JK-SEAD 2026
Resilience of NPPs Considering External Hazards (JAEA-KAERI Joint workshop)

Day2 #3

Stress classification approach for failure modes of piping elbow under seismic loads

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Including following published at academic conferences:

- Takito, et al., Development of seismic response analysis method of piping system; Proposal of the nonlinear spring model for piping support structures, PVP2023, (2023), PVP2023-108029
- Nakamura, Takito, et al., Benchmark analysis on pipe support structures for establishing inelastic seismic design, PVP2024, (2024), PVP2024-123075
- Takito, et al., Investigating the influence of analysis parameters in three-dimensional elasto-plastic finite element analysis of a gate-type piping support structure, PVP2024, (2024), PVP2024-122635
- 滝藤ほか、Natechリスク評価に資する配管系の損傷モード分類のための配管継手に対する加振試験、日本機械学会2024年度年次大会
- Takito, et al., Vibration tests for failure mode analysis of piping system toward Natech risk assessment, PVP2025, (2025), PVP2025-151224
- 滝藤ほか、産業施設の地震時配管系の機能維持性能評価に関する研究（配管系加振試験に基づく損傷モードの分析）、D&D2025
- Takito, et al., Stress Class Approach for Failure Modes of Piping Elbows Under Seismic Loads, PVP2026-177209
- 滝藤ほか、配管系の損傷モード分類のためのエルボ配管要素加振試験(損傷モードと発生モーメントの関係についての一考察)、日本機械学会2026年度年次大会

未来へげんき
To the Future / JAEA

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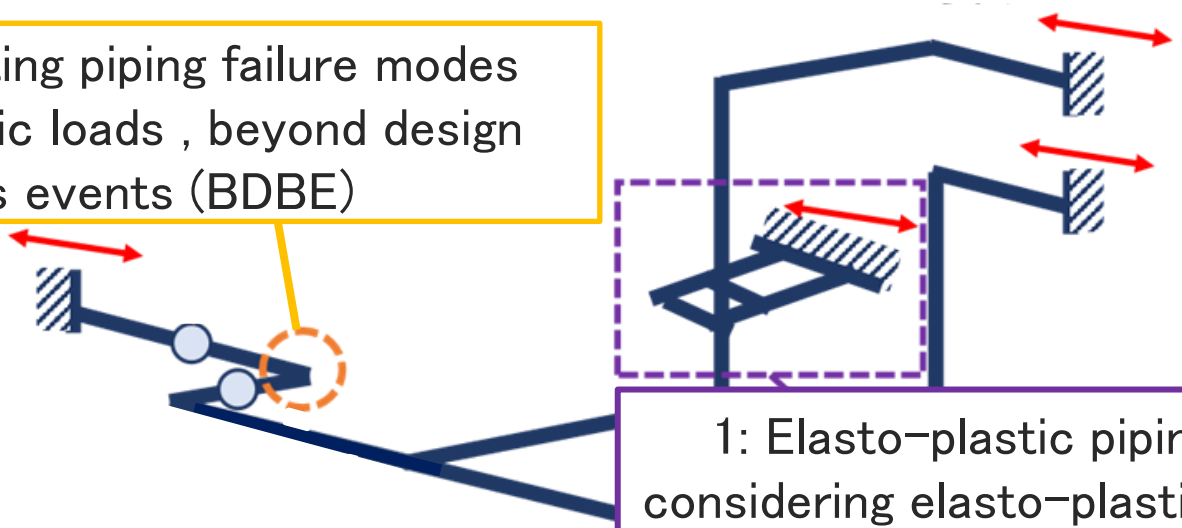
◆ **Outline:**

1. **Elasto-Plastic Piping Response with Piping Supports**
2. **Risk Assessment** (Natach Risk Assessment @ B/C class piping)

1 Piping supports; To consider the elasto-plastic response of piping systems with piping supports, static load tests were conducted on the supports (Okuda, et al. 2023). A load-displacement relation modeling method for the supports was proposed (Takito, et al., 2023, 2024c), and analytical parameters for their analysis were studied (Takito, et al. 2024b).

2: Investigating piping failure modes under seismic loads , beyond design basis events (BDBE)



K. Takito, et al., "Overview of the benchmark analysis for piping support structures in the task force phase 2-2", JSME Conf., 2023, Tokyo.

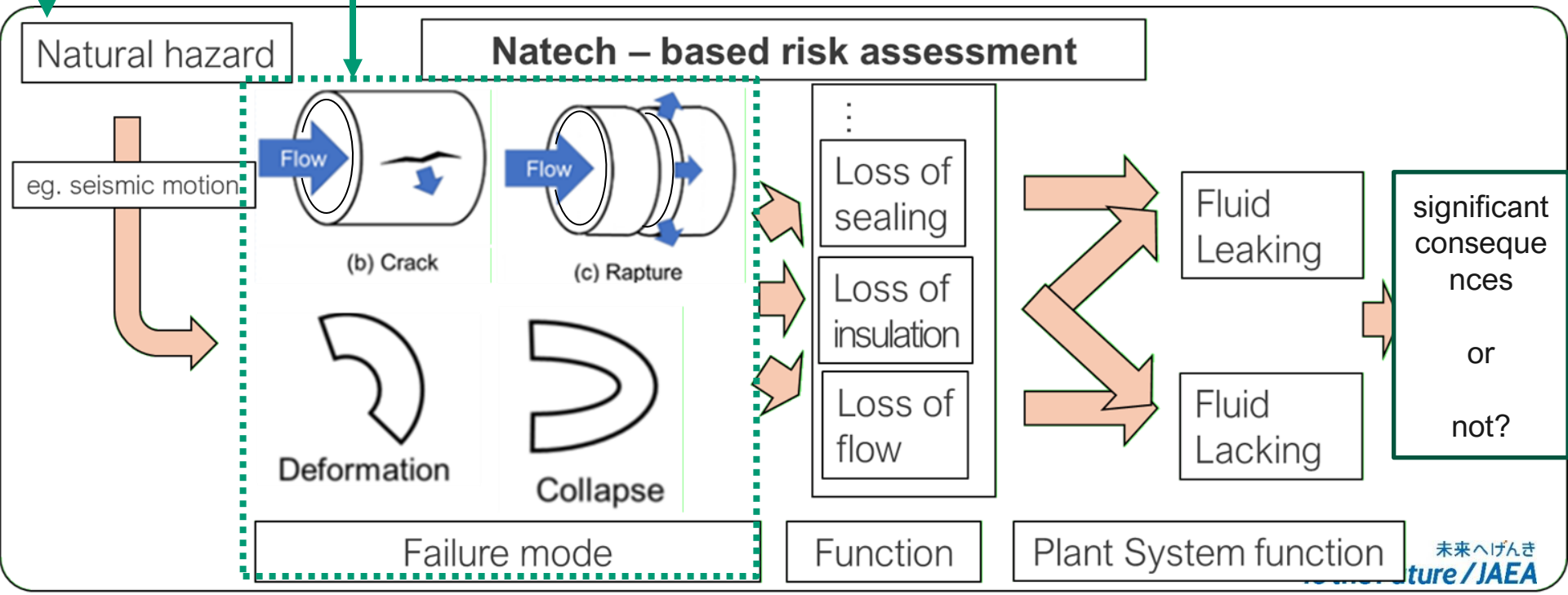
Takito, et al., Investigating the influence of analysis parameters in three-dimensional elasto-plastic finite element analysis of a gate-type piping support structure, PVP2024, (2024), PVP2024-122635

1: Elasto-plastic piping response considering elasto-plastic behaviour of piping supports

A schematic sketch of research scope

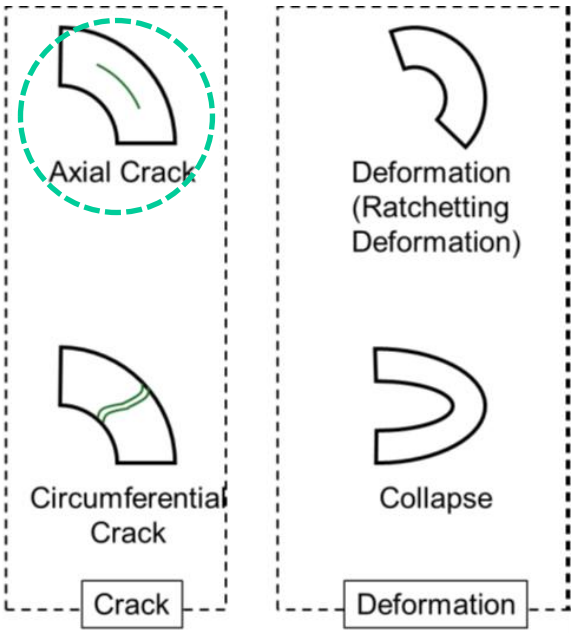
2 Natech based risk assessment; Natural hazard-triggered technological accidents (Natech) (Showalter & Mayer, 1992) has gained attention in the industry, following the Fukushima Daiichi nuclear power plant accident.

- It is necessary to clarify the relationship between required component functions and failure modes. i.e., it is crucial to investigate piping failure modes under seismic loads.

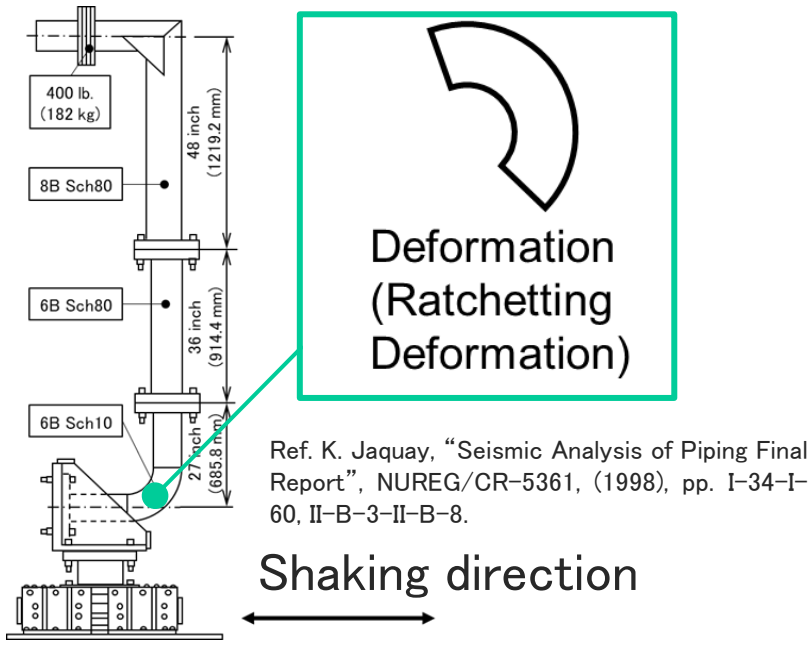


◆ **Background:** Considering Failure Modes

- Typical failure modes for elbows include axial cracking, plastic collapse, break, and ratchet deformation (Mano et al., 2023). A typical failure mode of piping under seismic motion is axial cracking on the elbow flank (◌).
- Collapse modes have been previously investigated in Pipe-Fitting Dynamic Reliability Program (PFDRP) test case #37 by the Electric Power Research Institute (EPRI) (Tagart et al., 1990).



Schematic Sketch of Failure Modes



PFDRP#37 test reported deformation

◆ Objectives

- ➢ It is necessary to develop a clearer understanding of the specific conditions that trigger each failure mode.
  - ✓ Focusing on the failure modes of a piping elbow / system test specimen during shaking table test. ☞ *JK-SEAD 2025 @ Tokyo*

⇩ What conditions can cause these failures?

  - ✓ Researching into piping failure mechanisms (for examples: fatigue, ratcheting, and plastic collapse) under dynamic loads. ☞ *today's topic*

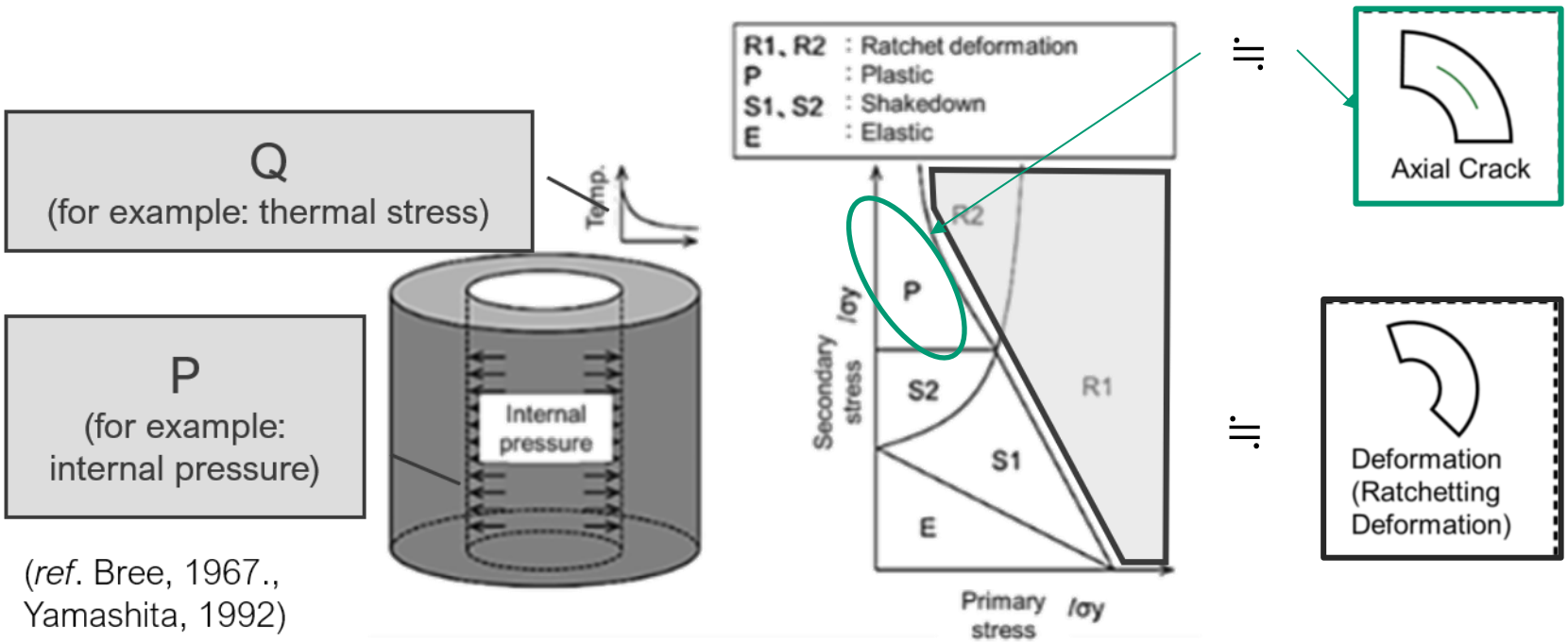
⇩ Two Primary Questions

☐ Which failure mode can occur? / How can the failure mode be interpreted?

- ✓ To interpret the previous shaking table test data and quantify the relationship between load combinations and failure modes, and propose an approach based on stress-classification.
- ✓ To demonstrate that the proposed approach can reproduce the observed failure modes at elbow joints, which exhibited ratcheting deformation and plastic collapse during the shaking-table tests.

◆ **Reviewing past studies:** Bree diagram

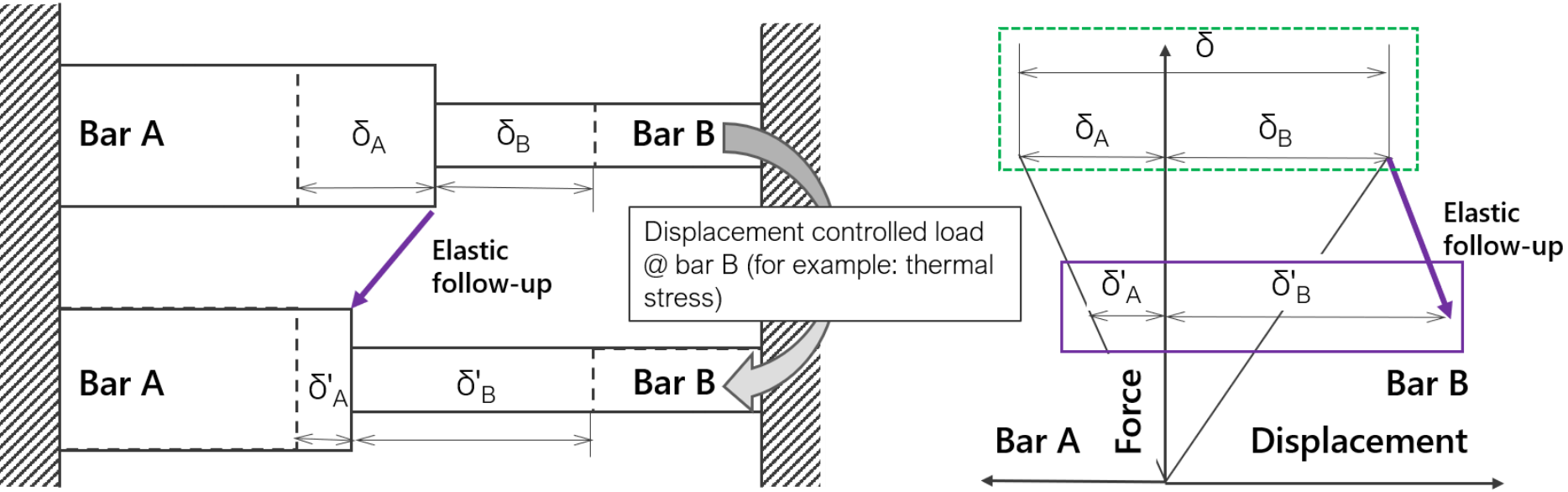
➢ The Bree diagram (see mid down figure) delineates the possible response regimes of the cylinder (elastic, shake-down, ratchet deformation, and plastic-cycle) and clarifies that the structural response depends on the combination of primary and secondary stresses.



Schematic Sketch of a cylinder under pressure and thermal stress (left side)
Bree Diagram (right side)

◆ **Reviewing past studies:** Elastic follow-up

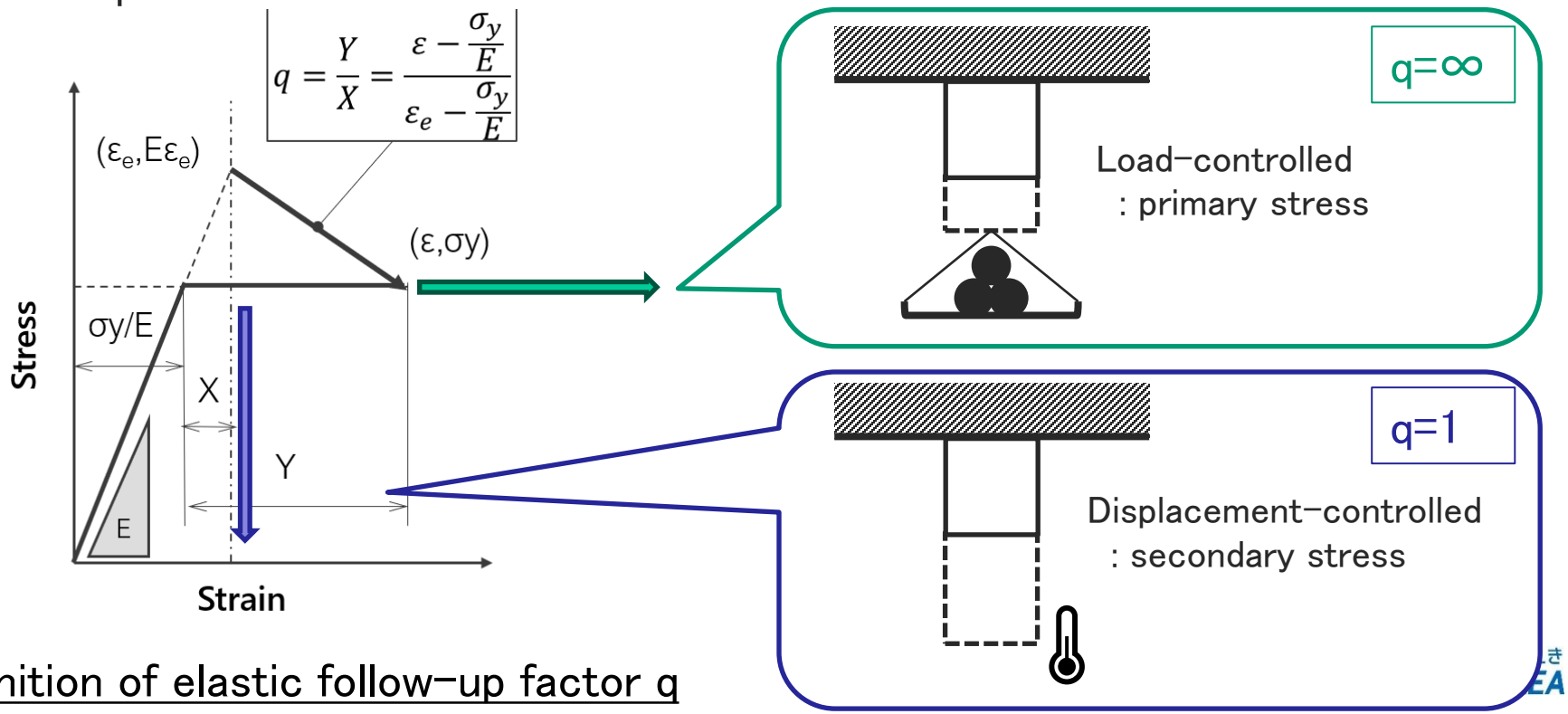
- Consider the simple textbook example of a high-stiffness bar A in series with a low-stiffness bar B. When a displacement ($\delta = \delta A + \delta B$) is applied to bar B, both bars deform elastically (see green broken lined box).
- If the assembly is then maintained at a high temperature, creep and / or plastic strain develops primarily in the more compliant bar B. This nonelastic deformation ($\delta'B$) causes stress relaxation, which in turn allows bar A to recover elastically (see purple lined box).



Two Bars Model (left side) and Force-Displacement Diagram (right side)

◆ **Reviewing past studies:** Elastic follow-up factor q

- The elastic follow-up factor q is then defined as the ratio Y / X.
  - ✓ where, Young's modulus E, and ε, σ are strain and stress when stress redistribution occurs due to elastic plastic and / or creep deformation.
- When q=∞under the (purely) load-controlled condition, q=1 under the displacement-controlled condition.

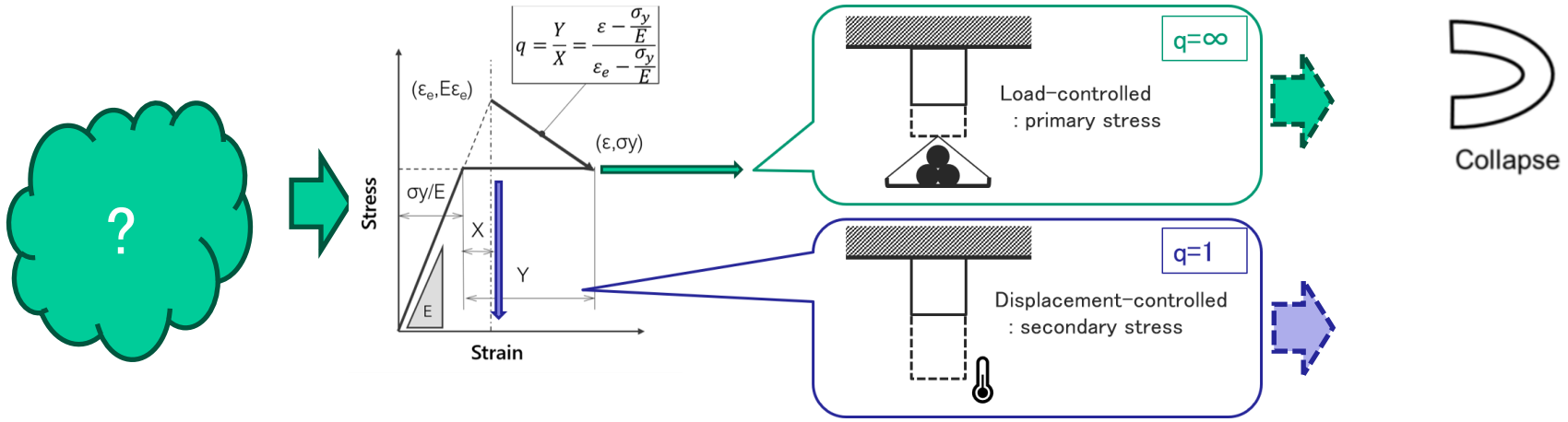


Definition of elastic follow-up factor q

◆ **Reviewing Past Studies:** Stress Classification with q

➢ Kasahara and Takasho (1999) described for a plate with holes: primary and secondary stress classification based on q

☞ Can this stress-classification approaches be applied to the elbow shaking-table test results using q?



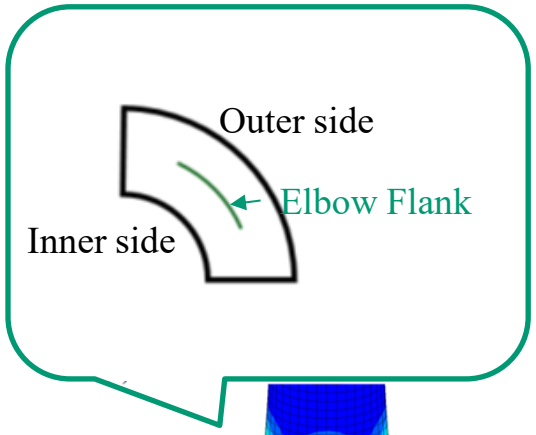
A Structure under loading | Stress Classification with q | Failure Modes

Note: Using elastic follow-up factor q in JSME design code

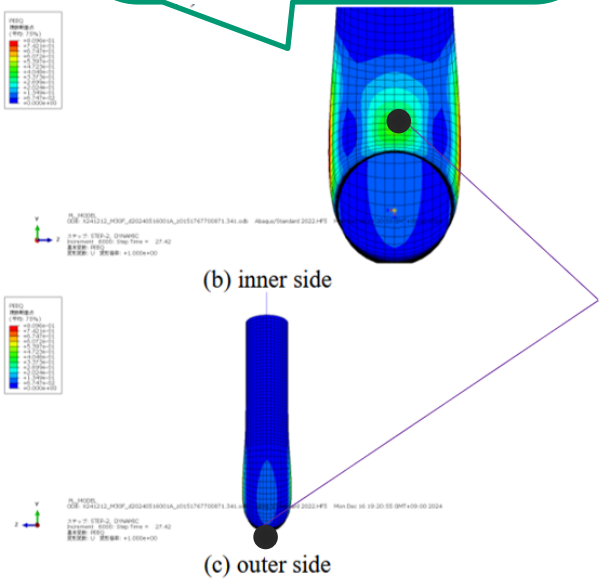
➢ In the current JSME design codes, a simplified elastic plastic analysis is employed: the stress amplitude is given by the product of the alternative stress obtained by elastic analysis and Ke factor (given by the elastic follow-up factor q).

Note: q=3.1 has been specified by the current design code as that envelopes the behaviour of structures (load-controlled)

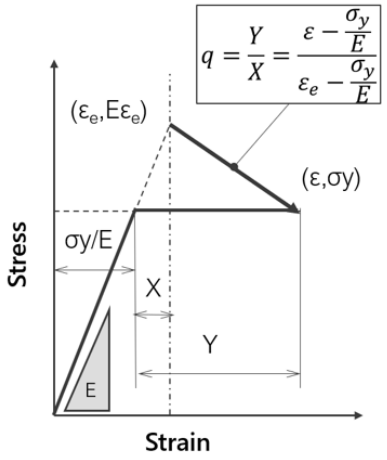
◆ Procedures:



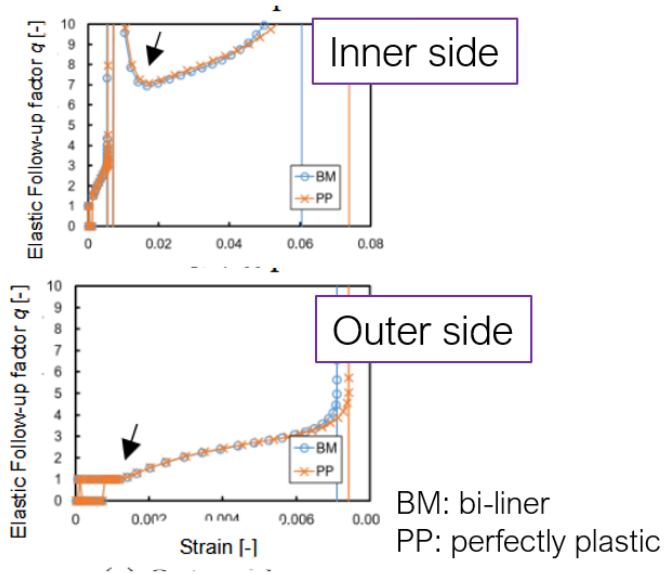
1. Compute total strain, stress σ at each time step through FEA.
2. Calculate q for inner and outer elbow surfaces through q's definition.
3. Focus on local minimum of q. (during the first 1.5 cycles)



STEP1



STEP2



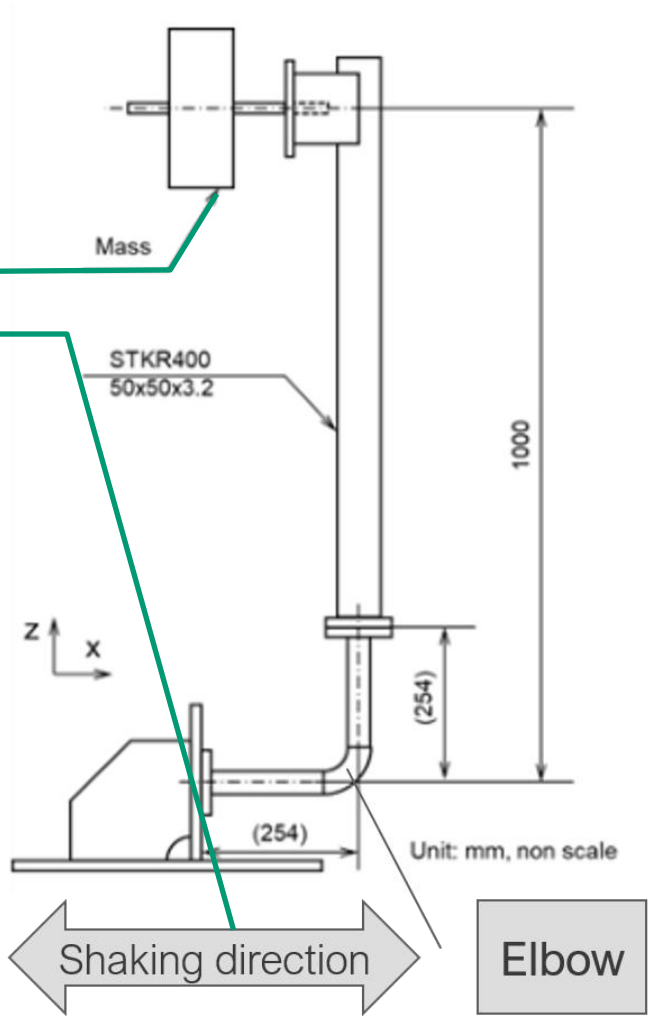
STEP3

Schematic Diagram: Three Steps Procedure

◆ Reminding the Test Specimen

(Takito et al. 2024, 2025)

- **Variable parameters:** Mass, Input
  - Weight 15 kg / 30 kg / 50 kg
  - Acceleration 20 – 1500 Gal*2
- **Specimen geometry:** Elbow
  Do = 34 mm, t = 3.4 mm*1
- **Results:** Failure Modes
  Collapse*3,
  Ratchet deformation*3
  Axial crack (at elbow flank)



Schematic Sketch:
Test Specimen

*1 JIS (Japan Industry Standard) B 2312
*2 Approx.
*3 Failure-mode identification criteria
(crack, ratchet deformation < 40° , collapse ≈ 40° rotation).

◆ Model properties

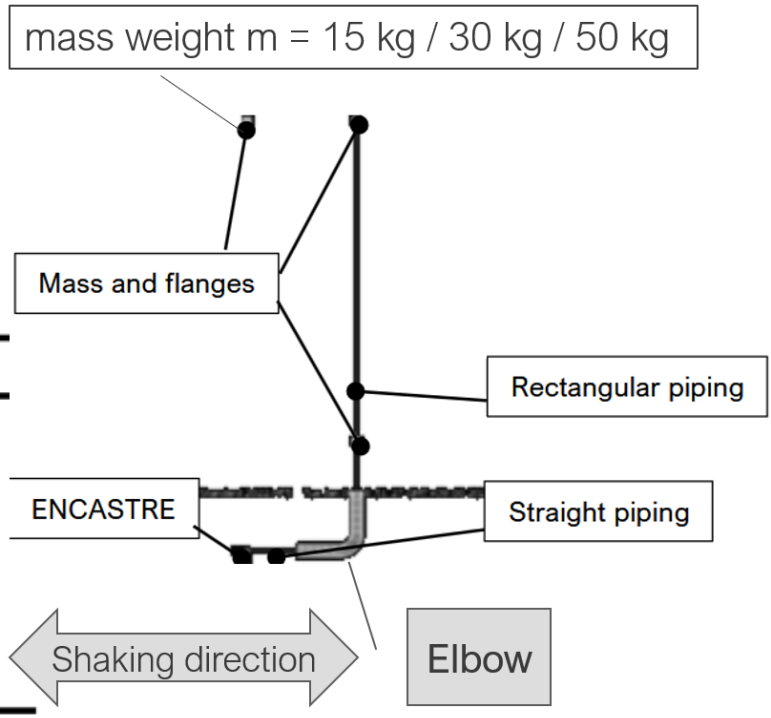
TABLE 2: MODEL PROPERTIES

Items	Properties
Analysis code	Abaqus 2022 FD5
Elbow	Shell (S4R) element Circumferential: 10 degrees Axial: 5 degrees
Straight piping	Pipe (PIPE31) element
Rectangular piping	Beam (B33) element

TABLE 3: MATERIAL PROPERTIES

Items	Properties
Modulus of elasticity (E)	202000 MPa
Poisson ratio	0.3
Yield stress (YS)*	Stright pipe: 340 MPa Elbow: 254 MPa
2nd modulus of elasticity (E')	BM: 2020 MPa (= E / 100) PP: 0 MPa

* Yield stress was given by the material certification report. Rectangular piping was assumed to be an elastic beam because of high stiffness. BM: bi-linear model, PP: Elastic perfectly plastic model.

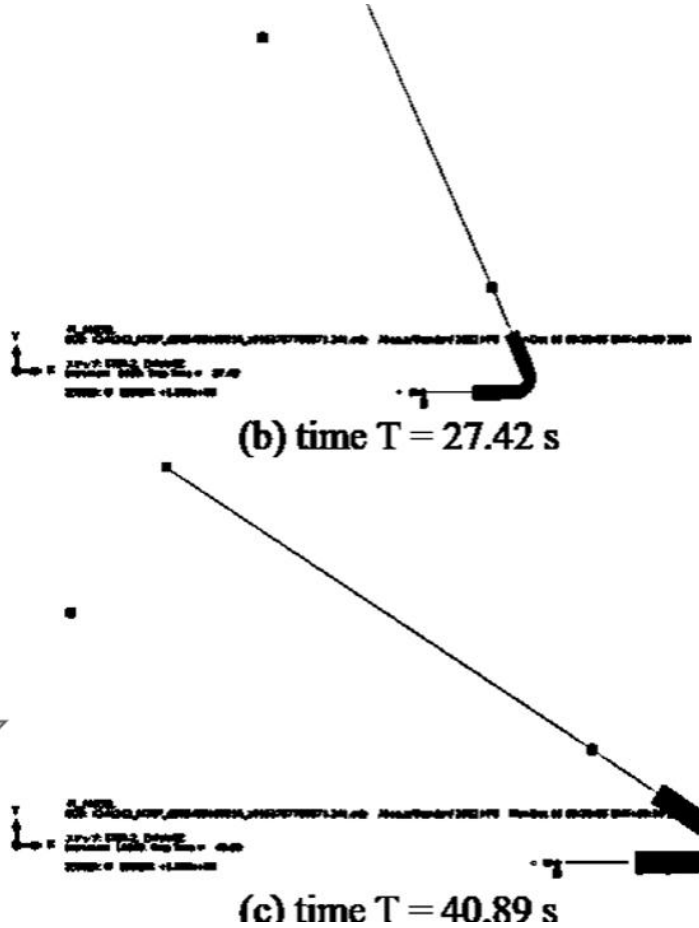


Schematic Sketch:
Test Specimen

◆ Example



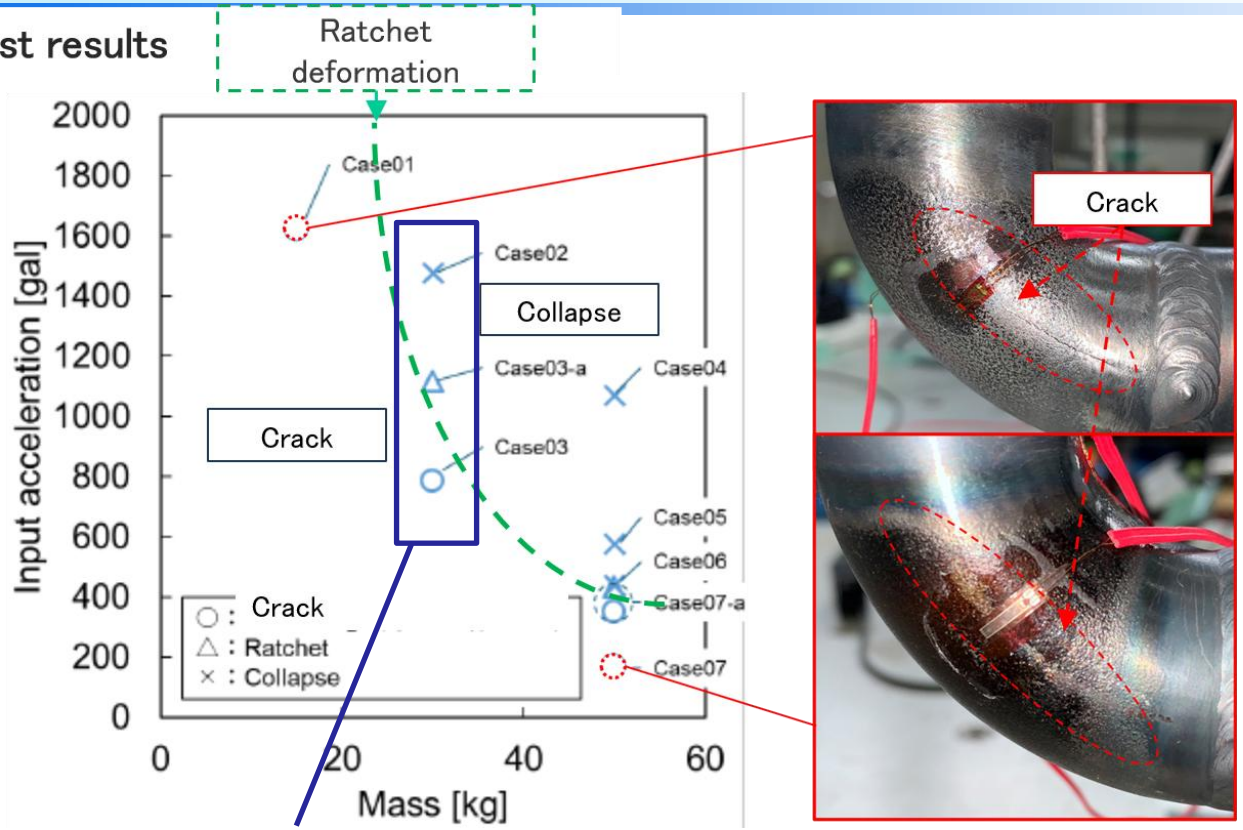
Ratchet
Deform
growth



Shacking Table Test
Result

FEA
Result

◆ Test results



◆ **Linking observed failure mode in shaking table test to *q*:**

Acceleration levels	Observed failure mode	*q* (outer, FEA)		*q* (inner, FEA)	
		BM	PP	BM	PP
800 Gal	Axial crack	1.00	1.00	6.95	7.07
1100 Gal	Ratchet	2.59	2.60	3.89	4.66
1500 Gal	Collapse	3.40	3.36	8.04	8.31

* minimum *q* values during 1.5 cycles

outer *inner*

$q = 1$, $q > 1$

$q > 1$, $q > 1$

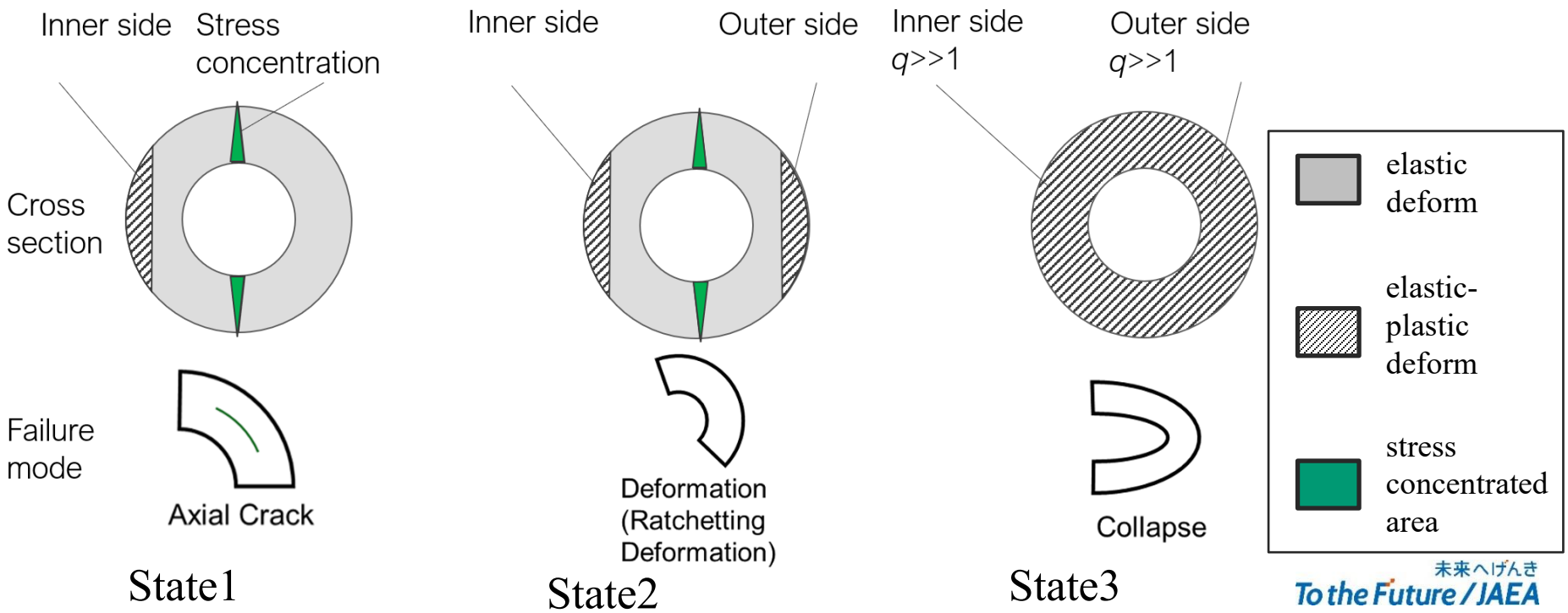
$q >> 1$, $q >> 1$

◆ **Linking q value to stress classification, modes:**

State 1: When q = 1.0 on the outer side and q > 1.0 on the inner side, the elastic deformation area prevents overall deformation.

State 2: When q > 1.0 both on the outer and inner sides, the plastically deformed area spreads, but the cross section can bear the stress.

State 3: When q >> 1.0 on both the inner and outer sides, divergence occurs in each loading cycle, and the primary stress can be dominated.



◆ Conclusions & Future Works:

- We proposed an approach to evaluate failure modes using q values for elbow piping.
- An approach through stress classification with q reproduced failure modes. Axal crack (fatigue), ratcheting and collapse can be distinguished.
  - ☞ If stress classification with q can predict each failure modes correctly, we will discuss this approach's validity.

What is our future work?

- Future work will investigate the conditions occurring each failure mode for other load conditions and other test specimens.

What is the future vision?

- Improving Natech risk assessments of seismic fragility in piping systems.
  - ☞ Through Moment based estimation with Mass–Acceleration diagram can explain test specimen's failure modes (plastic collapse vs. the other failure mode) qualitatively (Takito et al., 2026b).