International Symposium on Improvement of Nuclear Safety
Using Probabilistic Fracture Mechanics

PFM Applications to Seismic Safety Evaluation
- Seismic Fragility Evaluation Using PFM -

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Contents

Background

- ✓ On March 11, 2011, Fukushima Dai-ichi Nuclear Power Station (NPS) experienced an extremely massive earthquake (the Tohoku District - off the Pacific Ocean Earthquake) and a severe accident followed at an unprecedented scale and over a lengthy period.
- ✓ Many lessons have been learned from the Fukushima NPS accident. One of them is "Effective use of probabilistic safety assessment (PSA) in risk management" (Report of Japanese Government to the IAEA Ministerial Conference on Nuclear Safety, June, 2011)
- ✓ On the other hand, about one-third of the nuclear power plants (NPPs) in Japan have been operating for more than 30 years, and cracks due to age-related degradation mechanisms have been detected within some components including pipes.
- ✓ Therefore, seismic PRA and seismic safety evaluation considering aging mechanisms for aged components have become increasingly important.

Objective

- ✓ PFM has been recognized as a rational methodology for risk assessment of aged components, because it can evaluate the failure probabilities considering the age-related degradation mechanisms and the influence parameters with their inherent probabilistic distributions.
- ✓ In order to conduct seismic PRA considering aging mechanisms for aged components, a PFM analysis code for piping has been improved, considering typical aging mechanisms of pipes and fracture mechanics analysis models provided in Japan.
- ✓ Based on the analysis results of PFM code, failure probabilities, fragility curves of aged pipes were investigated. These data of failure probabilities and fragility curves are useful for seismic safety evaluation for aged components.

Applications to Seismic Safety Evaluation ④

- ✓ Application to safety advancement evaluation

　「実用発電用原子炉の安全性向上評価に関する運用ガイド」では経年事象や設計上の想定を超える事象を考慮したリスク評価や安全裕度の評価を求めている。

- ✓ Application to seismic PRA evaluation

　改訂中の原子力学会標準　地震PRA実施基準では経年事象を考慮したフラジリティ評価及びリスク評価を明記している。

- ✓ Application to risk evaluation and RI-ISI

　地震荷重の影響、検査の効果を考慮したリスク評価。リスク情報の活用、RI-ISIの評価。

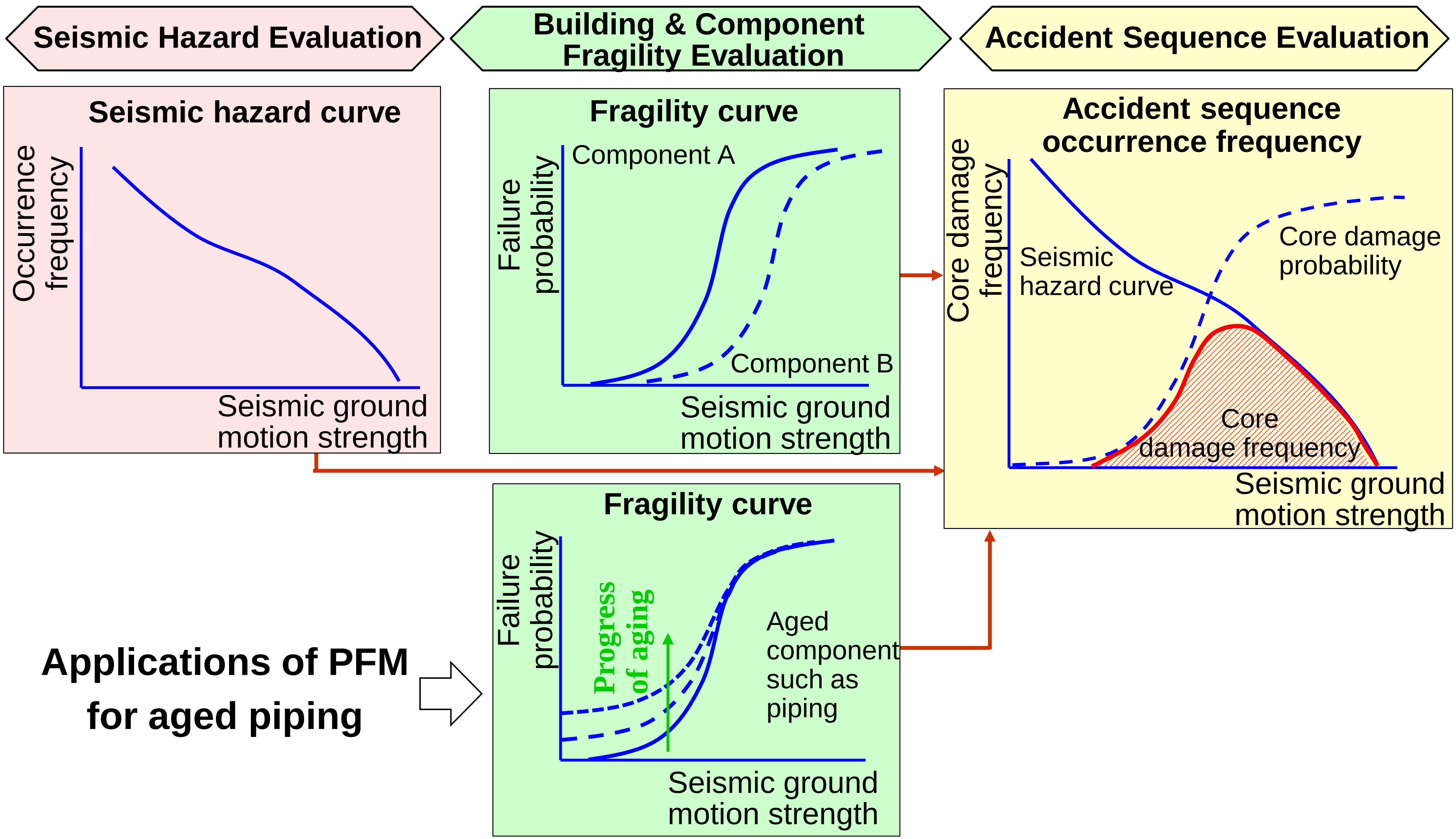
- ✓ Application to seismic safety margin evaluation

　偶然的不確実さ及び認識論的不確実さを考慮した信頼度評価及び裕度評価。

- ✓ Application to evaluation of combination effect of main-shock and after-shock, etc.

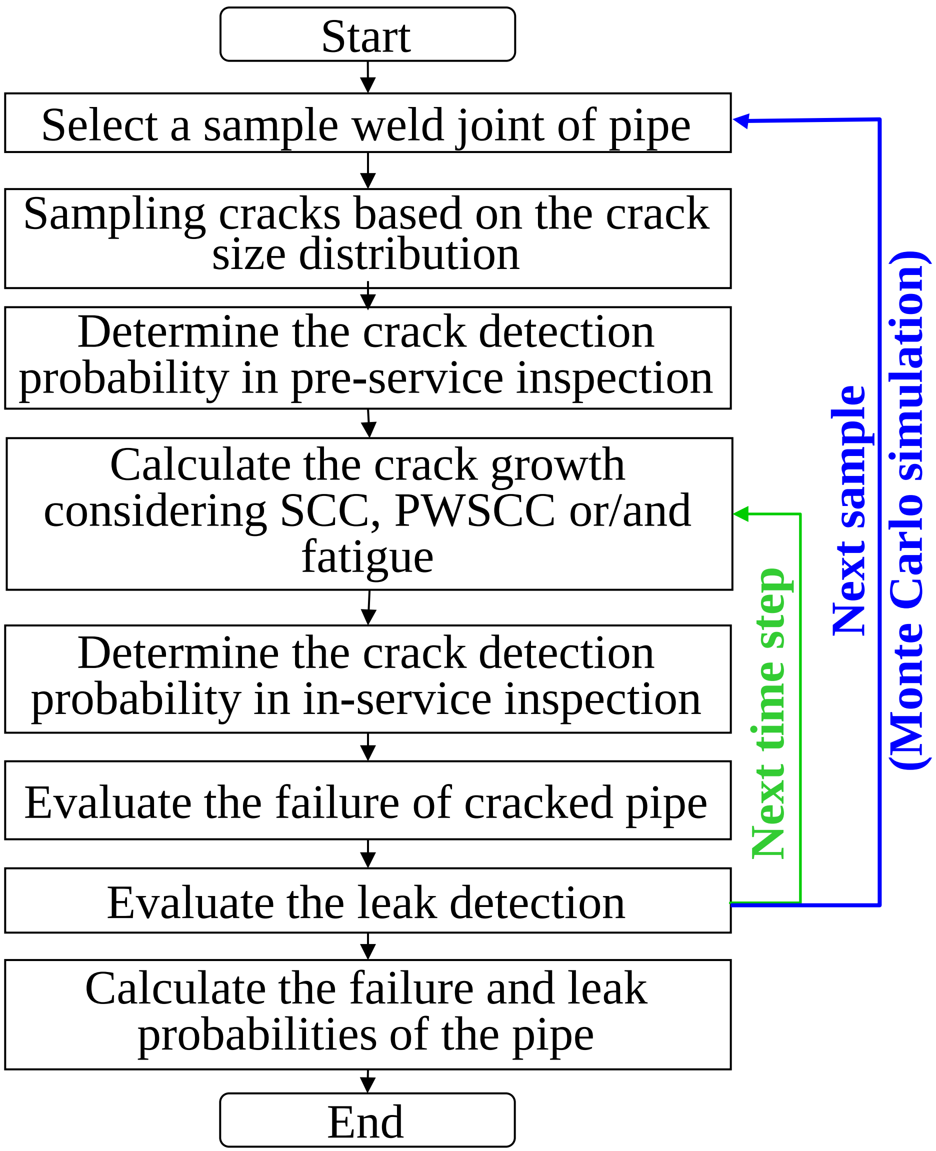
　本震と余震の重畳を考慮した経年配管のフラジリティ評価

Applications to Seismic Safety Evaluation



Process of seismic PRA and failure probability considering age-related degradation

PFM Analysis Code for Piping



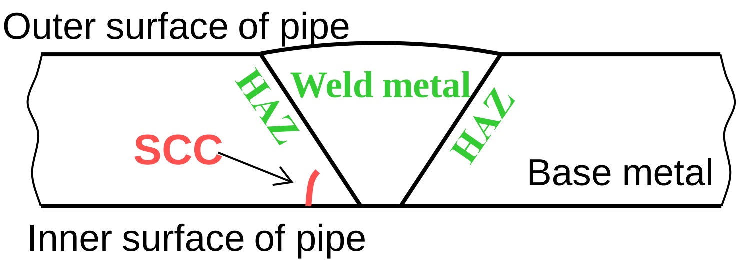
Example analysis flow of PFM code for piping

- ✓ **In order to conduct seismic PRA or seismic safety evaluation for existing NPPs, a PFM analysis code for aged piping has been developed to evaluate failure probabilities and fragility curves of cracked pipes considering aging mechanisms and seismic loads.**
- ✓ **To evaluate domestic aged piping at NPPs, this code has been improved based on the fracture mechanics analysis models and experimental data provided in Japan, such as:**
  - **Crack initiation and distribution due to SCC and PWSCC**
  - **Crack growth rates of SCC, PWSCC and fatigue**
  - **Solutions of stress intensity factor**
  - **Detection probability of in-service inspection**
  - **Failure evaluation of cracked pipe**

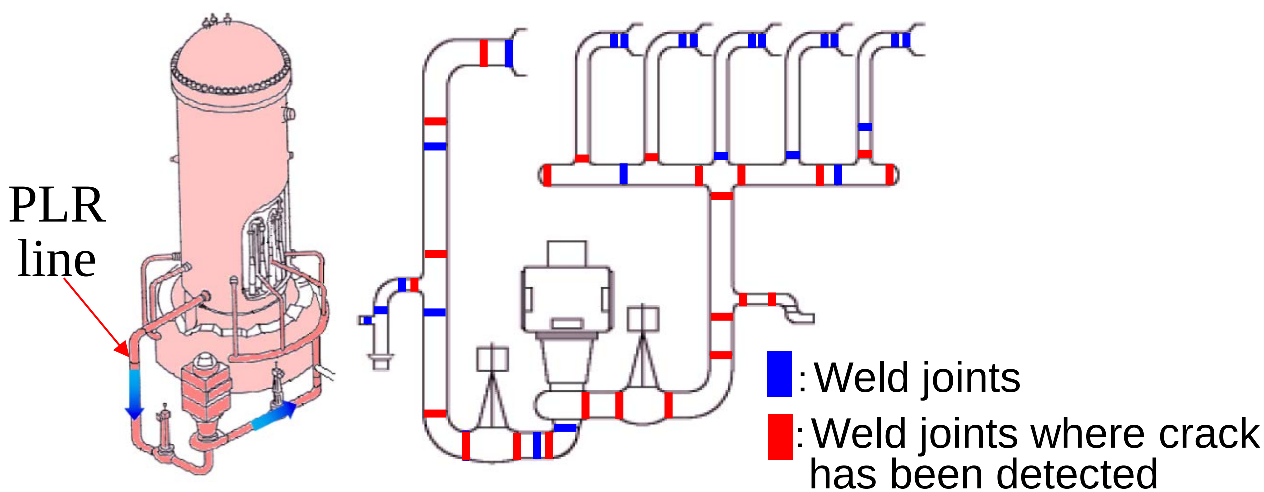
PFM Analysis Code for Piping

◆ Analysis function for BWR piping

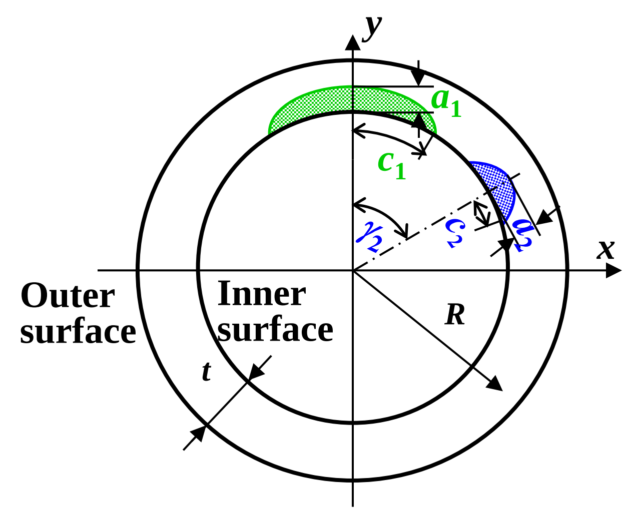
- ✓ Aging mechanisms: Cracks caused by SCC or initial cracks; Crack growth due to SCC and fatigue.
- ✓ Crack examples: Circumferential semi-elliptical surface cracks occurrence in weld joints.
- ✓ Crack initiation or distribution: Models based on Japanese measurement data.



SCC in a weld joint



Examples of SCC detected in BWR plants



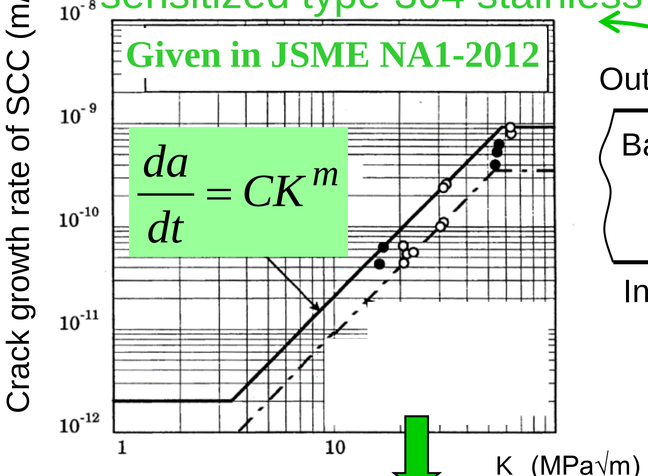
Circumferential semi-elliptical surface cracks in weld joints

PFM Analysis Code for Piping

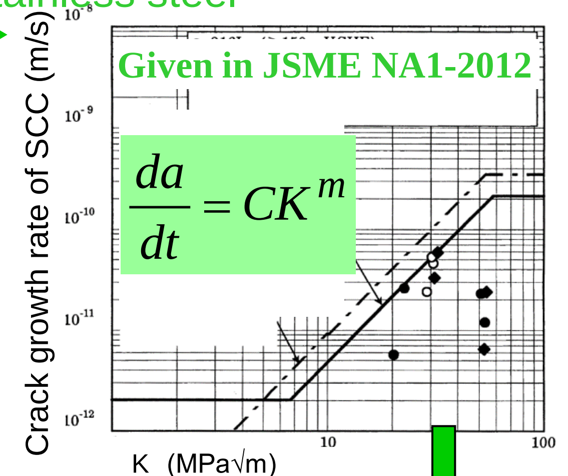
◆ Analysis function for BWR piping

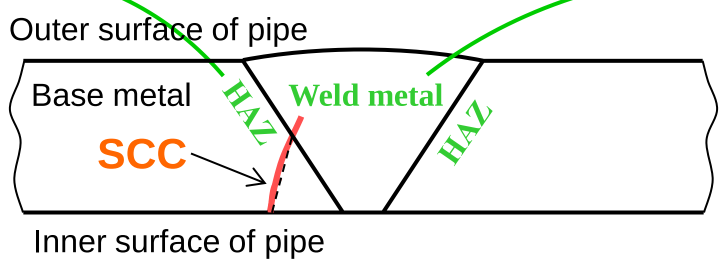
✓ **Probabilistic models of crack growth rates for both SCC and fatigue: Models based on the data provided in Japanese Fitness-For-Service Code (JSME NA1-2012)**

Crack growth rate (CGR) for sensitized type 304 stainless steel

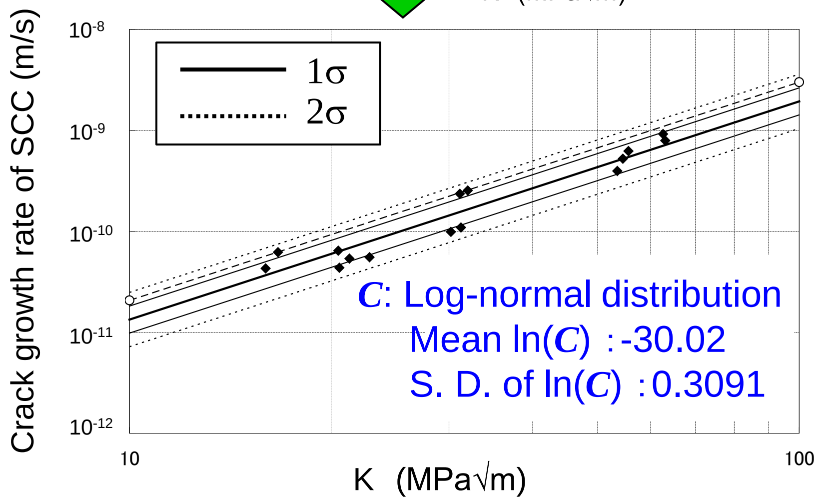


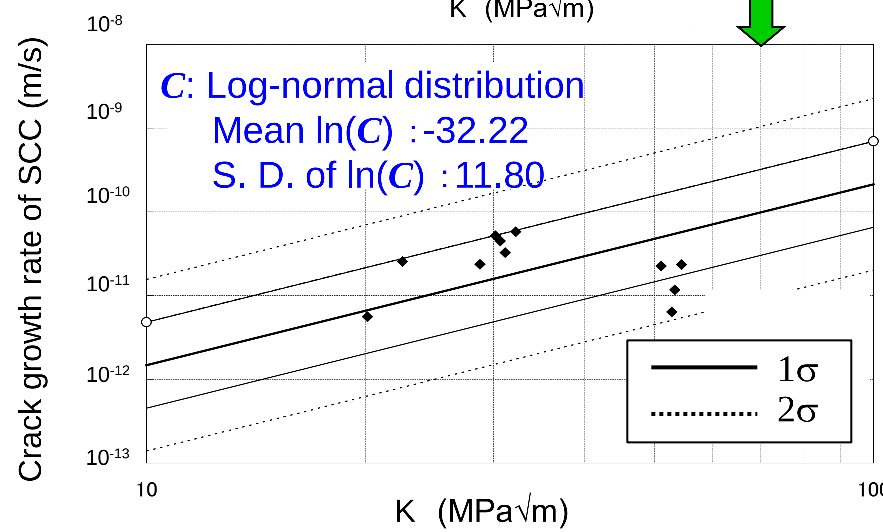
CGR for low carbon austenitic stainless steel





Crack growth model

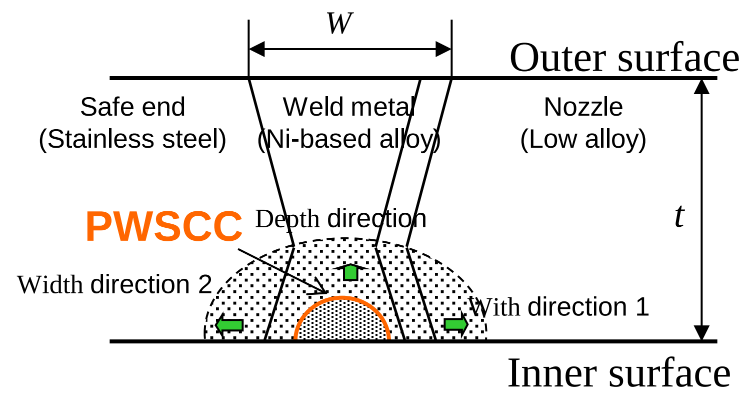




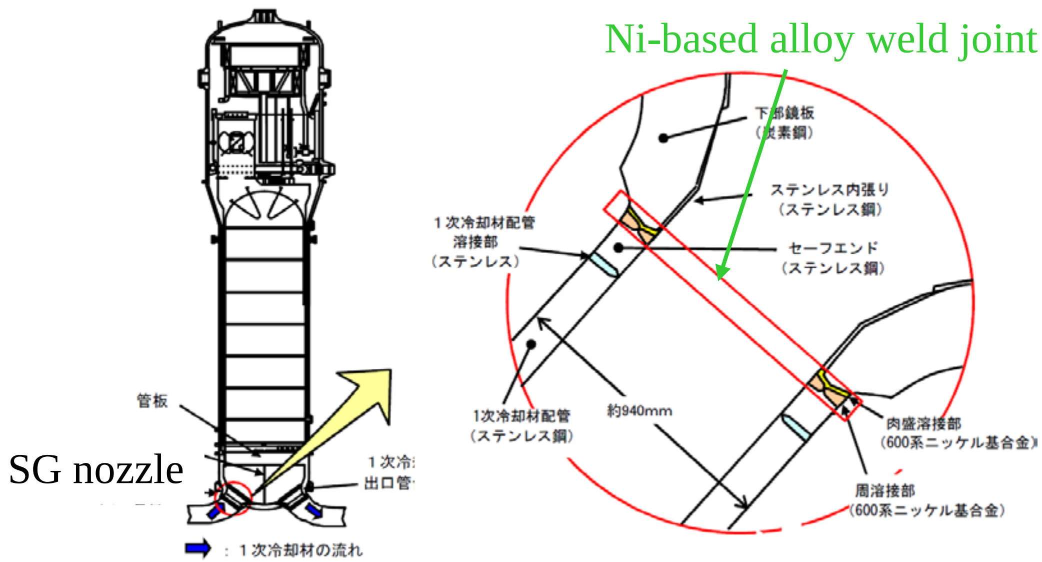
PFM Analysis Code for Piping

◆ Analysis function for PWR piping

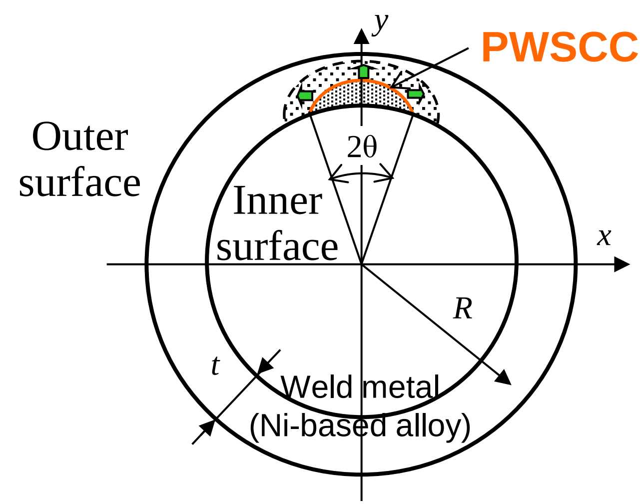
- ✓ Aging mechanisms: Cracks caused by PWSCC or initial cracks; Crack growth due to PWSCC and fatigue.
- ✓ Crack examples: Circumferential or axial semi-elliptical surface cracks occurrence in weld joints.
- ✓ CGR models: CGRs for different materials.
- ✓ WRS: WRS in dissimilar materials.



Axial semi-elliptical surface cracks in weld joints



Examples of PWSCC detected in PWR plants



Circumferential semi-elliptical surface cracks in weld joints

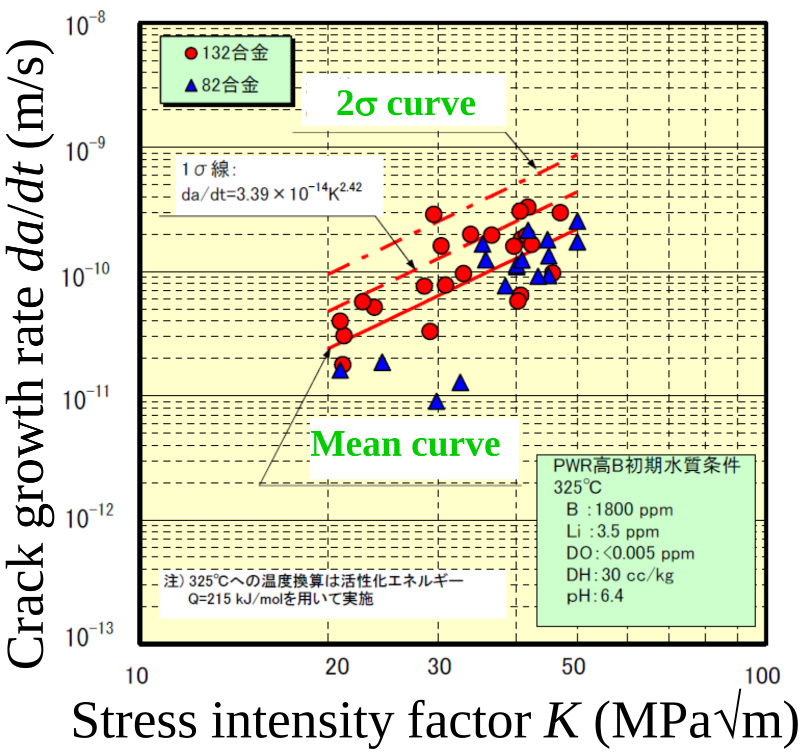
Analysis function for PWR piping

✓ CGR for PWSCC :

Models based on the data provided in JSME

$$\frac{da}{dt}=\exp\left[-\frac{Q_g}{R}\left(\frac{1}{T}-\frac{1}{T_{ref}}\right)\right]\alpha\left(K-K_{th}\right)^{\beta}$$

Q: thermal activation energy, R: universal gas constant
T: temperature, T_{ref}: reference temperature
α: CGR coefficient, β: CGR exponent

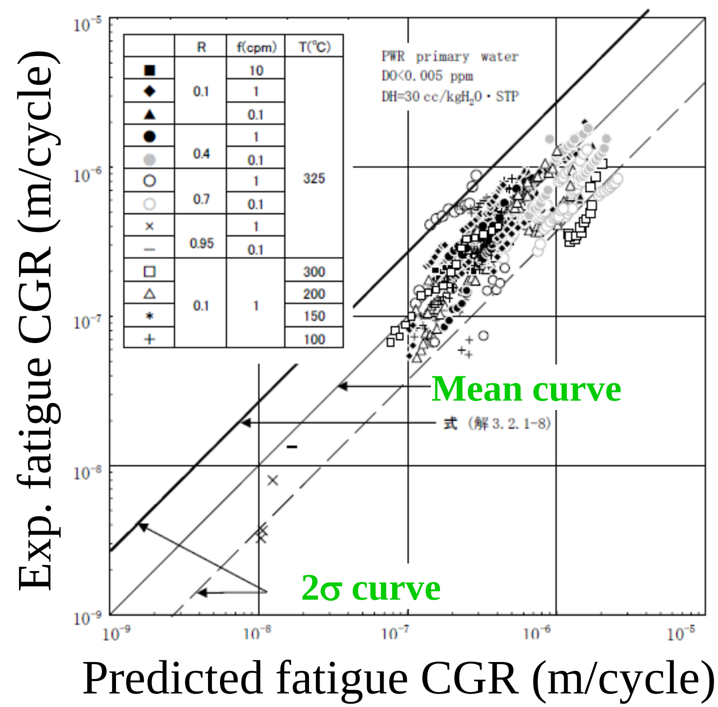


✓ CGR for fatigue:

Models based on the data provided in JSME

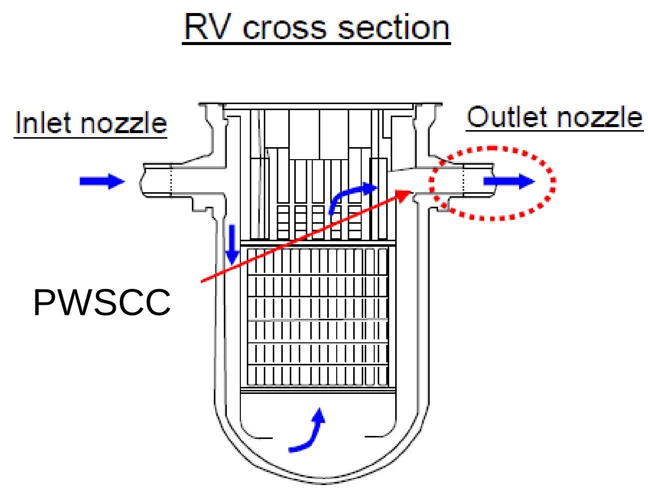
$$\frac{da}{dN}=\begin{cases} c_N T_c^{0.77} t_r^{0.24}\left(\Delta K\right)^{3.25}/\left(1-R\right)^{1.34} & \Delta K \ge \Delta K_{th} \\ 0 & \Delta K < \Delta K_{th} \end{cases}$$

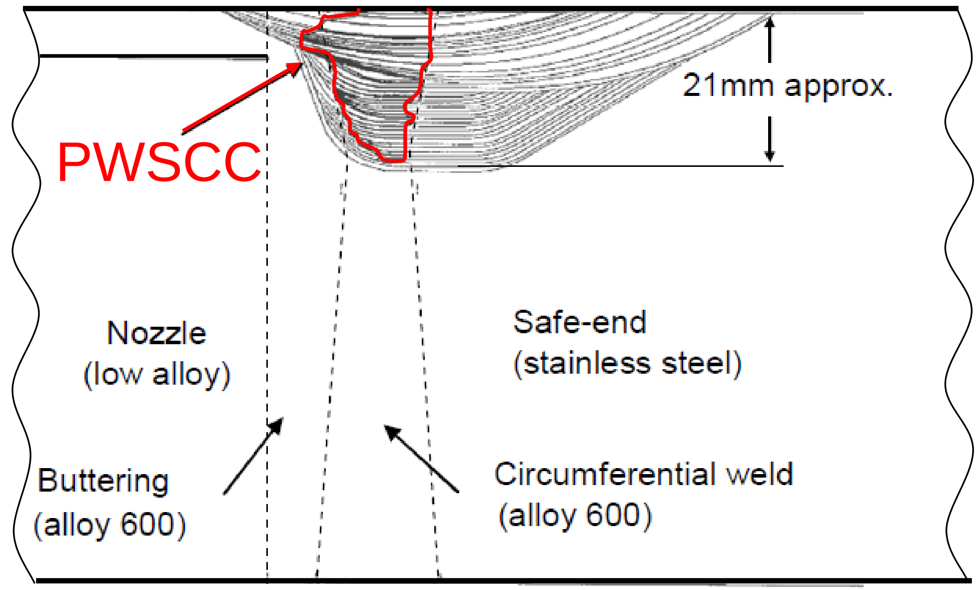
R:stress ratio, t_r: loading increasing time,
T_c:temperature, c_N : CGR coefficient



PFM Analysis Code for Piping

✓ Example PWSCC with large aspect ratio detected in NPPs





Outlet nozzle

✓ SIF solutions for semi-elliptical surface cracks with large aspect ratio in plates and cylinders

- a/ℓ = 0.5, 1.0, 2.0, 4.0
- a/t = 0.0, 0.1, 0.2, 0.4, 0.6, 0.8
- t/R_i = 0 (**plate**), 1/80, 1/40, 1/20, 1/10, 1/5, 1/2 (cylinder)

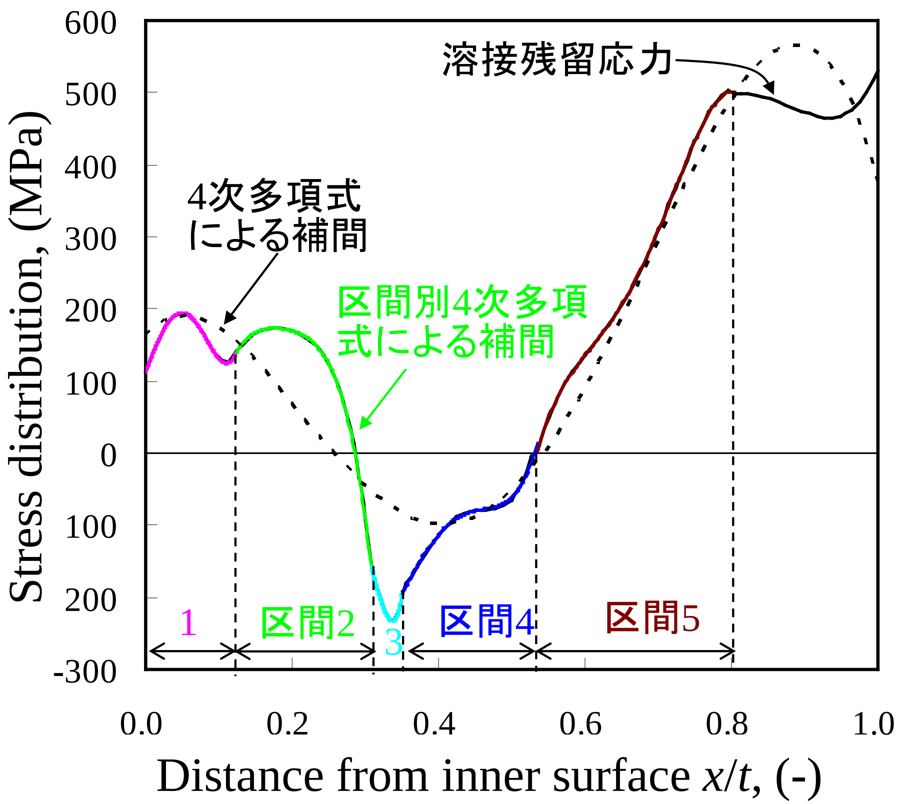
- Cracks in both circumferential and axial directions

PFM Analysis Code for Piping

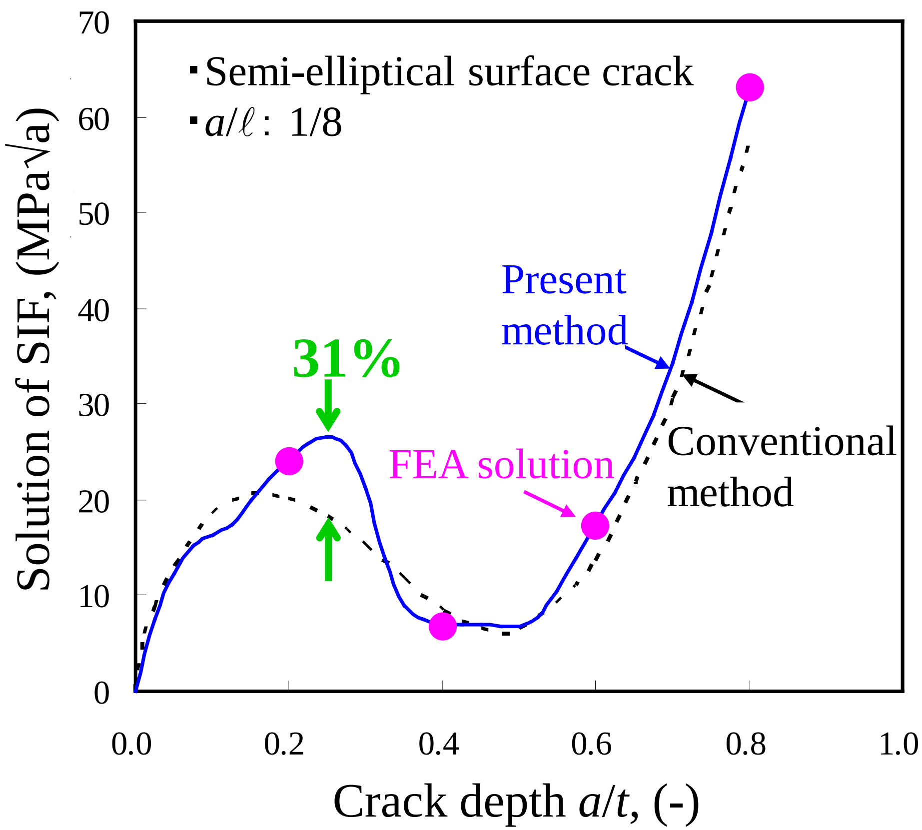
✓ SIF calculation method for complicated stress distributions

$$K_I = \sum_{j=1}^{m} \sum_{i=0}^{n_j} F_{ij} A_{ij} \left(\frac{a}{t}\right)^i \sqrt{\frac{\pi a}{Q}}$$

a: crack depth, ***Q*** : flaw shape parameter
m: number of divided segments
$\boldsymbol{n_j}$: order of polynomial at j-th segment
$\boldsymbol{A_{ij}}$: coefficients of stress polynomial distribution at segment ***j***
$\boldsymbol{F_{ij}}$: coefficients obtained from weight function



Curve fitting of stress distribution by segment division

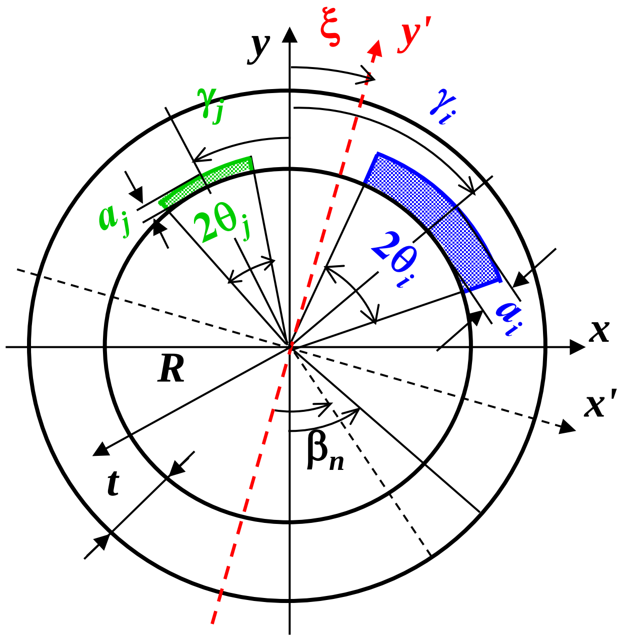


SIF solution using proposed method

PFM Analysis Code for Piping

✓ **The failure evaluation method for a pipe containing multiple cracks in the same cross section of pipe [1]:**

[1] *Y. Li. et al, PVP2009-77061*



Pipe section with multiple cracks

➢**The direction of coordinates that provides the minimum failure strength:**

$$\tan\xi = \frac{\sum_{i=1}^{n_i} a_i \sin\gamma_i \sin\theta_i - \sum_{j=1}^{n_j} a_j \sin\gamma_j \sin\theta_j}{\sum_{i=1}^{n} a_i \cos\gamma_i \sin\theta_i}$$

$\boldsymbol{n_i}$: number of cracks on the right side of y-axis

$\boldsymbol{n_j}$: number of cracks on the left side of y-axis

$\boldsymbol{n}$: total number of cracks

➢**The failure bending stress :** corresponding to (x', y') coordinates

$$\sigma_{bn}^{c} = \frac{2\sigma_f}{\pi}\left[2\sin\beta_n - \sum_{i=1}^{n}\frac{a_i}{t}\cos\gamma_i \sin\theta_i\right]$$

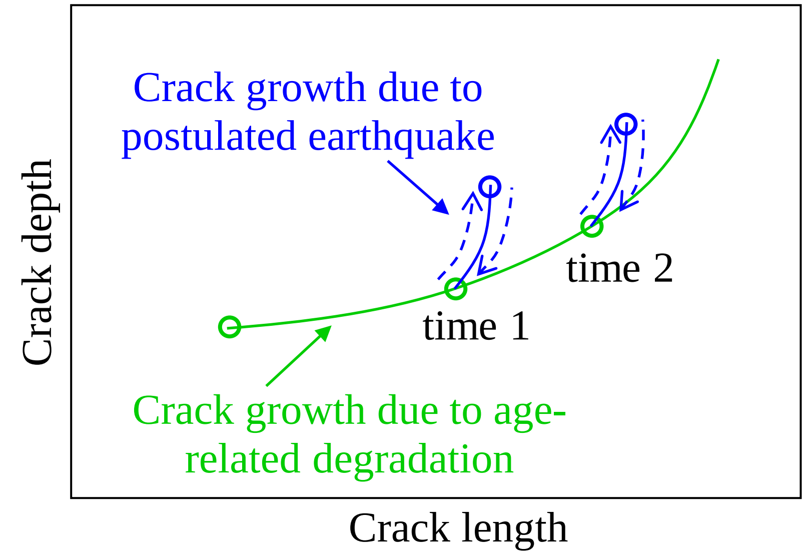
➢**The neutral angle :**

$$\beta_n = \frac{1}{2}\left[\pi - \sum_{i=1}^{n}\frac{a_i}{t}\theta_i - \pi\frac{\sigma_m}{\sigma_f}\right]$$

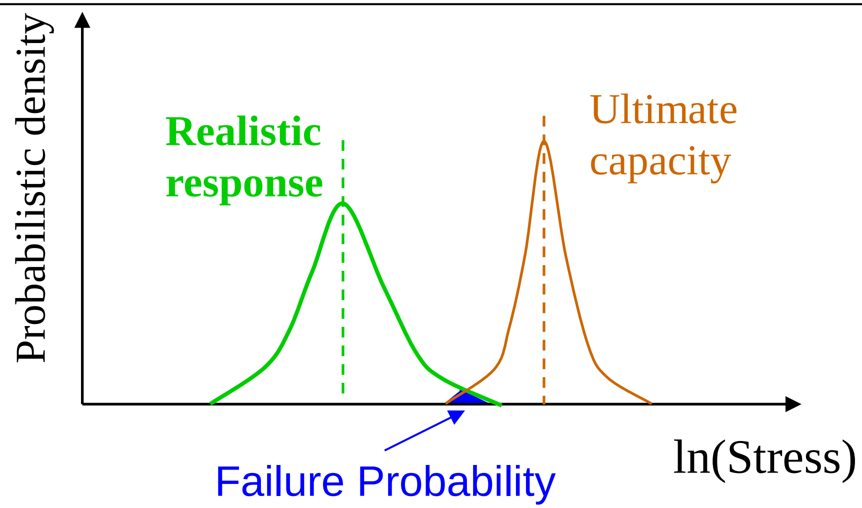
PFM Analysis Code for Piping

✓ Analysis function for seismic response stress

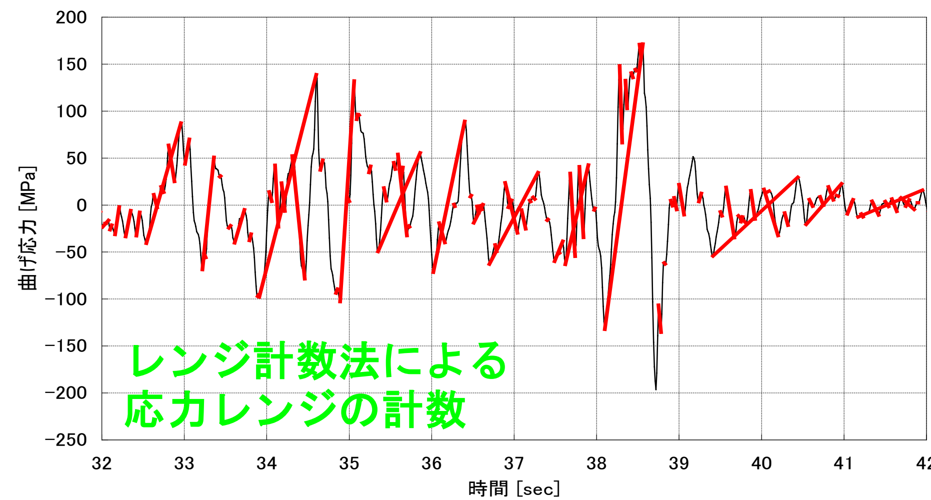
- Consideration of equivalent cyclic stress
- Consideration of uncertainty of seismic response stress
- Consideration of seismic waves
- Consideration of response stress from severe earthquake



Crack growth due to postulated earthquake



Uncertainty of seismic response stress

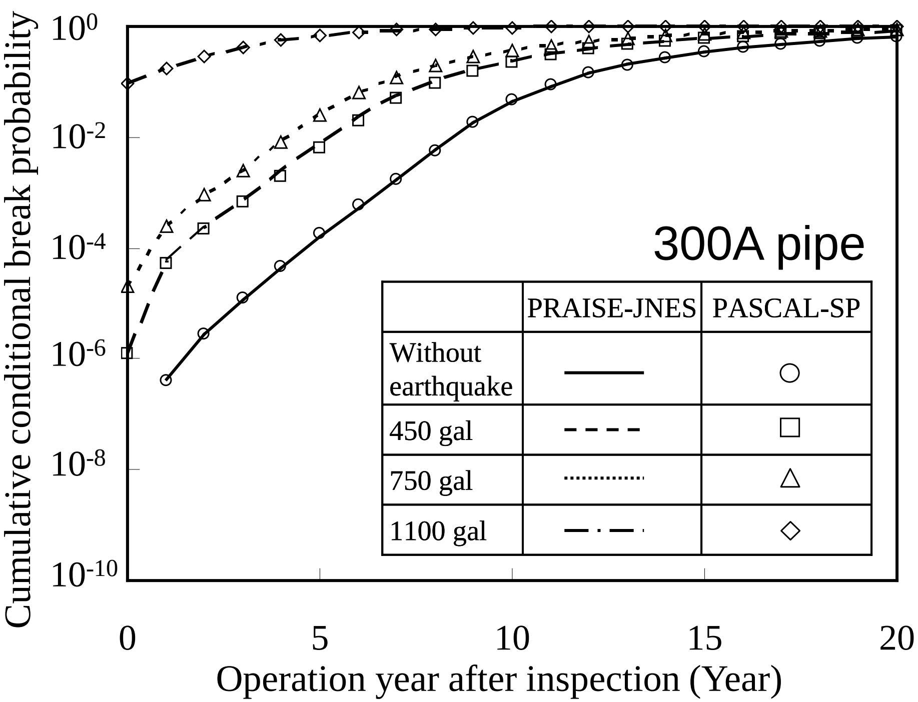


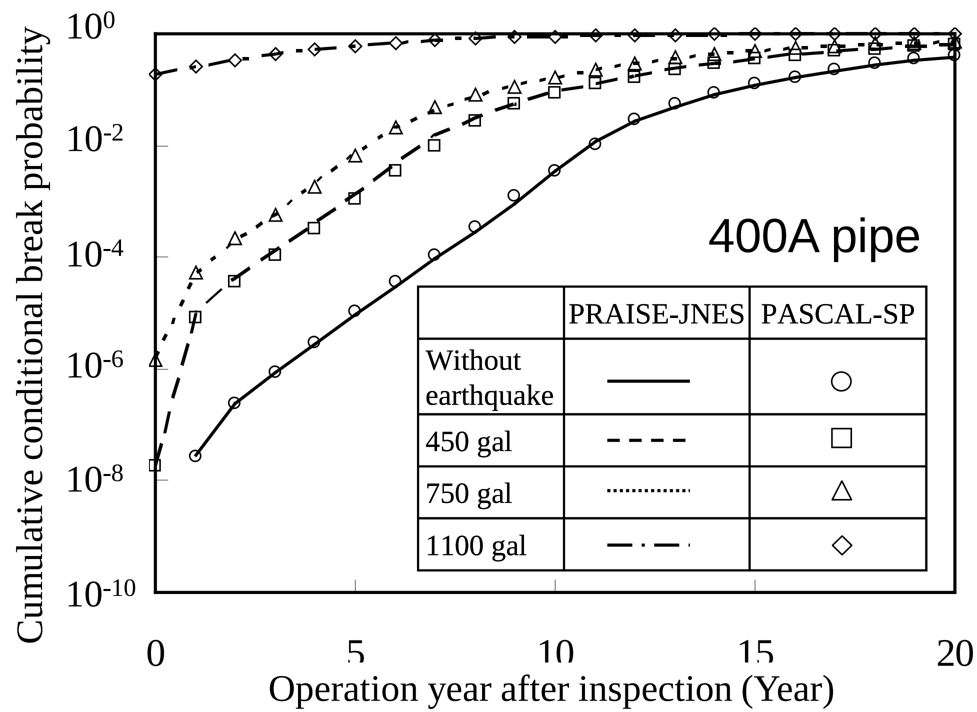
Consideration of seismic response waves

Benchmark Analysis Results

✓ Results considering crack initiated by SCC

- Objective：confirm the reliability of PFM codes developed by different organizations
- PFM analysis codes：PASCAL-SP (Developed by JAEA), PRAISE-JNES (Improved based on pc-PRAISE by JNES)
- Pipe：PLR pipe in BWR plant
- Crack: SCC; Circumferential inner surface semi-elliptical crack in weld joints
- Crack growth: crack growth due to SCC and fatigue
- Failure probability: with and without seismic loads



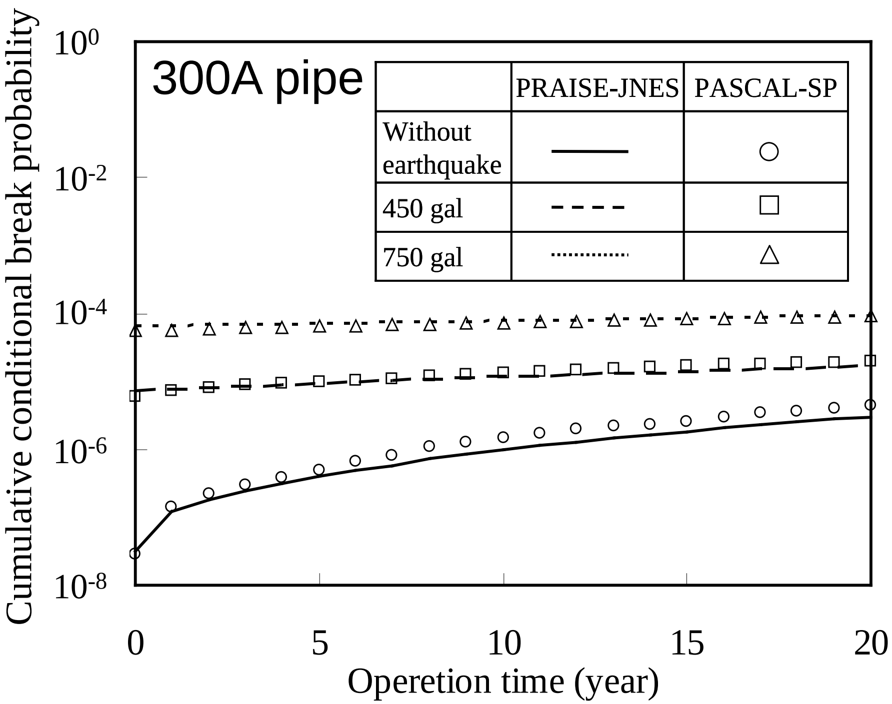


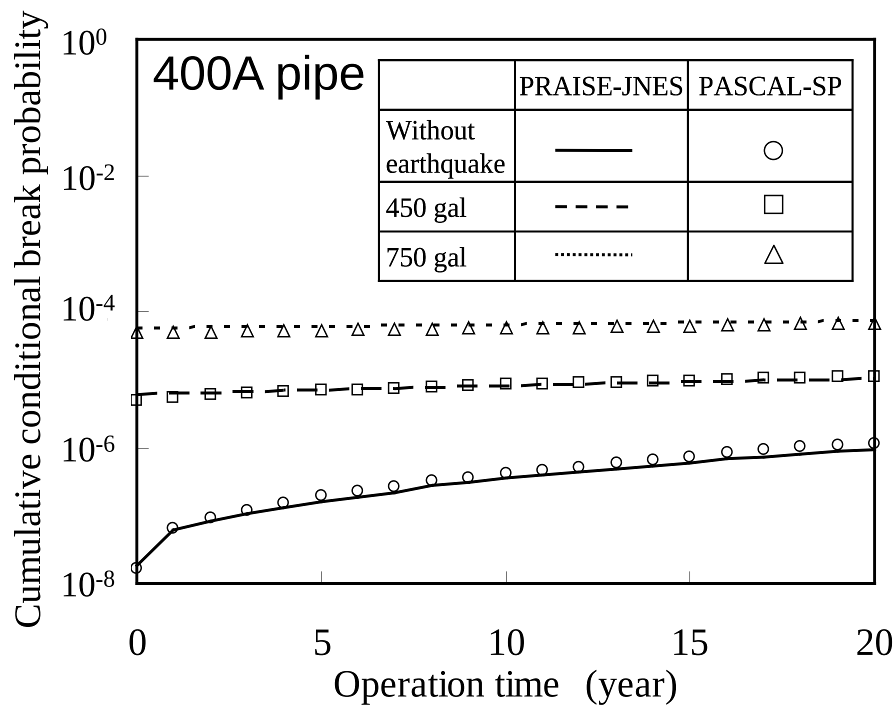
Example results of failure probability

Benchmark Analysis Results

✓ Results considering crack growth due to fatigue

- PFM analysis codes：PASCAL-SP (JAEA), PRAISE-JNES (JNES)
- Pipe：stainless pipe in BWR plant
- Crack: initial crack in weld joints caused by welding or etc.
- Crack growth: crack growth due to fatigue
- Failure probability: with and without seismic stresses

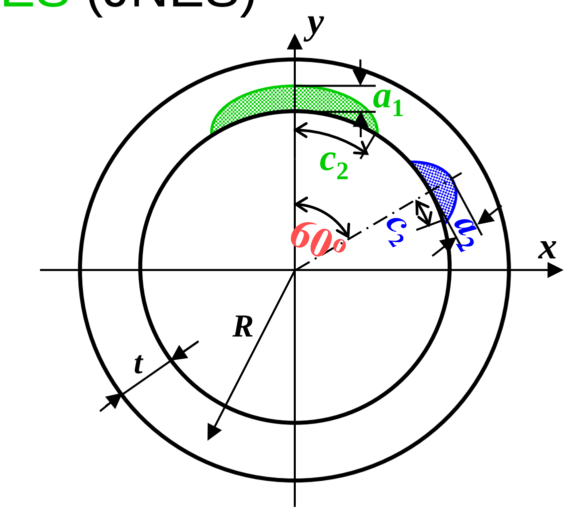


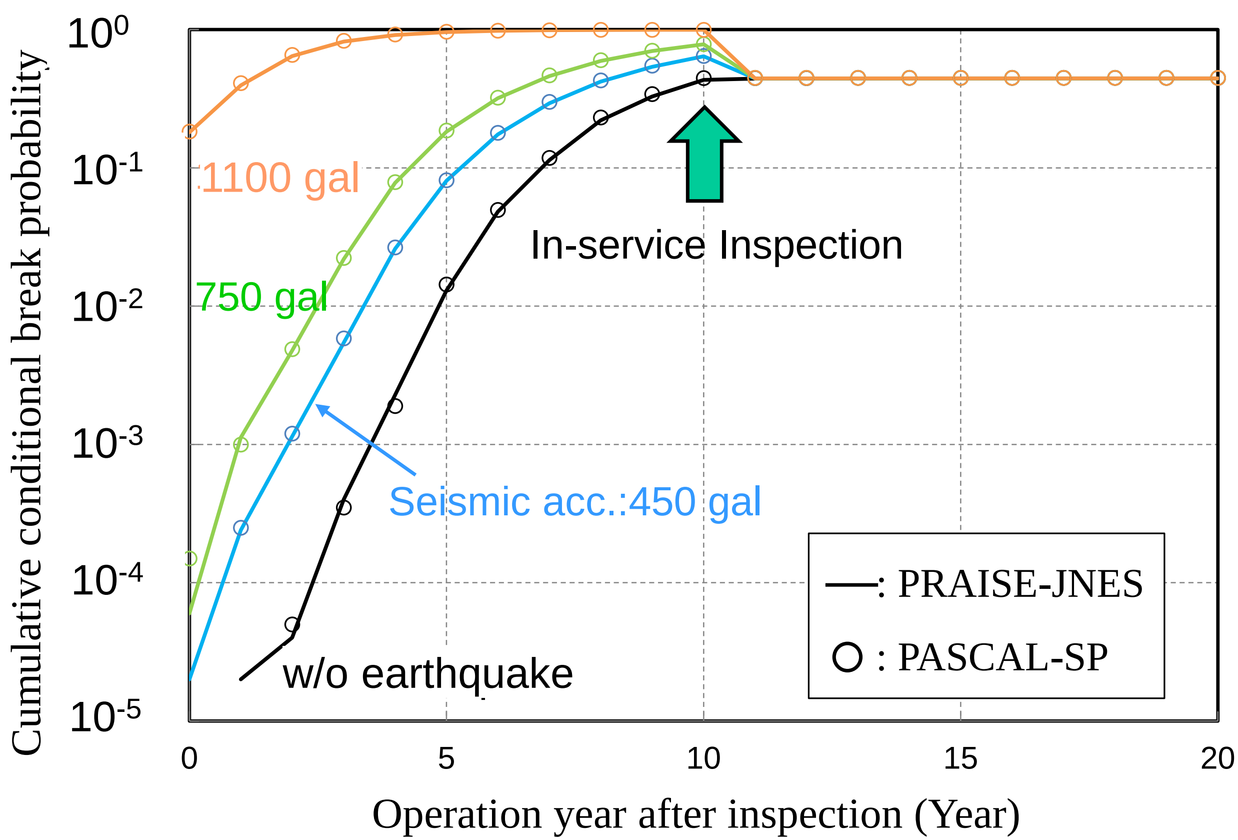


Example results of failure probability

✓ Results considering seismic stress and in-service inspection

- PFM analysis codes：PASCAL-SP (JAEA), PRAISE-JNES (JNES)
- Pipe：PLR pipe in BWR plant ･Cracks: SCCs
- Crack growth: crack growth due to SCC and fatigue
- Failure probability: with and without seismic stresses





- Analysis for two initial cracks
- Located at 0 deg. and 60 deg.

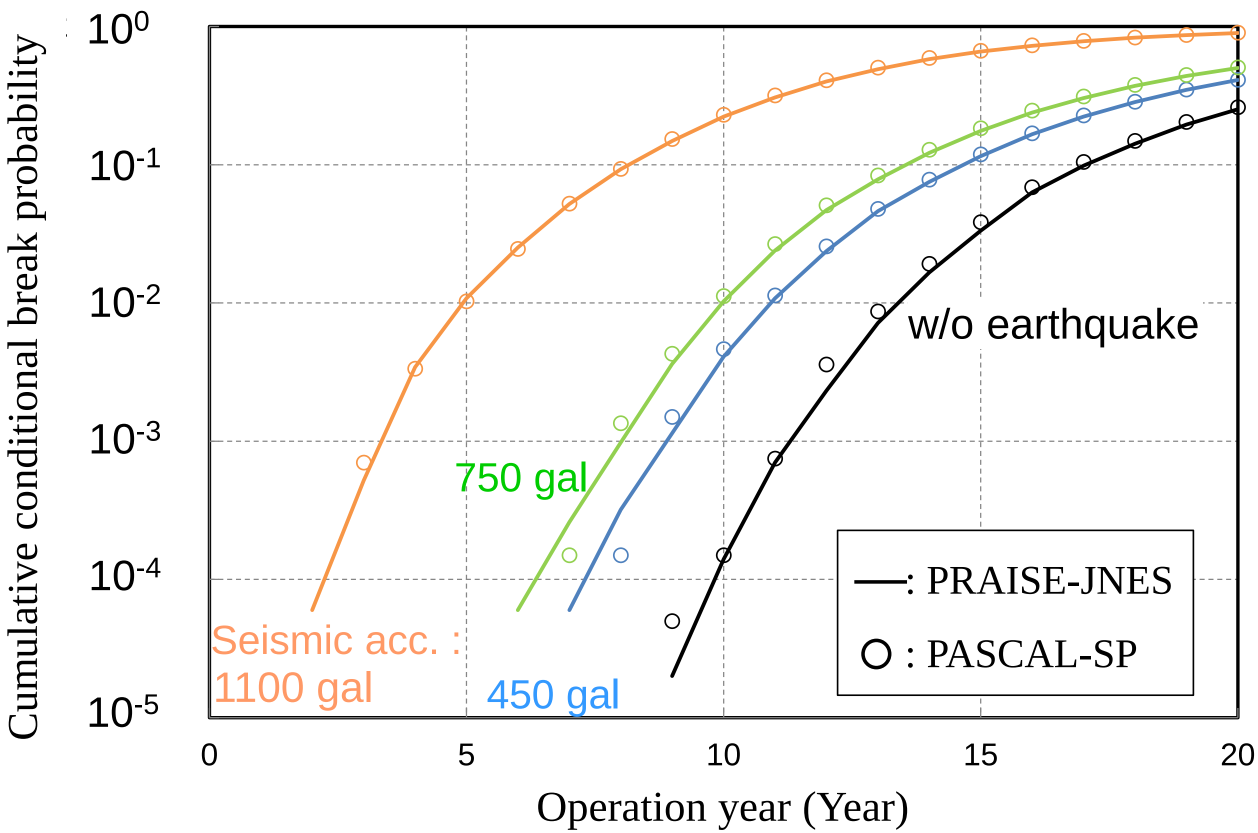
- Analysis model of detection probability: Proposed by Khaleel [1].
- Parameters: Corresponding to the “outstanding level” of the detection performance and crack due to SCC.

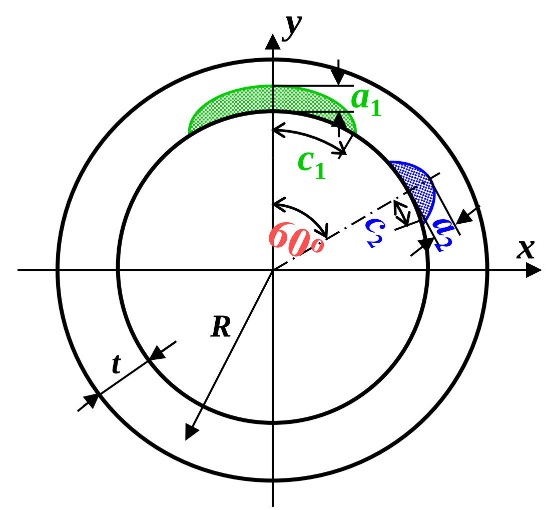
[1] *M. A. Khaleel et al, ASME PVP 1995.*

Benchmark Analysis Results

✓ Results considering crack initiation and growth due to SCC

- PFM analysis codes：PASCAL-SP (JAEA), PRAISE-JNES (JNES)
- Pipe：PLR pipe in BWR plant
- Cracks: SCCs; Multiple cracks;
  Circumferential inner surface semi-elliptical crack in weld joints
- Crack growth: crack growth due to SCC and fatigue
- Failure probability: with and without seismic stresses



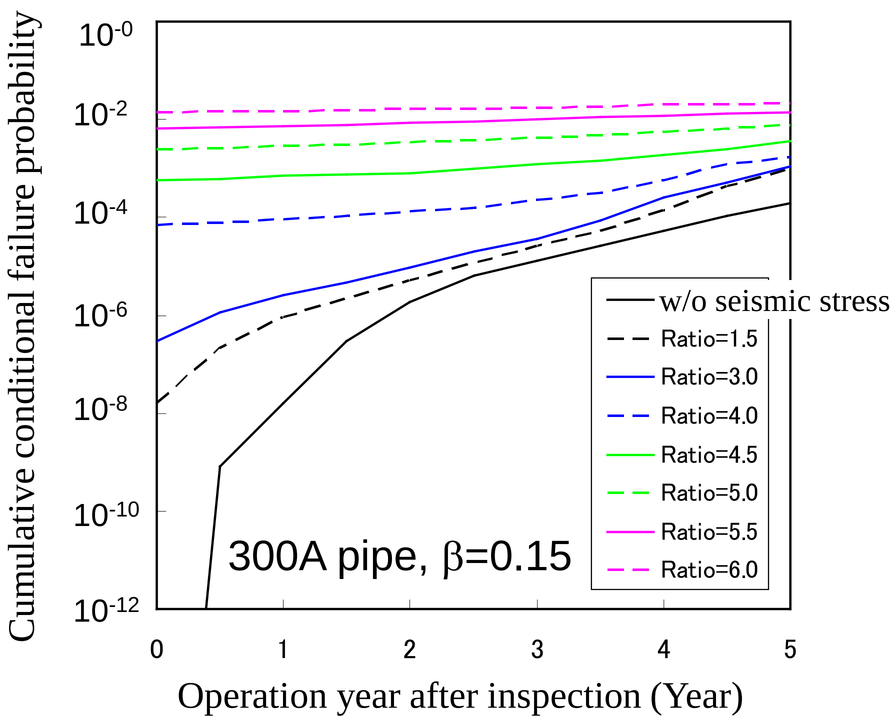


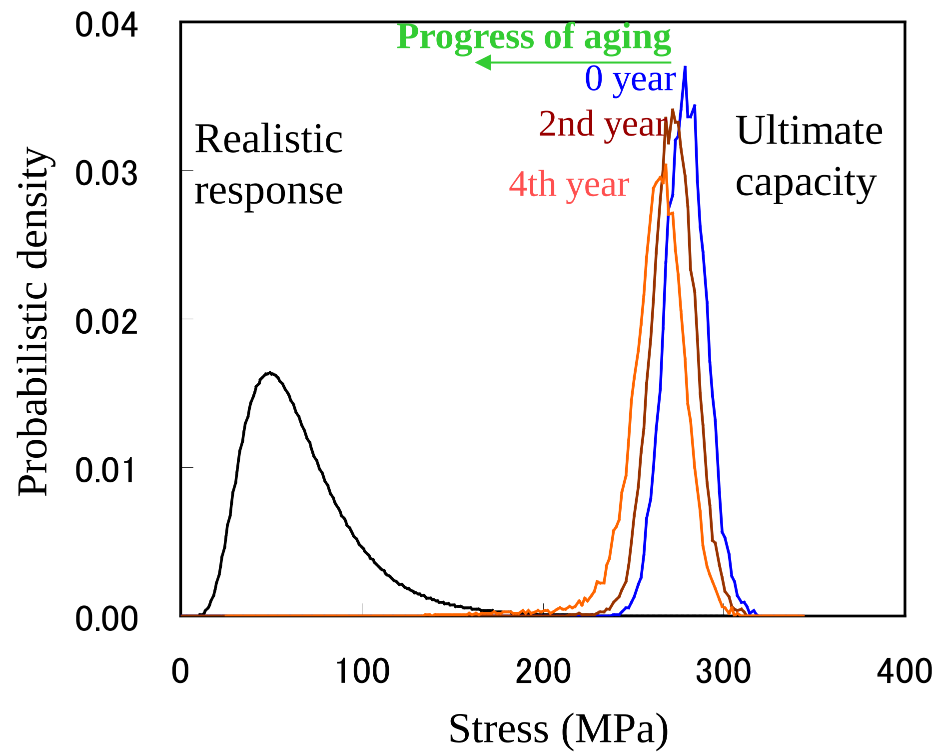
- Analysis for two initiated cracks
- Initiated at 0 deg. and 60 deg.

Example Analysis Results of Seismic Fragility ⑲

✓ Failure probabilities and probabilistic distribution of ultimate capacity

- Through PFM analyses, the failure probabilities considering the effects of age-related degradation and seismic stresses can be obtained.
- Corresponding to failure probabilities obtained from PFM, the probabilistic distribution of the ultimate capacity and its decrease due to progress of aging degradation can be evaluated.

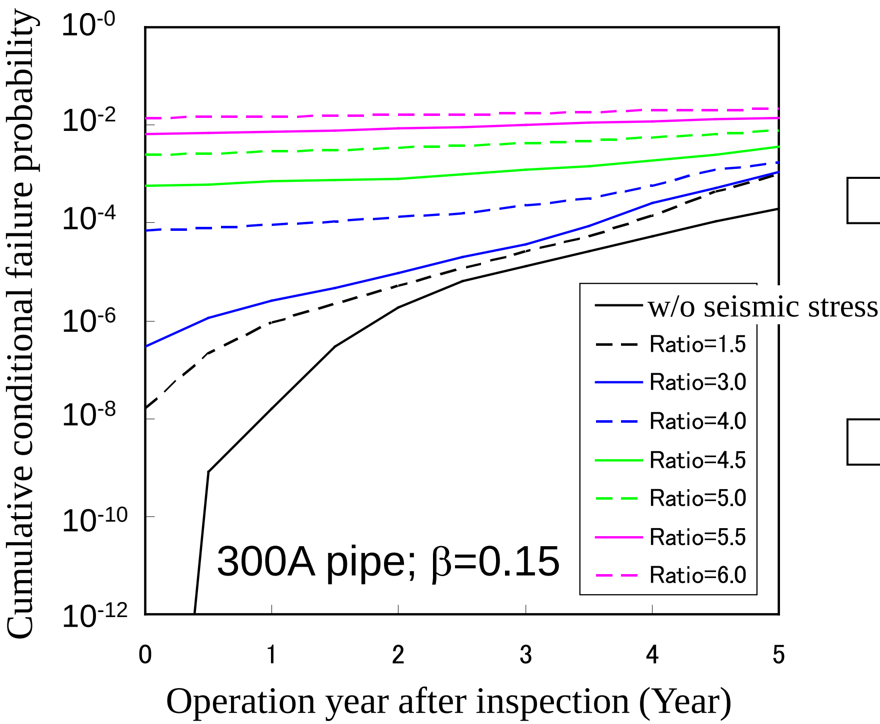


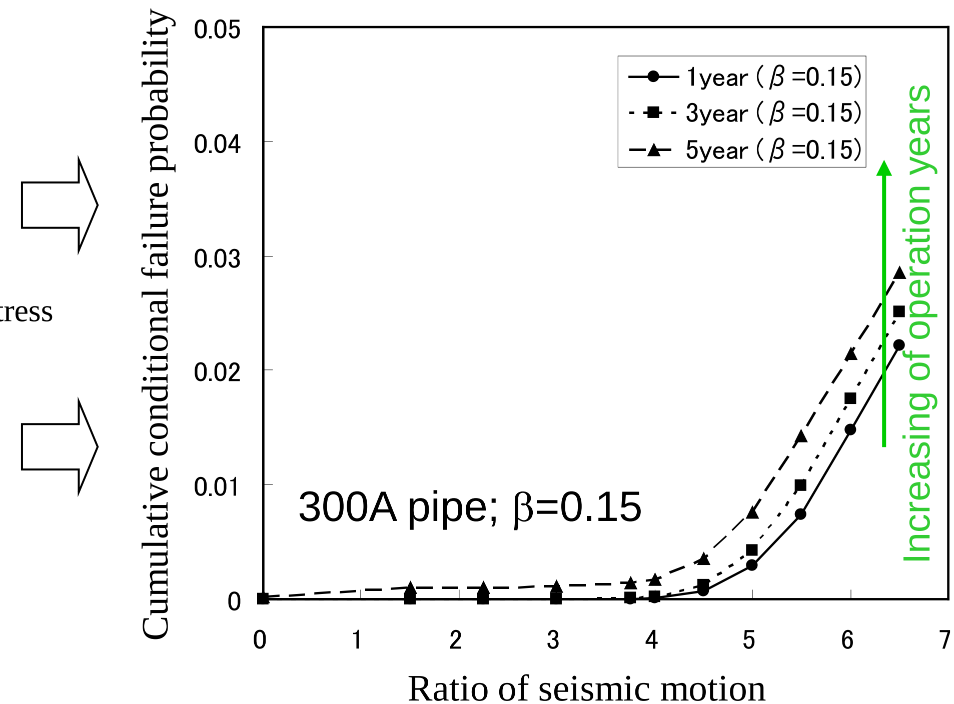


Failure probability considering seismic stress and probabilistic distribution of ultimate capacity

✓ Seismic fragility curves considering age-related degradation

- **Through PFM analyses, the failure probabilities considering the effects of age-related degradation and seismic stresses can be obtained.**
- **Based on the failure probabilities obtained from PFM, the fragility curves which are useful in risk evaluation can be obtained for different operation years.**
- **Comparing the general fragility curve, the fragility curve considering age-related degradation is a function of operation year. The fragility curve goes up with the increasing operation year, due to the progress of the aging mechanisms.**



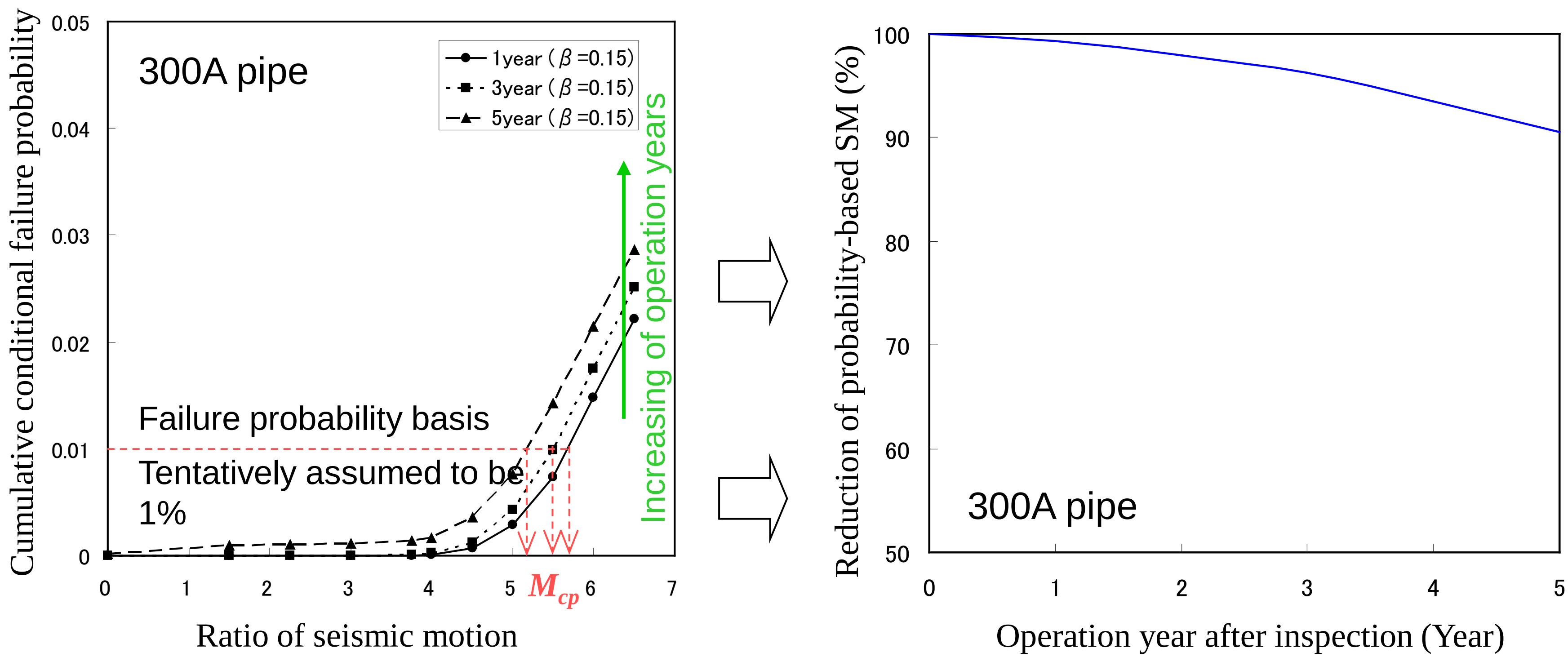


Failure probabilities and fragility curves considering age related degradation

Example Analysis Results for Seismic Fragility

✓ Seismic fragility curves and seismic safety margin

- **Based on the fragility curves and the assumed failure probability basis, the probability-based seismic margin and its reduction rate considering the age-related degradation can be obtained.**
- **Probability-based seismic margin decreases with the increasing of operation years. The reduction rate of seismic margin depends on the progress rate of age-related degradation, such as crack growth rate, the distribution of residual stress and so on.**

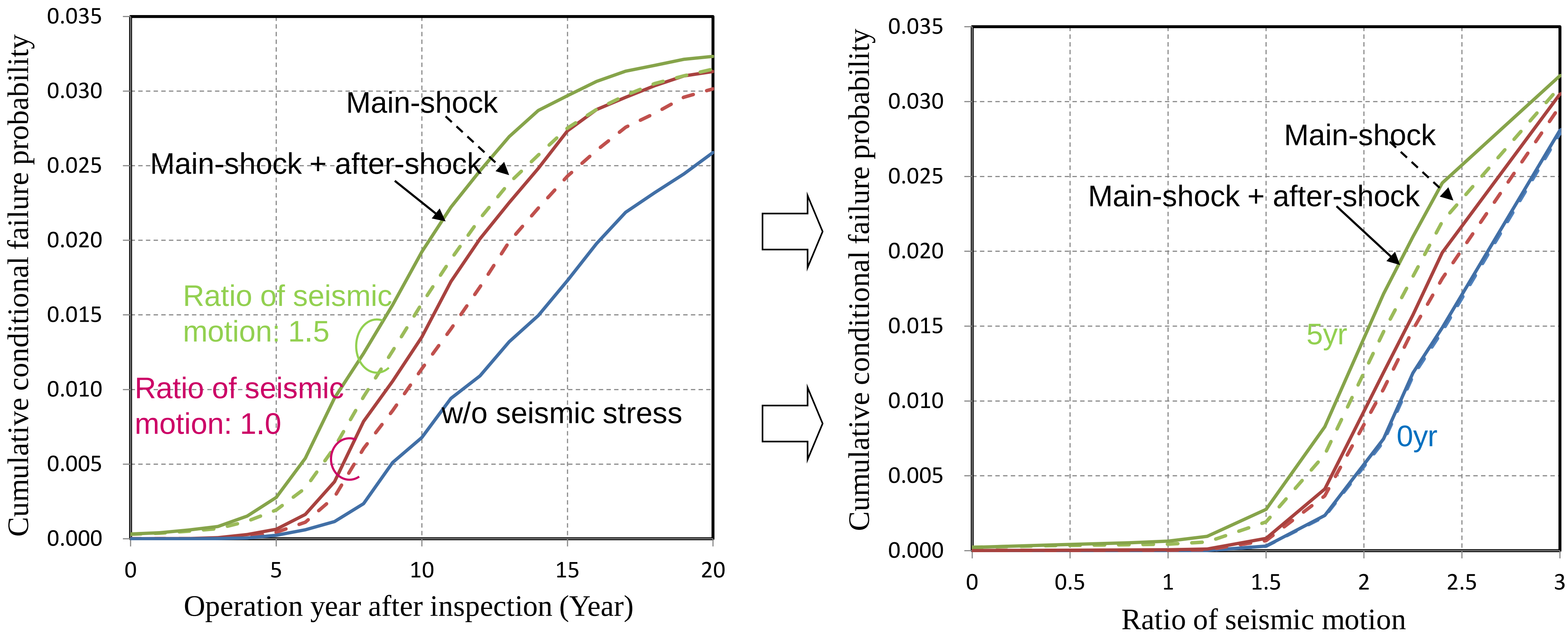


Failure probabilities and fragility curves considering age related degradation

Example Analysis Results for Seismic Fragility

✓ Seismic fragility curves considering the effect of after shock

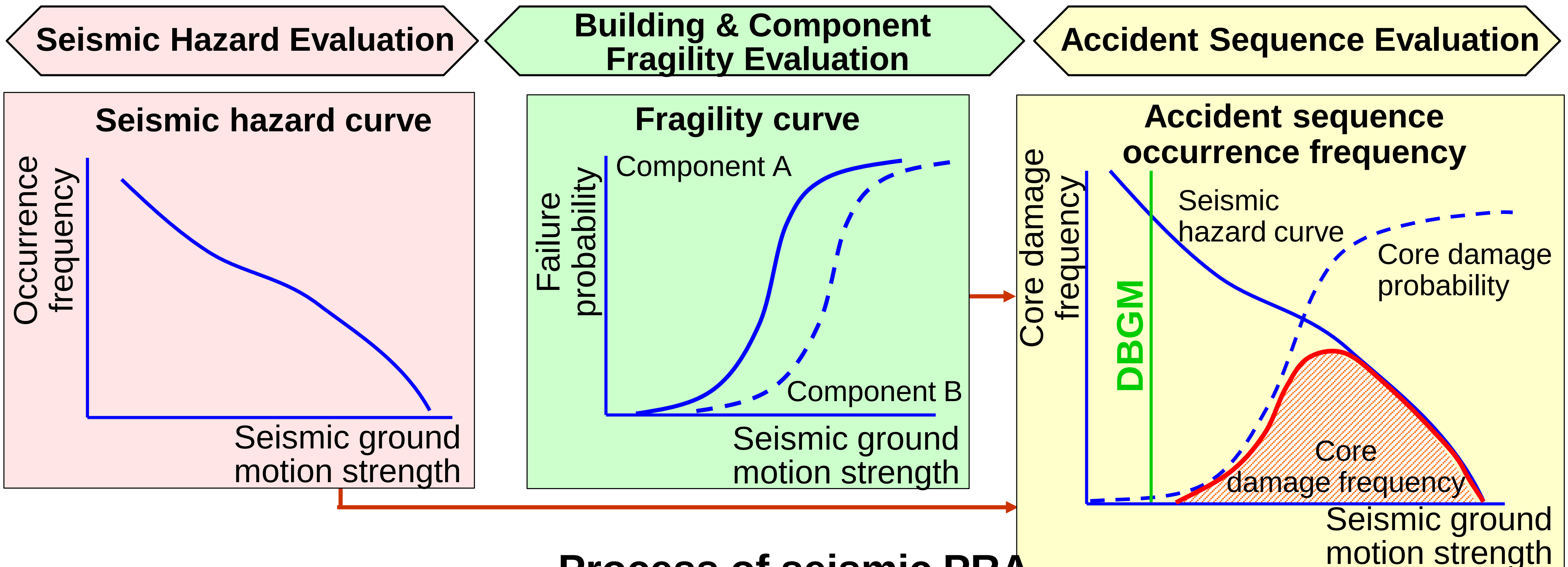
- **Because PFM can consider the age-related degradation in mechanism, it can evaluate the combination effect of main-shock and after-shock.**
- **In the following case, the after-shock occurred soon after the main-shock with a same magnitude is evaluated.**



Failure probability and seismic fragility curve with the effect of after-shock

CGR and Fragility for Severe Earthquake

- ✓ In order to contribute to the seismic PRA and seismic safety evaluation for aged components, it is necessary to consider the earthquake beyond design basis ground motion.
- ✓ Therefore, we are developing the evaluation methodology of crack growth rate (CGR) beyond the small scale yielding condition, considering large seismic stresses corresponding to response of severe earthquakes.

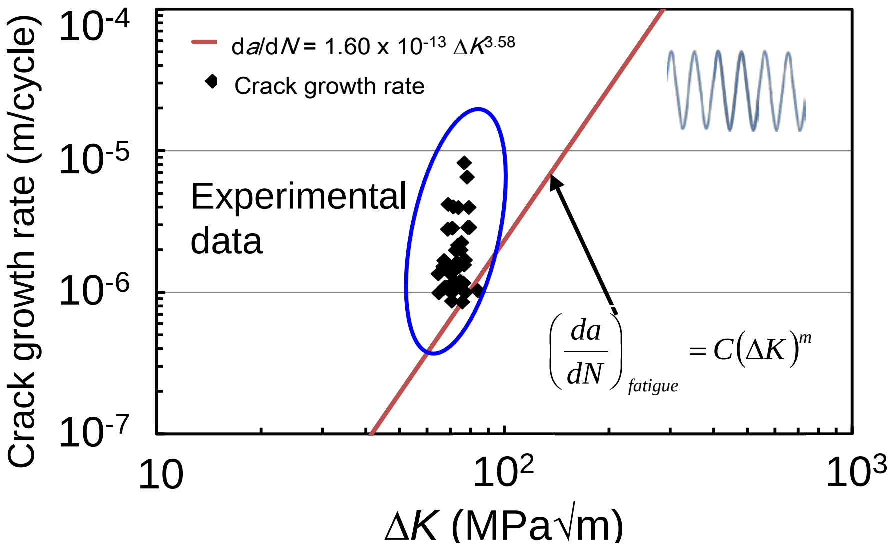


Process of seismic PRA

CGR and Fragility for Severe Earthquake

✓ CGR for large seismic stresses

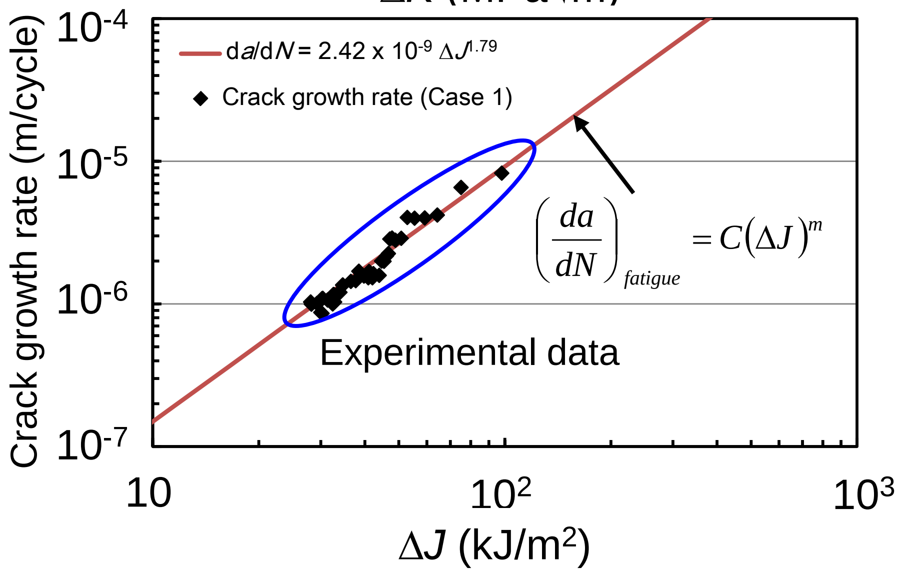
• For constant cyclic stress beyond small scale yielding condition (SSY)



CGR for cyclic stress under SSY:

$$\left(\frac{da}{dN}\right)_{fatigue} = C(\Delta K)^m$$

It can not represent the CGR for cyclic stresses beyond SSY.



CGR of ΔJ basis for cyclic stress beyond SSY:

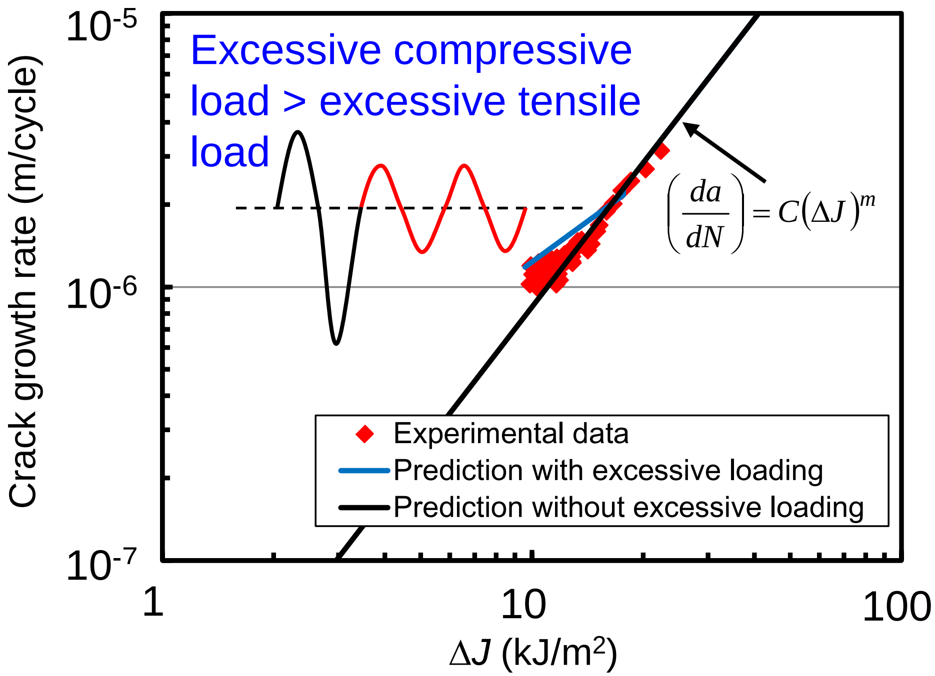
$$\left(\frac{da}{dN}\right)_{fatigue} = C(\Delta J)^m$$

It can represent the CGR for cyclic stresses beyond SSY.

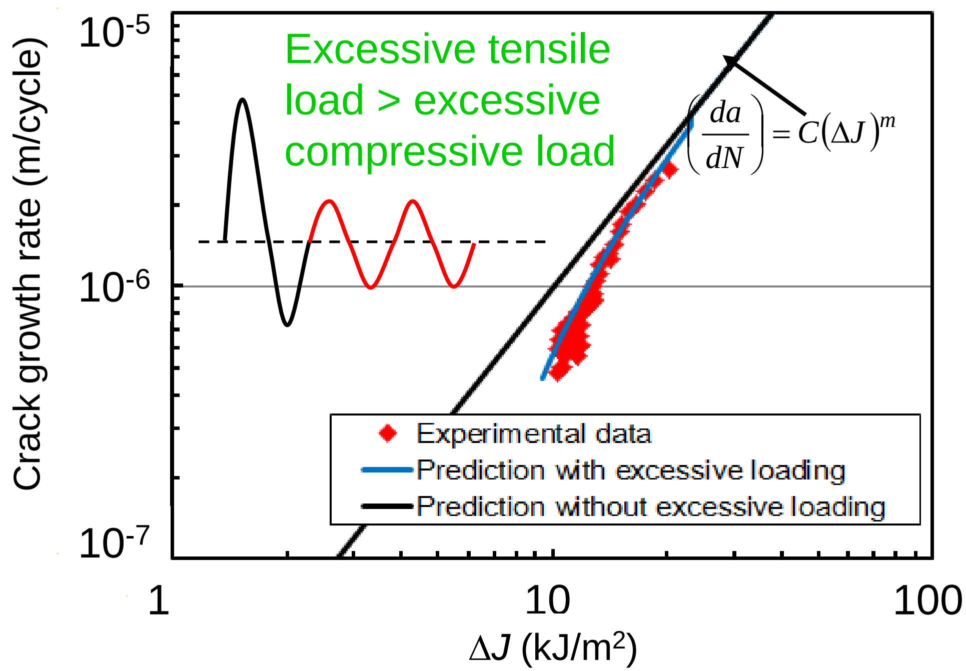
CGR and Fragility for Severe Earthquake

✓ CGR for large seismic stresses

- For random cyclic stress beyond SSY



The case that CGR is accelerated



The case that CGR is retarded

Evaluation method of CGR for large seismic stresses beyond SSY

$$\frac{da}{dN} = C'\left[\frac{\beta_a}{\beta_b}\Delta J(a_i)\left(\frac{r'_{pi}}{r'_{pel}+a_{el}-a_i}\right)^{\gamma R'} - \Delta J_{i=1}\left(\frac{J_{max,el}-J_{max,i}}{J_{max,el}-J_{max,1}}\right)\right]^{m'}$$

CGR and Fragility for Severe Earthquake

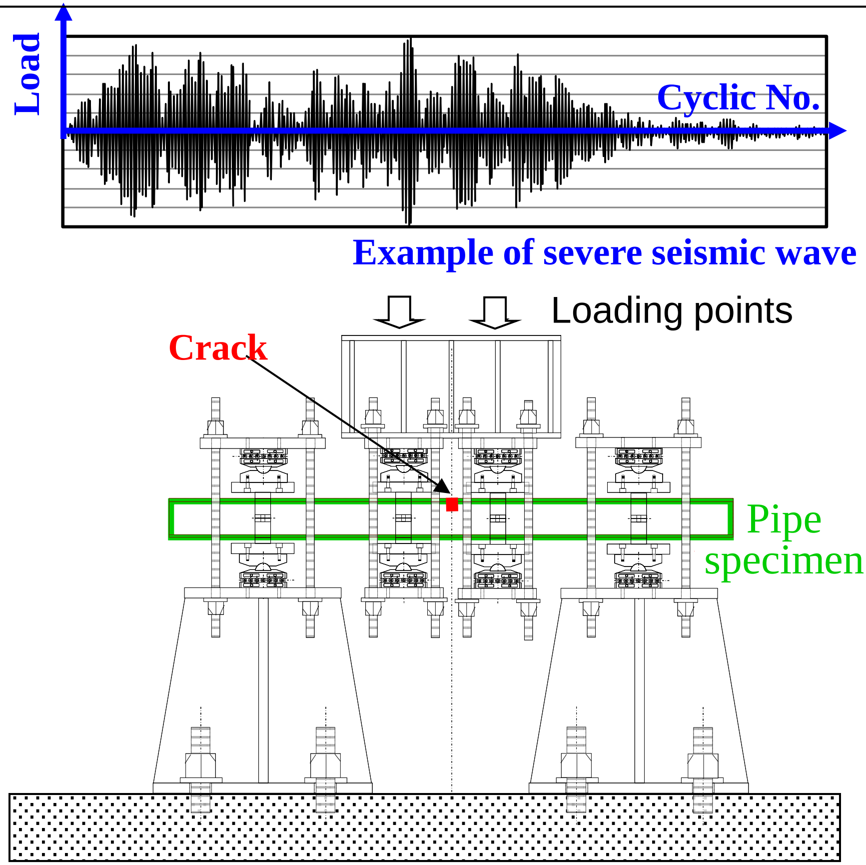
✓ Confirmation of CGR for large seismic stresses

Pipe/Materials

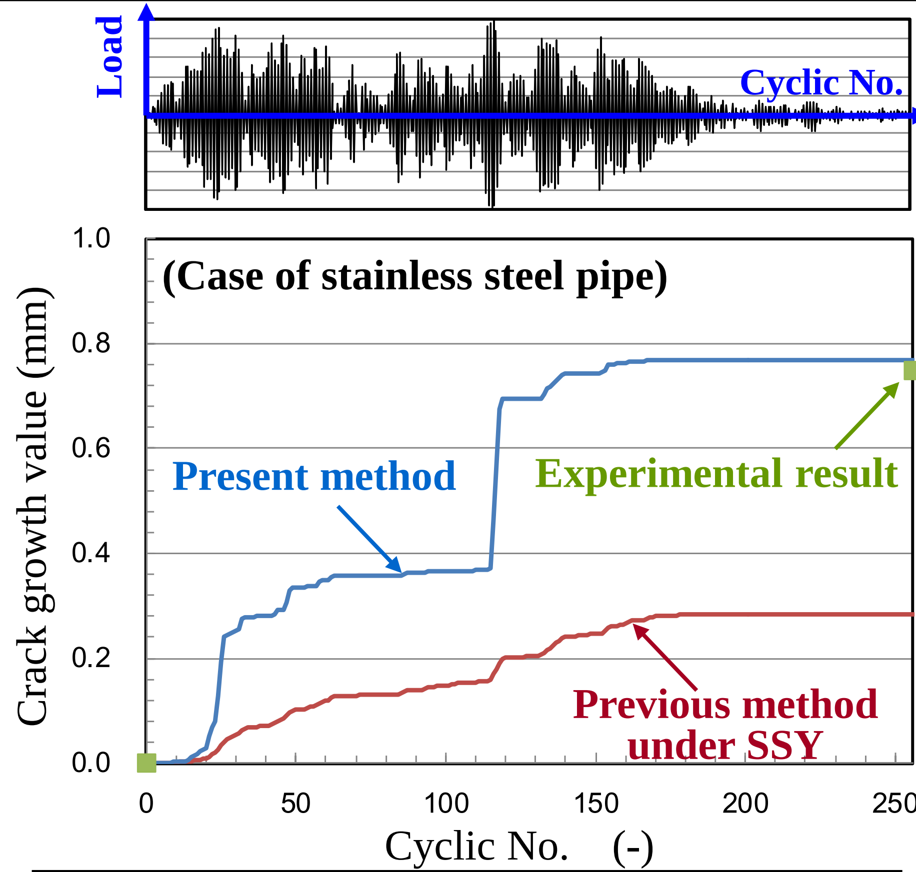
- Stainless steel pipe（SUS316）
- Carbon steel pipe（STPT410）

Dimension of pipe/crack

- D_o: 114.3 mm x t: 8.6 mm
- Circumferential through wall crack

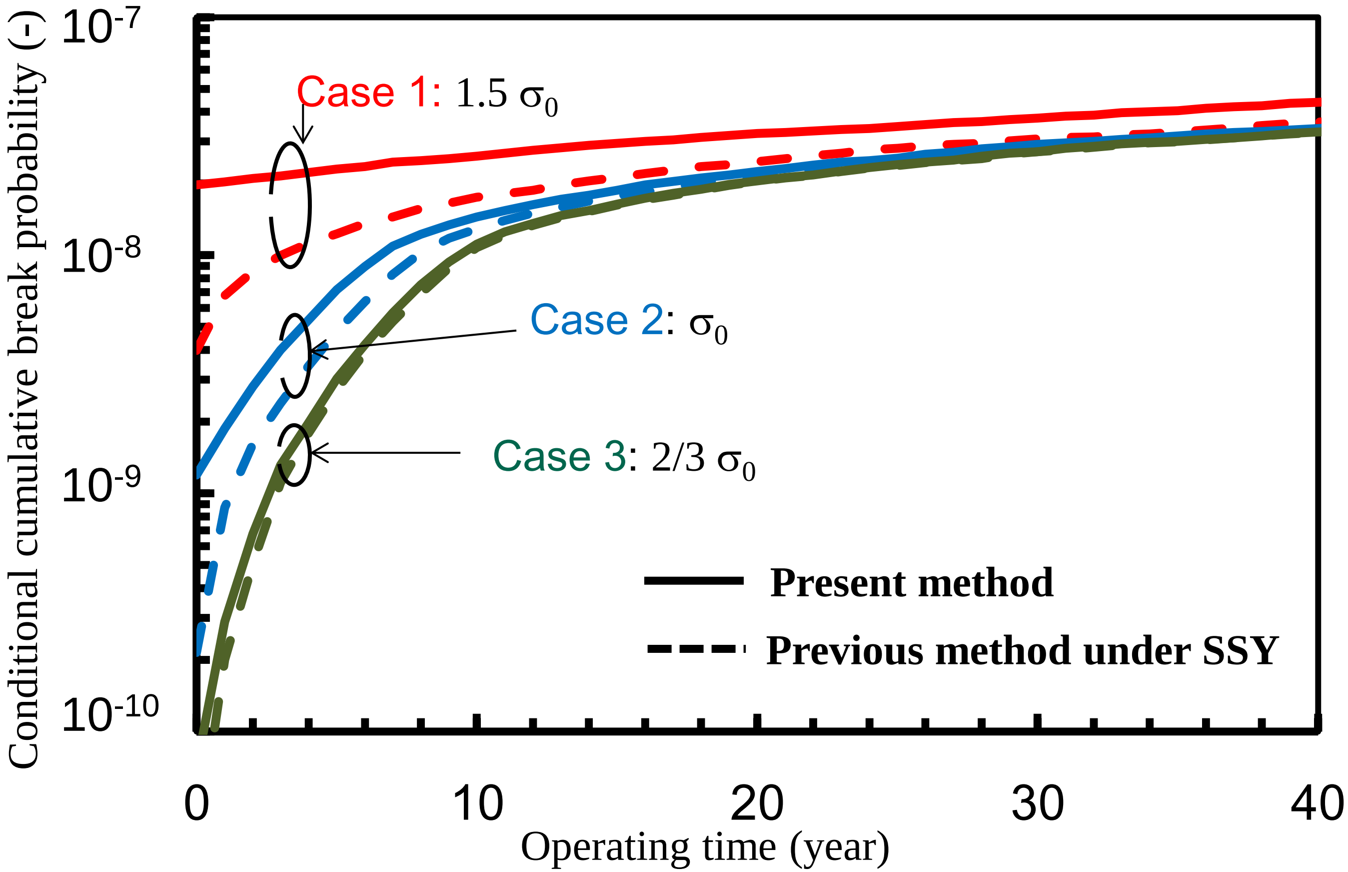


Experiment using seismic load and pipe specimen



Comparison of experimental and predicted results

✓ Failure probability evaluation considering different levels of seismic stresses



Analysis condition

- Pipe: stainless pipe in BWR plant
- Crack: initial crack in weld joints caused by welding or etc.
- Crack growth: fatigue

- When the maximum amplitude of the seismic stress is larger than the yield stress σ_0 , break probability based on the elastic fracture mechanics is not conservative.

Summary

- ✓ Seismic PRA and seismic safety evaluation considering aging mechanisms for aged components are important and the ongoing issues.
- ✓ Example applications to seismic fragility evaluation using PFM considering IGSCC and fatigue are introduced in this presentation.
- ✓ We are making efforts considering other important aged components and age-related degradation mechanisms such as
  - PWSCC
  - NiSCC
  - Flow Accelerated Corrosion
  - Thermal aging embrittlement
- ✓ We are also making efforts to link with seismic hazard and accident sequence evaluation, and to utilize failure probabilities considering age-related degradation mechanisms and seismic stresses.