5^{th} International Symposium on
Probabilistic Methodologies for Nuclear Applications
October 7-9, 2024, Tokyo, Japan

A Methodology for Risk-Informed and Performance-Based Structural Design and Maintenance for Nuclear Passive Components

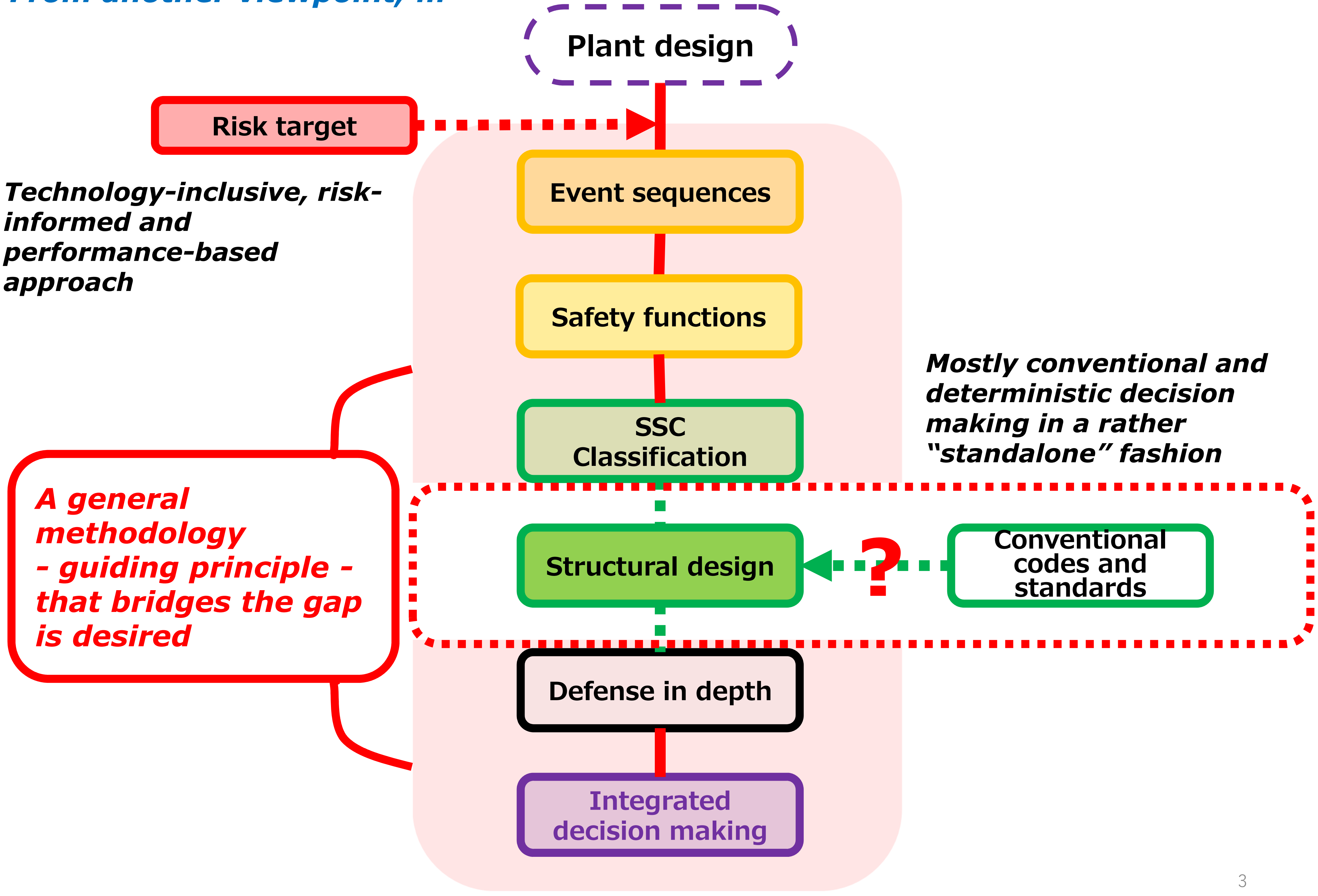
Tai Asayama and Satoshi Okajima

Japan Atomic Energy Agency

Purpose of this presentation

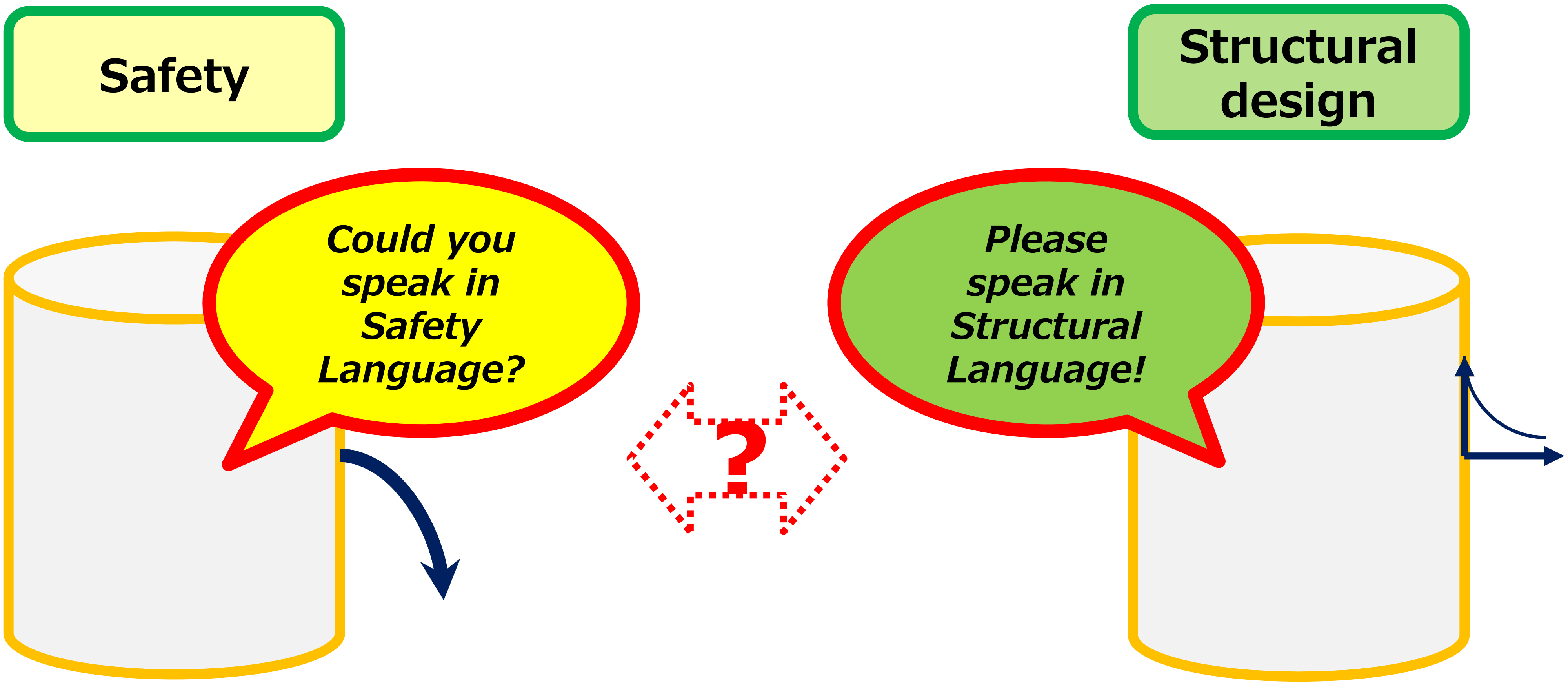
- **"JSME Guidelines on Reliability Target Establishment and Conformity Evaluation for Passive Components" has implemented a methodology that embeds structural design of passive components more explicitly into the risk-informed and performance-based framework.**
- **This presentation elaborates the technical aspects of the methodology.**

From another viewpoint, …



Key words

- **Action**: a technical conduct on the SSC(s) of interest of which conformity to reliability targets is evaluated using the methodology.
- **Structural limit state**: a structural state that corresponds to the **loss of safety function of the SSC(s)**. For example, if the safety function is a coolant boundary function, this state could be defined as a state where penetrated crack(s) exist in the wall of the SSC.
- **Challenges**: attributes that have the potential to cause **the loss of functions of the SSC(s)**. Include loading due to normal operation, internal hazards and external hazards
- **Reliability target**: structural reliability which the SSC(s) needs to maintain for the plant to meet its higher-level safety requirements. Conceptually, derived as a conditional probability to reach the **structural limit state** given **challenges** occurred, from the **permissible frequency of loss of safety functions** and the **frequency of challenges**.



Loss of boundary function
$<ax10^{-b}$/plant-year

Function oriented

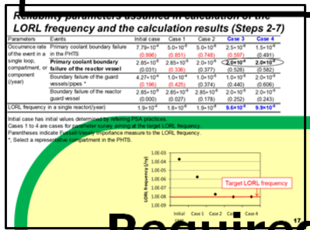
Material, geometry, welding,･･･
Stress<x, strain<y, damage<z, ･･･

Mechanical state oriented

Not only language but …

Function based

Required safety function



Required function
Ex. : Coolant boundary function

Maximum permissible frequency of loss of required function
Ex. : <ax10^{-b}/plant-year

?

- Materials Code
- Design Code
- Welding Code
- Fitness-for-Service Code

Structural integrity based

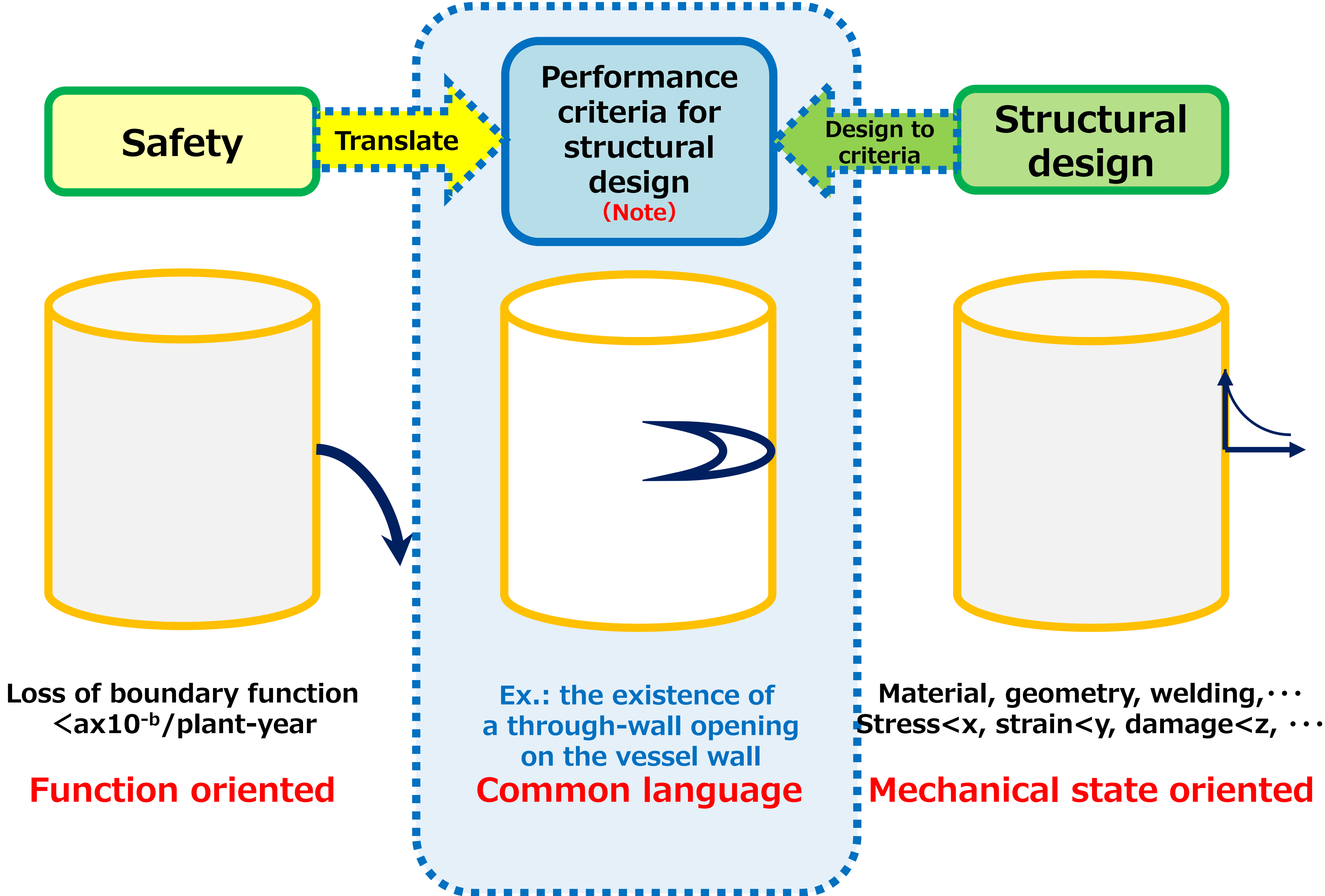
Criterial for structural design

● Standalone

Component classification, service levels

OO code	Allowable stresses
OO code	Strain limits
OO code	Fatigue damage limit
OO code	Prevention of buckling
	…

- Material
- Structure
- Welding
- Maintenance
- …



Safety
Translate
Performance criteria for structural design
(Note)
Design to criteria
Structural design
Loss of boundary function
<ax10^{-b}/plant-year
Function oriented
Ex.: the existence of a through-wall opening on the vessel wall
Common language
Material, geometry, welding,･･･
Stress<x, strain<y, damage<z, ･･･
Mechanical state oriented

※ Ando, M., Yada, H., Tsukimori, K., Ichimiya, M. and Anoda, Y., Experimental Study on the Deformation and Failure of the Bellows Structure Beyond the Designed Internal Pressure, ASME Journal of Pressure Vessel Technology, DECEMBER 2017, Vol. 139 / 061201-1

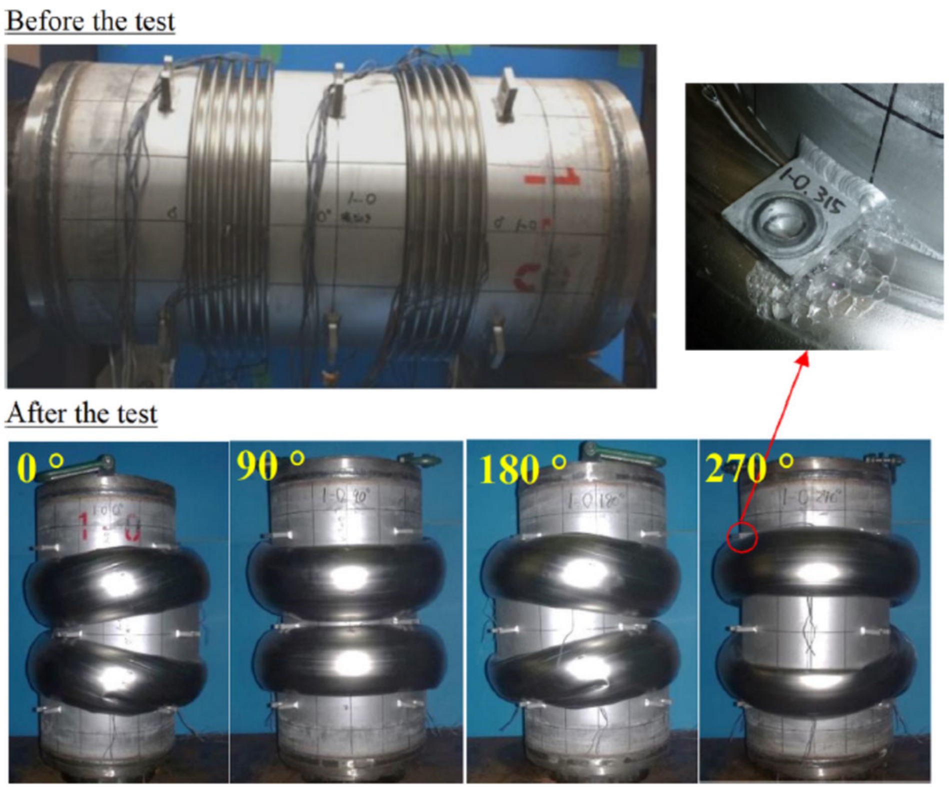
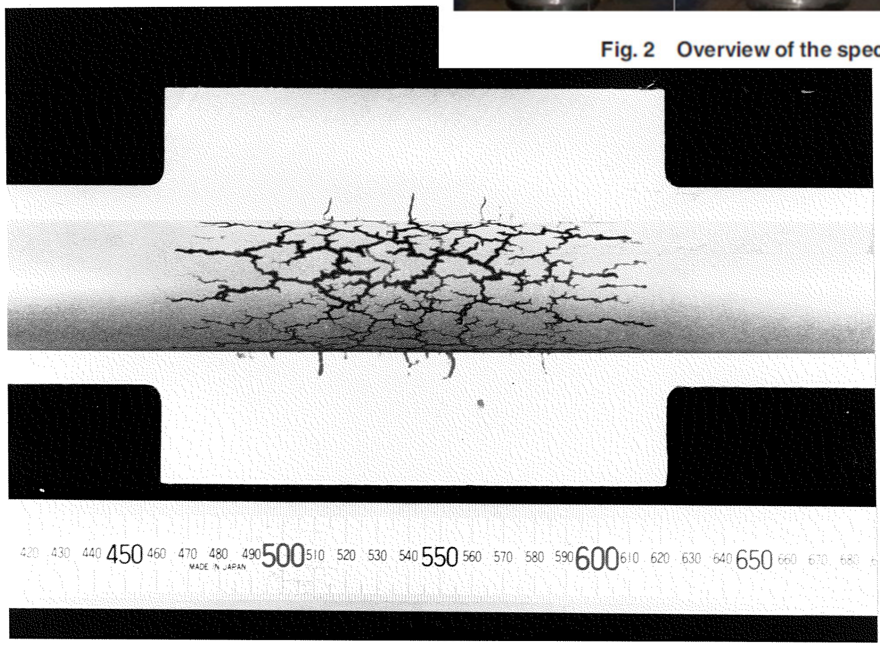


Fig. 2 Overview of the specimen before and after the test (CV1)



※ Asayama, T., Takasho, H., Kato, T., Probabilistic Prediction of Crack Depth Distributions Observed in Structures Subjected to Thermal Fatigue, ASME Journal of Pressure Vessel Technology, FEBRUARY 2009, Vol. 131

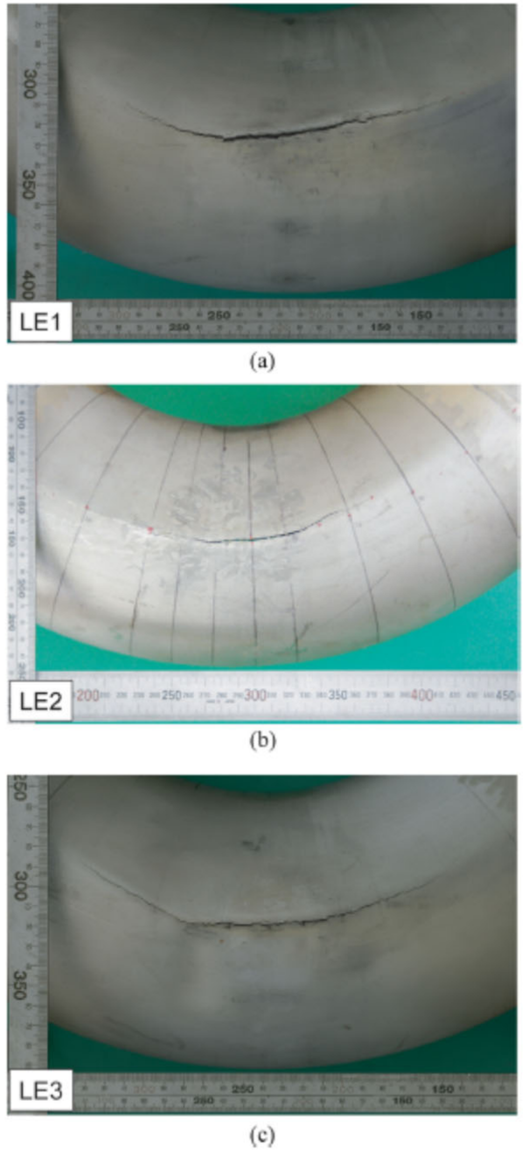
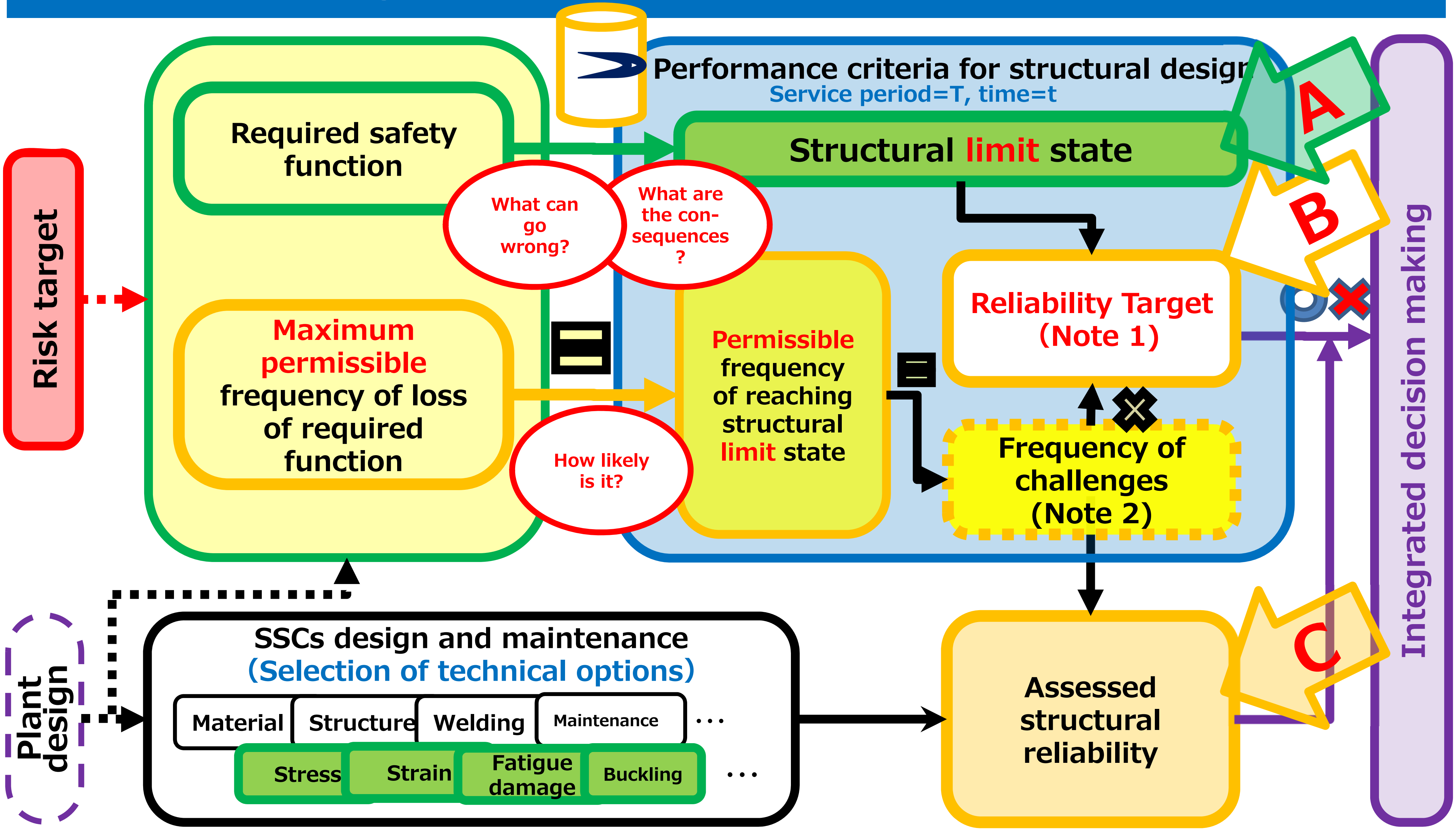


Fig. 5 Observation of crack at the elbows: (*a*) LE1, (*b*) LE2, and (*c*) LE3

※ Watakabe, T., Tsukimori, K., Kitamura, S. and Morishita, M., Ultimate Strength of a Thin Wall Elbow for Sodium Cooled Fast Reactors Under Seismic Loads, ASME Journal of Pressure Vessel Technology APRIL 2016, Vol. 138 / 021801-1

Propagation/transformation of the risk triplet



(Note 1) Maximum permissible probability of reaching structural limit state given challenges
(Note 2) Challenges, which can be deemed as given conditions, are included in performance criteria for the sake of convenience, because they are inseparable from the permissible frequency of reaching structural limit state.

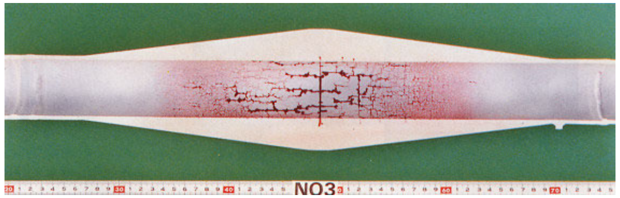
A. Structural limit state

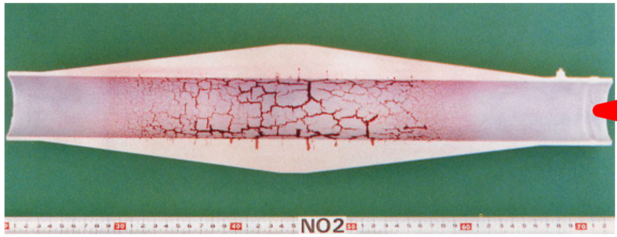
1. **Define the safety function and specify the structural state in (beyond) which the function is no longer performable**
   - Boundary function, support function, …
   - Openings in the wall, reduction in load bearing capacity, excessive deformation, …
2. **Clarify your data, knowledge and confidence in the causes and paths that could lead to the limit state**
   - Consensus code based approach, conservative analysis, mechanism-based analysis approach, …
   - Consider detectability, controllability, cliff edge effects, …
3. **Recall why you are using this particular methodology**
   - Set the limit state so that it best materializes your design intention - enhance safety, improve economy, …

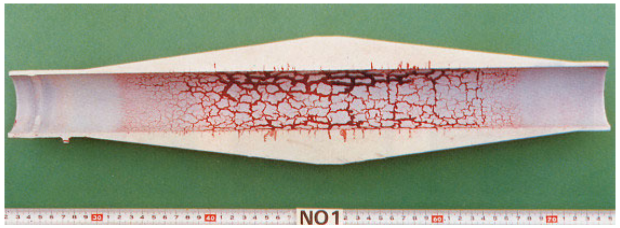
A. Structural limit state

Function: coolant boundary
Challenge: thermal fatigue
SLS: opening on wall

Before crack initiation







Small leak

Break

Example 1: Conventional and conservative

- *The point where accumulated creep-fatigue damage has reached a code defined value*
- *No further clarification is necessary*

Example 2: More mechanism-and-data based

- *The point where the balance between thermal and seismic resistance is optimal*
- *Not harmful thermal cracks may emerge, may need further reinforced technical background*

Example 3: Special purpose evaluation

- *For leak-before-break evaluation to optimize inservice inspection requirements*

Data, knowledge, confidence

Note that structural reliability must always be in combination with a structural limit state

B. Reliability target

1. **Determine the permissible frequency of loss of safety function for the SSC using risk evaluation methods**
   - **Probabilistic risk assessment (PRA), semi-quantitative, and qualitative**
2. **Identify possible challenges that the SSC may experience in the evaluation period**
   - **Start ups and shut downs, etc., internal hazards, and external hazards**
3. **Derive the maximum permissible probability of reaching structural limit state given challenges**

B. Reliability target

Permissible frequency of reaching structural limit state

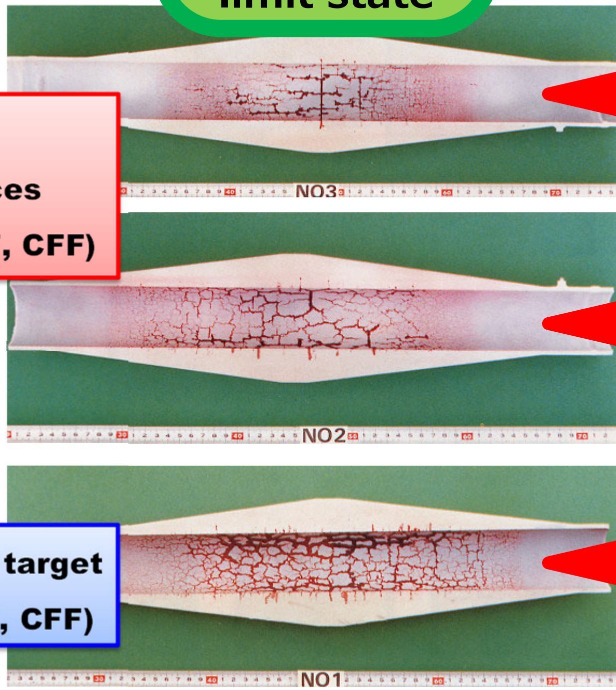
Frequency of challenges

Structural limit state

- Structural reliability
- Human reliability
- External hazard frequency
- ⋮
- Etc.

PRA analysis models

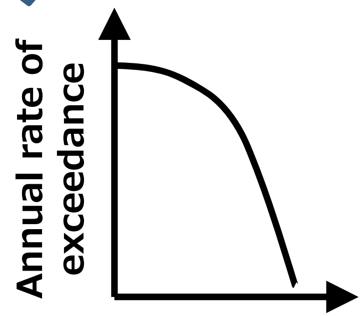
Risk indices (CDF, CFF)



Start ups/shut downs

Internal pressures

Earth-quakes



- Target structural reliability
- Human reliability
- External hazard frequency
- ⋮
- Etc.

PRA analysis models

Risk target (CDF, CFF)

Reliability Target

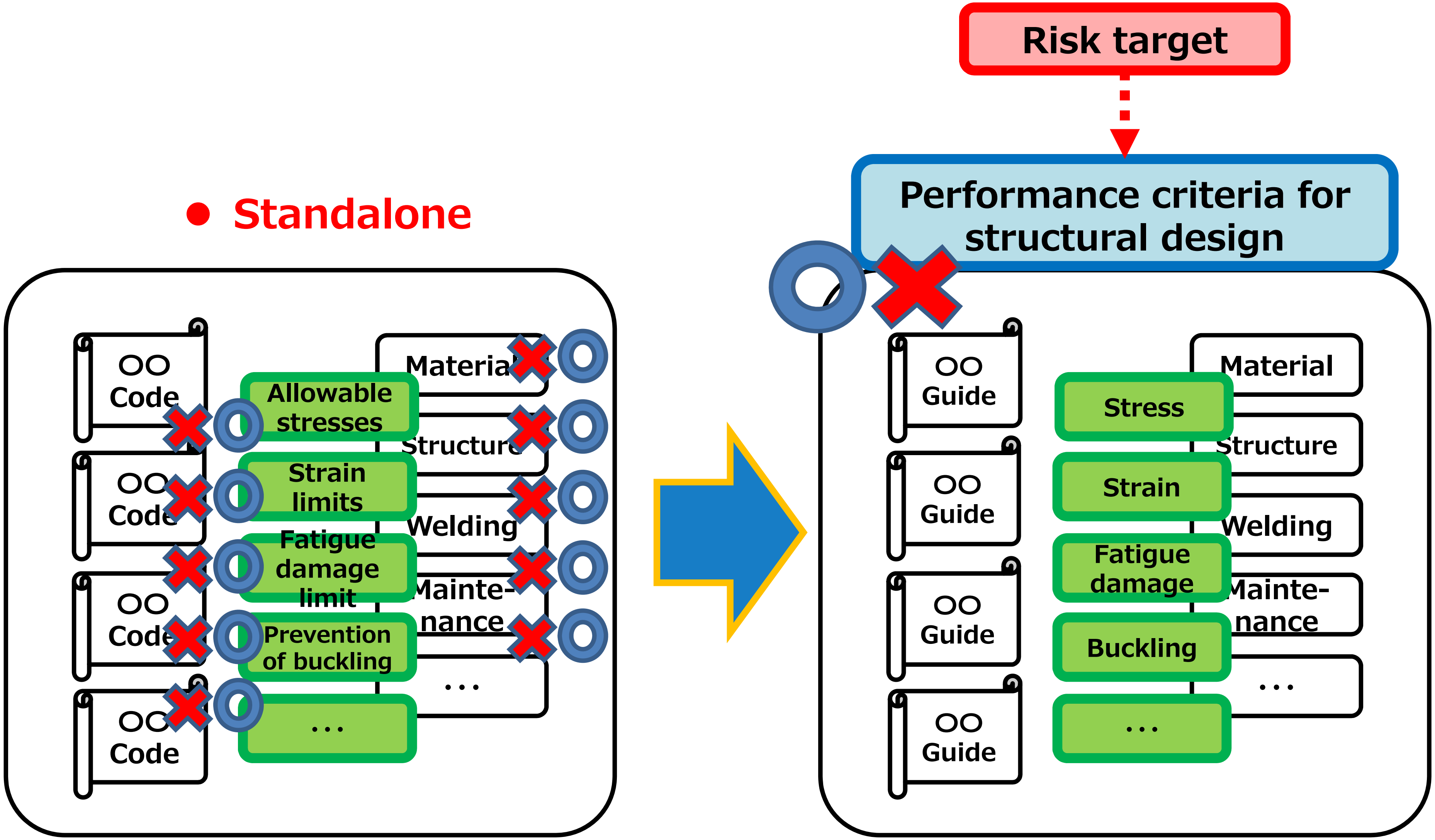
- A reliability target is, conceptually, the maximum permissible probability of reaching structural limit state given postulated challenges occur
- Depending on challenges, formula for derivation may change

C. Structural reliability assessment

1. **Select a set of technical options most effectively materialize the design concept**
   - **Presume no conventional prescriptive criteria in consensus codes and standards**
2. **Perform structural reliability evaluation against the structural limit state**
3. **Judge the conformity of the assessed reliability to the reliability target in an integrated fashion**
   - **Evaluation performed in an integrated fashion, not by comparing numerical values only but by ensuring the validity of assessments, adequate treatment of uncertainties, and consistency with the defense-in-depth philosophy**

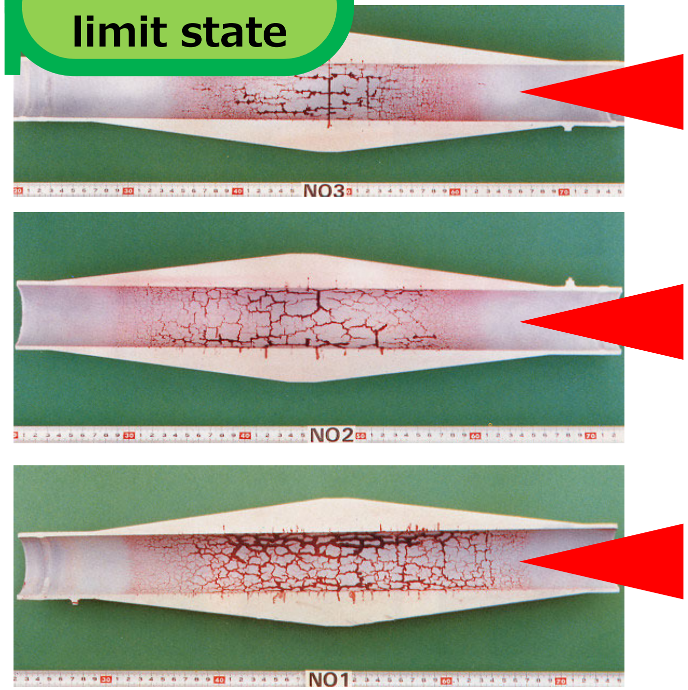
Conventional

Envisioned

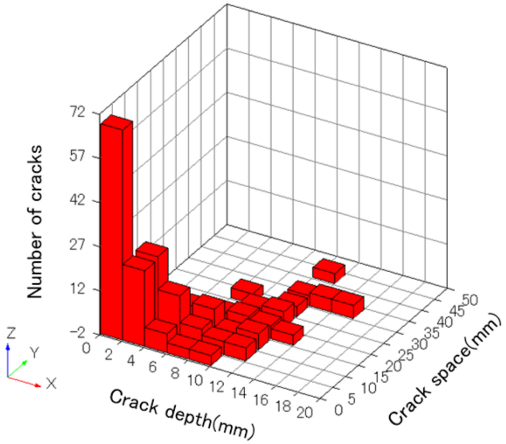


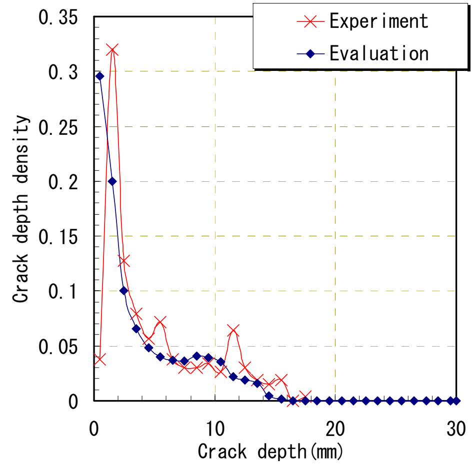
C. Structural reliability assessment

Structural limit state



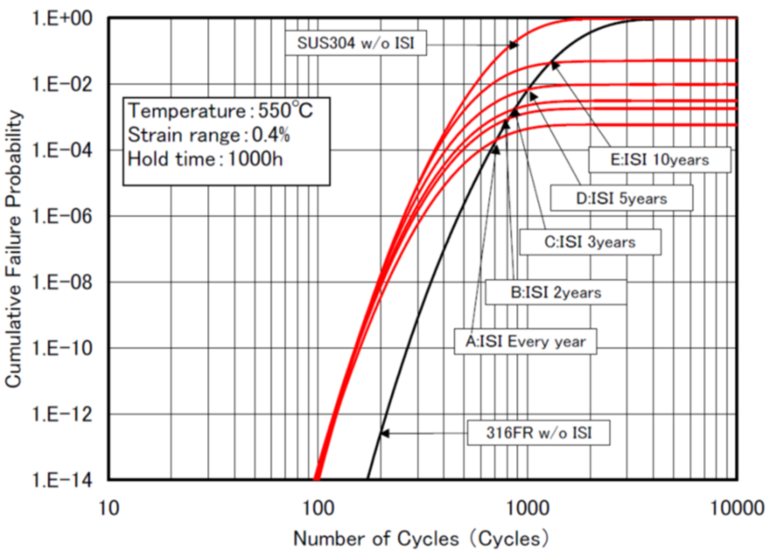
PFM is a powerful tool





Reproduction of thermal crack distribution

Asayama, T., Takasho, H., Kato, T., Probabilistic Prediction of Crack Depth Distributions Observed in Structures Subjected to Thermal Fatigue, ASME Journal of Pressure Vessel Technology, FEBRUARY 2009, Vol. 131



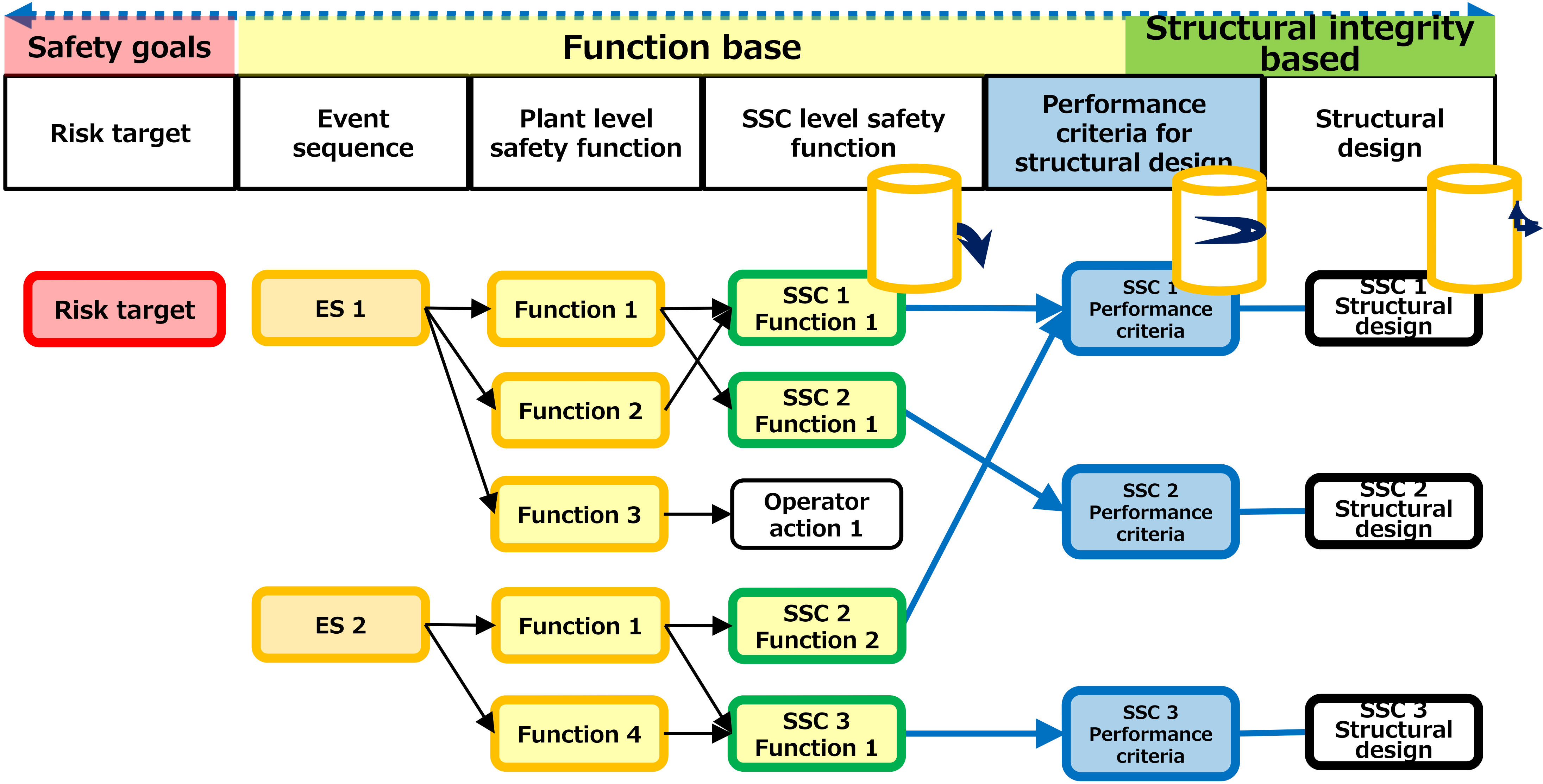
Guidance documents also readily available

- JIS B 9955:2017 General principles on reliability for mechanical products
- JSME Guidelines on Reliability Evaluation of Fast Reactor Components - JSME S NX7 – 2022
- …

Conceptual study on the tradeoff between material selection and inservice inspection

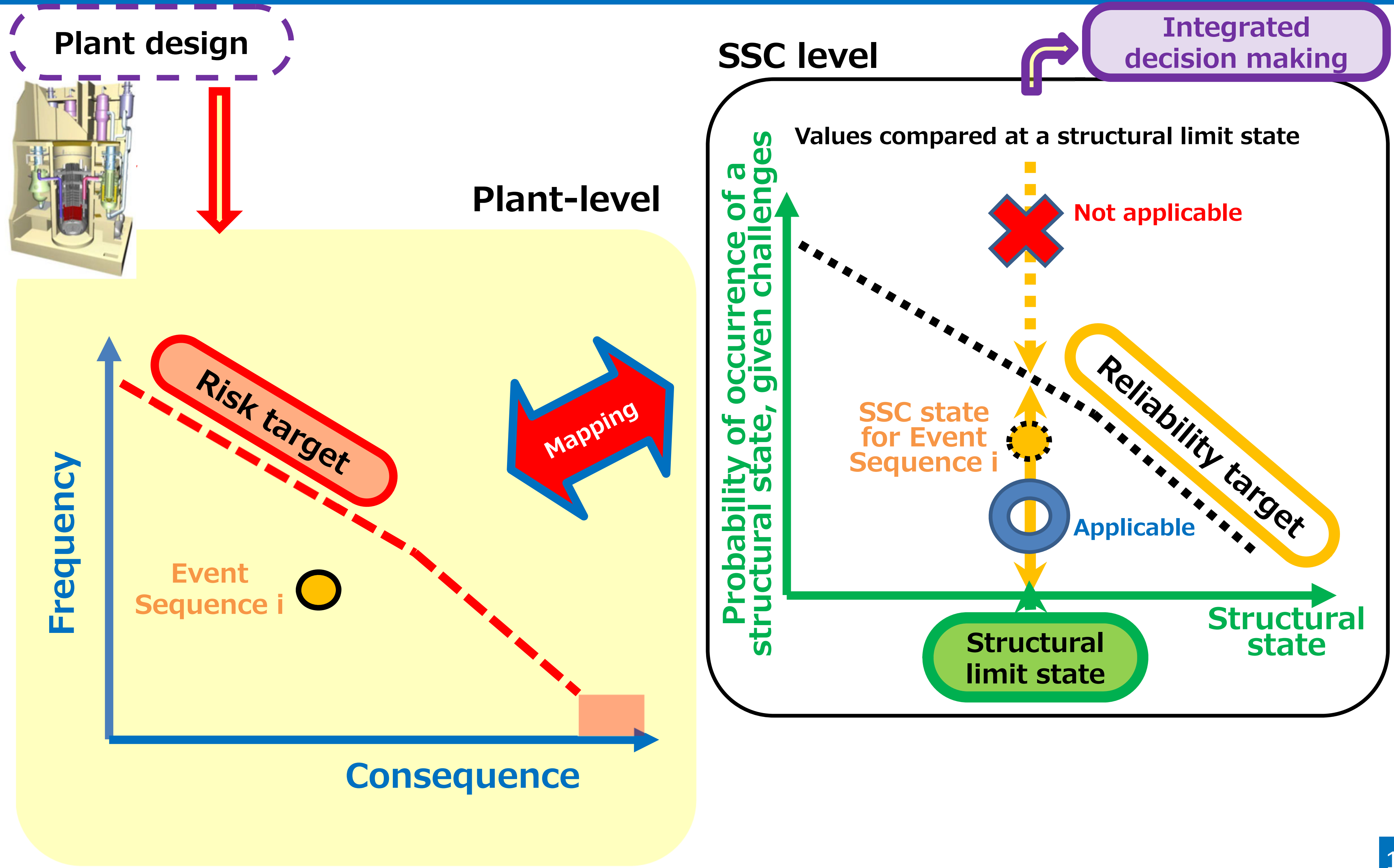
Asayama, T., Kawasaki, N., Morishita, M., Shibamoto, H. and Inoue, K., Balancing material selection and inspection requirements in structural design of fast breeder reactors based on “System Based Code” concept, Nuclear Engineering and Design, Vol.238 (2008) pp.417–422

Risk-Informed and Performance-Based Structural Design and Maintenance



Everything seamlessly connected all the way down to SSC specifications

Risk triplet propagation/transformation analogous to mapping



Concluding remarks

- **The methodology in the JSME Guidelines for risk-informed and performance-based structural design and maintenance for nuclear passive components embeds structural design into the risk-informed framework.**
- **This is done by setting performance criteria for structural design which are comprised of the structural limit state and reliability target.**
- **The performance criteria help propagate/transfer the risk triplet from safety evaluation to structural integrity evaluation and, *if relevantly set*, allow for fully utilizing the potential of materials and structures.**

Thank you for your attention.