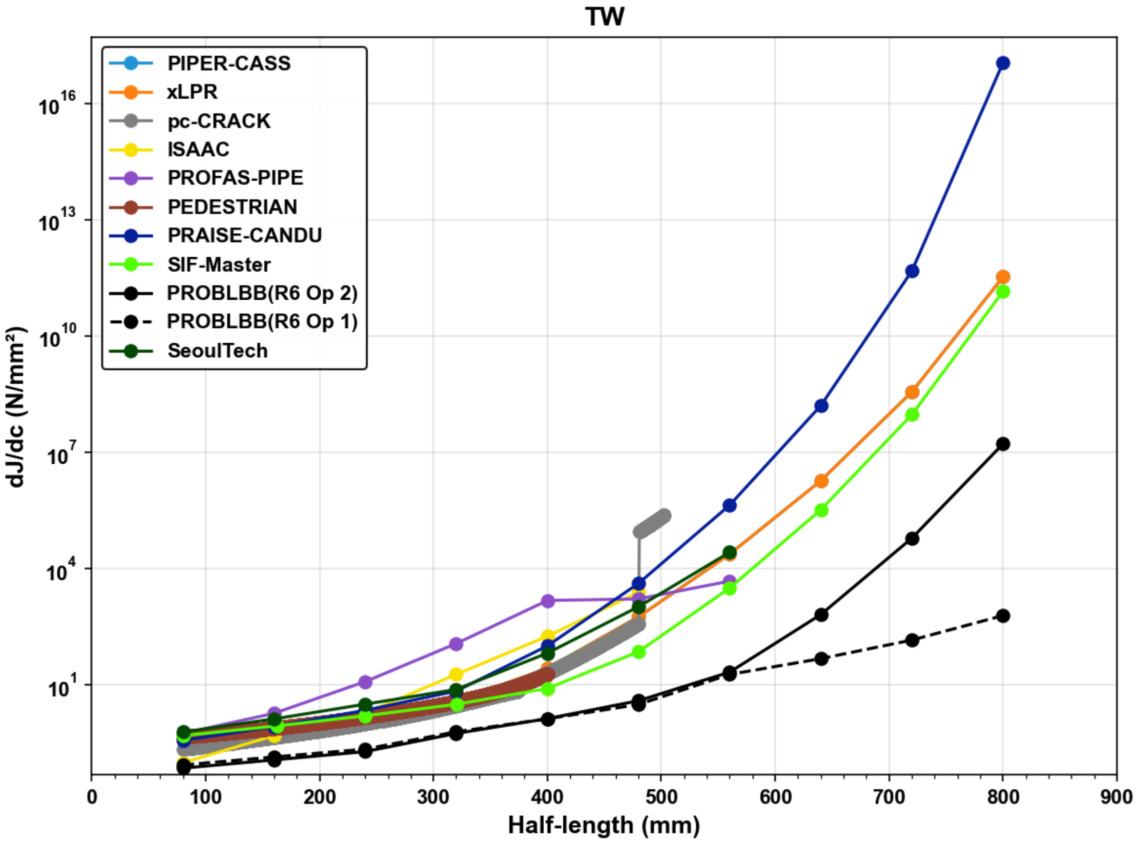
Set	1	2	3	4	5	6	7	8	9	10
Crack Half-Length (mm)	80	160	240	320	400	480	560	640	720	800

Through-Wall J-Integral Results

J-Integral

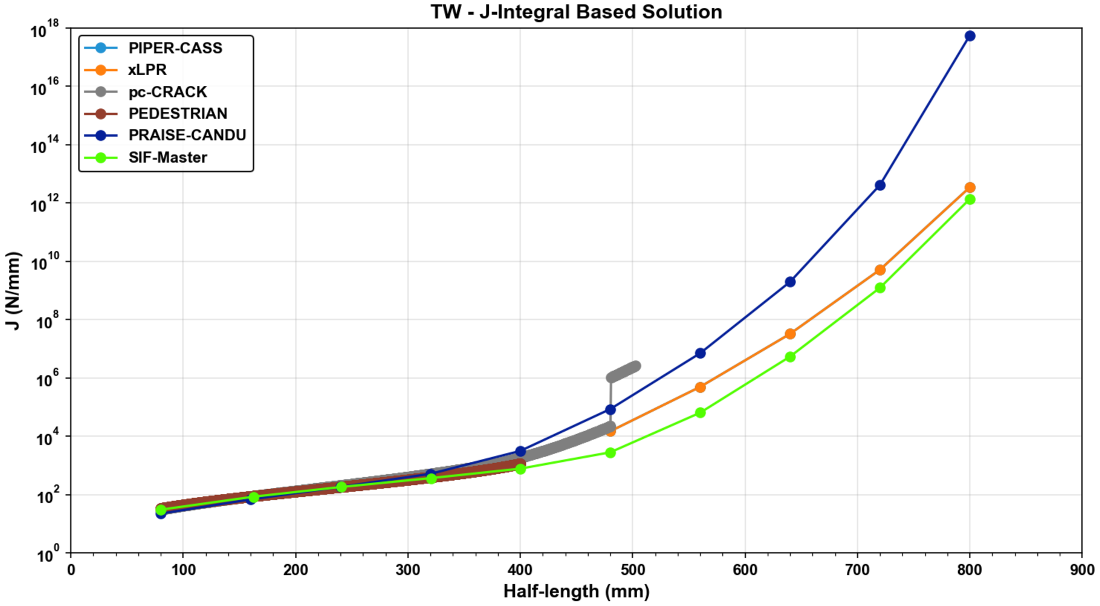


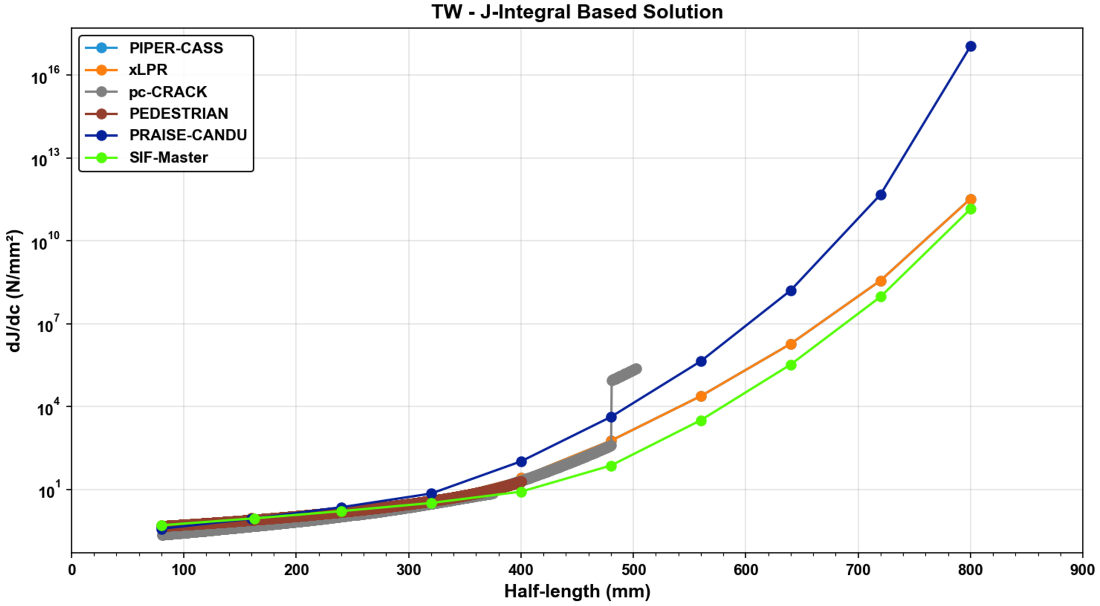
Derivative

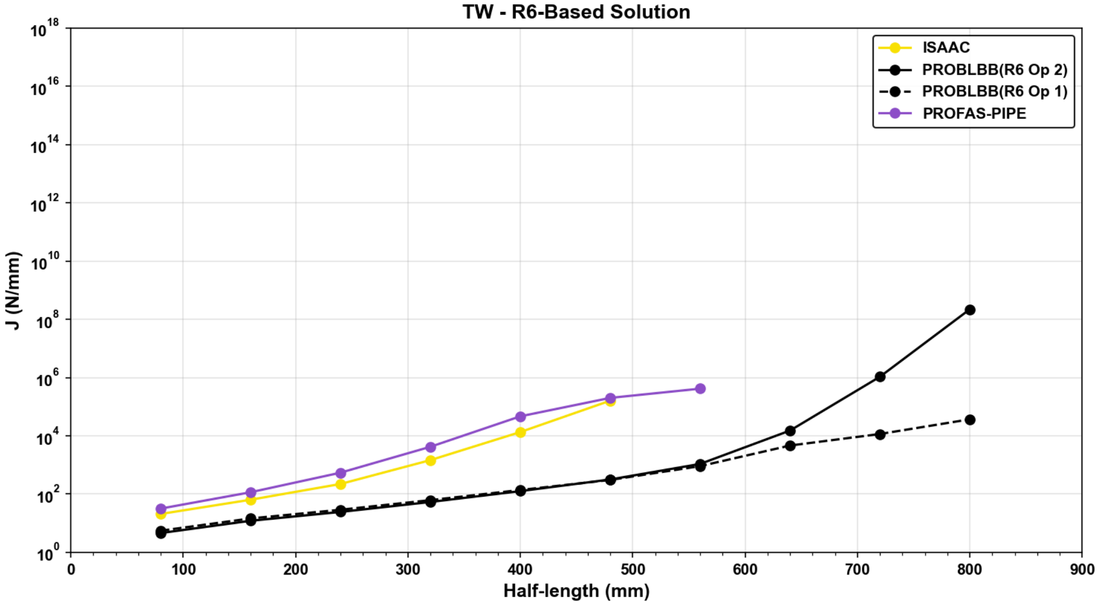


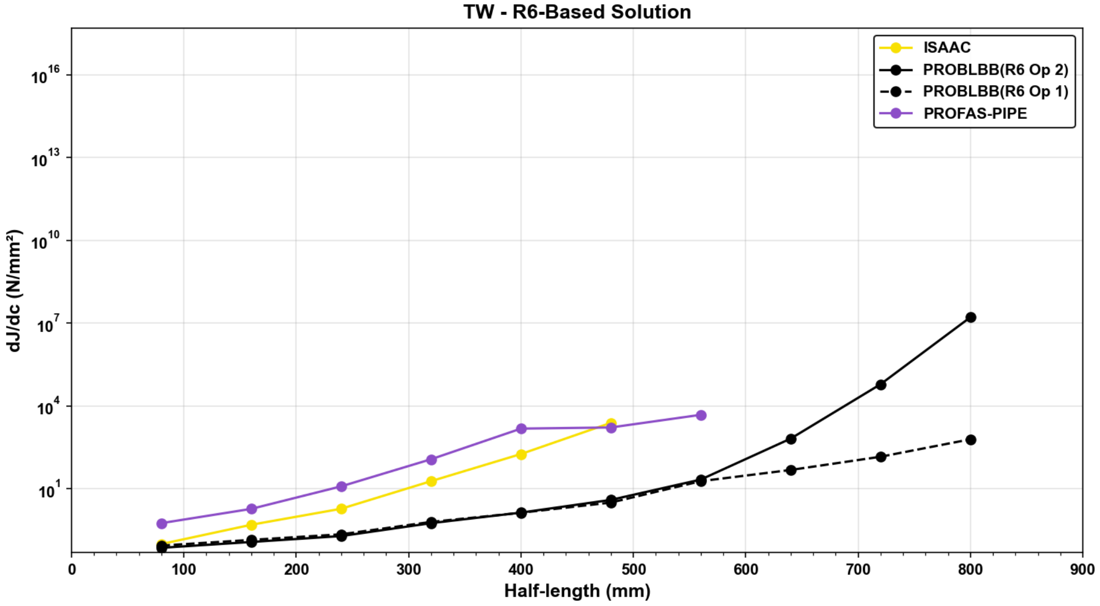
ISAAC results for inner surface crack tip shown

Comparison by EPFM Methodology



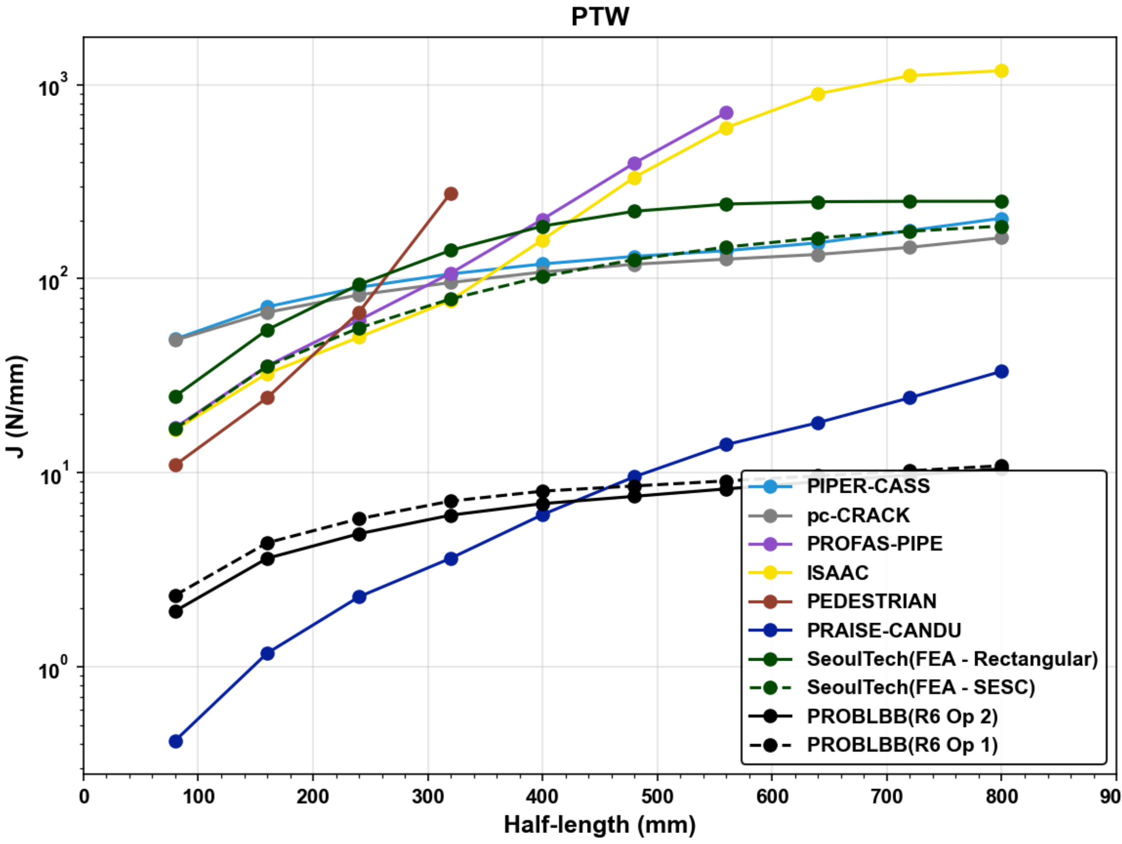




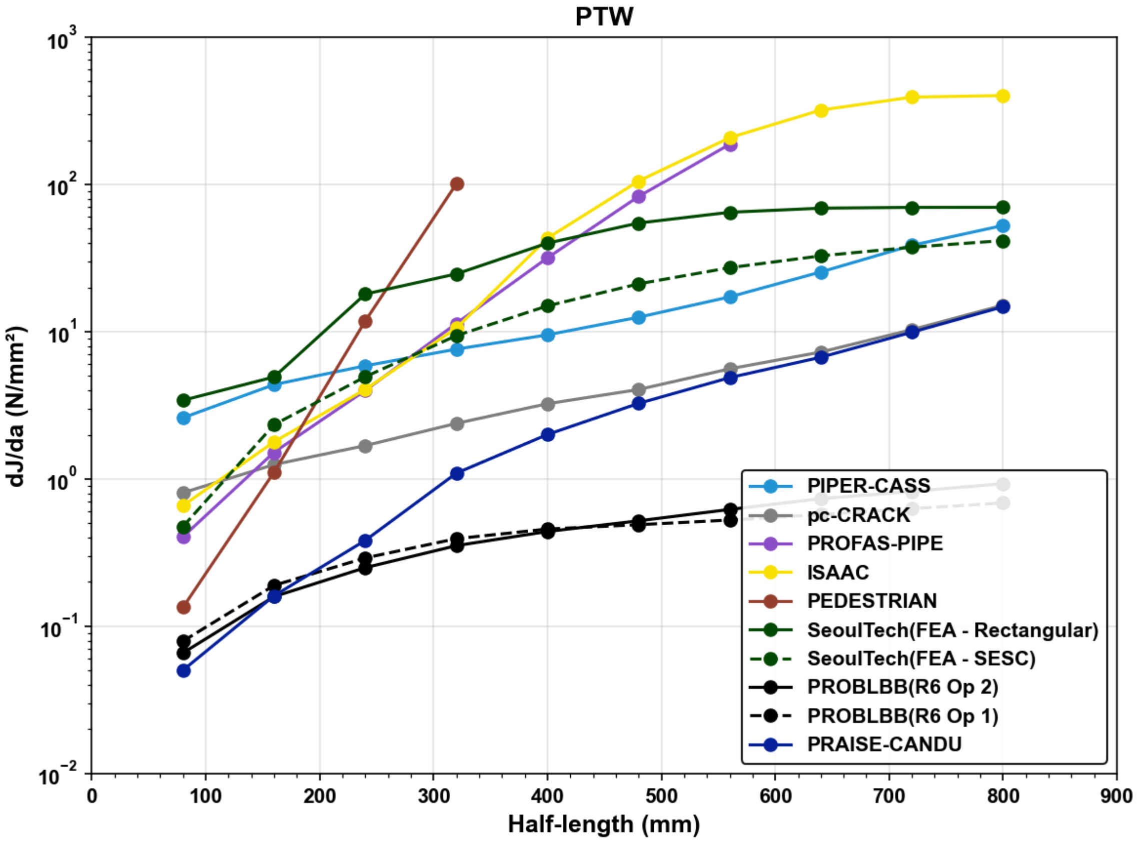


Surface Flaw J-Integral Results

J-Integral

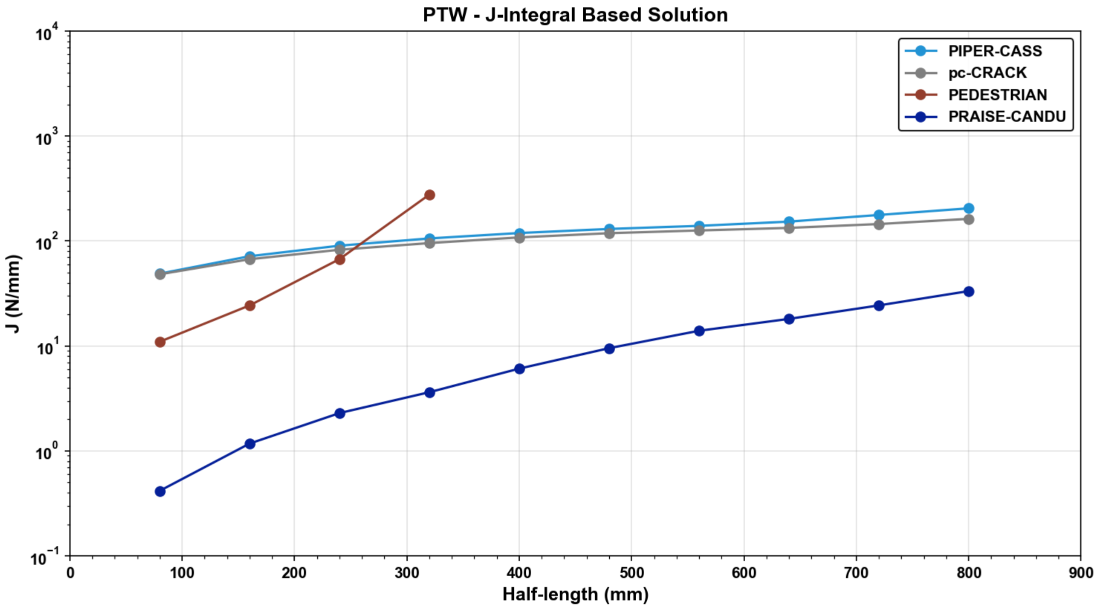


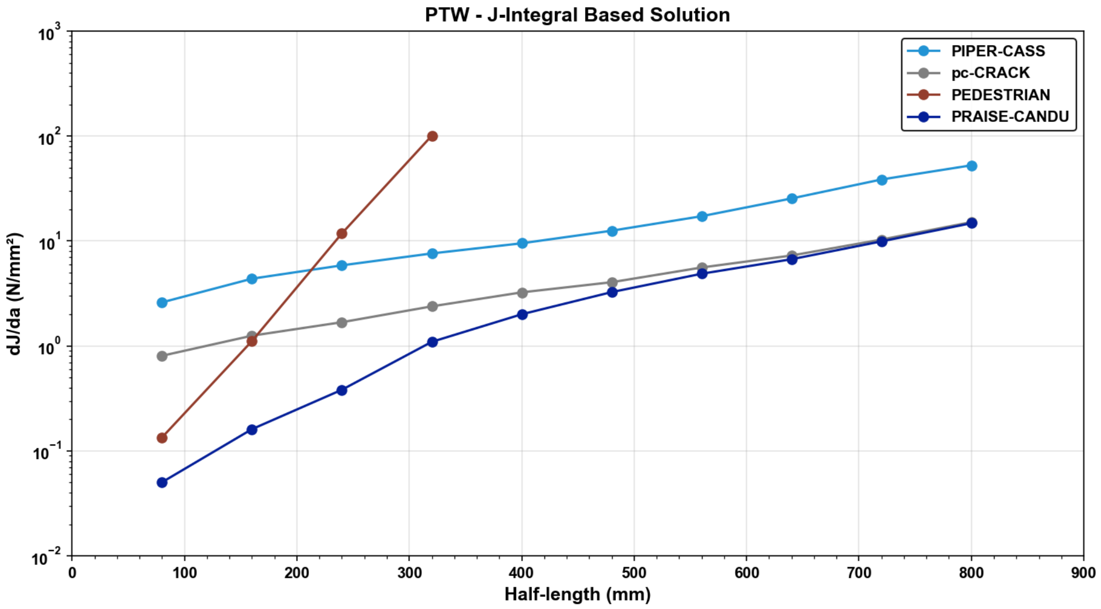
Derivative

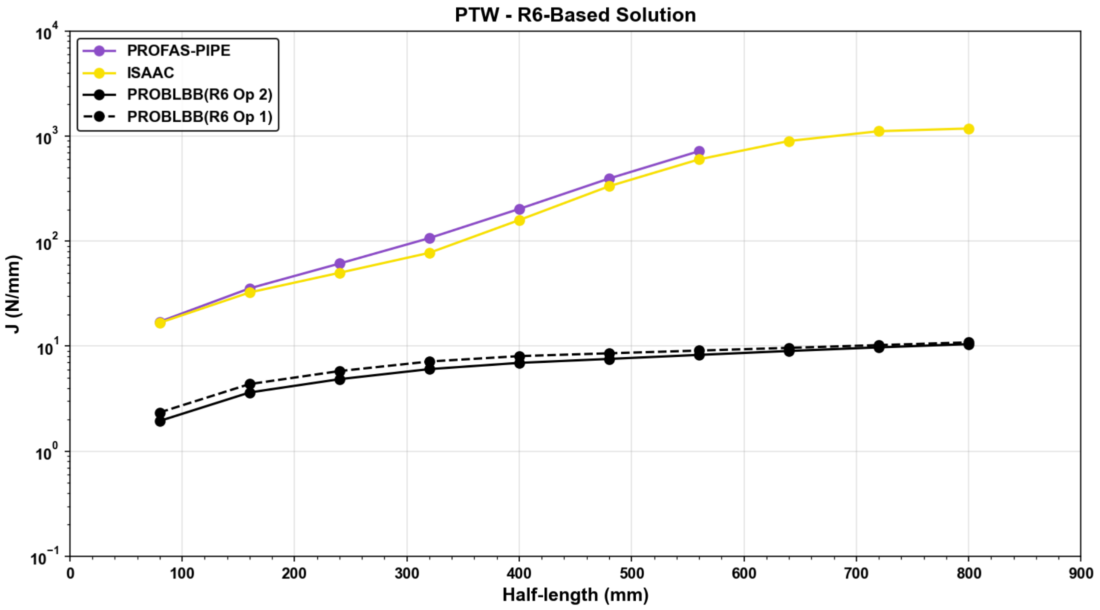


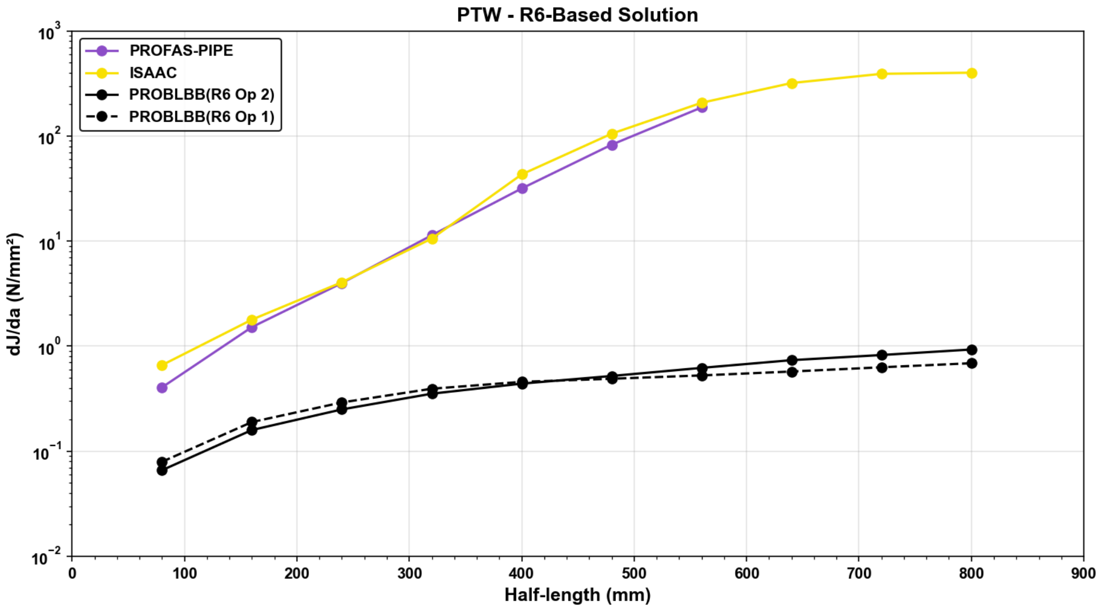
ISAAC results including crack face pressure shown

Comparison by EPFM Methodology


PTW - J-Integral Based Solution

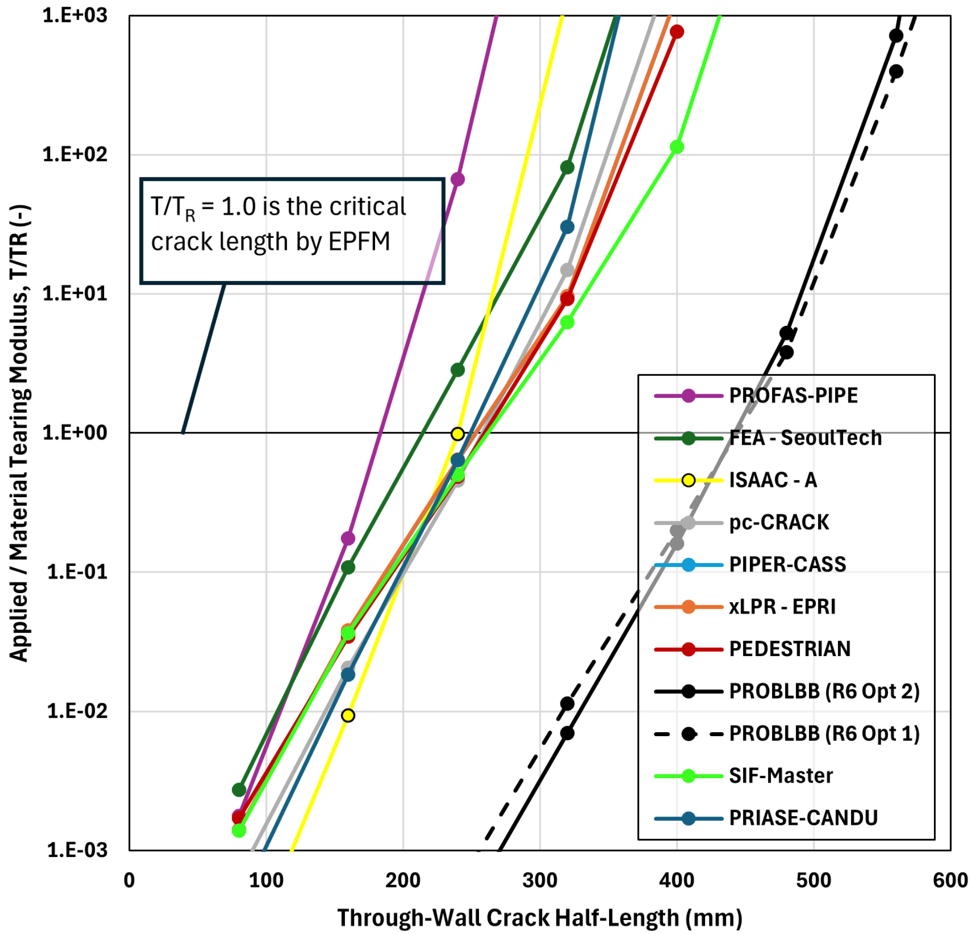

PTW - J-Integral Based Solution


PTW - R6-Based Solution


PTW - R6-Based Solution

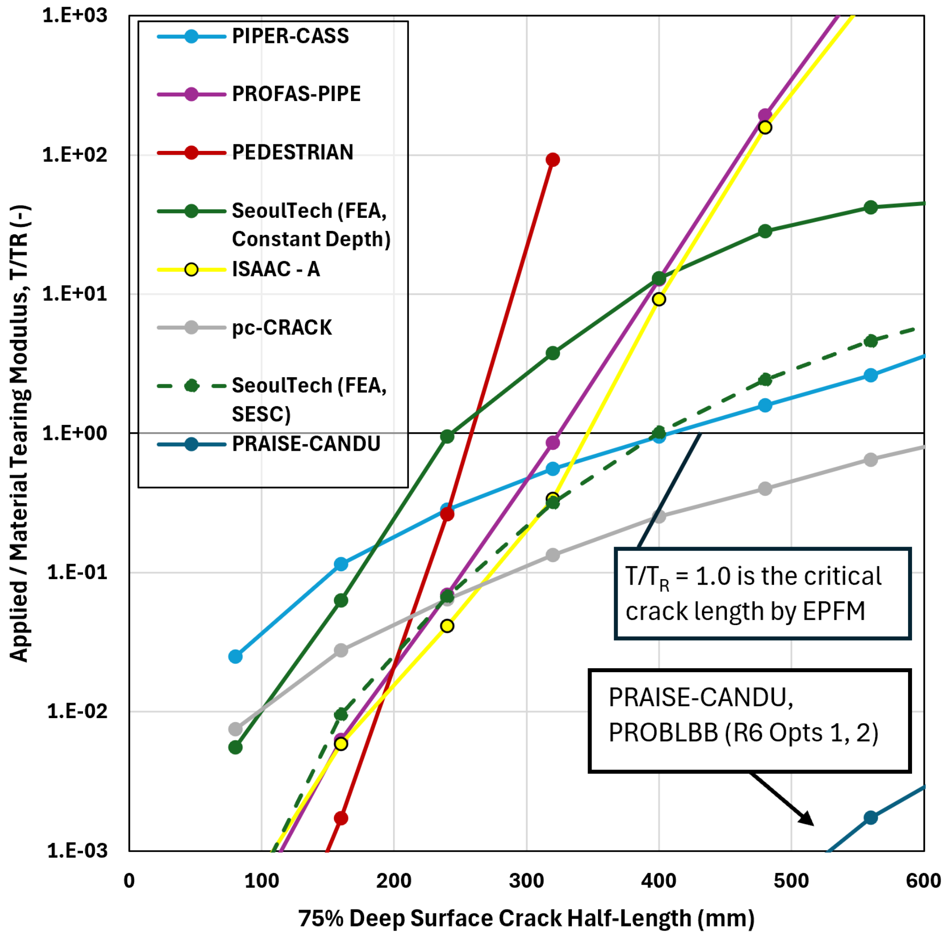
Normalized Tearing Modulus vs Crack Length

Through-Wall Flaw



$T/T_R = 1.0$ is the critical crack length by EPFM

Surface Flaw



$T/T_R = 1.0$ is the critical crack length by EPFM

PRAISE-CANDU, PROBLBB (R6 Opts 1, 2)

Findings and Discussion

- Better agreement observed among TW predictions than for surface flaw predictions
- As expected, variability in shape of J-estimation curves for surface flaws reflected in varying critical size curve shapes
- PROBLBB predictions differ relative to other R6-based approaches (ISAAC, PROFAS-PIPE) in both the Surface and TW crack cases
- PRAISE-CANDU surface crack J results differ significantly from pc-CRACK/CASSPAR and PIPER-CASS, although the Cho solutions are utilized by each code

Phase 3: Probabilistic Benchmark Introduction

Overview of Problems

- Like the deterministic benchmark, the probabilistic benchmark will consist of separate problems focusing on fatigue crack growth and flaw stability
- Plan to leverage previous EPRI analyses to link the benchmark to existing methodologies
- Fatigue crack growth probabilistic benchmark problem will be based on the flaw tolerance evaluation of EPRI TR-106092, *Evaluation of Thermal Aging Embrittlement for Cast Austenitic Stainless Steel Components in LWR Reactor Coolant Systems*
- Flaw stability probabilistic benchmark problem will be based on PFM evaluations described in: *Technical Basis for ASME Section XI Code Case N-838 – Flaw Tolerance Evaluation of Cast Austenitic Stainless Steel (CASS) Piping Components (MRP-362 Rev. 1)*

Probabilistic FCG Problem Overview

- Flaw tolerance evaluation from EPRI TR-106092 used to support initiation fracture toughness ($J_{2.5}$) of 255 kJ/m^2 as threshold criterion for which thermal aging effects need not be considered
- Deterministic, “worst-case” evaluation performed to demonstrate that structural integrity will not be challenged for materials of sufficient toughness
  - Fatigue crack growth over 40 years simulated
  - Maximum SIF compared against K_{IC} (calculated from $J_{2.5}$ at fully aged condition)
- For this benchmark, the problem will be investigated using a probabilistic approach to quantify the probability of the flaw reaching instability

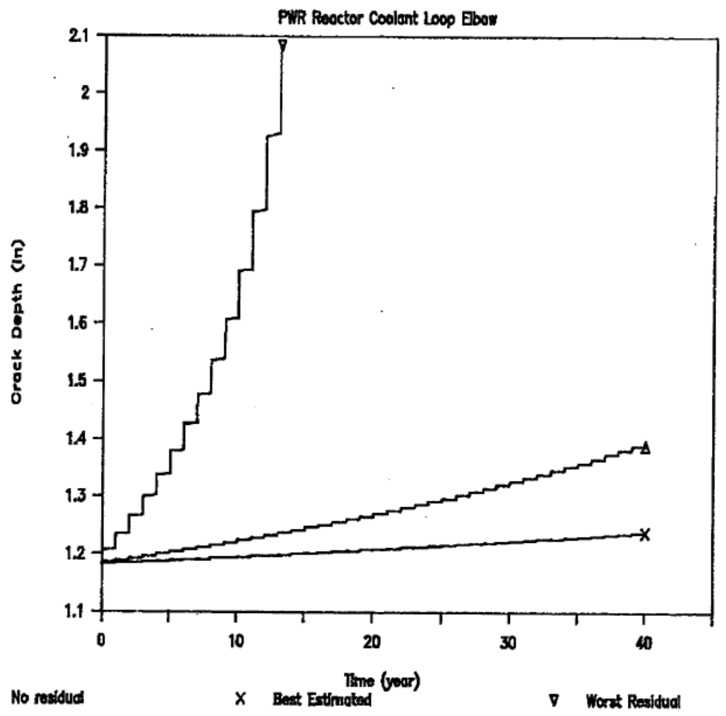


Figure B-9. Fatigue Crack Growth (30 mm Initial Defect)

Probabilistic Stability Evaluation Overview

- The probabilistic flaw stability evaluations described in MRP-362 R1 were performed to calculate tolerable flaw sizes that can be used in CASS piping flaw tolerance evaluations per ASME Code Case N-838
  - Probabilistically sampled material properties (strength, toughness inputs) used to perform Monte-Carlo analysis of flaw stability
  - Tolerable flaw depths calculated as the maximum depth for which the probability of instability is less than or equal to the conditional failure probability for the associated service level
- Benchmark problem will consist of calculating the tolerable sizes for a subset of the cases (Service Level, flaw length, stress ratio)

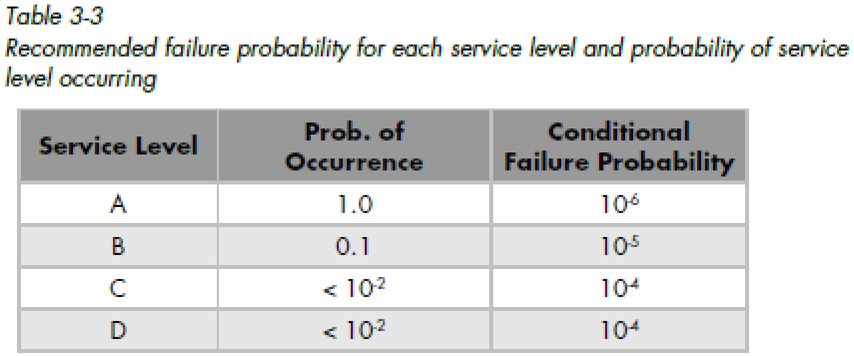


Table 3-3
Recommended failure probability for each service level and probability of service level occurring

Service Level	Prob. of Occurrence	Conditional Failure Probability
A	1.0	10^{-6}
B	0.1	10^{-5}
C	< 10^{-2}	10^{-4}
D	< 10^{-2}	10^{-4}

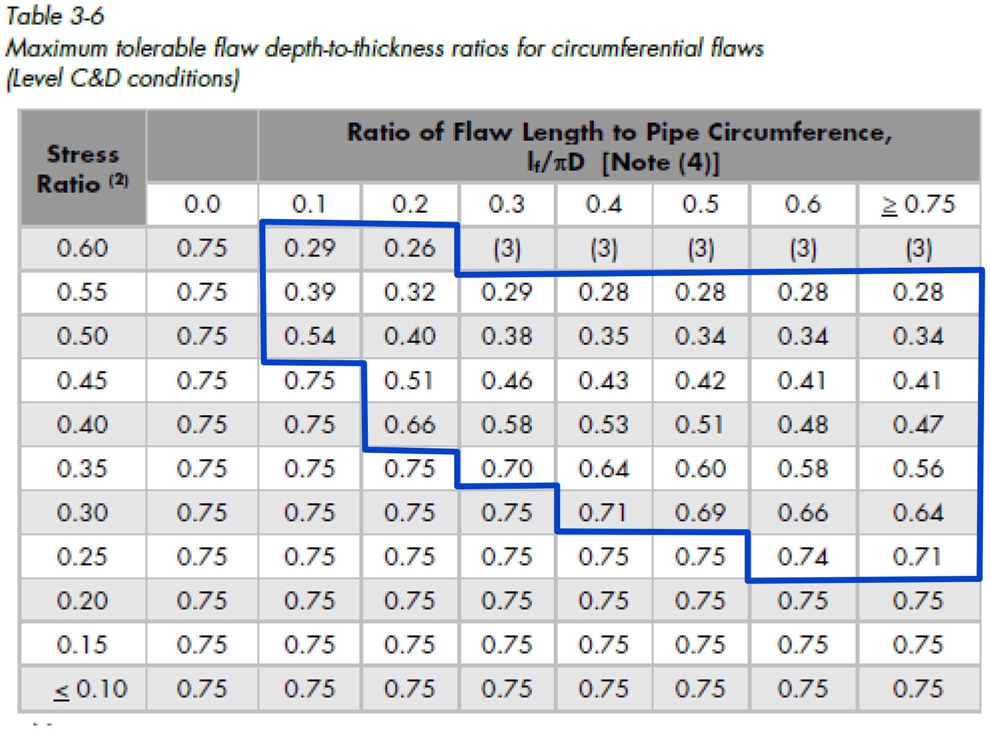


Table 3-6
Maximum tolerable flaw depth-to-thickness ratios for circumferential flaws (Level C&D conditions)

Stress Ratio (2)	Ratio of Flaw Length to Pipe Circumference, $l_f/\pi D$ [Note (4)]							
	0.0	0.1	0.2	0.3	0.4	0.5	0.6	≥ 0.75
0.60	0.75	0.29	0.26	(3)	(3)	(3)	(3)	(3)
0.55	0.75	0.39	0.32	0.29	0.28	0.28	0.28	0.28
0.50	0.75	0.54	0.40	0.38	0.35	0.34	0.34	0.34
0.45	0.75	0.75	0.51	0.46	0.43	0.42	0.41	0.41
0.40	0.75	0.75	0.66	0.58	0.53	0.51	0.48	0.47
0.35	0.75	0.75	0.75	0.70	0.64	0.60	0.58	0.56
0.30	0.75	0.75	0.75	0.75	0.71	0.69	0.66	0.64
0.25	0.75	0.75	0.75	0.75	0.75	0.75	0.74	0.71
0.20	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75
0.15	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75
≤ 0.10	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75

Upcoming Schedule

- Targeting mid-May for release of the probabilistic benchmarking problem set
  - Plan to schedule a call following release of the problems to answer questions from participants and to make revisions based on feedback
- Based on the observed timeline of the deterministic phase, it will be requested that participants submit results within 10-12 weeks of receipt of problem set

Overall Project Schedule

Phase	Schedule Item	Date
1	Capabilities Survey	March 2025
2	Release deterministic benchmark problem to participants	April 2025
	Execute deterministic benchmark problems	May-September 2025
	Hold virtual meetings to discuss deterministic benchmark results	September 30th/October 1st, 2025
	Share summary of deterministic benchmark results	October 2025
	Release add-on deterministic benchmark problems to participants	November 2025
	Execute add-on deterministic problems	November 2025-April 2026
	Hold virtual meetings to discuss add-on deterministic benchmark results	April 29th/April 30th, 2026
3	Release probabilistic benchmark problem to participants	May 2026
	Hold virtual meetings to discuss probabilistic problem set	June 2026
	Execute probabilistic benchmark problems	May 2026-September 2026
	Hold virtual meetings to discuss probabilistic benchmark results	November 2026
	Share summary of probabilistic benchmark results	November 2026
	Provide draft report for participant comments	December 2026

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