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# Fracture Data Acquisition Approach for Reliability Assessment of RAFM Steel in Fusion DEMO Reactors

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# Validation is necessary for qualification, but validation alone does not establish fitness for a specific DEMO application

## Verification = Correct implementation

**Are the calculations and tests performed correctly?**

- Numerical and code correctness
- Correct implementation of constitutive equations
- Accuracy and integrity of experimental procedures

Example
- An FE model reproduces an analytical benchmark solution.
- The test system accurately measures load and displacement.

## Validation = Physical adequacy and predictive capability

**Does the model adequately represent the relevant physical behavior?**

- Comparison of predictions with experiments
- Confirmation of governing mechanisms
- Assessment of predictive capability and applicability range

Example
- A cleavage-fracture model reproduces the observed toughness distributions.
- A ductile-damage model reproduces the measured J-R curves.

## Qualification = Application-specific acceptance decision

**Is the material acceptable for a defined DEMO component and service condition?**

- Design requirements and failure modes
- Validated material and fracture models
- Manufacturing quality and variability
- Inspection and monitoring strategy
- Reliability and risk assessment

Example
- RAFM steel is accepted for use in a defined DEMO blanket component under specified loading, irradiation, and inspection conditions.

**IFMIF-DONES provides critical validation evidence supporting qualification.**

# Why qualification of RAFM steel is different for DEMO

**Conventional systems**

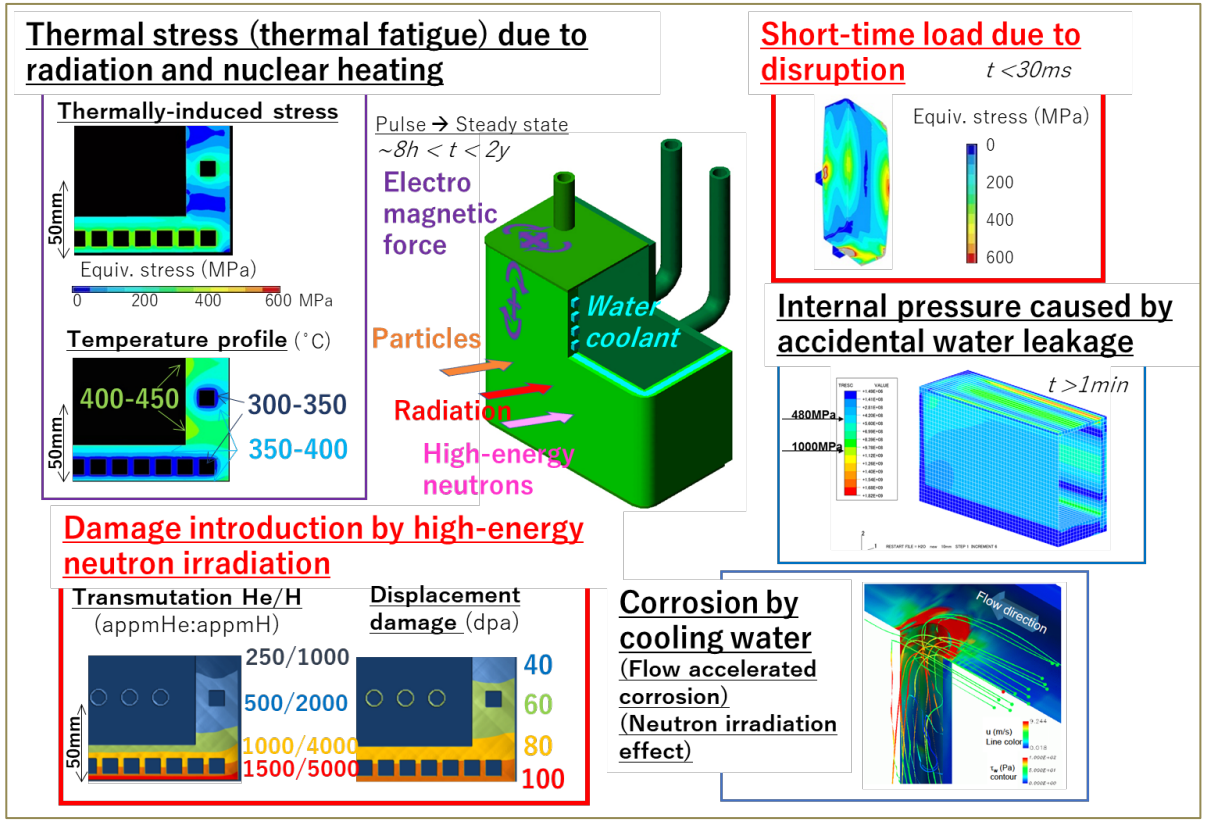
- Material qualification is supported by service experience, long-term operational data, and validation under representative conditions.

**Fusion DEMO**

- When qualification decisions must be made, no structural component will have experienced the actual fusion neutron environment throughout its intended lifetime.
- Qualification must therefore be established through a combination of irradiation experiments, mechanistic understanding, numerical modeling, and structural integrity assessments.

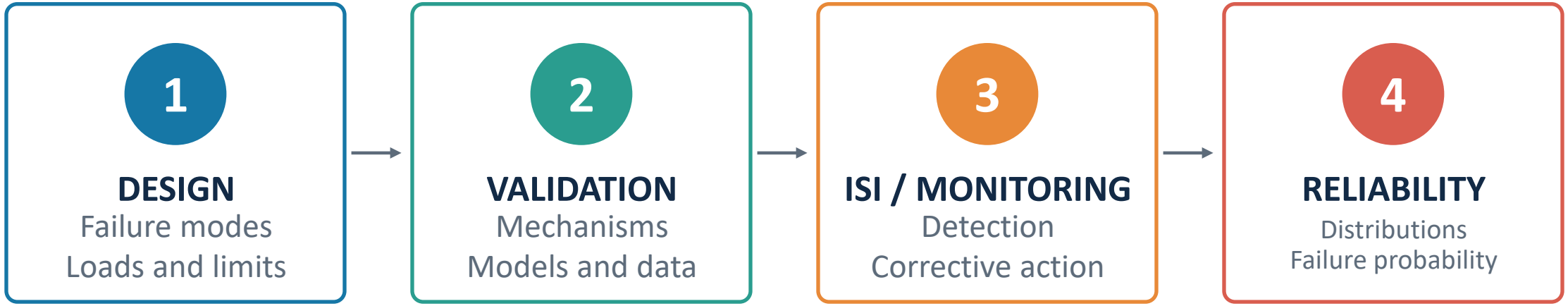
**Required response**

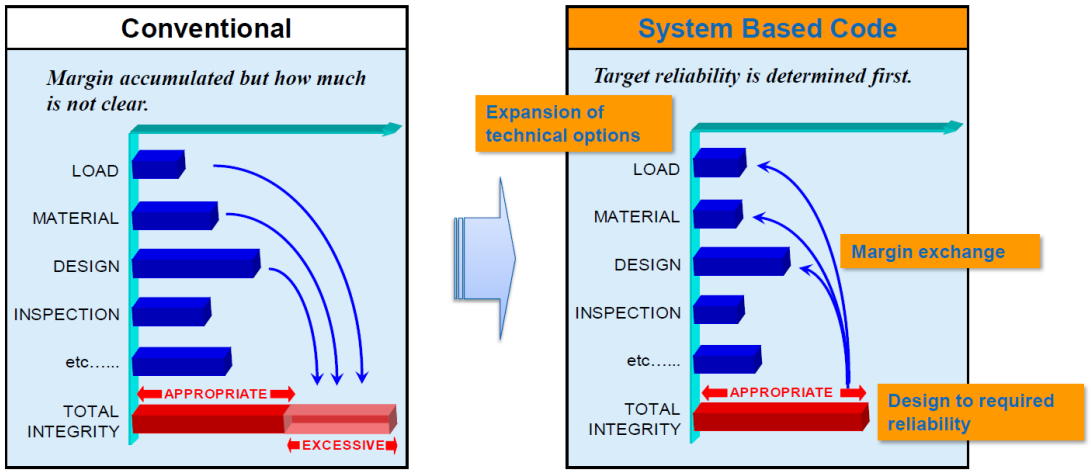
- The challenge is not only generating data, but demonstrating that the available evidence provides sufficient confidence for design and operation.




**DEMO qualification is an evidence-integration problem under limited data.**

# Qualification must integrate design, validation, ISI and reliability




Asada, Y., Tashimo, M. and Ueta, M., 2002, "System Based Code—Principal Concept," Proc. 10th International Conference on Nuclear Engineering, ICONE10-22730.

- If a region can be inspected, detected flaws can be managed through maintenance or corrective actions.
- Many locations in fusion in-vessel components, however, will be difficult or impossible to inspect. In such cases, qualification must rely more strongly on postulated defects and reliability-based evaluations.

**Qualification is a component-level decision based on the combined strength of these four elements.**

# Inspectability determines the required level of fracture evidence

**DIRECTLY INSPECTABLE**

Flaw detection
Inspection interval
Corrective action

Moderate reliance on lower-tail extrapolation

**INDIRECTLY MONITORABLE**

Leakage / temperature
Flow / displacement
Plant response

Couple detection capability with fracture assessment

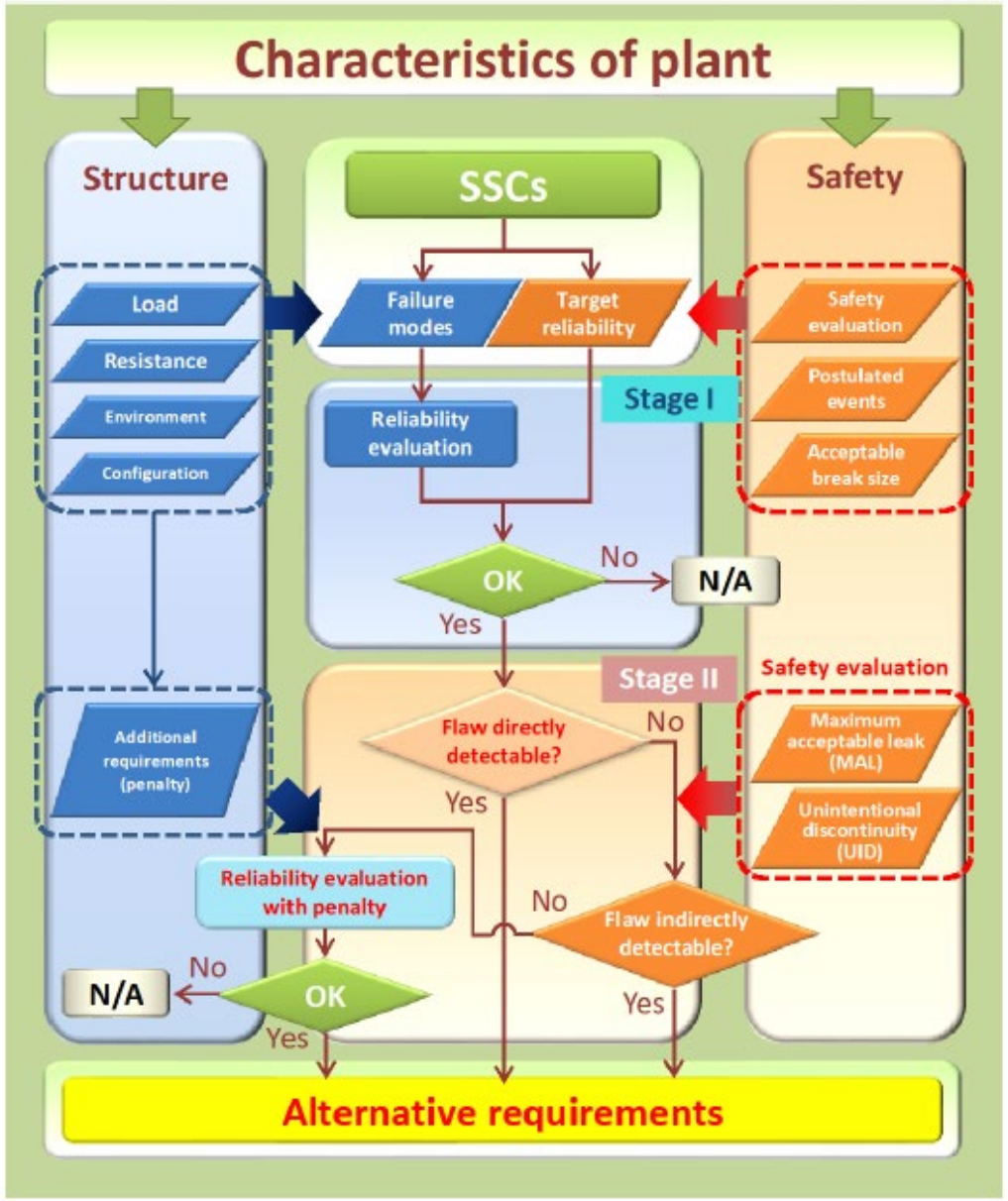
**NON-INSPECTABLE**

Postulated initial flaws
Conservative defect distribution
Reliability penalty

Highest demand on fracture-data quality

- For inspectable regions, structural integrity can benefit from flaw detection and corrective actions.
- For non-inspectable regions, this defense layer is unavailable. As a result, structural integrity must rely more heavily on assumptions regarding defect populations and material resistance distributions. In other words, fracture data become part of the primary safety barrier.
- The lower-bound behavior of the material and the associated uncertainties become increasingly important as inspectability decreases.

Takaya, S. et al., 2015, ASME J of Nuclear Rad Sci, Vol. 1, Paper #011004.




**As inspectability decreases, confidence in the lower tail of fracture resistance becomes increasingly important.**

# IFMIF-DONES as a validation platform for DEMO qualification

Fusion-relevant irradiation → Small-specimen fracture tests → Mechanism & model validation → Statistical parameters → Component reliability → Qualification decision

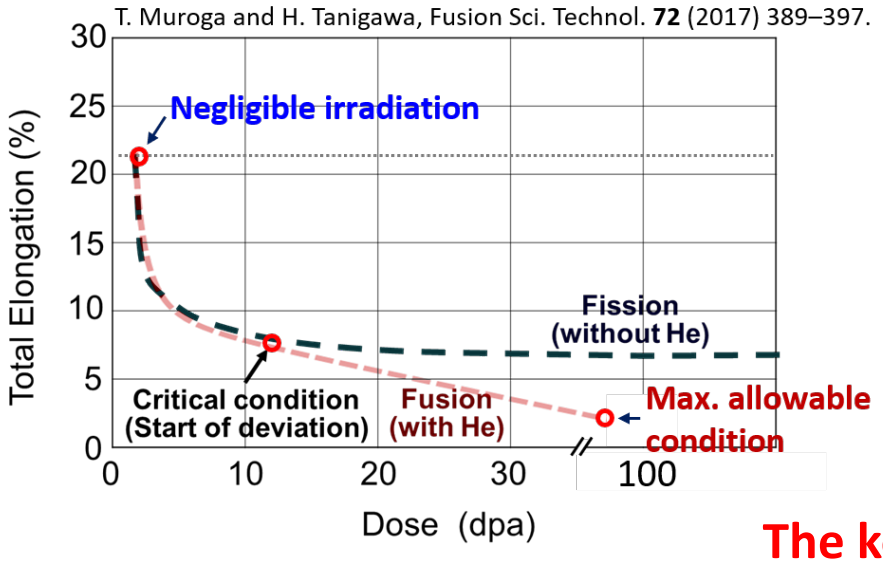
**NOT ENOUGH**

**Average values from a few specimens**

**QUALIFICATION EVIDENCE**

**Validated and transferable evidence**

- **Material-property distributions**
- **Lower-tail behavior**
- **Fracture mechanisms**
- **Model applicability and uncertainty**




**Basic Strategy:**

- Predict irradiation-induced property changes using fission-neutron data and mechanistic models.
- Update and validate the predictions using fusion-neutron data from IFMIF-DONES.
- Transfer the validated parameters to component-level reliability assessment.

**The key output of IFMIF-DONES should not be irradiation data alone, but validated and transferable evidence supporting qualification decisions.**

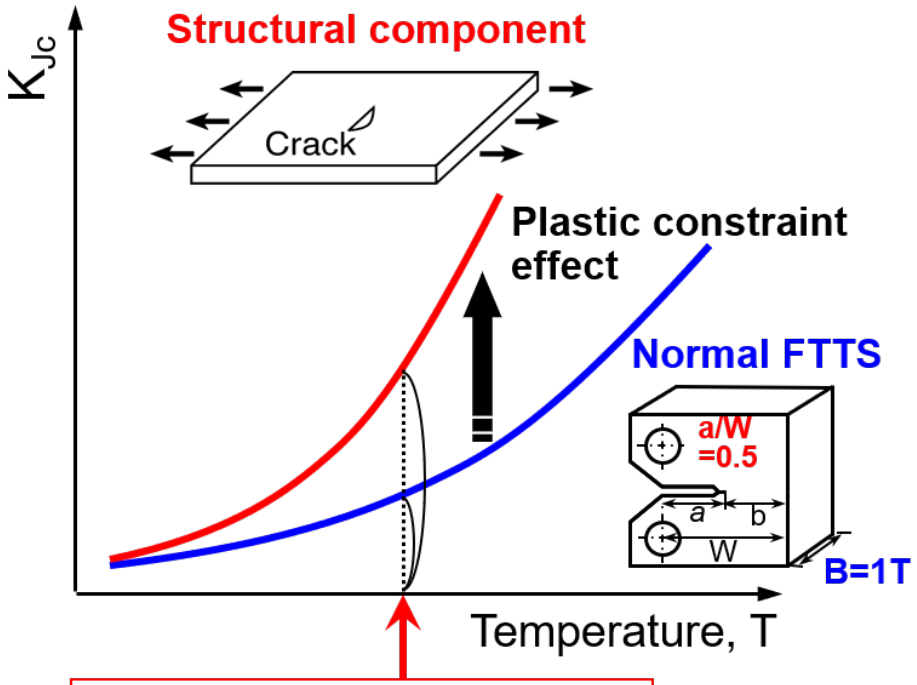
# Proposed fracture data acquisition matrix for IFMIF-DONES

| QUALIFICATION QUESTION | EXPERIMENTAL EVIDENCE | MODEL / RELIABILITY OUTPUT |
|---|---|---|
| How does irradiation change constitutive behavior? | Miniature tensile tests | Stress-strain relationships and property distributions |
| How does irradiation affect the distribution of cleavage initiation? | Deep- and shallow-crack miniature 3PB tests | $K_{Jc}$ distribution, $T_0$, Weibull parameters |
| How does irradiation affect ductile crack initiation and growth? | Miniature fracture and notched-tension tests | J-R / CTOD-R behavior and ductile-damage parameters |
| Can small-specimen data be transferred to component geometries? | Multiple crack depths, geometries, and 3D FE analyses | Constraint- and size-transfer parameters |
| Does irradiation alter the governing fracture mechanism or model applicability? | Fractography, microstructural characterization, and model comparison | Validated applicability range and uncertainty |

**Design the irradiation test matrix backward from the evidence required for qualification and probabilistic reliability assessment.**

This is a proposed framework, not a prescribed IFMIF-DONES test matrix.

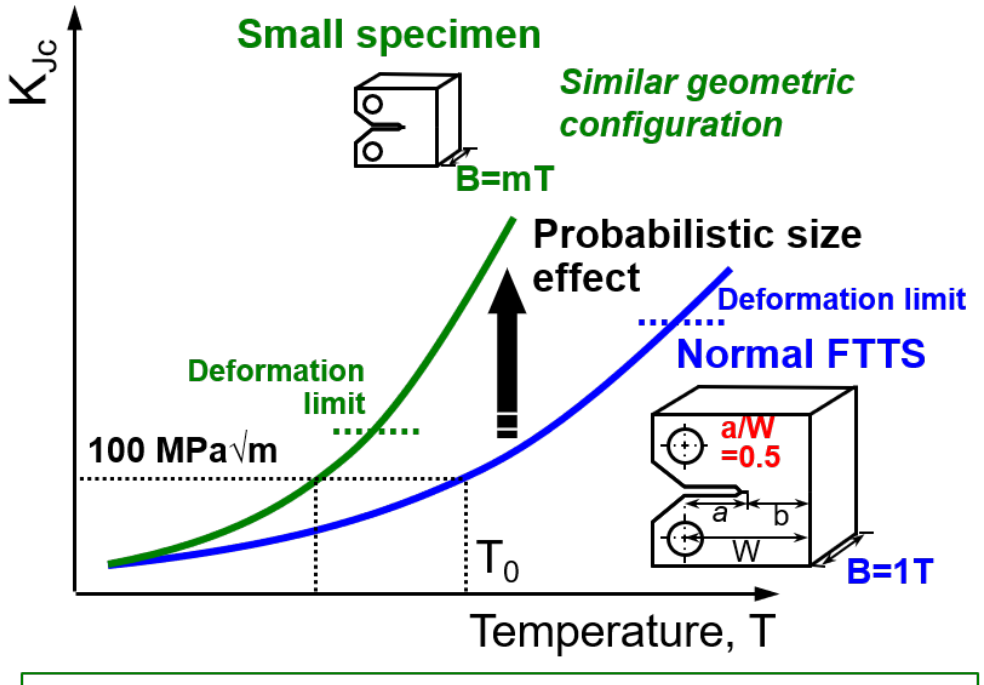
# Brittle fracture: Why miniature-specimen data require a Local Approach
## - Cleavage fracture without preceding ductile crack growth -




**Toughness correction ratio**

Is dependent on

- n, YR : material work hardening
- m : Weibull shape parameter



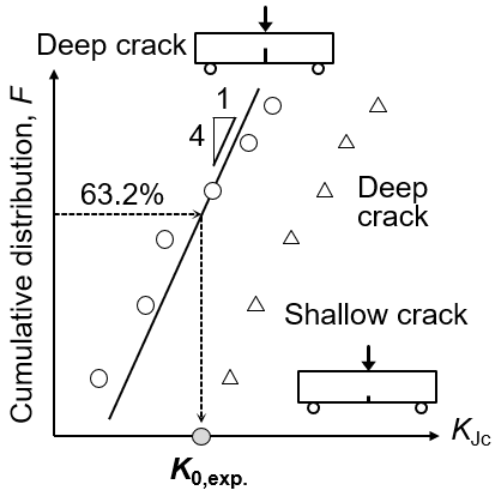

**Small specimen lowers a transition temperature**

**Guideline for determining a Weibull shape parameter m using small specimen**

**A measured toughness distribution cannot be transferred directly from a miniature specimen to a component.**

# Statistical identification of the Weibull shape parameter

**Step I** Fracture toughness testing for two sets of specimen with different crack depth



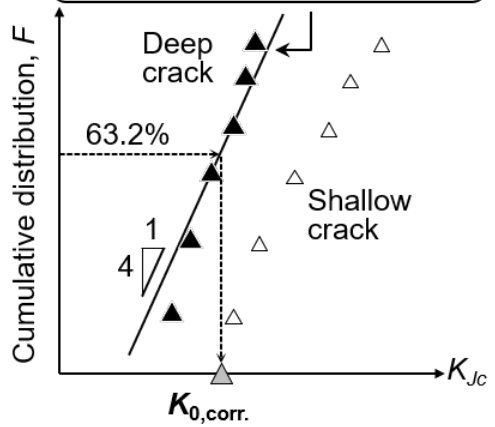

I-1 Maximum likelihood estimation with data censoring
(censoring limit : $K_{J,limit}$ (ASTM E1921))

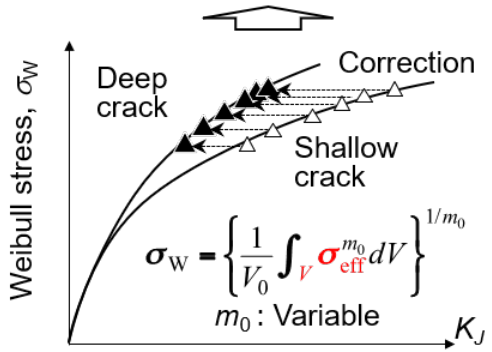
$$F(K_{Jc}) = 1 - \exp\left\{-\left(\frac{K_{Jc} - K_{min}}{K_0 - K_{min}}\right)^4\right\}$$

$$\begin{cases} K_{Jlimit} \le \sqrt{\dfrac{Eb\sigma_{0.2}}{M_{limit}(1-\nu^2)}} \\ M_{limit} = 30 \end{cases}$$

**Step II** Correction of plastic constraint effect on critical $K_{Jc}$

II-2 Maximum likelihood estimation with data censoring ($K_{J,limit}$)

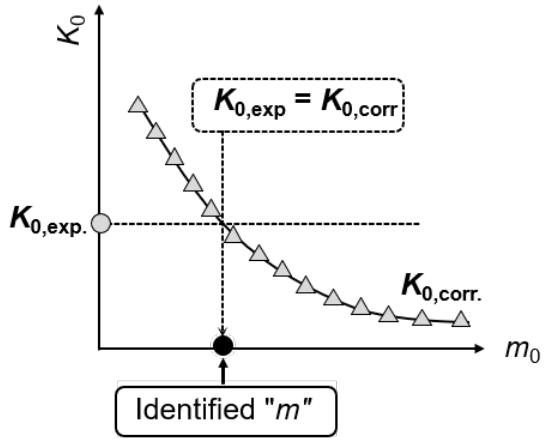



II-1 Calculation of Weibull stress (3D FE-analysis)

**Step III** Identification of Weibull shape parameter, m

III-1 Relationship between $m_0$ and $K_{0,corr.}$



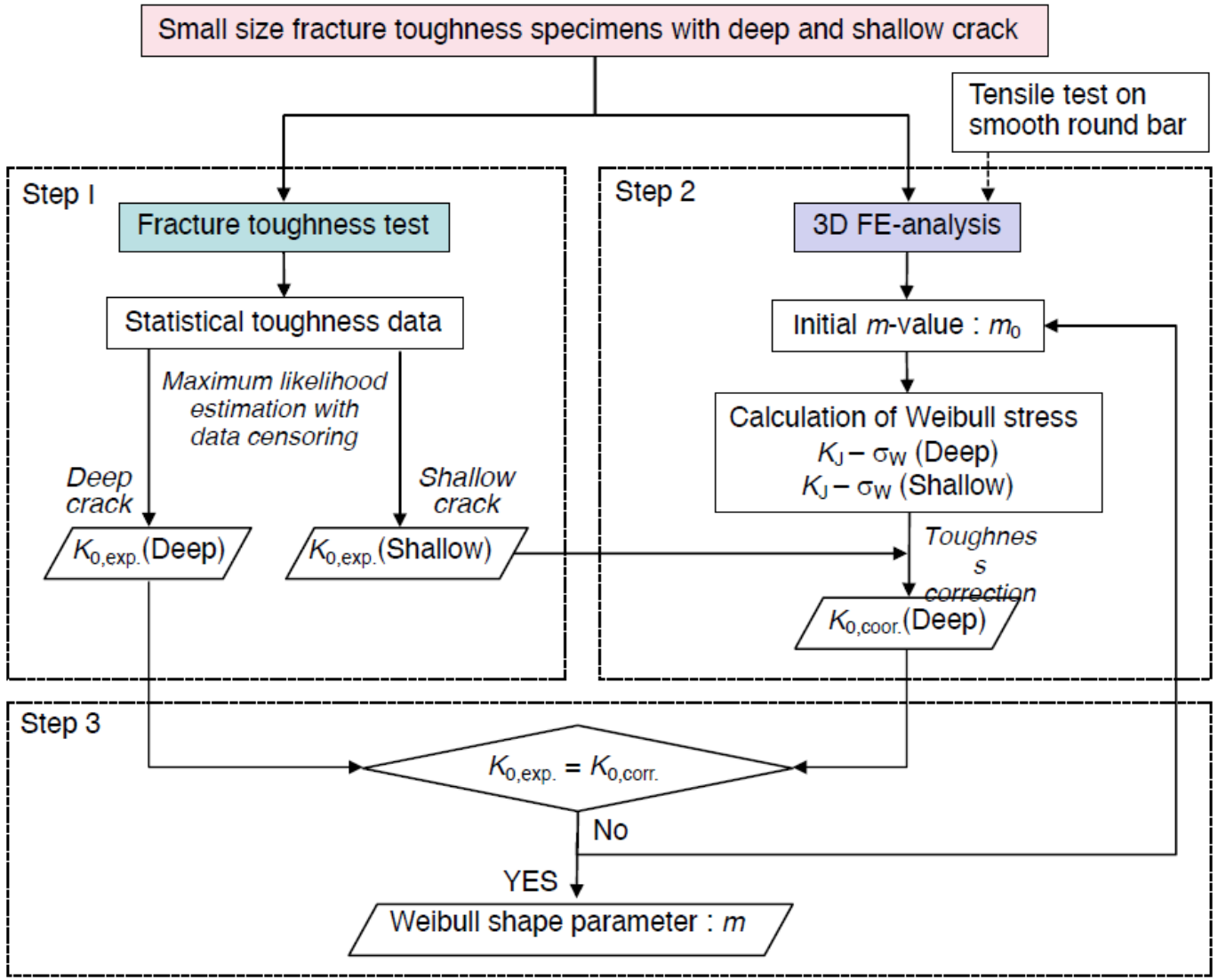

* $K_{0,corr.}$ : $K_0$ for the corrected fracture toughness of deep crack specimen from those of shallow crack specimen

**Original idea** : X. Gao, C. Ruggieri and R.H. Dodds, Jr, Int. J. Fract., 92 (1998), 175-200)

**Two constraint levels allow material statistics to be separated from specimen-geometry effects.**

# Practical workflow for irradiated miniature specimens

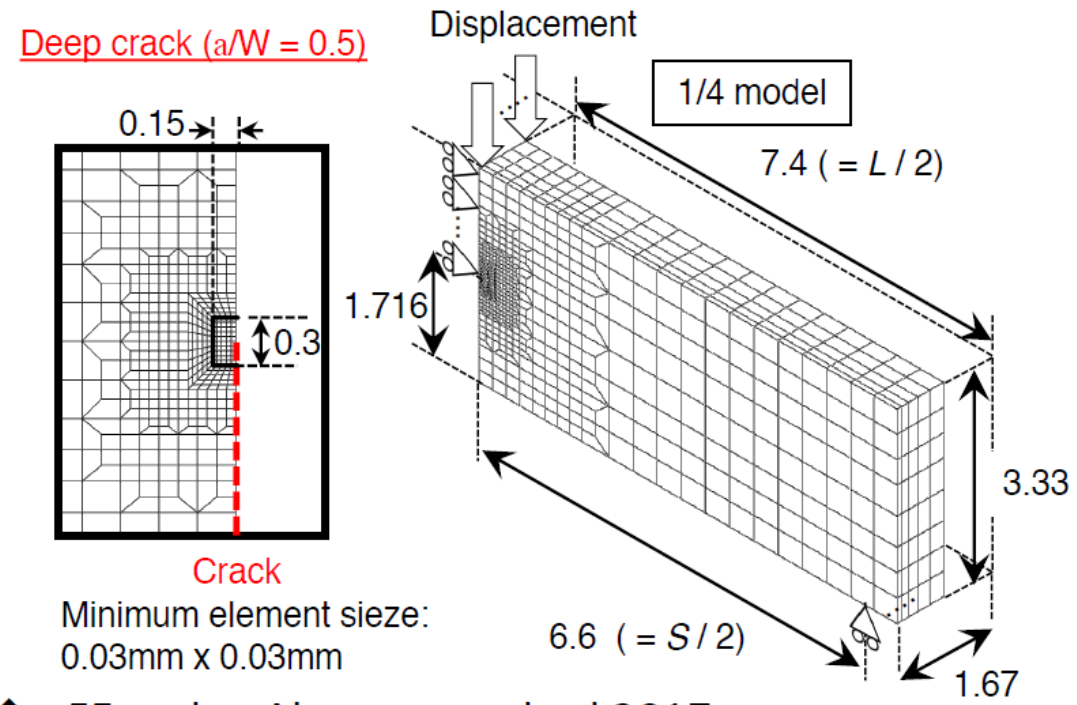
- The statistical identification principle is translated into an experimental and numerical workflow suitable for limited irradiated volumes.



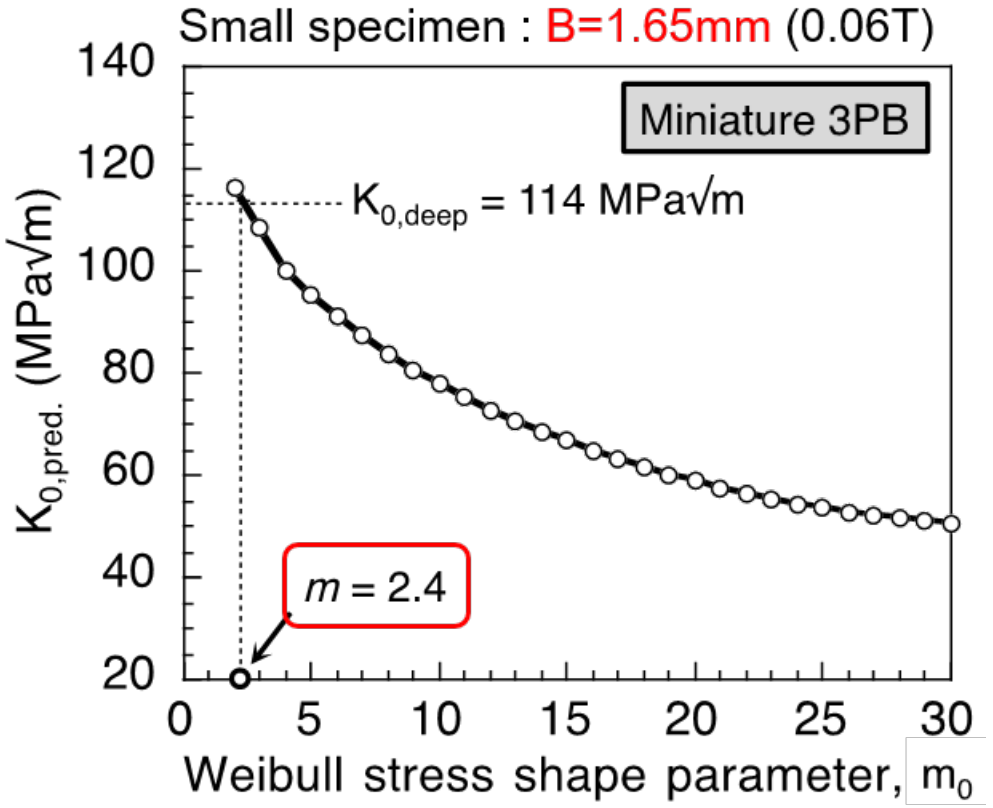

**Tensile and fracture data are combined to identify transferable cleavage-fracture parameters.**

# Identification of the Weibull shape parameter using miniature 3PB specimens

- Small-size 3PB specimen with a/W=0.5 and 0.2
  (B=1.65mm (0.06T))
- Mesh division of FE-model




- FE-code : Abaqus standard 2017




**Miniature specimens can identify a transferable statistical fracture parameter when constraint differences are explicitly incorporated.**

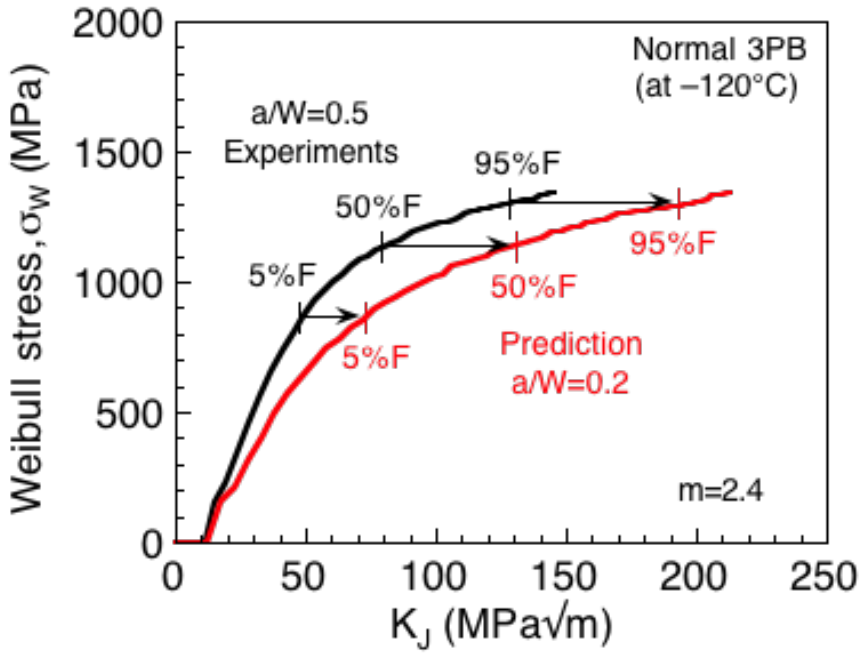
# Validation of constraint transfer from miniature to standard fracture specimens - Prediction of the plastic-constraint effect on $K_{Jc}$ using the Local Approach -

◆ Weibull shape parameter *m* = 2.4 (Size and Temperature independence)

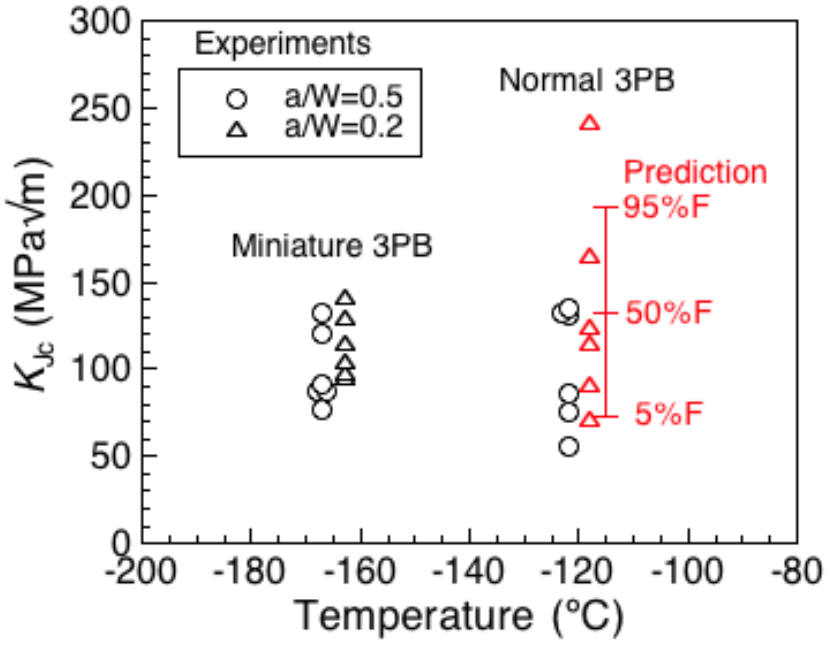
**(Parameter identified from a miniature specimen (**B=1.65mm (0.06T)) at T = –165°C)

◆ Prediction of $K_{Jc}$ for Normal 3PB (a/W=0.2) from fracture toughness obtained with Normal 3PB (a/W=0.5) at -120° C

☐ Weibull stress calculation with m=2.4




☐ Predicted result




**A Weibull parameter identified using miniature specimens predicts the effect of crack-tip constraint in larger fracture specimens.**

# Ductile fracture: Conceptual framework of the damage model

- **Damage evolution** $dD = (1-D)dE_m^p$

$$D^* = \begin{cases} D & for, \quad D \le D_c \\ D_c + K(D - D_c) & for, \quad D > D_c \end{cases}$$

$D_c$ : Critical damage fraction for acceleration

***Key idea (Phenomenological)***

**Incorporation**

Effect of

- Stress triaxiality $\sigma_m / \bar{\sigma}$
- Lode parameter $\mu = \dfrac{2\sigma_2 - \sigma_1 - \sigma_3}{\sigma_1 - \sigma_3}$

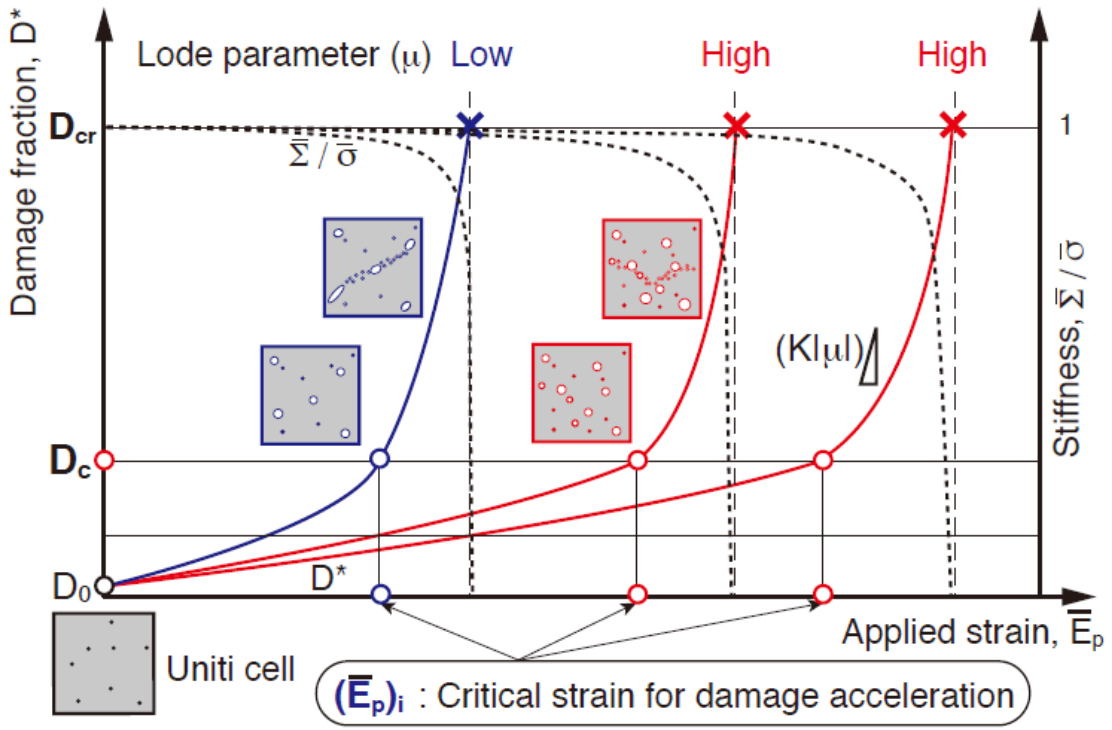
$(0 \le |\mu| \le 1)$

← Shear dominant

- **Plastic potential (yield function)**

$$\Phi = \left(\frac{\bar{\Sigma}}{\bar{\sigma}}\right)^2 + a_1 L(|\mu|) D^* \exp\left(a_2 \frac{\Sigma_m}{\bar{\sigma}}\right) - 1 = 0$$

$$L(|\mu|) = 1 - a_3 (1 - |\mu|)^{a_4}$$



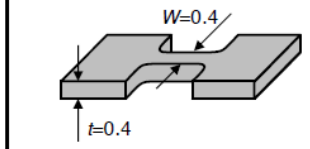
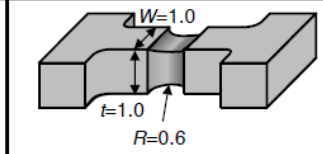
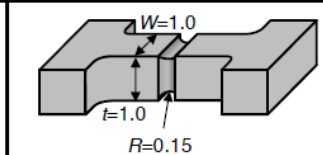

**The objective is not merely to measure an R-curve, but to predict it under component-relevant stress states.**

# Identification of ductile-damage parameters using multiple stress states

- Different miniature geometries are used to cover a wide range of stress triaxiality and Lode parameter.

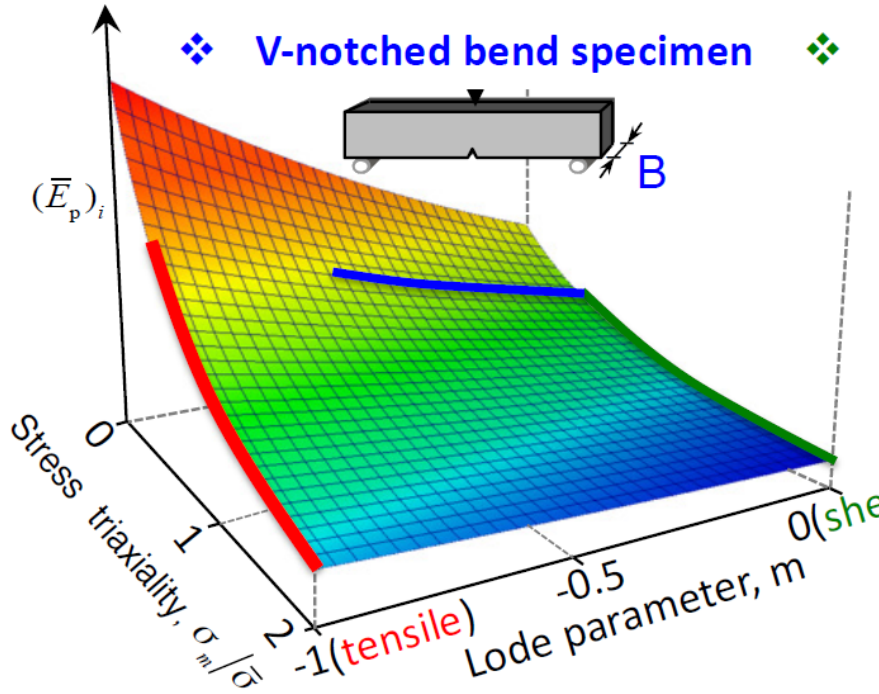
$$(\bar{E}_{\mathrm{p}})_i = A_1 \exp\left( A_2 \left.\frac{|\Sigma_{\mathrm{m}}|}{\bar{\Sigma}}\right|_{\mathrm{const.}} \right)\left\{1 - A_3\left(1 - |\mu|_{const.}|\right)^{A_4}\right\} \qquad \begin{cases} A = \dfrac{2}{a_1 a_2} \ln \dfrac{(1-D_0)D_c}{(1-D_c)D_0} \\ A_2 = -a_2,\ A_3 = a_3,\ A_4 = a_4 \end{cases}$$

❖ Small-size specimen

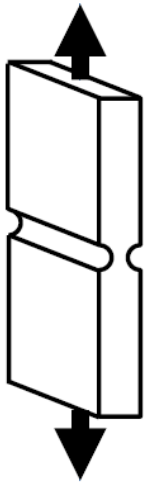
| | |
|---|---|
| FBT_smooth (Smooth Flat-Bar) |   |
| AENT_R06 (All-Edged Notch Tension) |   |
| AENT_R015 (All-Edged Notch Tension) |   |

μ= -1

❖ V-notched bend specimen




❖ Double notched plate

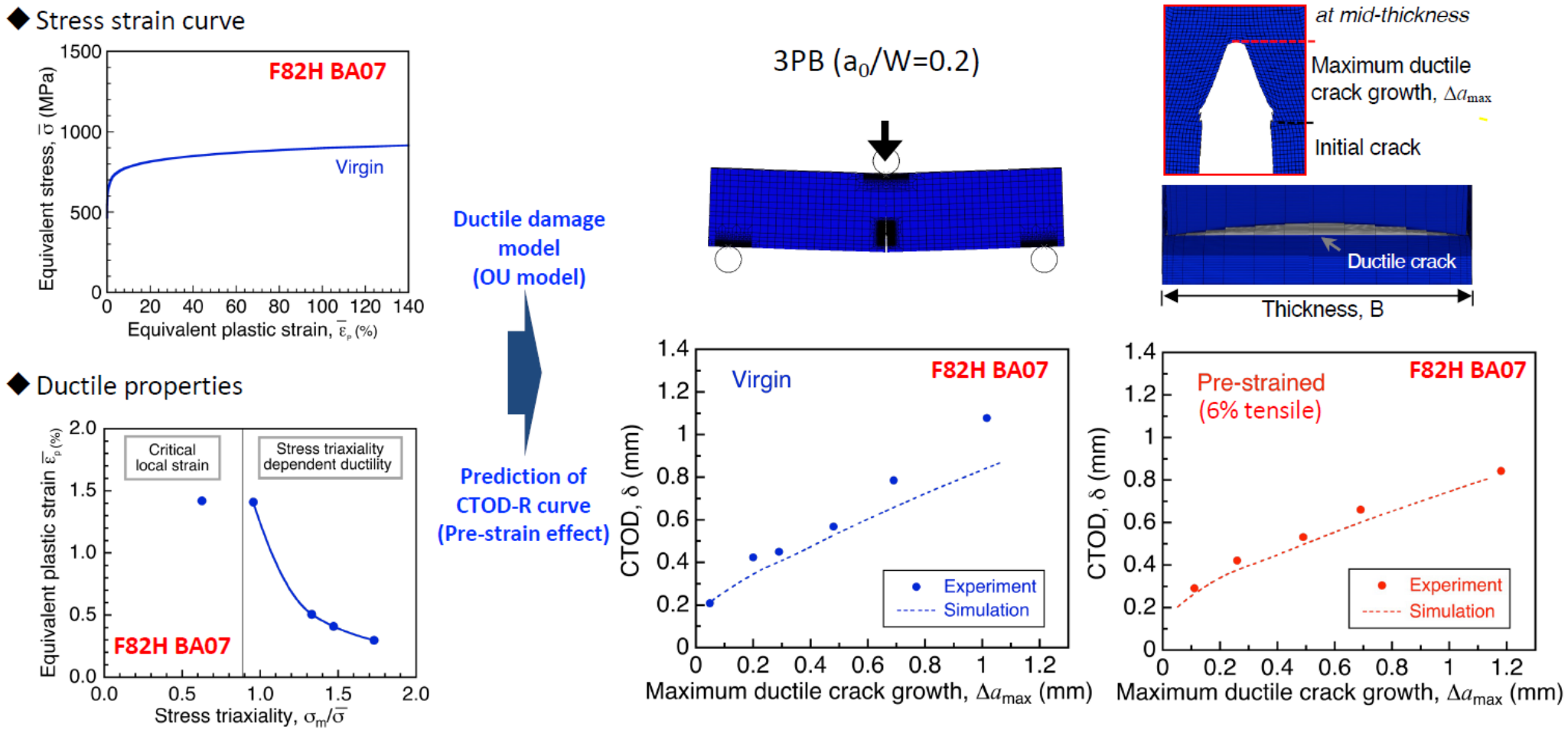


μ= 0

**This approach provides a basis for identifying damage parameters from a limited volume of irradiated material. The identified parameters are then used to predict crack initiation and the J-R curve.**

# Prediction of the ductile-fracture J-R curve using the local approach

- Can damage parameters identified from tensile and notched specimens reproduce crack-growth resistance?



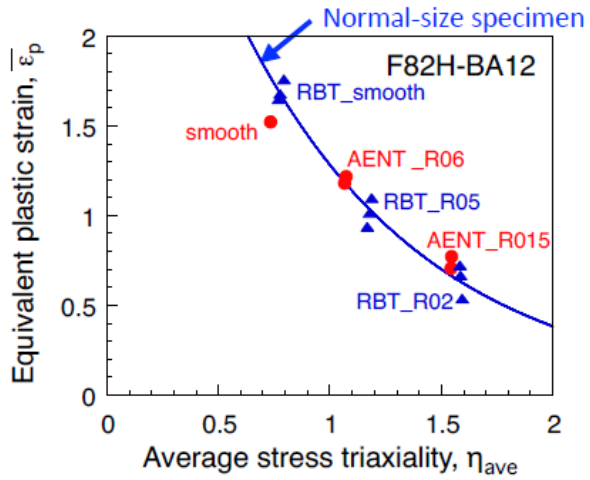

The model reproduces the observed initiation and crack-growth resistance for the evaluated F82H condition.

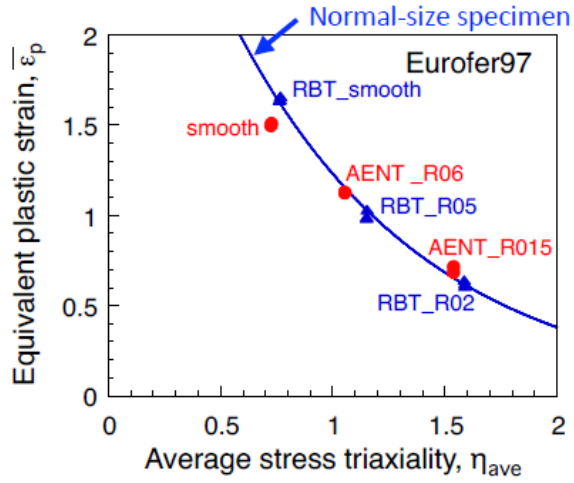
**Mechanism-informed parameters enable prediction of the J-R response beyond a single calibration geometry**

# Transferability of the ductile-damage framework

- The same framework is assessed across different specimen configurations and material conditions.

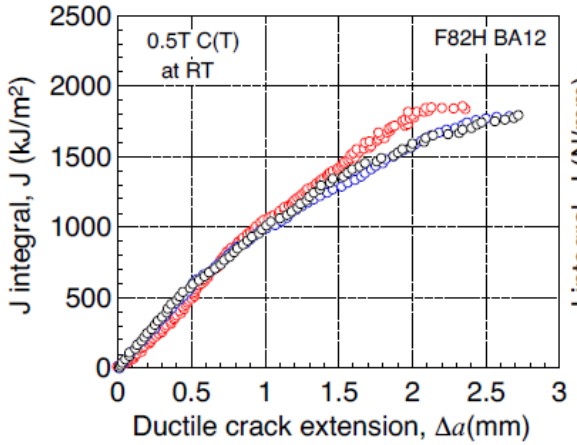
◆ **Stress triaxiality dependent ductility**

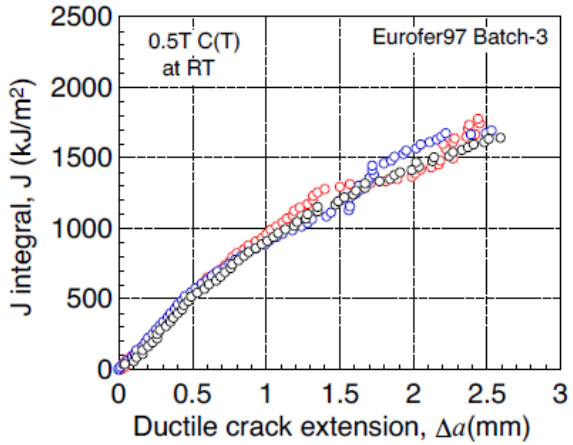


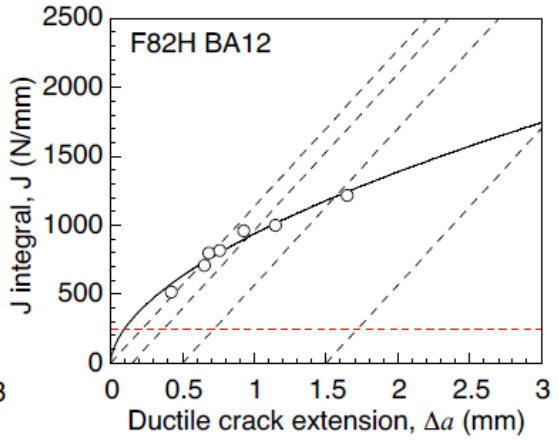

**Ductile damage model (OU model)**

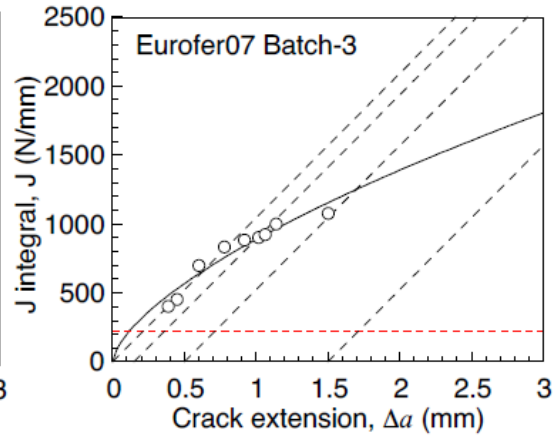
◆ **0.5T C(T): B=12.5mm**



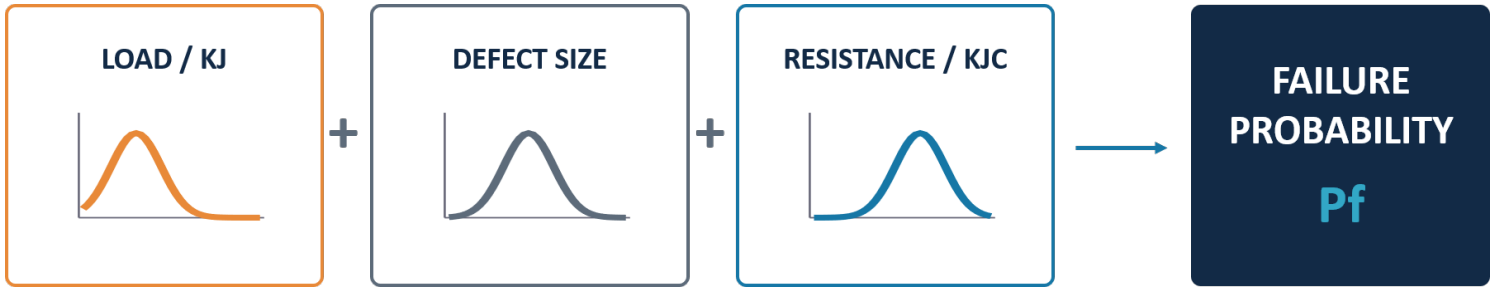

◆ **KLST, 3PB(a/W=0.25) : B=3mm**




**Transferability across stress states is essential before the model can be applied to irradiated specimens and structural components.**

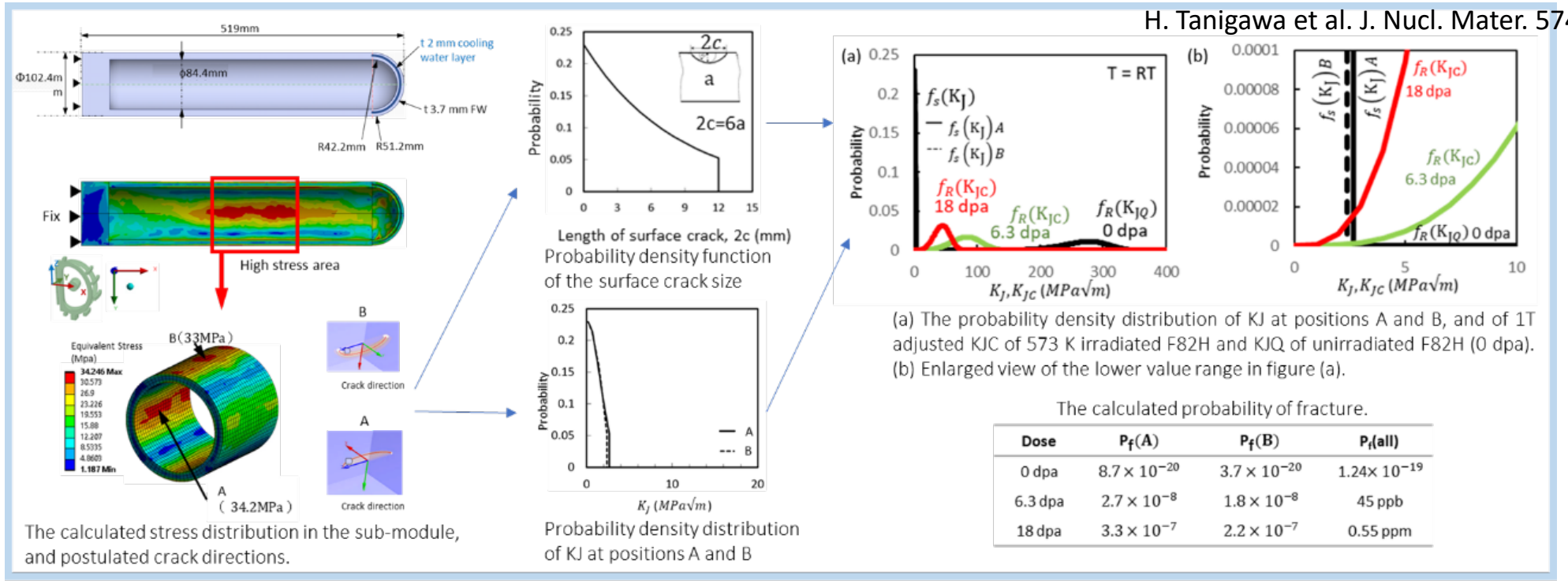
# PRA demonstration: From fracture data distributions to component reliability




## Why the lower tail matters

- The lower tail of fracture resistance can strongly influence the calculated failure probability, particularly when combined with uncertain flaw and load distributions.
- Even a small component-level failure probability may become significant when accumulated across a highly modular blanket system.

H. Tanigawa et al. J. Nucl. Mater. 574 (2023) 154148




The calculated stress distribution in the sub-module, and postulated crack directions.

(a) The probability density distribution of KJ at positions A and B, and of 1T adjusted KJC of 573 K irradiated F82H and KJQ of unirradiated F82H (0 dpa). (b) Enlarged view of the lower value range in figure (a).

The calculated probability of fracture.

| Dose | $P_f(A)$ | $P_f(B)$ | $P_f$(all) |
|---|---|---|---|
| 0 dpa | $8.7 \times 10^{-20}$ | $3.7 \times 10^{-20}$ | $1.24 \times 10^{-19}$ |
| 6.3 dpa | $2.7 \times 10^{-8}$ | $1.8 \times 10^{-8}$ | 45 ppb |
| 18 dpa | $3.3 \times 10^{-7}$ | $2.2 \times 10^{-7}$ | 0.55 ppm |

The calculated probability is a demonstration of the methodology and should not be interpreted here as an acceptance criterion.

**PRA translates fracture-data distributions and uncertainties into explicit requirements for the statistical quality of the IFMIF-DONES database.**

# Summary: What should IFMIF-DONES deliver for qualification?

| | | |
|---|---|---|
| 1 | **Qualification is broader than validation** | It integrates design requirements, validated material behavior, manufacturing quality, inspectability, and reliability. |
| 2 | **Deliver validated and transferable fracture evidence** | Acquire material parameters, distributions, mechanisms, and quantified uncertainties, rather than isolated mean values. |
| 3 | **Combine miniature specimens with mechanics-based transfer methods** | Explicitly address geometry, crack-tip constraint, and statistical size effects. |
| 4 | **Design the irradiation test matrix from qualification and PRA requirements** | Prioritize the evidence that most effectively reduces uncertainty in qualification decisions. |

**Maximize the qualification value of every irradiated specimen**

**IFMIF-DONES should provide not only fusion-neutron irradiation data, but the validated evidence needed to support defensible DEMO qualification decisions.**