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SIR 고려대학교 신뢰성평가연구실
Structural Integrity and Reliability Lab

Fracture Modeling of Nuclear Components using FE Damage Analysis

한국 원자력학회 워크샵 E
계산과학/AL 활용 핵연료 및 원자력 재료 연구
2022. 10. 19
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Acknowledgement

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고려대학교 기계공학부 신뢰성평가연구실

졸업생

재학생

Research Definition

- Predict failure (ductile, brittle, creep) of large-scale nuclear components (piping, vessel) using FE analysis

- Use meso-scale phenomenological damage model (based either on inelastic strain or inelastic strain energy)

- Input: Tensile and fracture test data (minimum)

- Output: Fracture prediction of nuclear components under harsh loading / aging conditions

Requirements

- For industrial/practical use, the method should be simple, clear and transparent

- Input for the analysis should be readily available

- The method can treat complex problems in nuclear plant problems such as multiple cracks, aging and embrittlement, seismic loading, severe accident etc

Contents

1. Monotonic loading - Ductile fracture modeling

2. (Very low) Cyclic loading (Earthquake seismic event)
   – Ductile fracture modeling

3. Thermo-mechanical monotonic loading (Severe accident)
   – Ductile fracture modeling

4. Impact loading (Collison / Penetration)
   – Ductile fracture modeling

Ductile Fracture Simulation

5. Combined ductile/cleavage fracture modeling for ductile-brittle transition temperature (not today)

Monotonic Loading – Ductile Fracture Modeling Examples

Input

Model	Required data
Constitutive model	Monotonic tensile test data
Damage model	Monotonic fracture toughness data

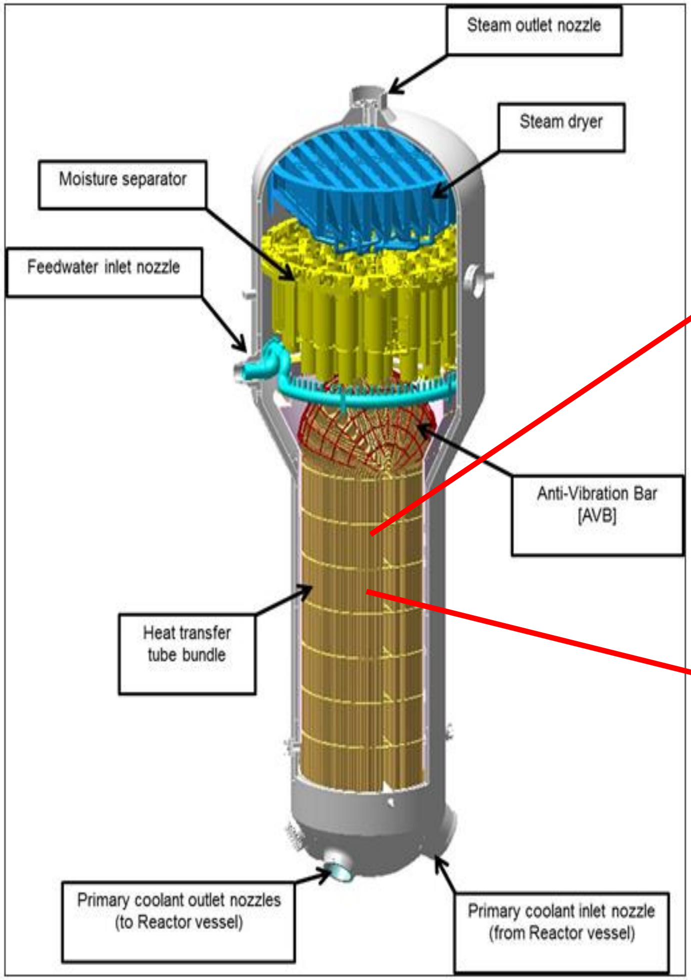
Output

Crack initiation/growth, maximum load and unstable fracture of nuclear components

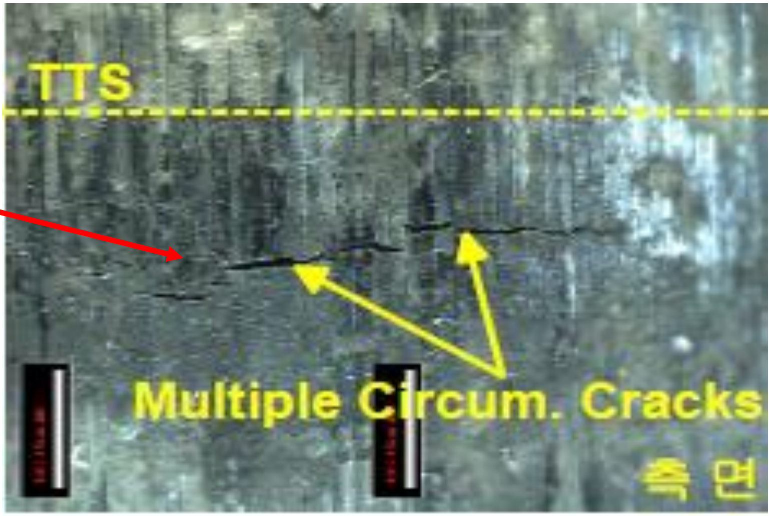
Multiple Cracks in Steam Generator Tubes

- Due to SCC, multiple cracks often found

  → assessment of multiple surface cracks

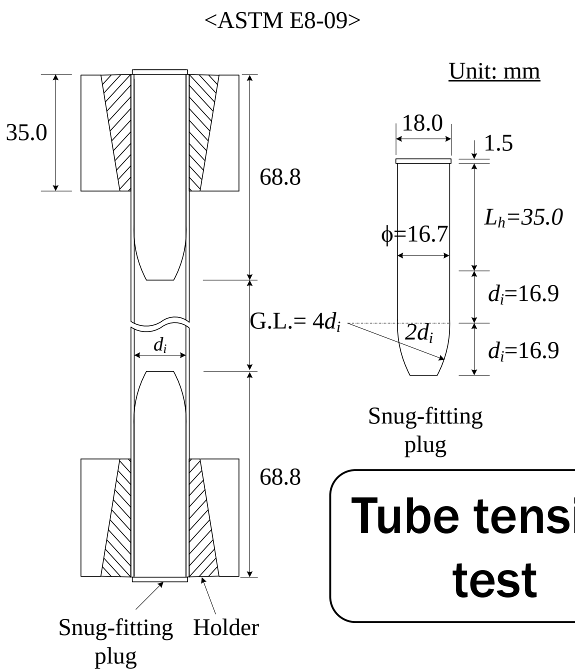


[SCC and Rupture of U-4 SG Tube]

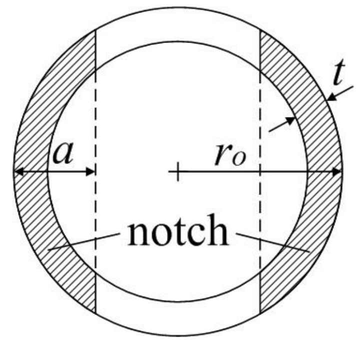


[Multiple SCCs in K-1 SG Tube]

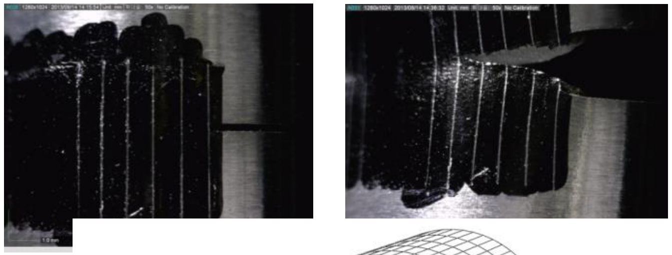
Test to Determine the Damage Model

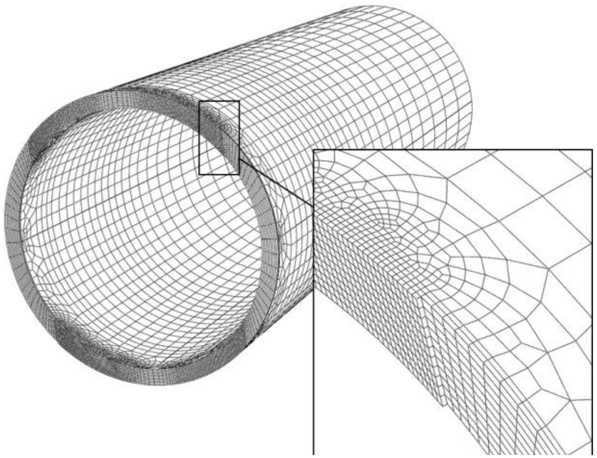


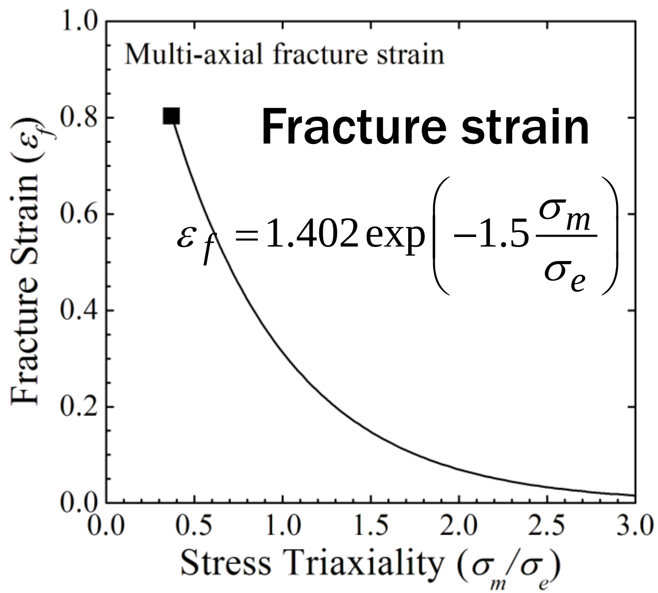
Tube tensile test

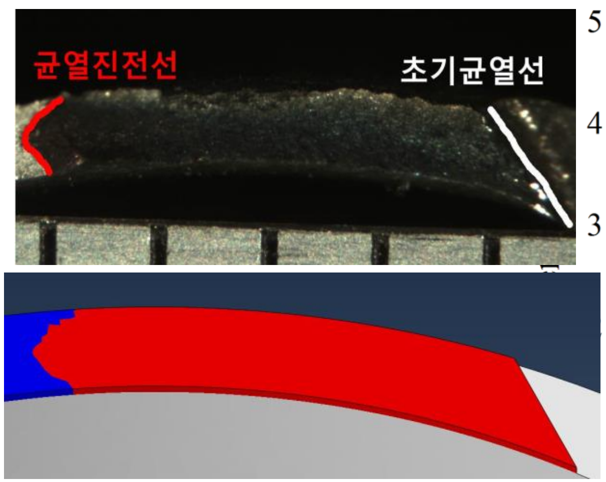


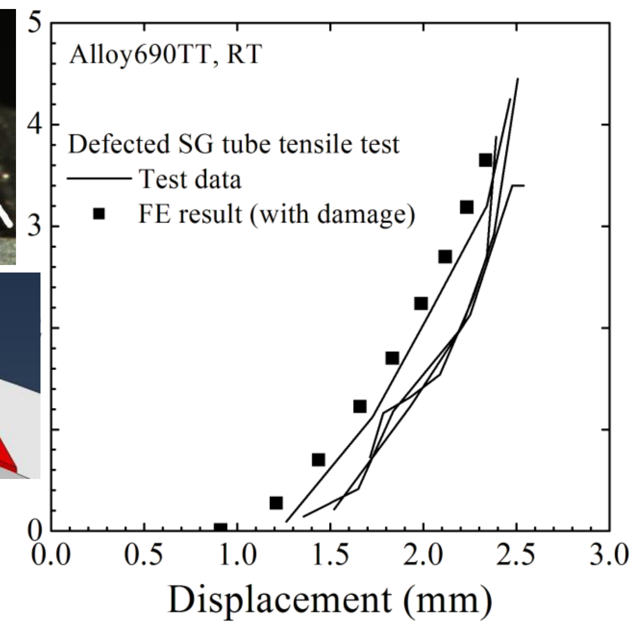
Notched Tube Fracture test





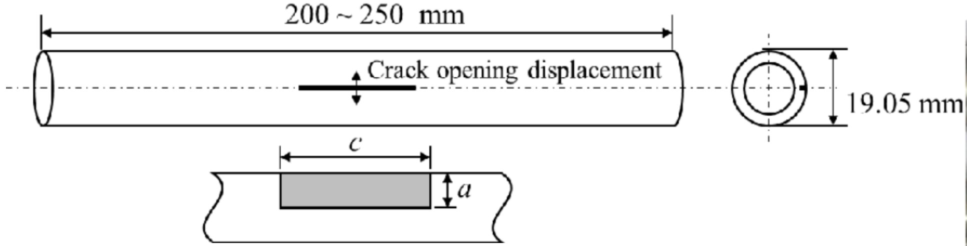


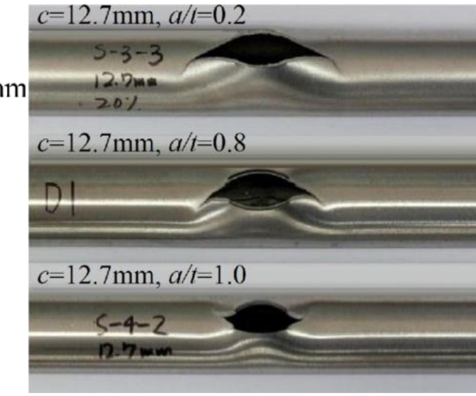


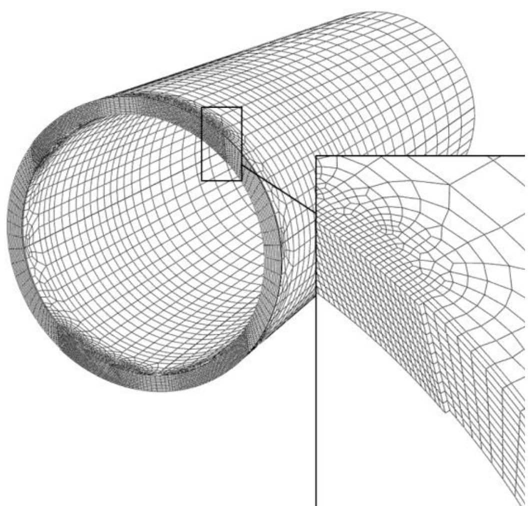


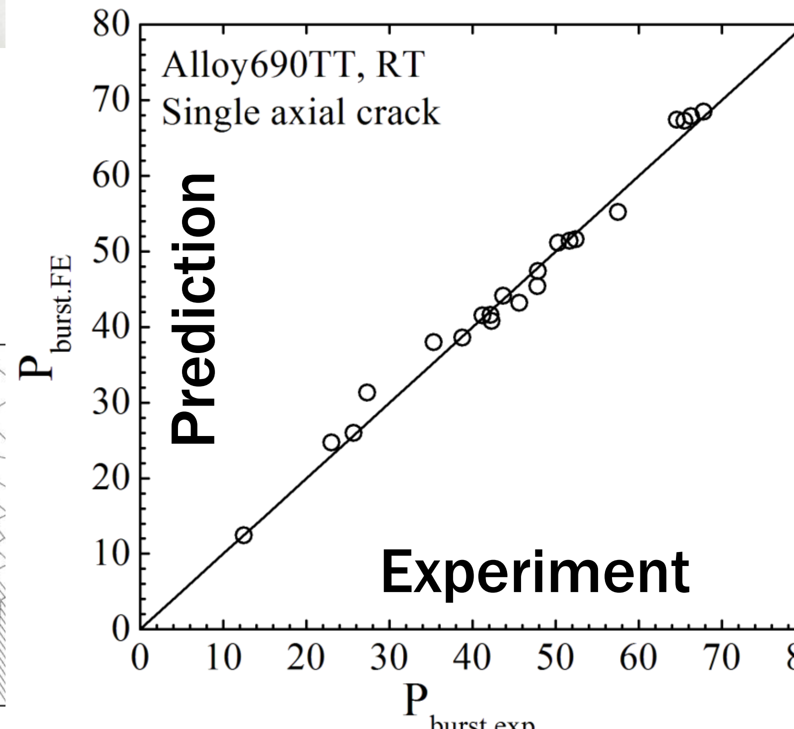
Comparison with Experimental data: Single Surface Cracks (KHNP)

c (mm)	a/t	P_b^{test} (MPa)
6.0	0.2	67.8
	0.4	57.5
	0.6	47.9
	0.8	42.3
	1.0	42.2
12.7	0.2	66.3
	0.4	52.4
	0.5	47.8
	0.6	41.2
	0.8	27.3
	1.0	25.7
25.4	0.2	65.5
		66.0
	0.4	51.7
	0.5	43.7
	0.6	38.8
	0.8	23.0
		23.0
	1.0	12.5
50.8	0.2	64.6
	0.4	50.3
	0.5	45.6
	0.6	35.3



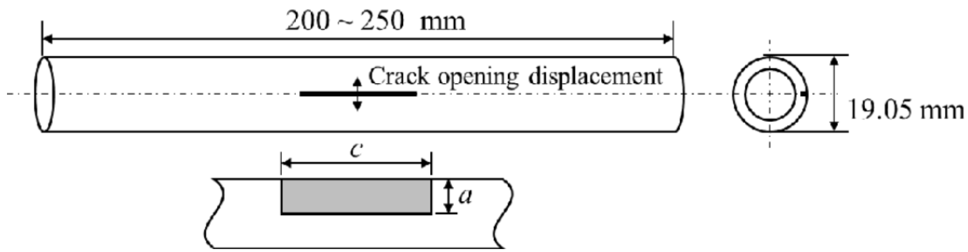


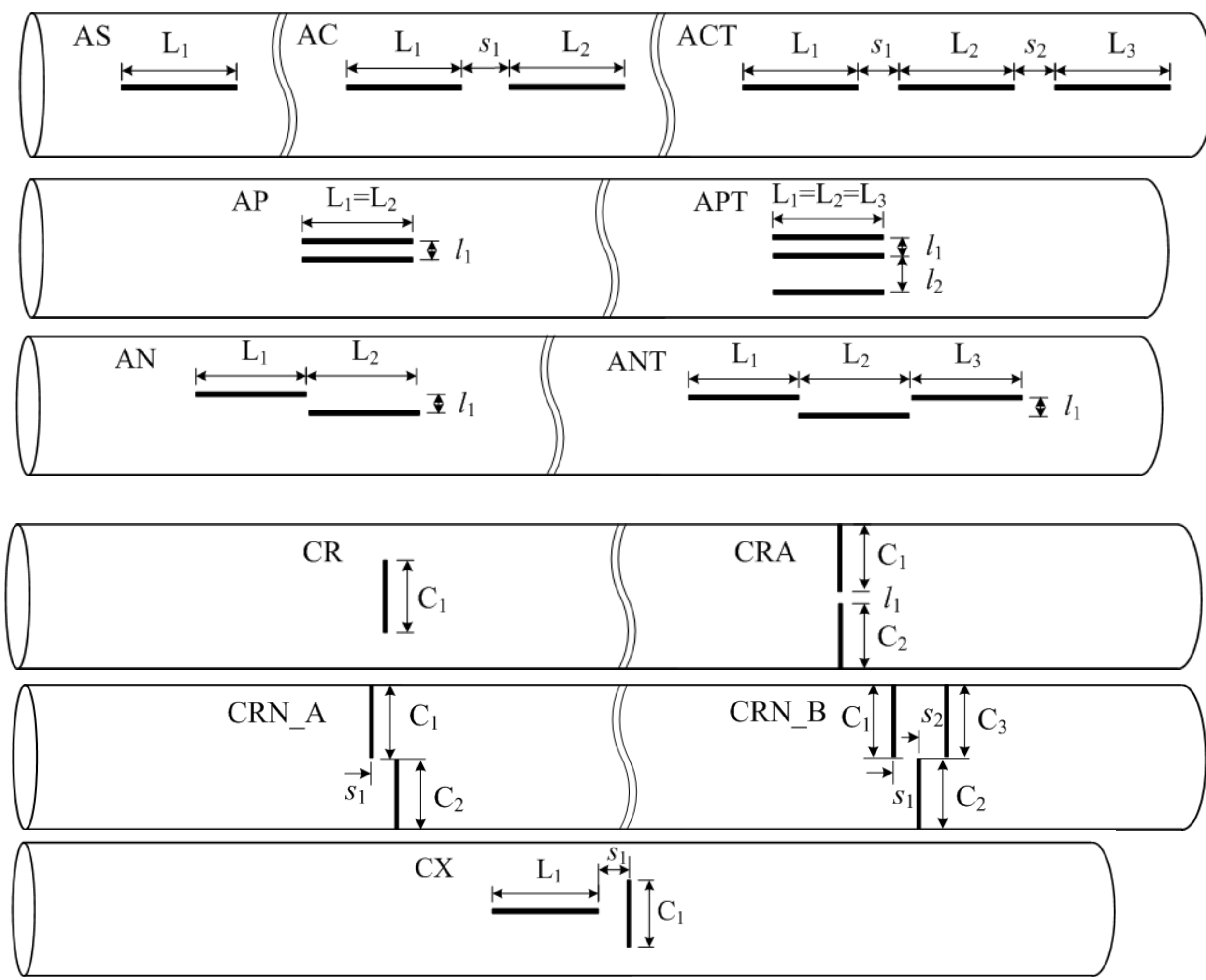




Test: Multiple-Cracked SG Tubes (Chosun Univ)

CHOSUN UNIVERSITY





Collinear (12 cases)

Parallel (8 cases)

Non aligned (9 cases)

Aligned (3 cases)

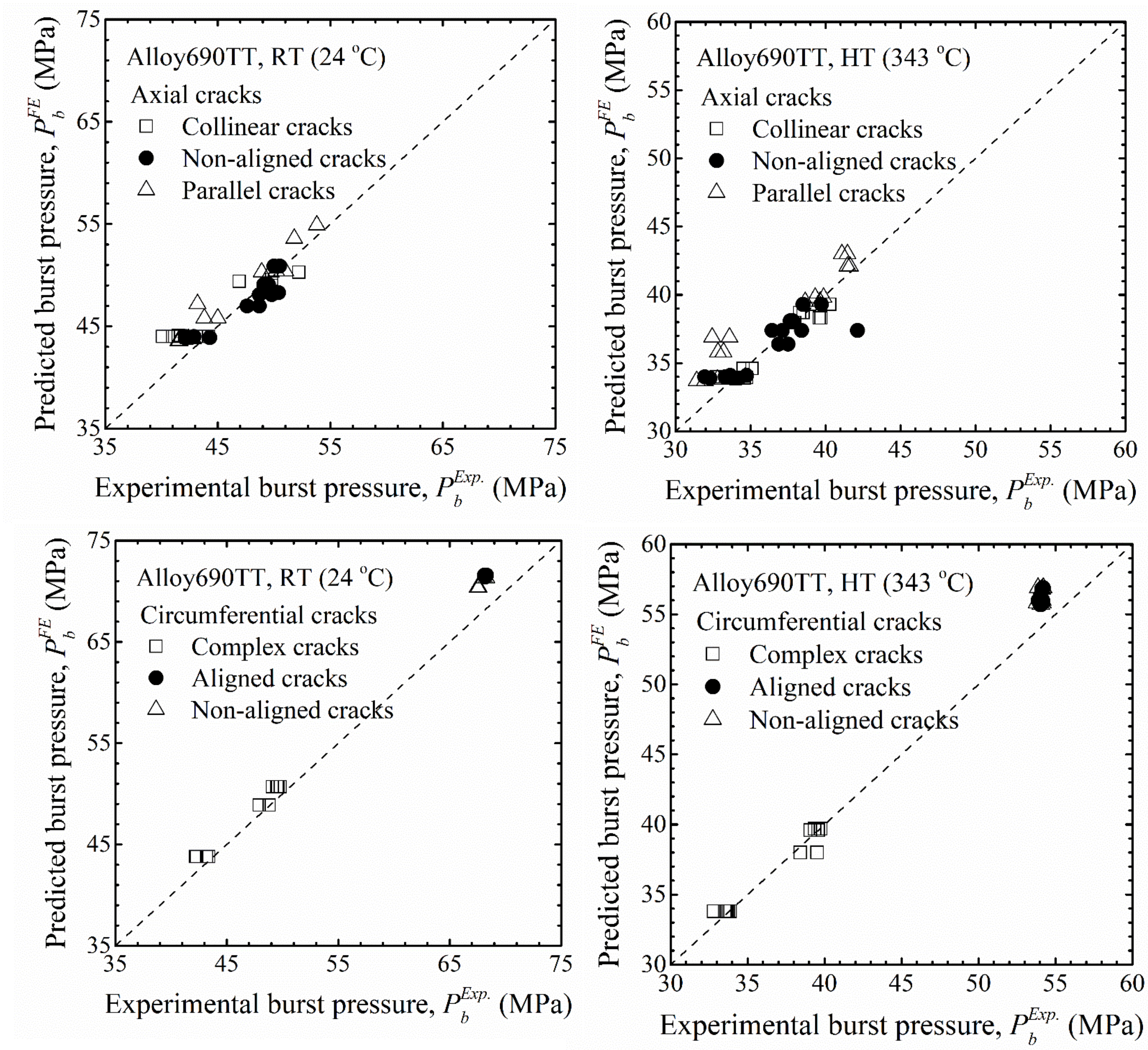
Non aligned (2 cases)

Composite (6 cases)

High Temp
Room Temp
80 cases

a/t=0.5
For all cases

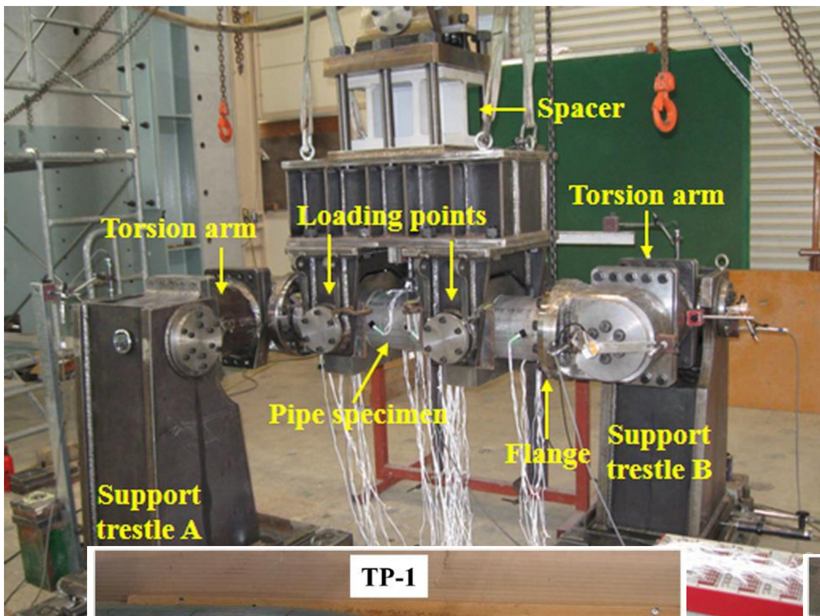
Comparison with Predictions

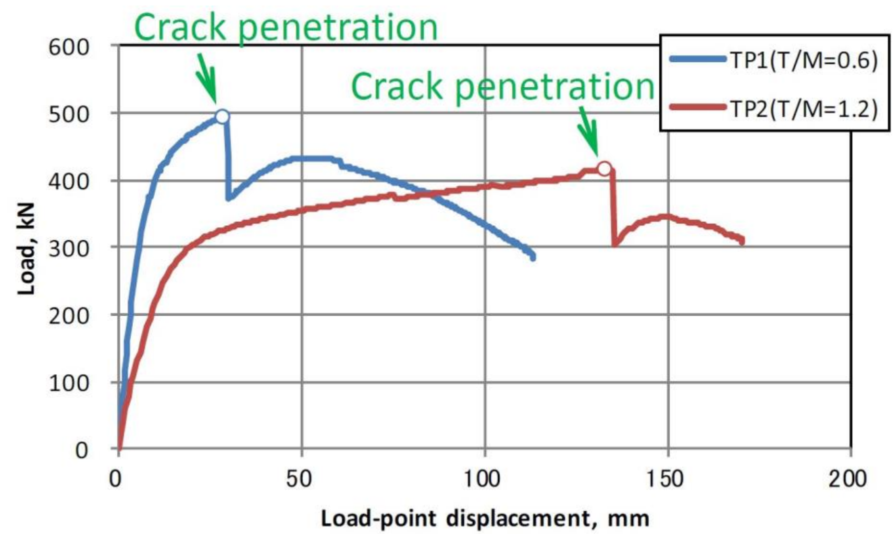


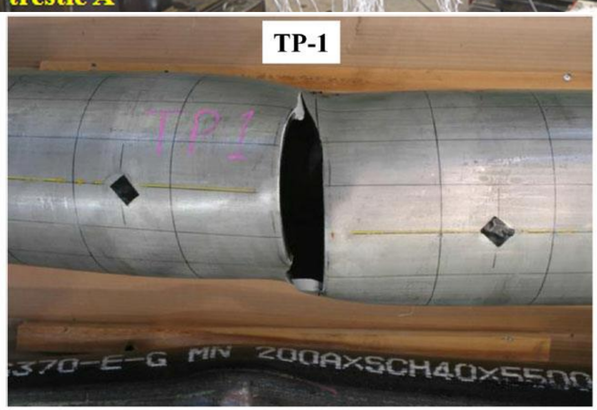
On-Going Works

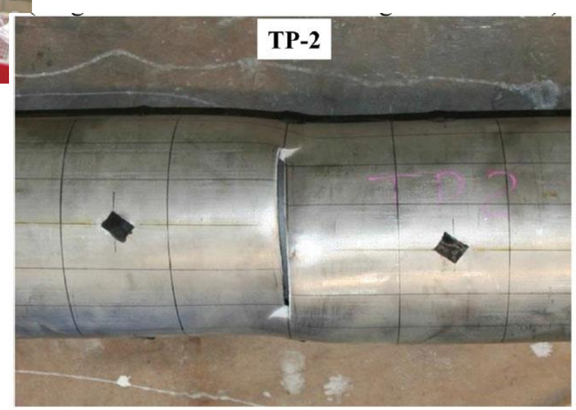
CRIEPI
Central Research Institute of Electric Power Industry

❖ Crack growth modeling of cracked pipes under combined bending (tension) and torsion









Very Low Cyclic Loading – Ductile Fracture Modeling Examples

Input

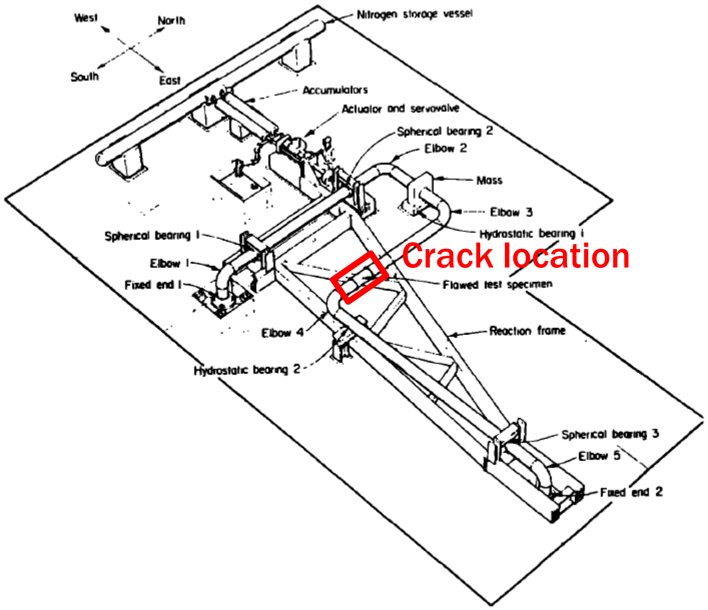
Model	Required data
Constitutive model	• Monotonic tensile test data • ε-N data (Code / Report) • Cyclic tensile test data (optional)
Damage model	Monotonic fracture toughness data

Output

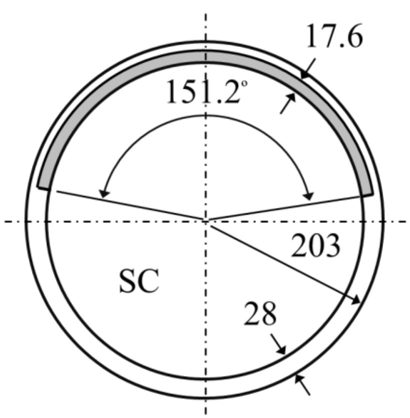
Fracture toughness under cyclic loading
Crack initiation/growth, maximum load and unstable fracture of nuclear components under cyclic (seismic) loading

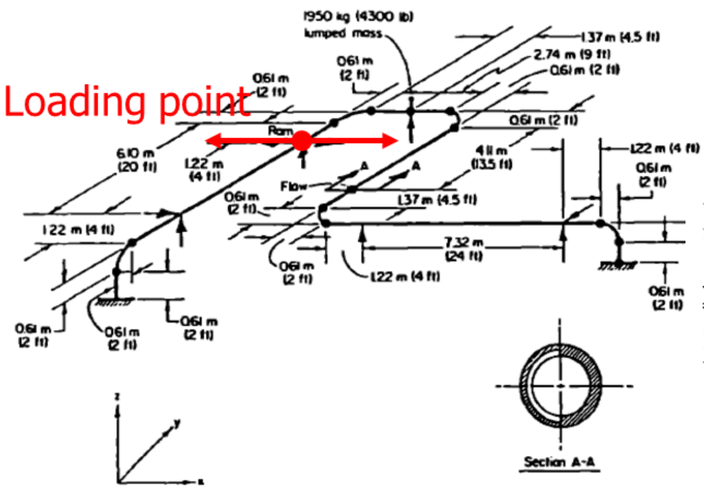
Piping Integrity under Seismic Loading

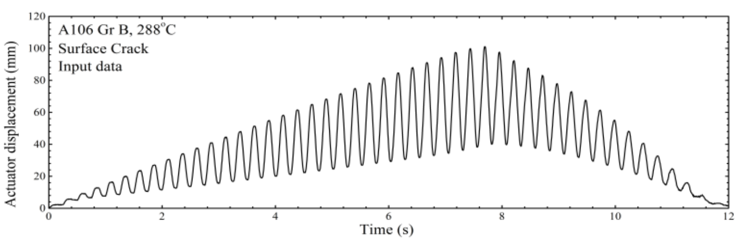
Piping System Test under simulated seismic loading (Battelle)



Surface crack







Energy-based Damage Model

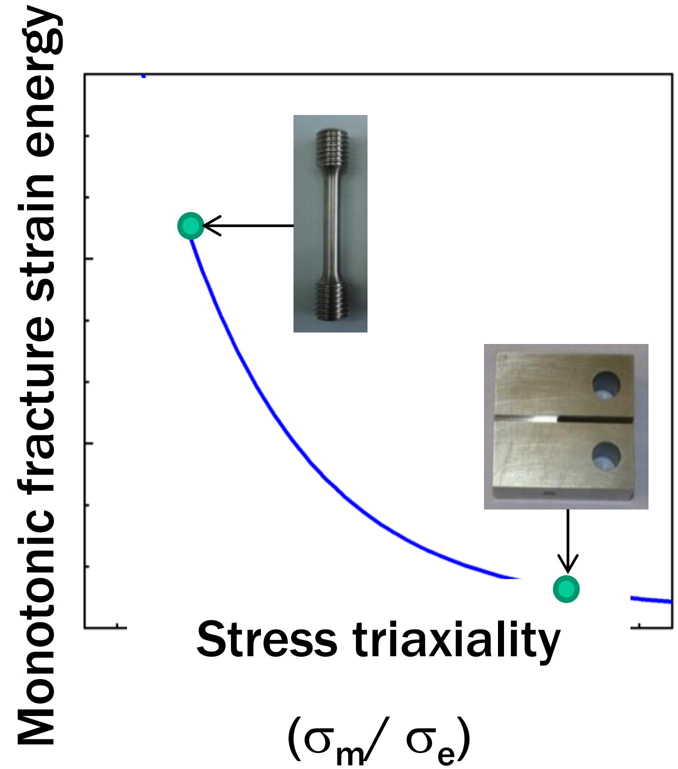
- **Monotonic fracture strain energy, $(W_f)_M$**

$$\left(W_f\right)_M = A\cdot\exp\left(1.5\left(n+1\right)\cdot\frac{\sigma_m}{\sigma_e}\right)+B$$

***A*, *B* : material constants**

***n* : monotonic strain hardening exponent**

Determined from
tensile and fracture toughness test



- **Cyclic fracture strain energy, $(W_f)_C$**

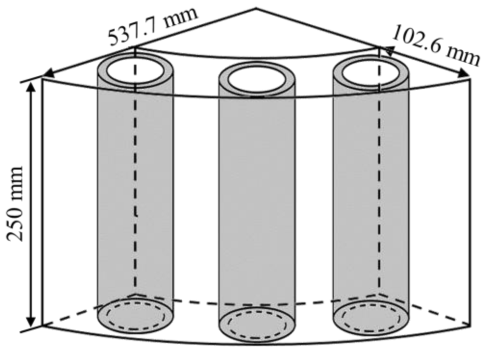
$$\left(W_f\right)_C = \left(W_f\right)_M\cdot\left[2N\right]^{\alpha+1}\cdot\left[\frac{1-R}{2}\right]^{-\frac{0.5\alpha}{\beta}}$$

α, β : material constants

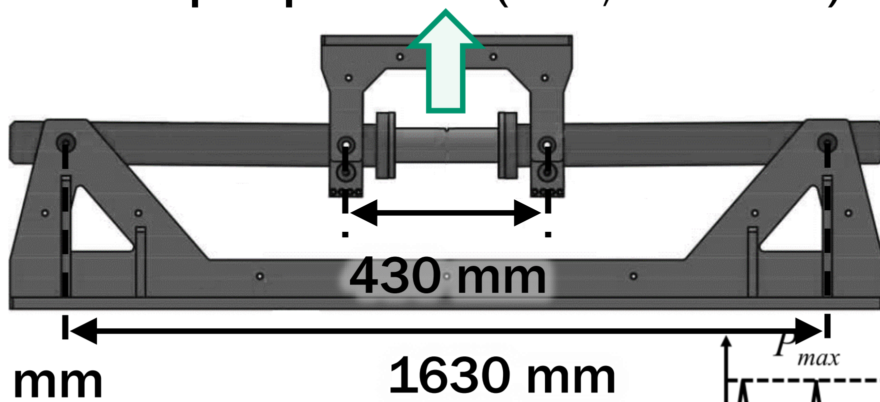
R : load ratio (=P_{min}/P_{max})

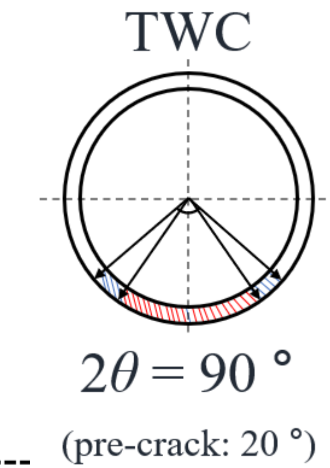
HS Nam, Int J Mech Sci, 2018
JH Hwang., Eng Fract Mech, 2020a, 2020b
Morrow, ASTM Int 1965
Dowling, FFEMS, 2009
JH Hwanr, Int J Mech Sci, 2022

Monotonic/Cyclic Through-Wall Cracked Pipe Test



Pipe specimen (90º, 250 mm)





D_{out}=72.5 mm, t=8.5 mm

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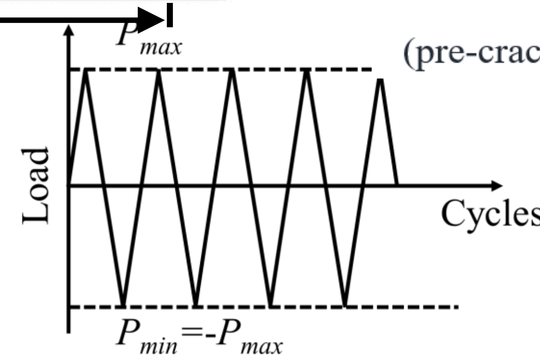
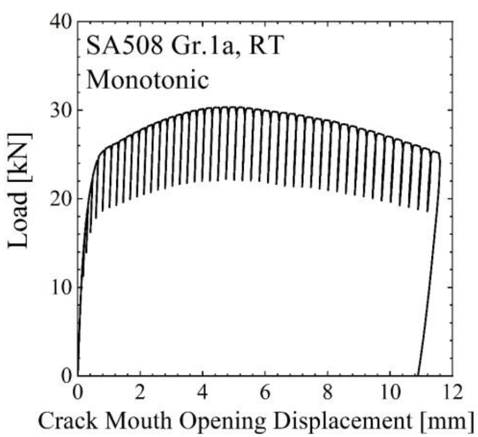




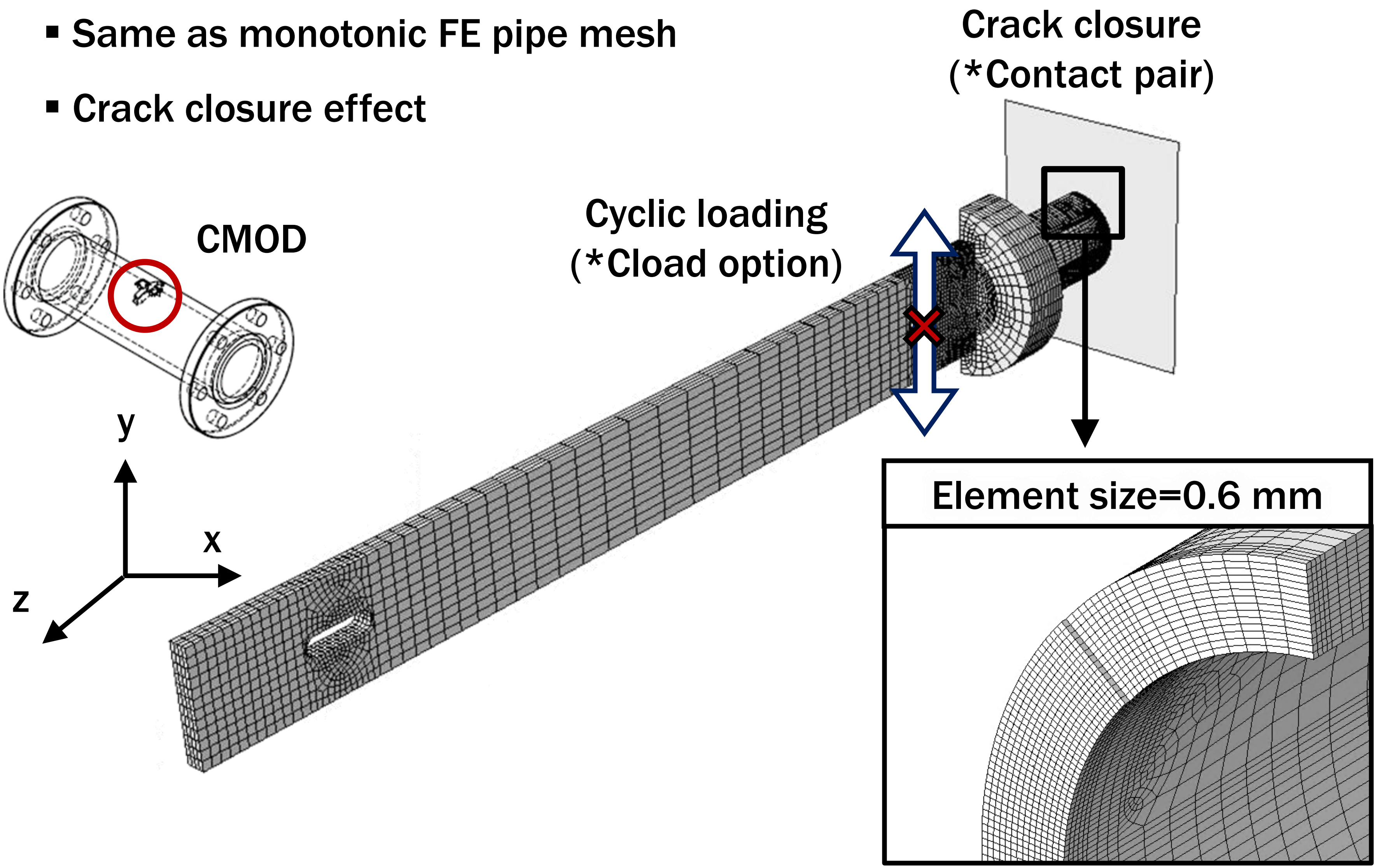
- Load-controlled very low cycle fatigue loading

Load [kN]	Load ratio *R*	P_{max}/P_M	Failure cycle
±25.8	-1	0.85	21
±22.8		0.75	76
25.8/-12.9	-0.5	0.75	74

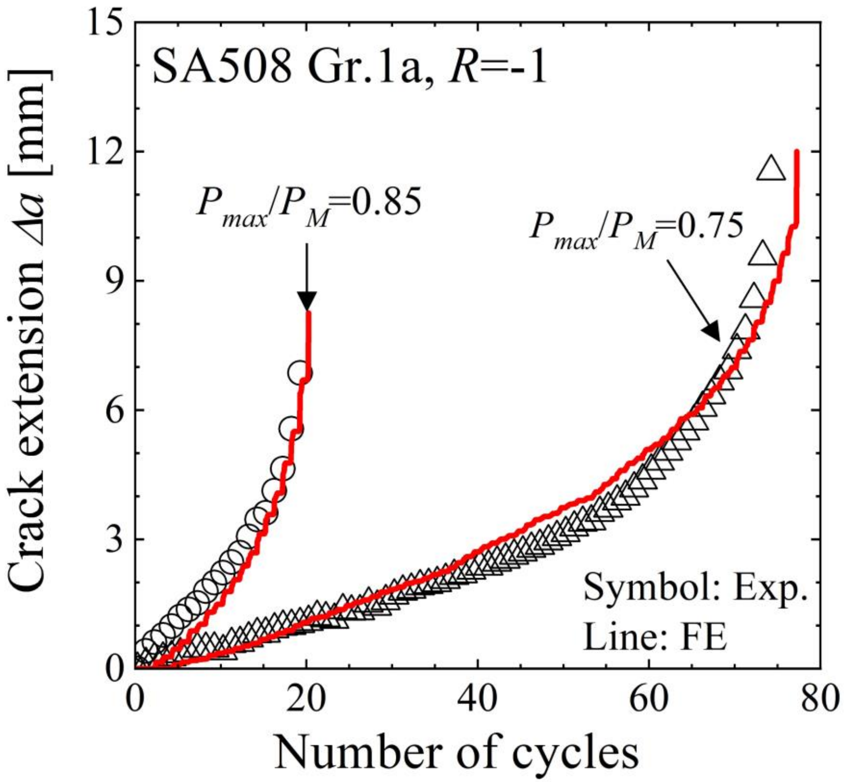
Maximum load in monotonic pipe test data (P_M=30.kN)

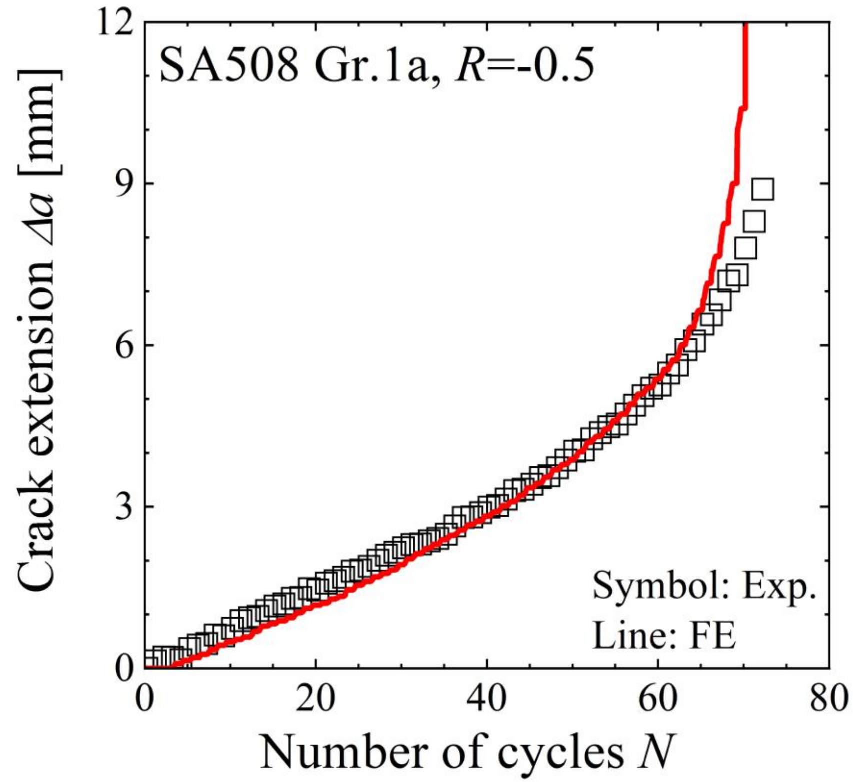
Cyclic FE Pipe Fracture Analysis Model

- Load controlled VLCF → Cload in ABAQUS option
- Same as monotonic FE pipe mesh
- Crack closure effect



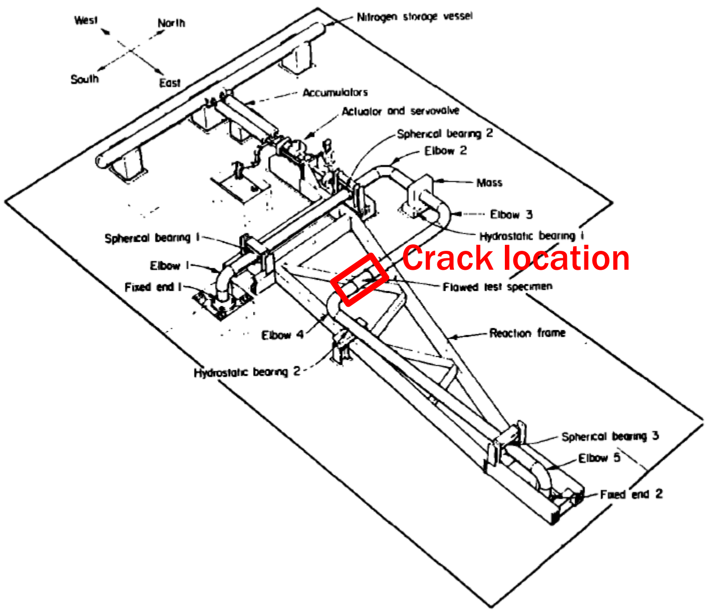
Pipe Crack Growth and Fracture Prediction



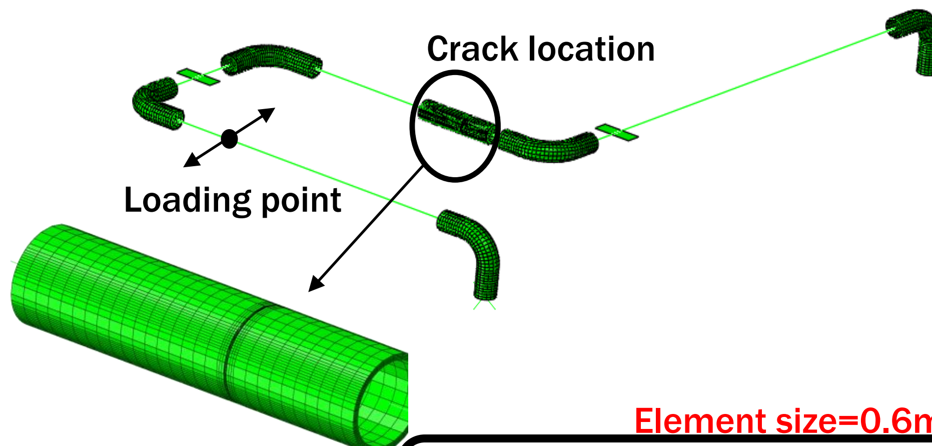


P_{max}/P_M	Load ratio R	Failure cycle (Exp.)	Failure cycle (FE)
0.85	-1	21	21
0.75		76	77
0.75	-0.5	74	70

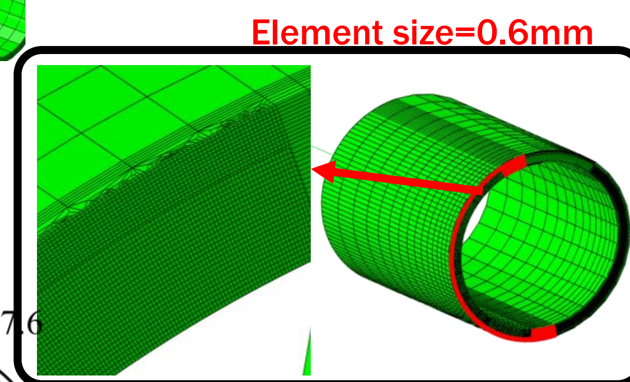
FE Mesh (Solid + Beam Hybrid FE Model)



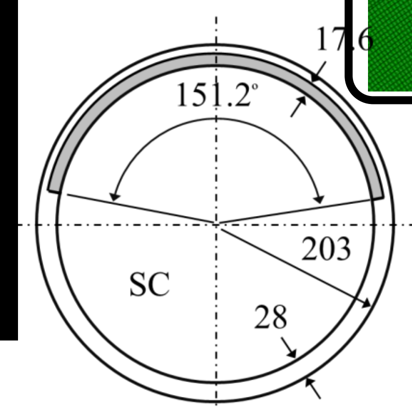
- FE analysis model



Crack plane

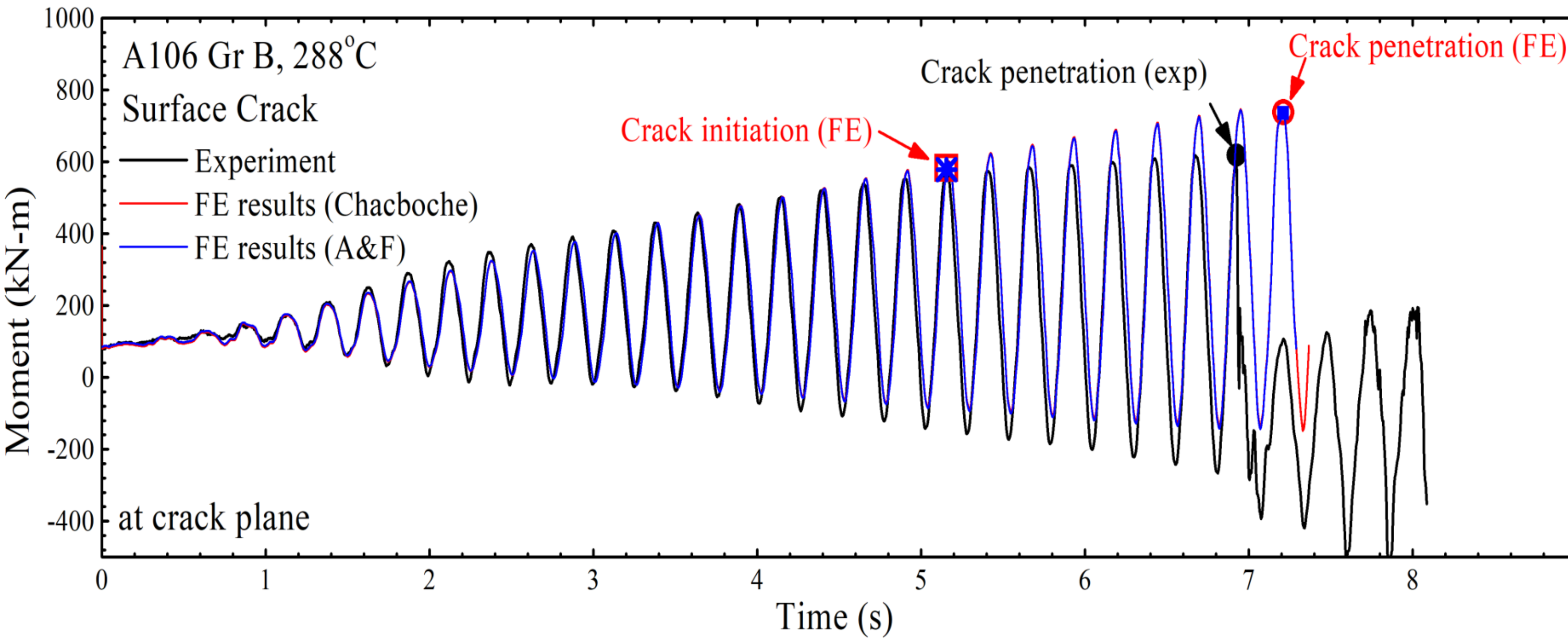


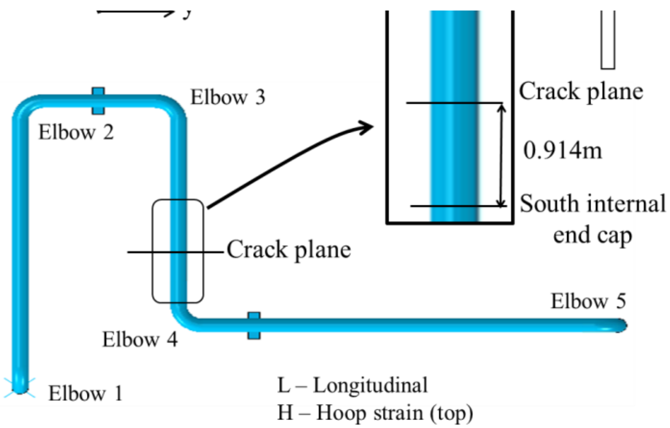
Surface crack



FE Results

- **Comparison of FE results with experiment results (Moment at crack plane)**

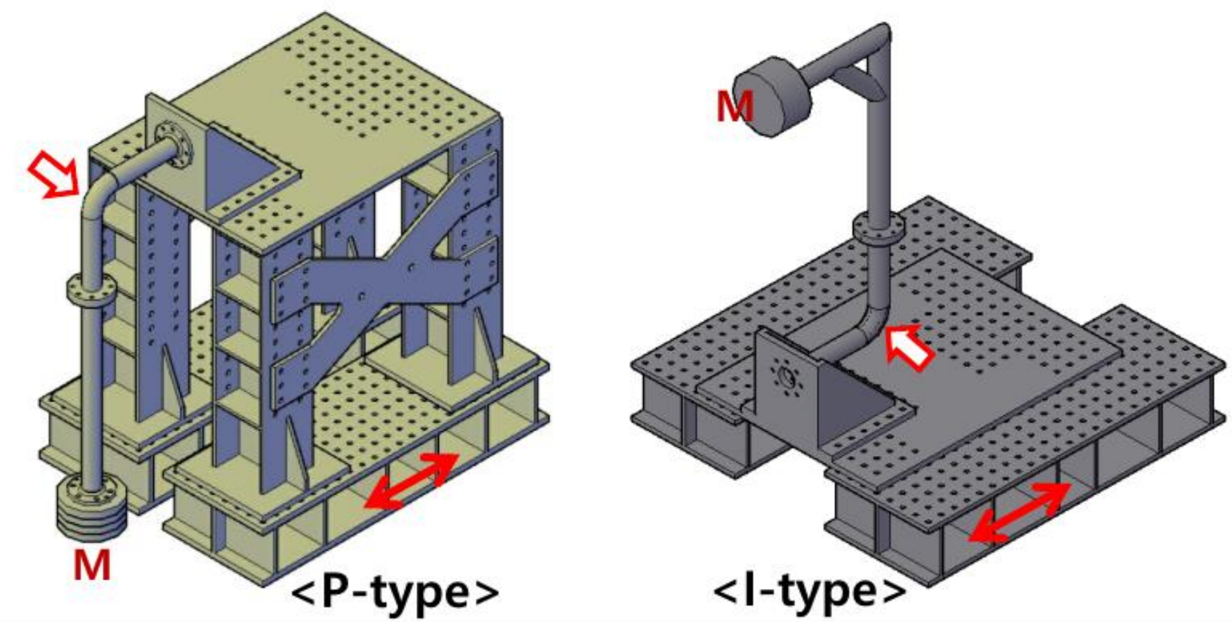




On-Going Works

CHOSUN UNIVERSITY

❖ Application to fracture assessment of un-cracked elbows under quasi-static and dynamic cyclic loading



Thermo-Mechanical Mechanical Loading – Ductile Fracture Modeling Examples (Severe Accident)

Input

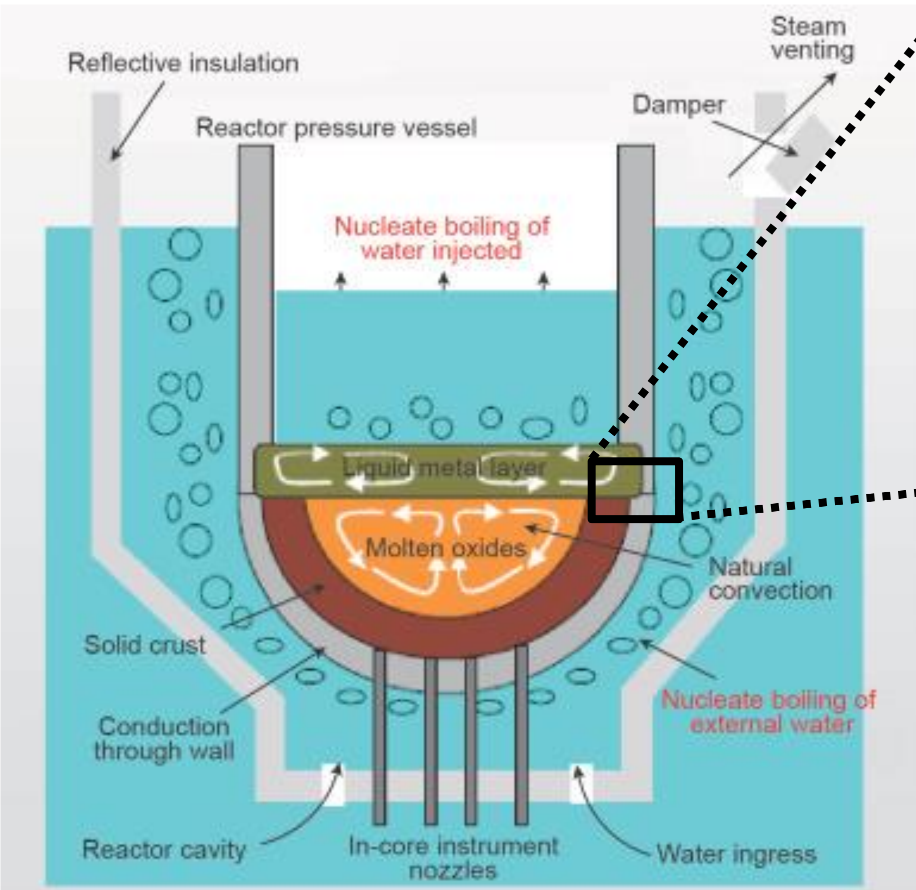
Model	Required data
Constitutive model	Temperature-dependent monotonic tensile test data
Damage model	Temperature-dependent uni-axial fracture strain data

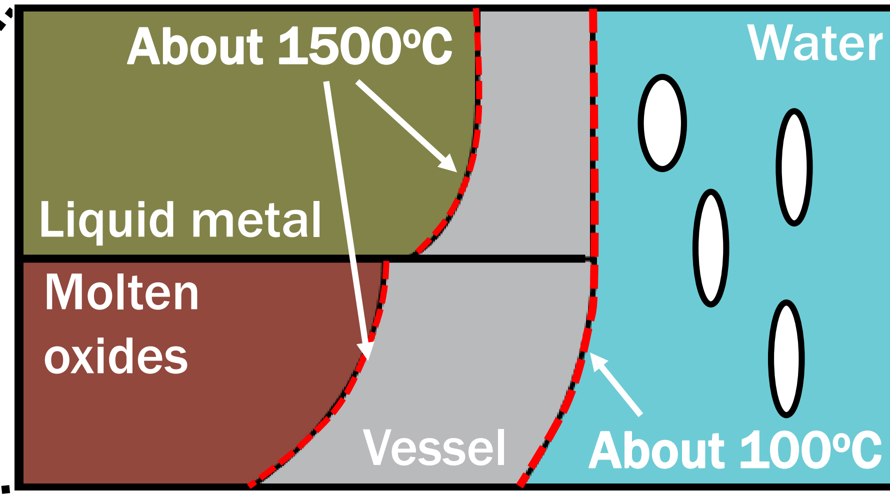
Output

Under severe accident condition,
Deformation, failure time and size of vessel components

IVR-ERVC (In-Vessel Corium Retention – External Reactor Vessel Cooling)

➢ Severe Accident Management strategy





Harsh temperature and pressure transient conditions

→ Prediction of vessel failure time and location important

→ Understanding of temperature-dependent deformation and fracture behavior

Visco-plastic constitutive law

CRIEPI Central Research Institute of Electric Power Industry

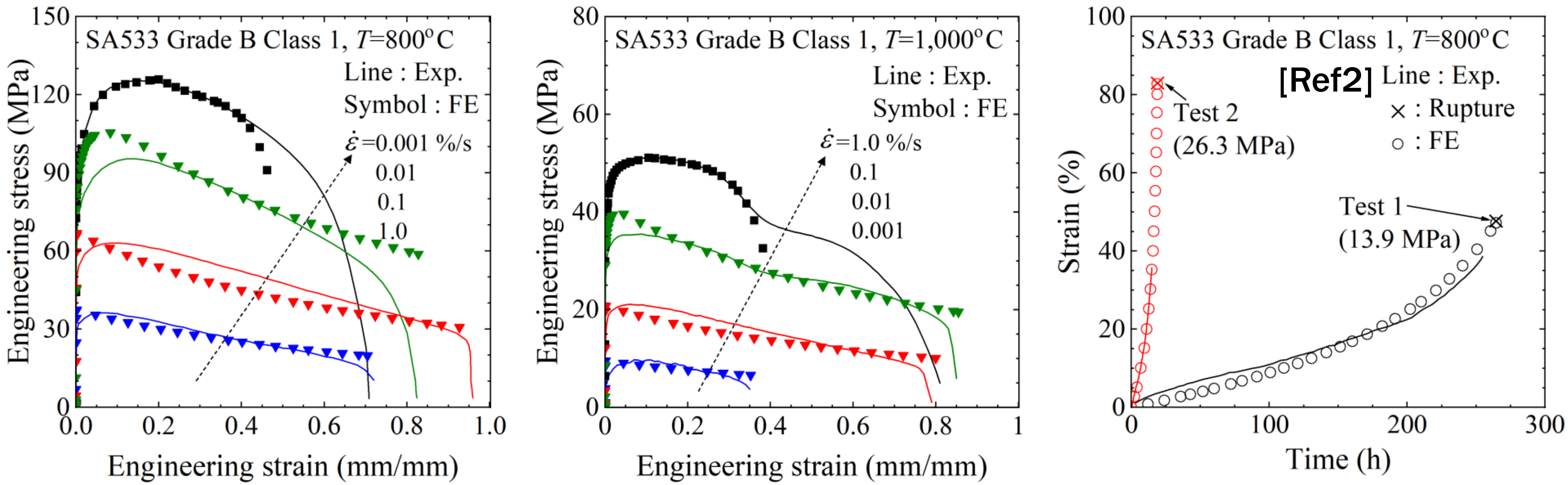
➢ Plastic deformation model[Ref1]

$$\sigma = \sigma_y + \int \frac{d\sigma}{d\varepsilon_{in}} d\varepsilon_{in} \quad \Leftarrow \quad \frac{d\sigma}{d\varepsilon_{in}} = \sigma_0^{\ m} \left[\frac{1}{m\sigma^{m-1}} - \frac{\left\{ \left(1 + A\varepsilon_{in} \right) \sigma \right\}^p}{\sigma_r^{\ m+p-1}} \right]$$

- σ_y: yielding strength
- ***m*, *p*, *A* :** material constant
- σ_0: strain hardening parameter dependent on Temperature & Strain rate
- σ_r: strain softening parameter dependent on Temperature & Strain rate

➢ Creep model

$$\dot{\varepsilon} = K(T)\sigma^{n(T)}$$

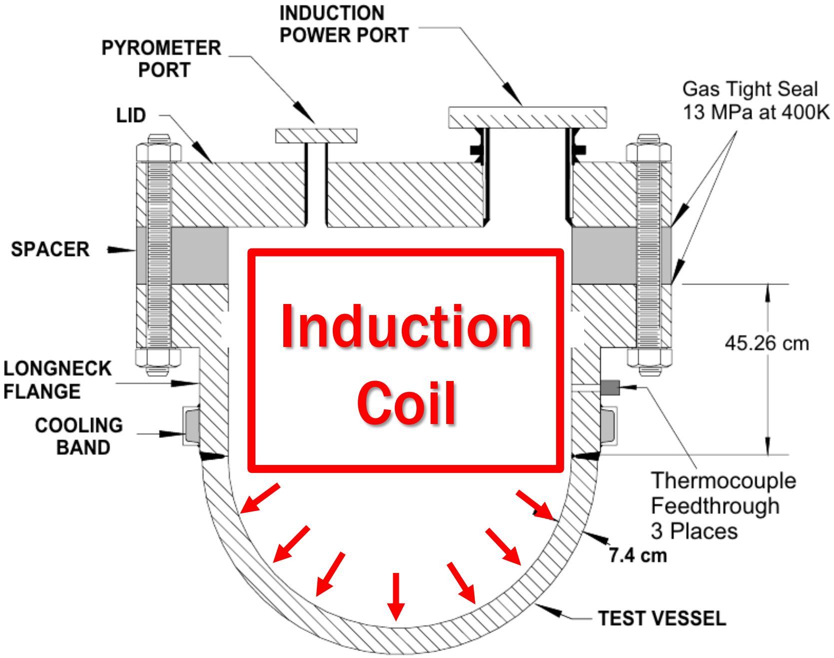


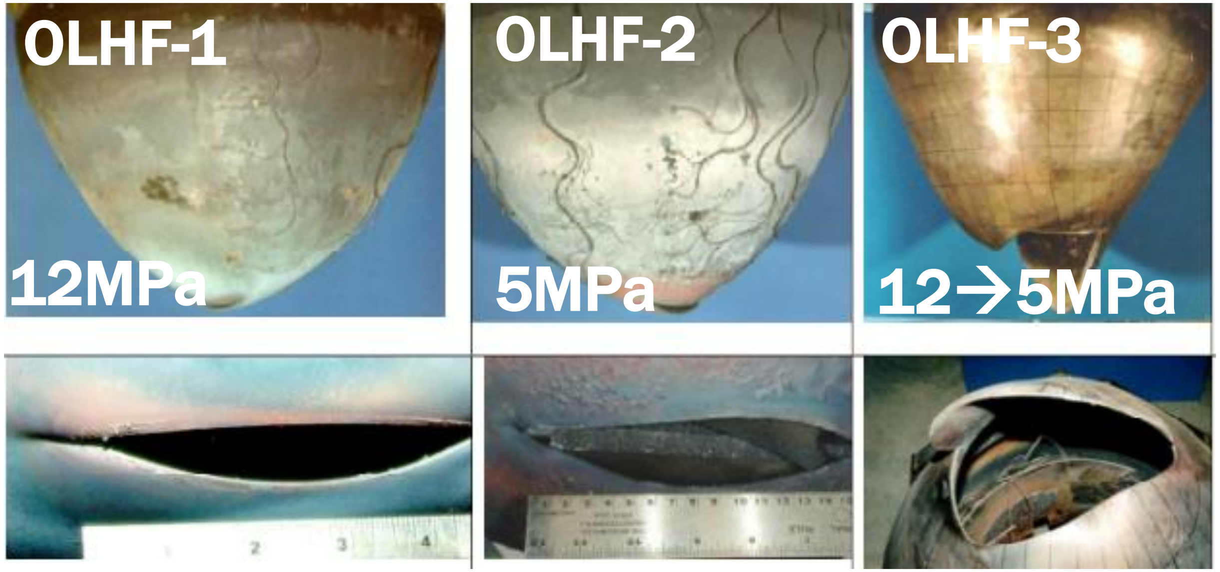
[Ref1] Y. Takahashi. Unified constitutive modeling of three alloys under a wide range of temperature, IJPVP, 2019.
[Ref2] J.L. Rempe et al. Light Water Reactor Lower Head Failure Analysis, NUREG/CR-5642, 1993

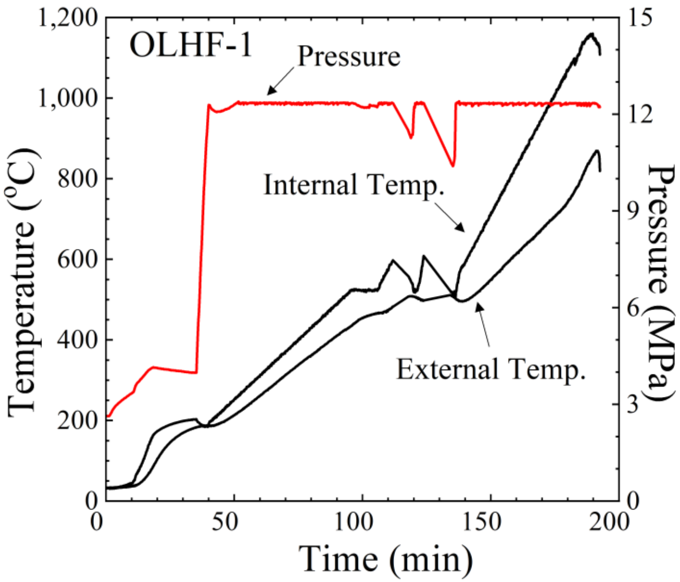
OLHF (OECD Lower Head Failure)

Vessel Material : SA533B1

Figure 2.9 Assembled vessel on test stand

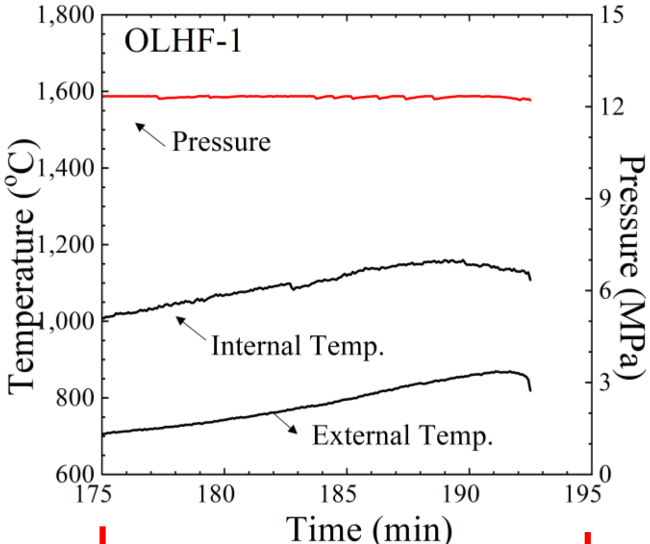


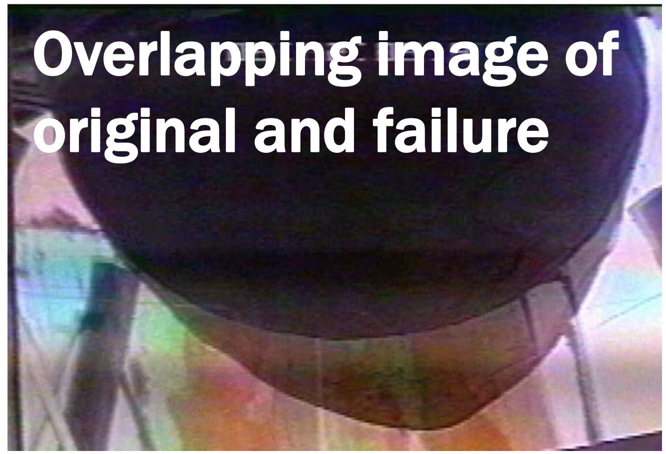


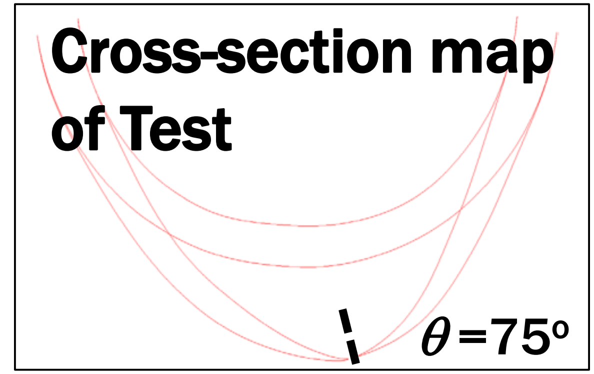


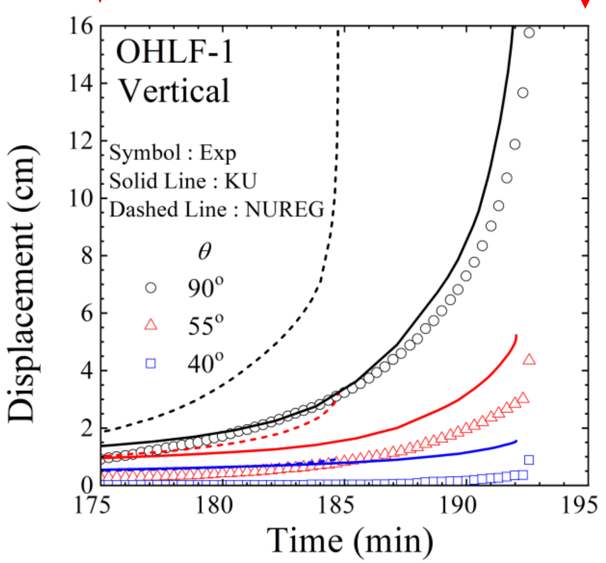
[Ref] L.L. Humphries et al. OECD Lower Head Failure Project Final Report, Sandia National Laboratories, 2002.

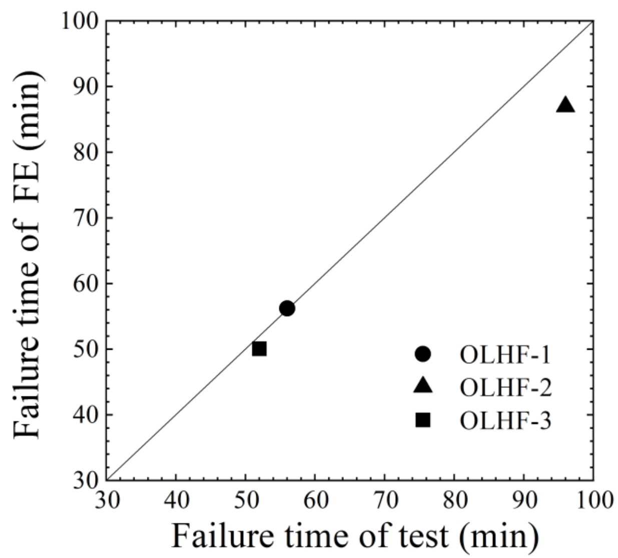
OLHF Simulation

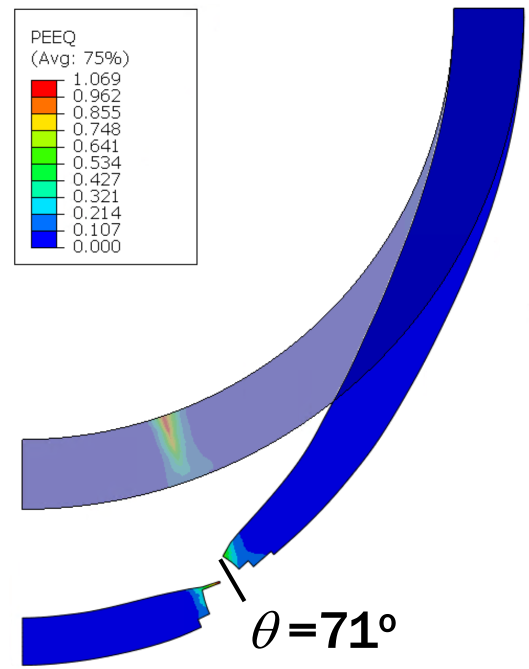








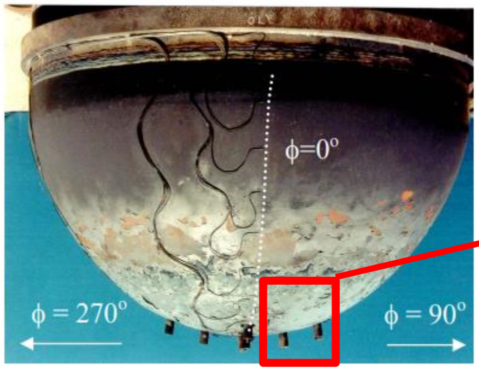




[Ref] L.L. Humphries et al. OECD Lower Head Failure Project Final Report, Sandia National Laboratories, 2002.

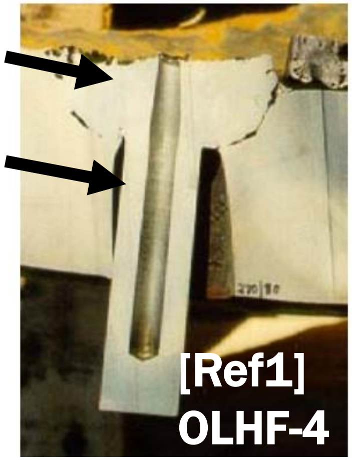
On-Going Works

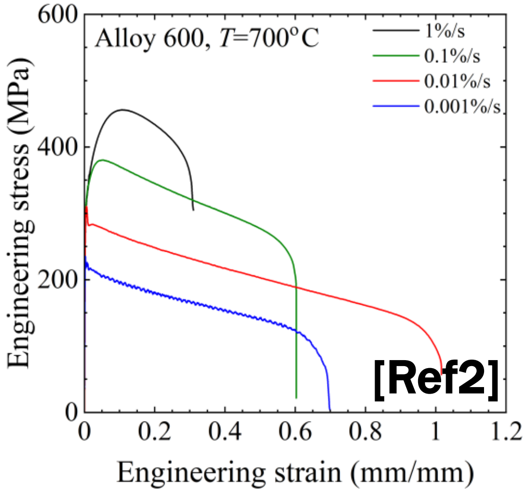
- ❖ Development of temperature-dependent visco-plastic deformation and fracture strain models for Alloy 600 / SUS 316 / Alloy 82/182

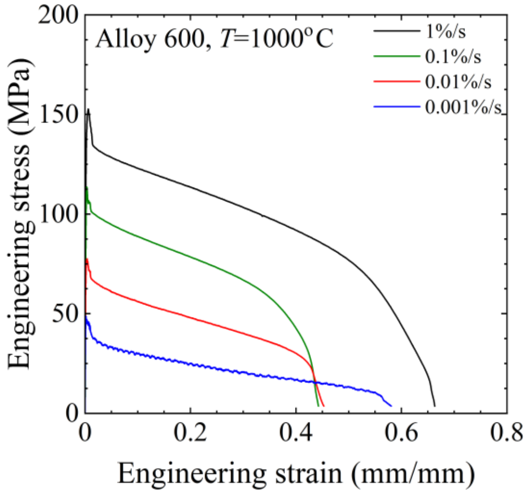


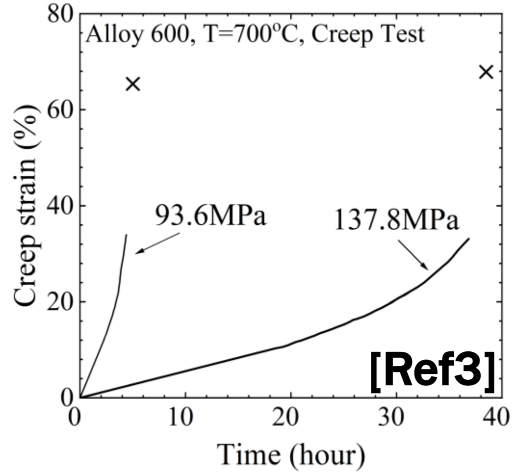
Alloy182

Alloy600









[Ref1] L.L. Humphries et al. OECD Lower Head Failure Project Final Report, Sandia National Laboratories, 2002.
[Ref2] Y. Takahashi. Unified constitutive modeling of three alloys under a wide range of temperature, IJPVP, 2019.
[Ref3] J.L. Rempe et al. Light Water Reactor Lower Head Failure Analysis, NUREG/CR-5642, 1993

Impact Loading (Collision/Penetration) – Ductile Fracture Modeling Examples

Input

Model	Required data
Constitutive model	Temperature dependent monotonic tensile test data
	Strain rate dependent monotonic tensile test data
Damage model	Temperature dependent uni-axial fracture strain data
	Strain rate dependent uni-axial fracture strain data

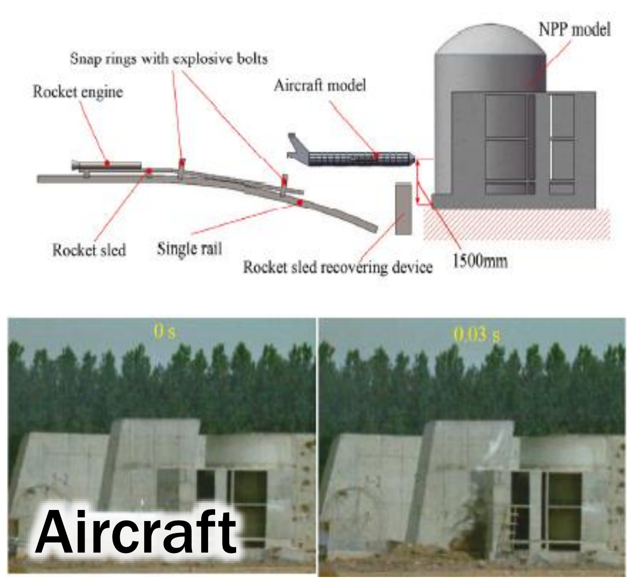
Output

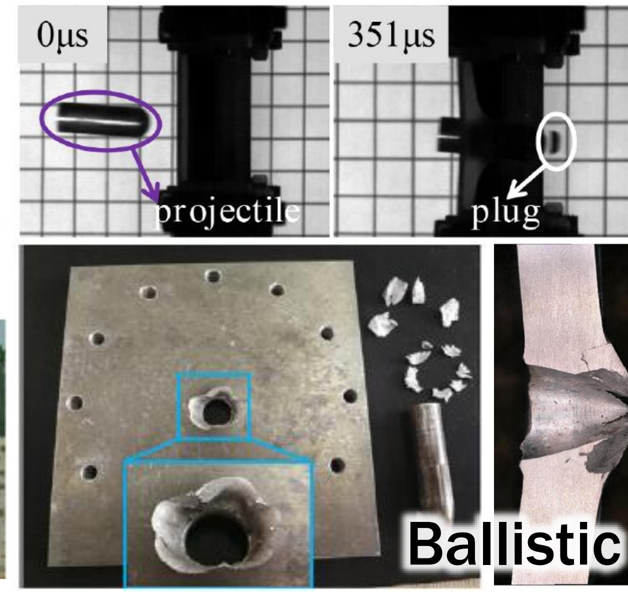
Under collision/drop accident condition,
Deformation, fracture or penetration

Impact Loading (Collision/Penetration) – Problems in Nuclear Power Plant

❖ Spent-fuel storage cask, Small modular reactors

→ Risk assessment against drop, crash and attack





❖ High strain rate and temperature, mixed stress state

[X] K.S. Kim, Dynamic impact characteristics of KN-18 SNF transport cask–Part 1: An advanced numerical simulation and validation technique, *Ann Nucl Energy*, 2010.

[X] Z.R. Li, Damage and vibrations of nuclear power plant buildings subjected to aircraft crash part II: Numerical simulations. Nucl Eng Technol, 2021.

[x] Y Wang, Effect of Lode angle incorporation into a fracture criterion in predicting the ballistic resistance of 2024-T351 aluminum alloy plates struck by cylindrical projectiles with different nose shapes. Int J Impact Eng, 2020.

Deformation Properties for Impact Loading
Strain rate / Temperature

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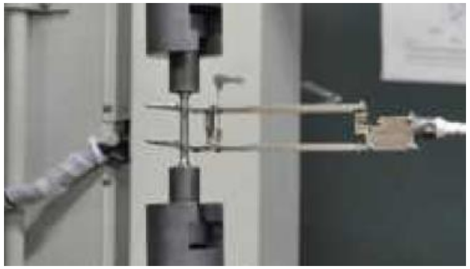
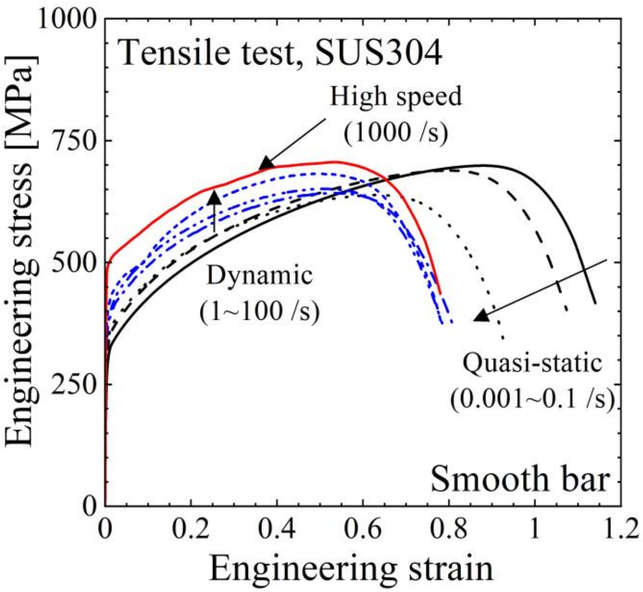
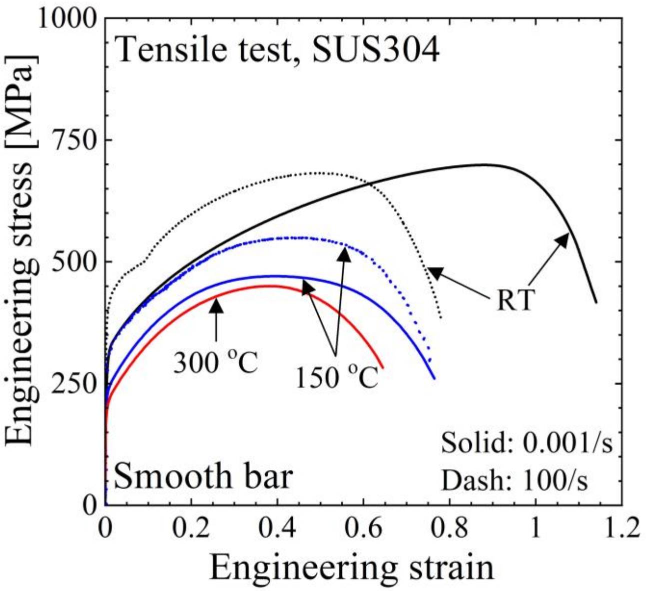


Tensile test
(Quasi-static, dynamic)

Split-Hopkinson Bar
(High speed: >1000/s)

- Temperature: RT, 150 °C, 300 °C
- Strain rate: Quasi-static, dynamic, high speed





Johns-Cook (J-C) constitutive model:

$$\sigma_{eq} = \left[A + B\varepsilon_{eq}{}^{n} \right]\left[1 + C_1 \ln \dot{\varepsilon}^{*} \right]\left[1 - T^{*m} \right]$$

[x] JM Seo, Modification of the Johnson–Cook model for the strain rate effect on tensile properties of 304/316 Austenitic stainless steels, J Press Vessel Technol, 2022

Fracture Properties for Impact Loading
Strain rate / Temperature

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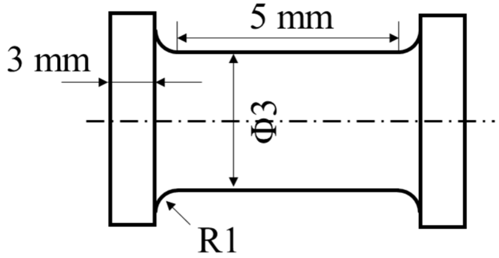
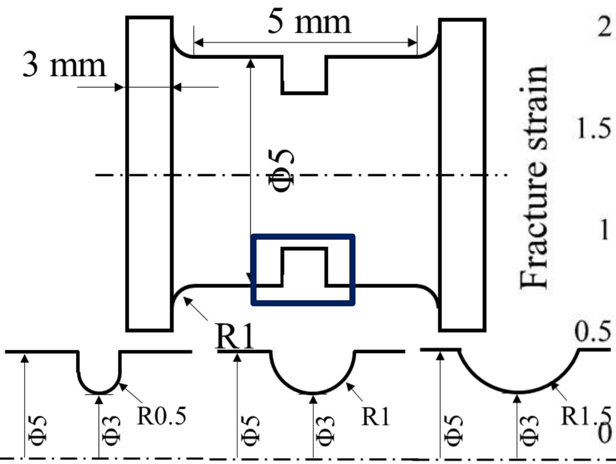
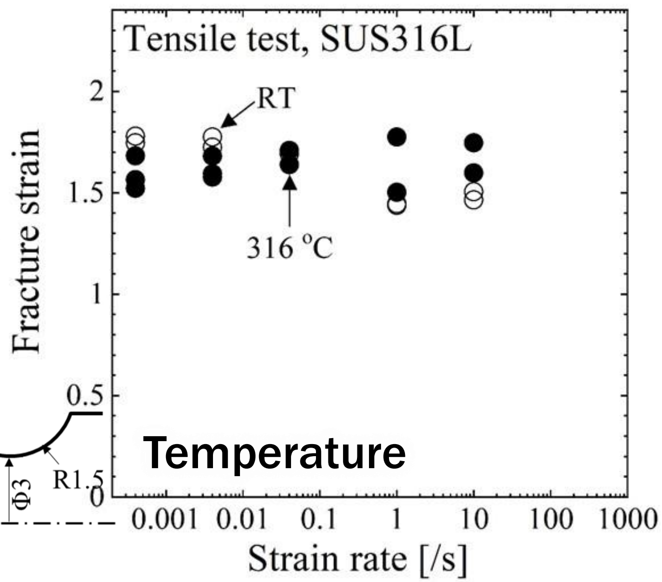


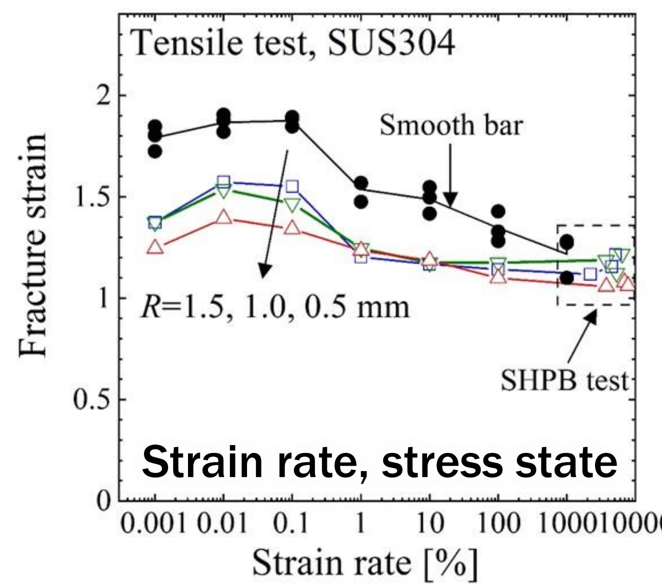
Smooth bar

- **Temperature: RT, 310 ºC**
- **Strain rate: Quasi-static, dynamic, high speed**
- **Stress state: Smooth bar, notched bare**



Notched bar
(R=0.5, 1, 1.5 mm)





Johns-Cook (J-C) damage model:

$$\varepsilon_f = \left[D_1 + D_2 \exp\left(D_3 \eta\right)\right]\left[1 + \dot{\varepsilon}^*\right]^{D_4}\left[1 - D_5 T^*\right]$$

[x] JM Seo, Modification of the Johnson–Cook model for the strain rate effect on tensile properties of 304/316 Austenitic stainless steels, J Press Vessel Technol, 2022

Penetration Test for SUS316L (CRIEPI, Japan)

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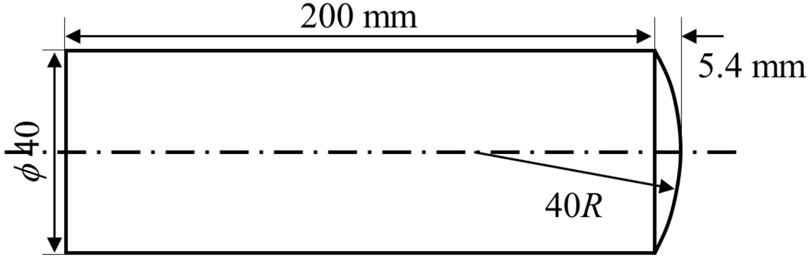
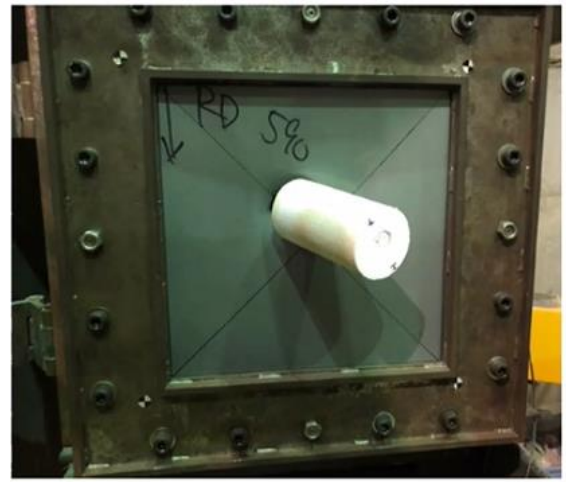
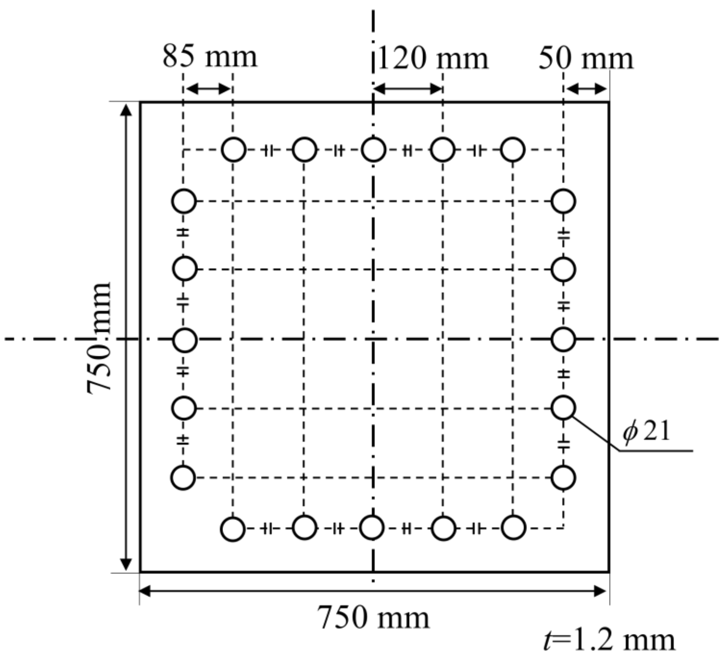
- Bullet (*D*=40 mm)

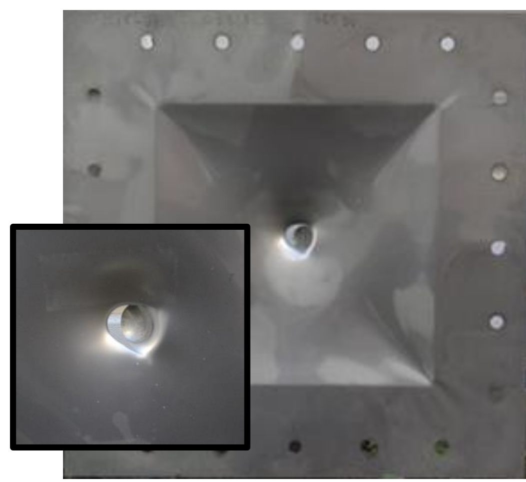




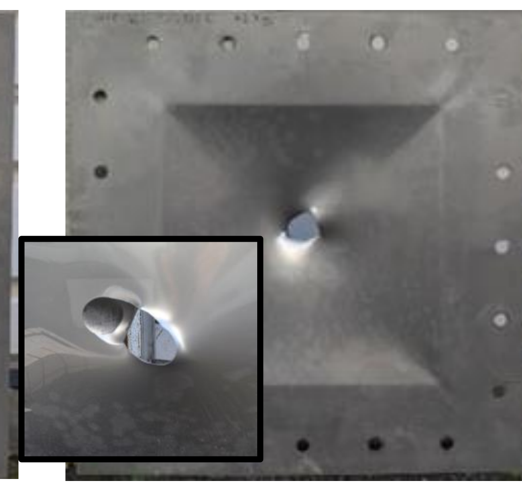
- Impact velocity: 33 ~ 50 m/s
- Ballistic limit: ~ 45 m/s

- Thin plate (*t*=1.2 mm)



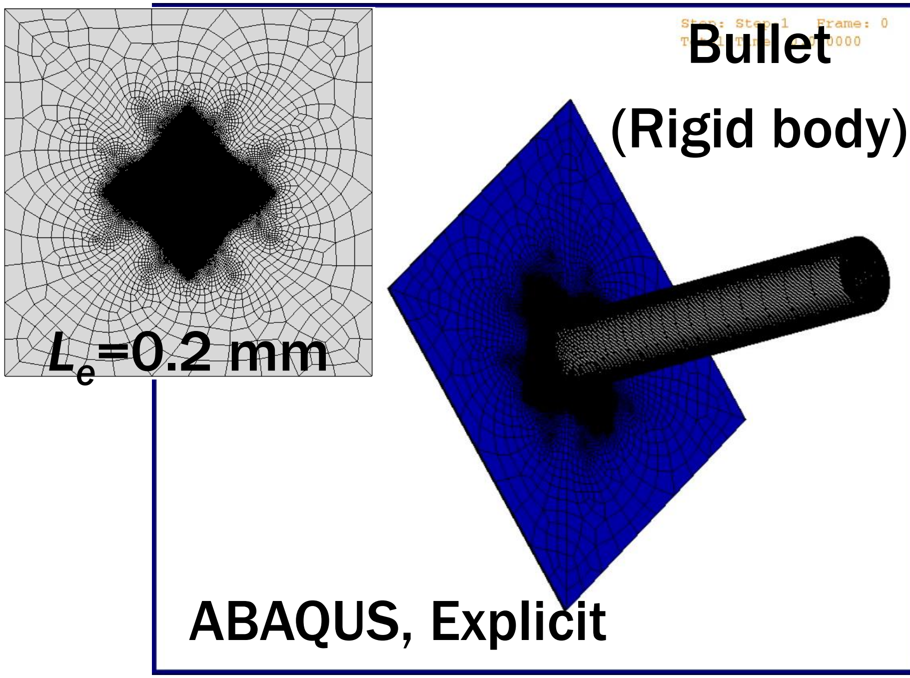


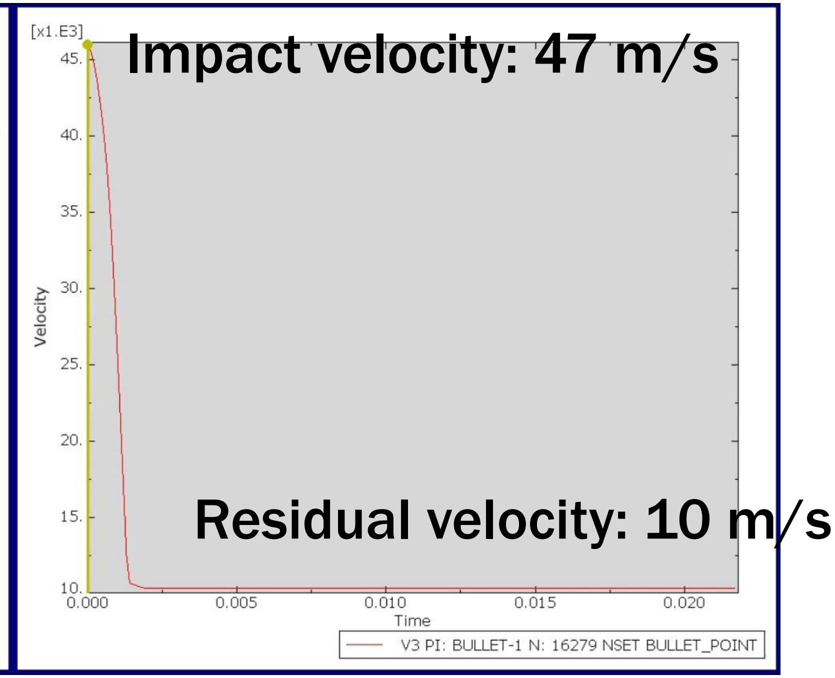
No penetration / Crack
(44 m/s)

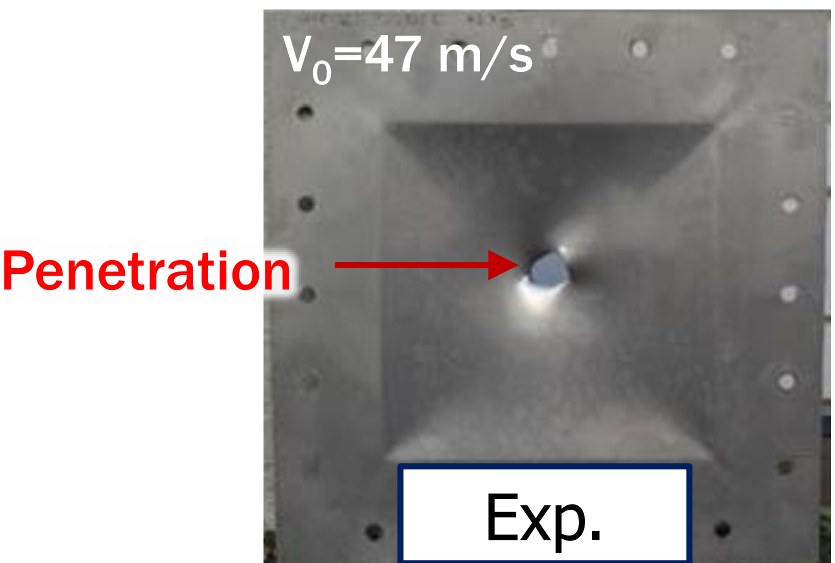


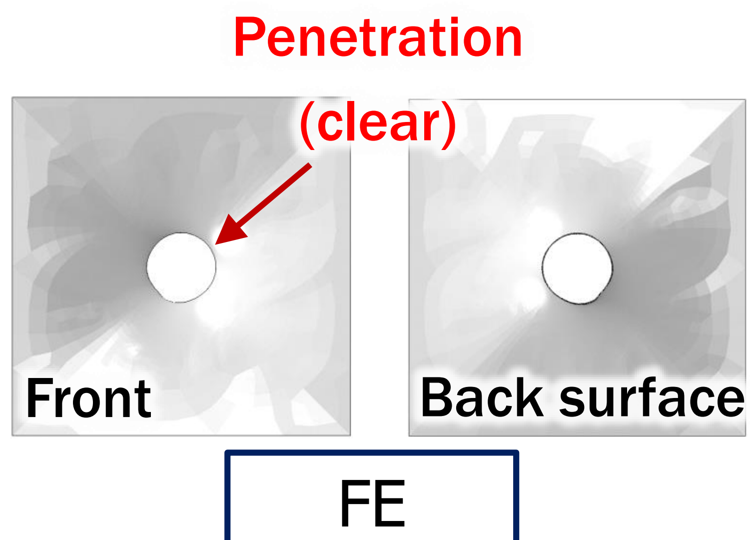
Penetration
(47 m/s)

Penetration Simulation (Penetration: 47 m/s)

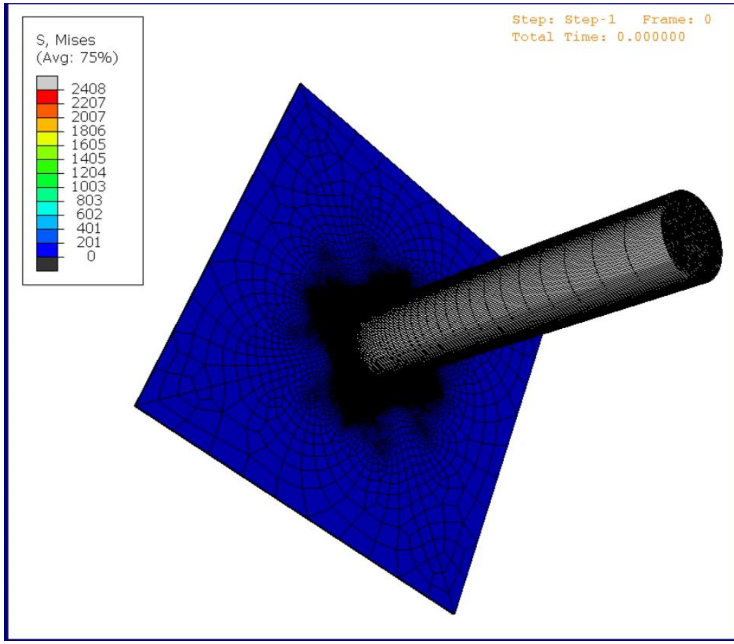


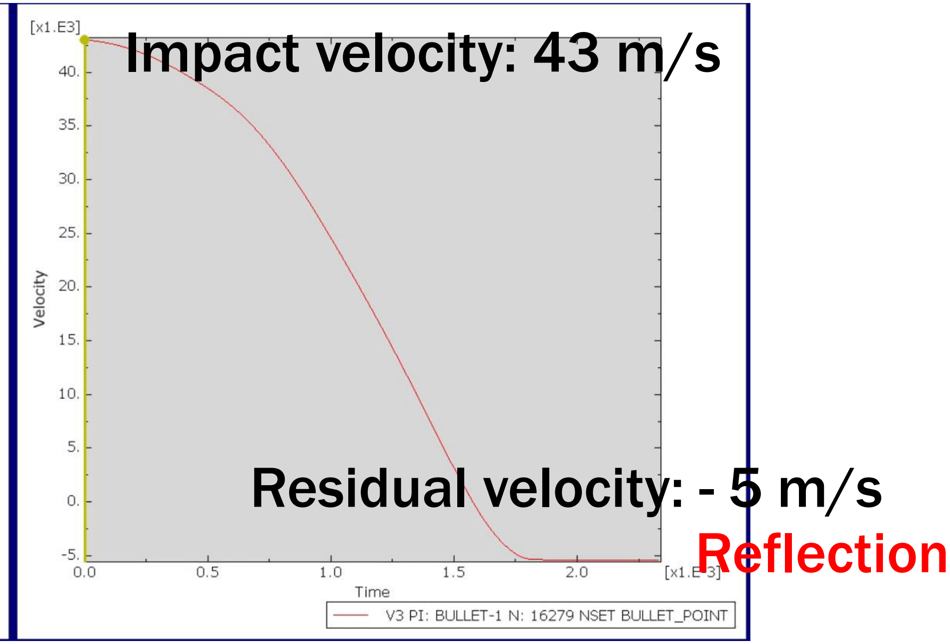


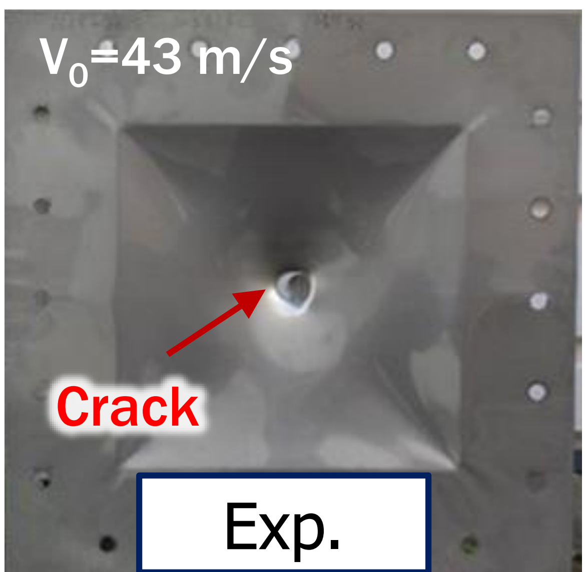


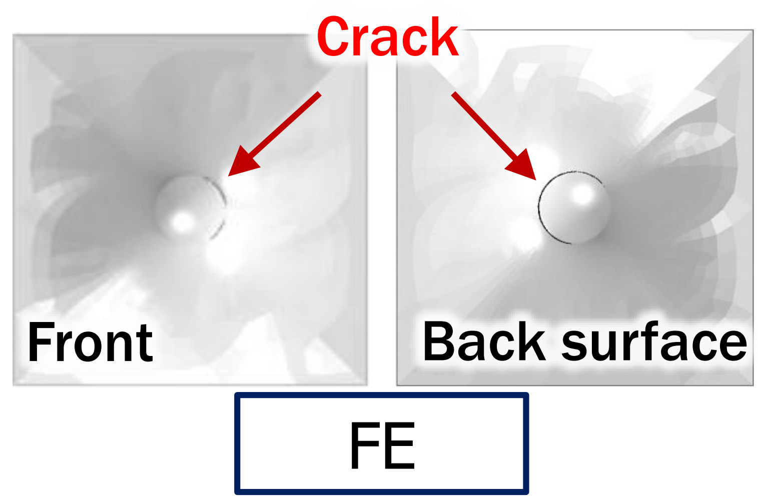


Penetration Simulation (No penetration: 43 m/s)

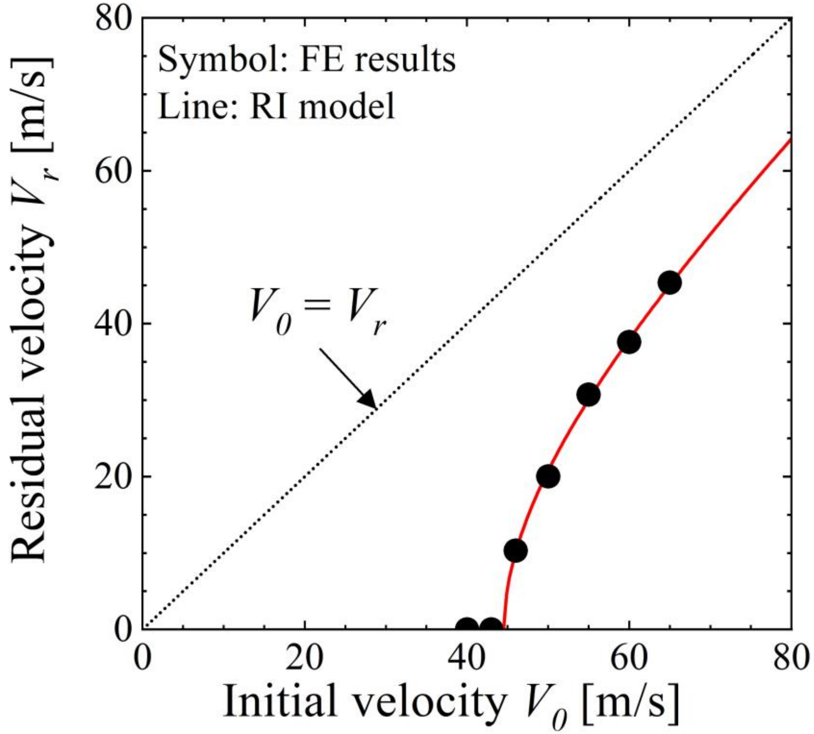








Penetration Simulation Results (RI model)



- Recht and Ipson (RI) model
→ Proven model to predict residual velocity

$$V_r = a\left(V_0{}^p - V_{bl}{}^p\right)^{1/p} \qquad a = \frac{m_p}{m_p + m_{pl}} \approx 1$$

- V_{bl}: ballistic limit (V_r=0, max. V_0)
- p: material constant

Experimental ballistic limit is expected to be about 44~46 m/s

Residual velocity can be well predicted using FE penetration simulation

On-Going Works

- Penetration experiments : Effects of the thickness and nose shape for carbon steel / SUS304 / SUS304L / SUS316L

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- Further development of temperature, strain-dependent visco-plastic deformation and fracture strain damage model for penetration simulation

Thank you
Very much