Application of probabilistic fracture mechanics to seismic fragility analysis of piping systems

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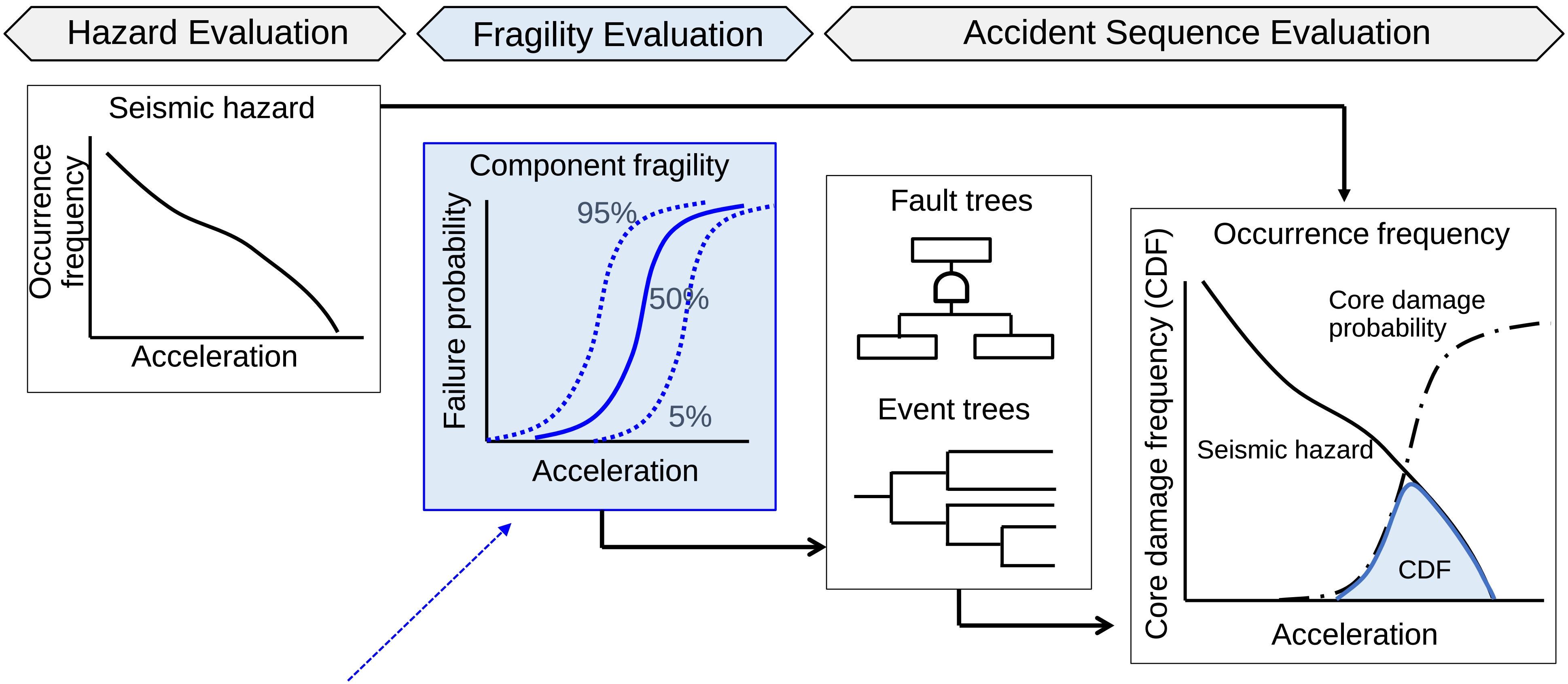
Backgrounds

Lessons learned from the TEPCO Fukushima Daiichi accident indicate the importance of risk assessment for extreme external events.

In Japan, the new safety regulation requires nuclear operators to conduct periodic and comprehensive safety assessments including Seismic Probabilistic Risk Assessment (SPRA) .

The SPRA is one of the standard methods to quantify the seismic risk of operating nuclear power plants.

Process of SPRA

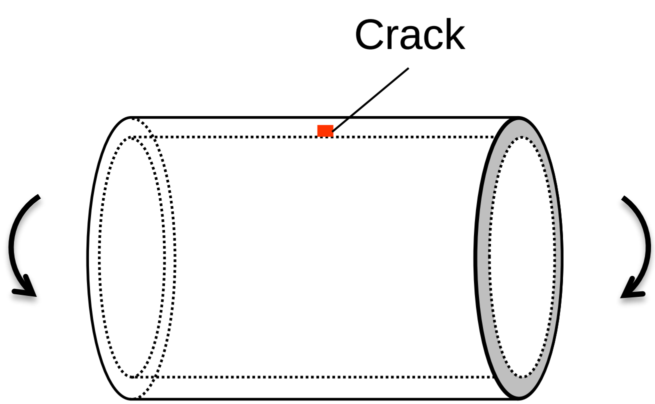


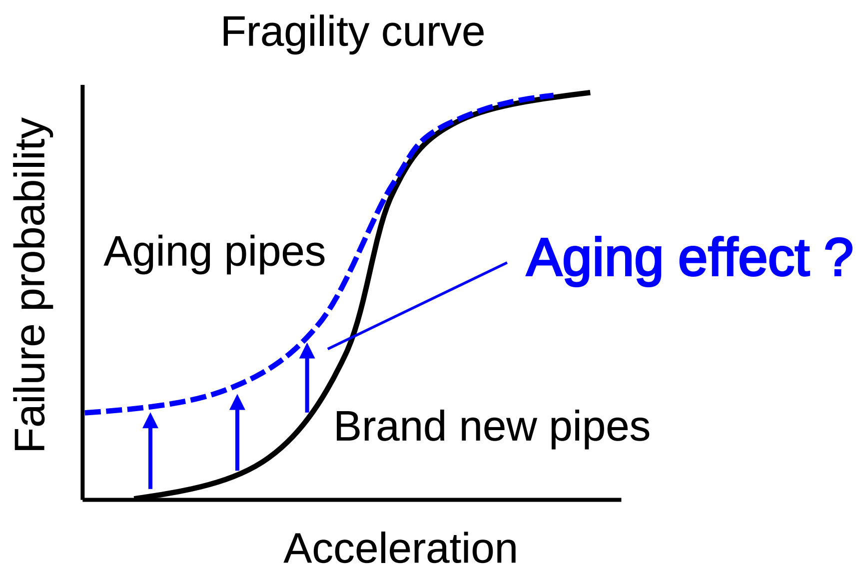
One of the major factors that affect the results of the SPRAs is the quality of a seismic fragility analysis.

Seismic fragilities represent the capacities of components under earthquakes and the associated uncertainties.

Seismic fragility of aging pipes

However, seismic fragility data of aging pipes are not readily available due to the complex behavior under seismic loading.





It is unclear how aging effects can affect the seismic fragility of a piping system.

Objectives

Regulatory Standard and Research Department, Secretariat of Nuclear Regulation Authority is carrying out a research project to evaluate seismic fragilities by probabilistic fracture mechanics (PFM).

Long-term objectives of the project are:

- To develop a methodology for evaluating failure probability of aging pipes subjected to strong seismic motions.
- To quantify relative differences between the seismic fragilities of brand new pipes and those of aging pipes.

The scope of this presentation is to outline the methodology of our pilot study, and to demonstrate the results.

Case 1: Carbon steel

Overview of a pilot study - Case 1

Case 1: Carbon steel pipe subjected to seismic loadings

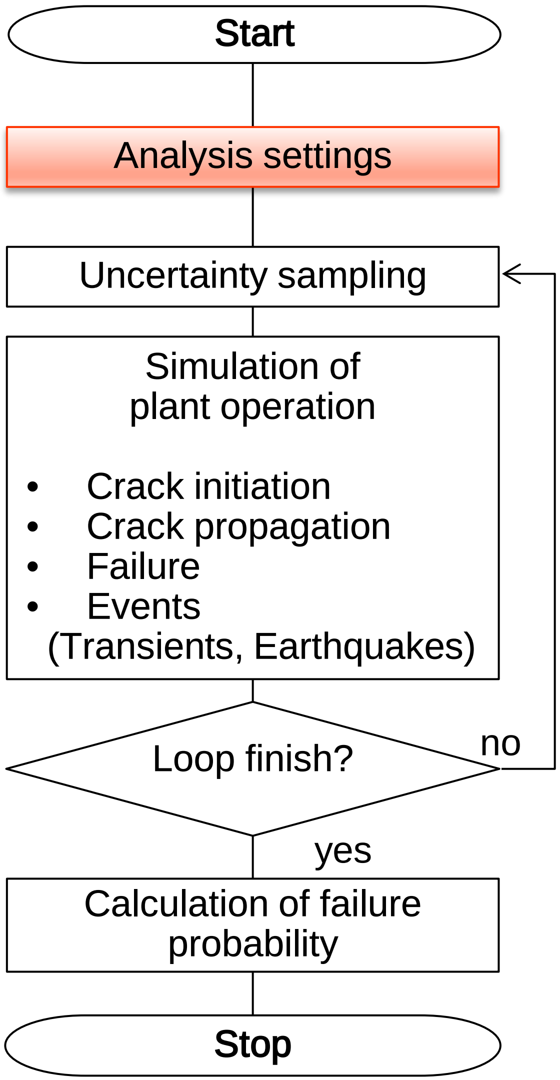
We chose one of the simplified cases as a pilot study using PASCAL-SP* code.

- Welding cracks were considered as initial cracks.
- All cracks were modeled as circumferential internal surface cracks.
- Fatigue crack growth was considered without mitigation and inspection.
- All cracks were subjected to the identical operational loadings and seismic loadings.
- A simplified model for seismic loads at crack location was adopted.
- The absolute values of the failure probabilities have not been validated.

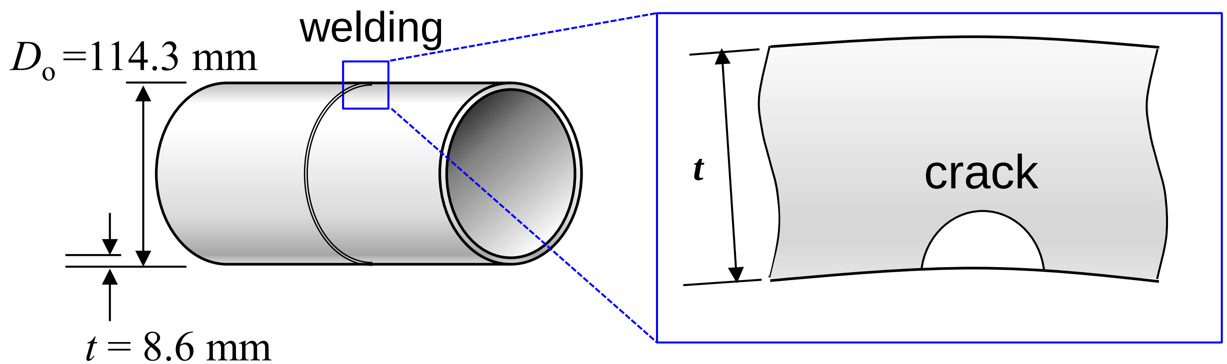
*H. Itoh, et. al., "User's Manuals of Probabilistic Fracture Mechanics Analysis Code for Aged Piping, PASCAL-SP," JAEA-Data/Code 2009-025,(2010)

Analysis settings

Flowchart for PASCAL-SP code



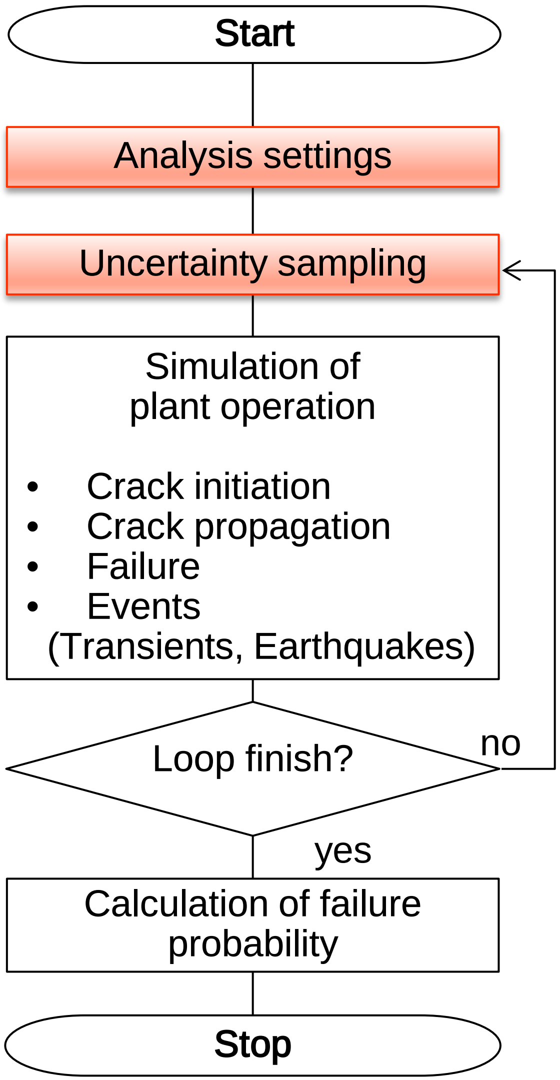
PFM analysis for circumferential surface cracks in carbon steel pipes

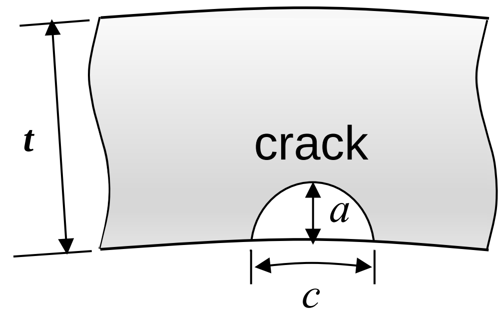


Piping system	Reactor core isolation cooling system in BWR (100A, Sch100)
Material	Carbon steel: JIS STPT410 (ASTM A106 Gr.B)
Crack type	Circumferential internal surface crack
Crack initiation	Fabrication cracks in welded joints
Method of K_I determination	(1) Surface crack: JSME FFS code (2) Through wall crack: D.J. Shim, 2014

Parameter uncertainty

Flowchart for PASCAL-SP code





Log-normal distribution

$$f(x) = \frac{C}{\sqrt{2\pi}\sigma x} \exp\left(-\frac{1}{2}\left(\frac{\ln\left(x/\mu\right)}{\sigma}\right)^2\right)$$

μ: mean

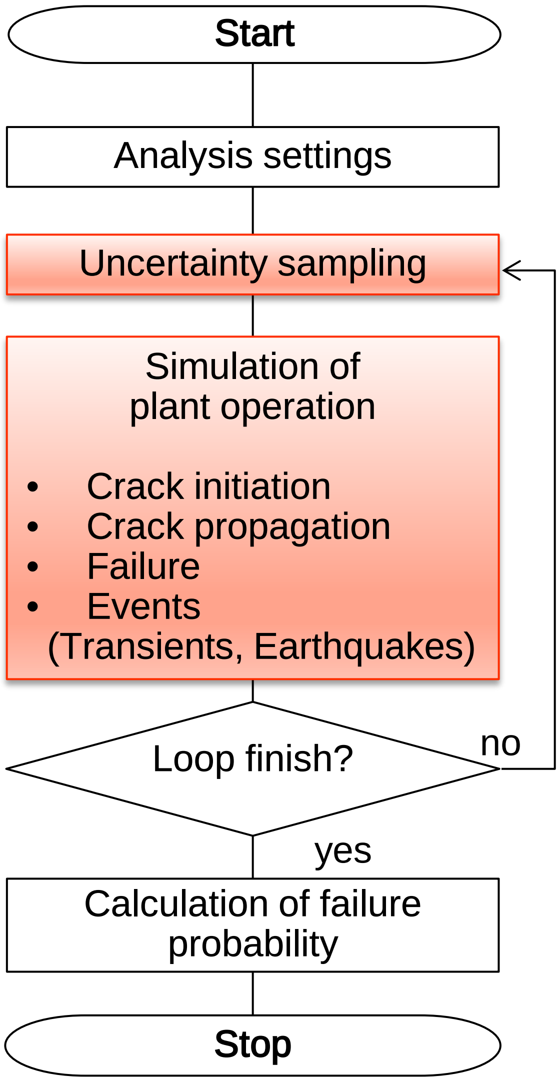
σ: standard deviation

C : coefficient

Flow stress (288°C)	Log-normal distribution where $\mu = 332.1$ MPa, $\sigma = 16.04$, $C = 1.0$
Crack depth a (A. Bruckner, 1982)	Log-normal distribution where $\mu = 0.294$ mm, $\sigma = 1.61$, $C = 1.0$
Crack aspect ratio a/c $(a/c \leq 1.0)$ (NUREG/CR-2189)	Log-normal distribution where $\mu = 1.336$, $\sigma = 0.538$, $C = 1.419$
Seismic load	Log-normal distribution where $\mu = 60\,N$ MPa, $\sigma = 0.2$, $C = 1.0$ $N = 1,2$, or 3

Fatigue crack growth analysis

Flowchart for PASCAL-SP code



Transient loadings (JSME S ND1-2002)

Event ID	Frequency (times/year)	Membrane (MPa)		Bending (MPa)	
		Min.	Max.	Min.	Max.
1	7	0.0	122.0	0.0	0.0
2	18	48.8	183.0	0.0	0.0
3	320	91.5	122.0	0.0	0.0
4	8	0.0	0.0	-122.0	122.0
5	16	0.0	0.0	-61.0	61.0
6	330	0.0	0.0	-12.2	12.2

Seismic loadings

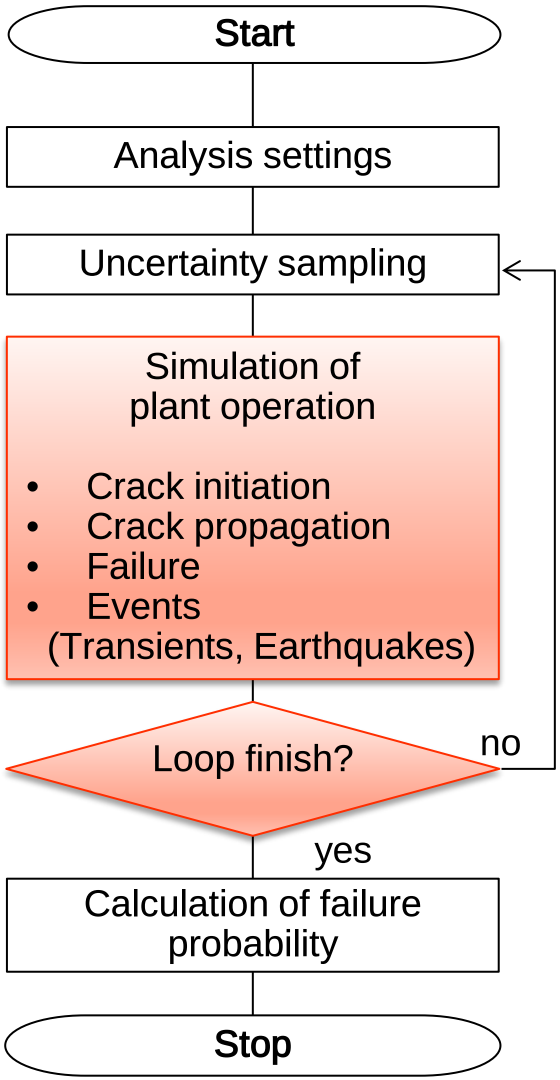
Bending stress	60 × N MPa where N is coefficients
Load cycle	100

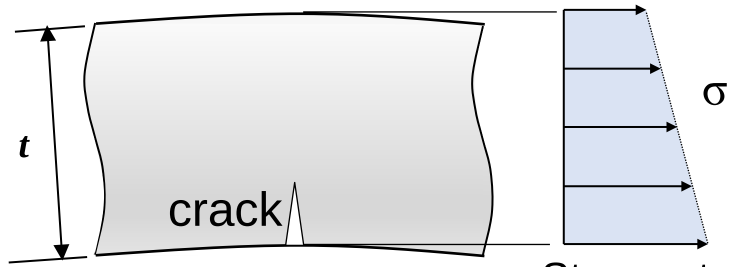
Fatigue crack growth

Fatigue crack growth rate (Harris, 1998) (Yamaguchi, 2011)	Probabilistic model $$\frac{da}{dN} = C\Delta K^n$$ where C and n are material properties.

Failure evaluation

Flowchart for PASCAL-SP code





Stress at gross section
(Membrane and bending)

Seismic loadings

Bending stress	$60 \times N$ MPa where N is coefficients
Load cycle	100

Other mechanical loadings

Membrane stress	29.9 MPa
Bending stress	25.0 MPa
Secondary stress	0.0 MPa

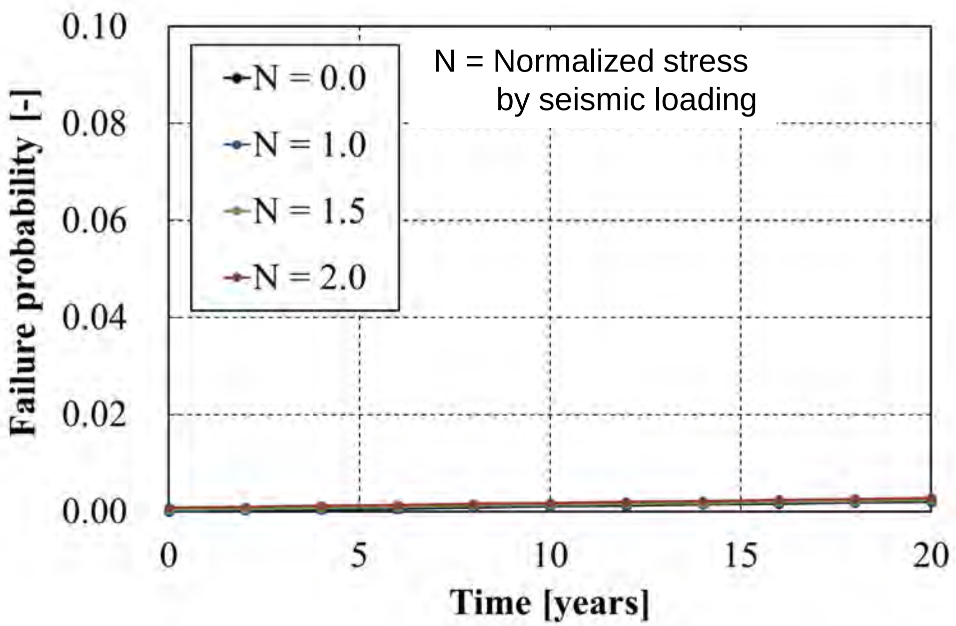
Failure evaluation

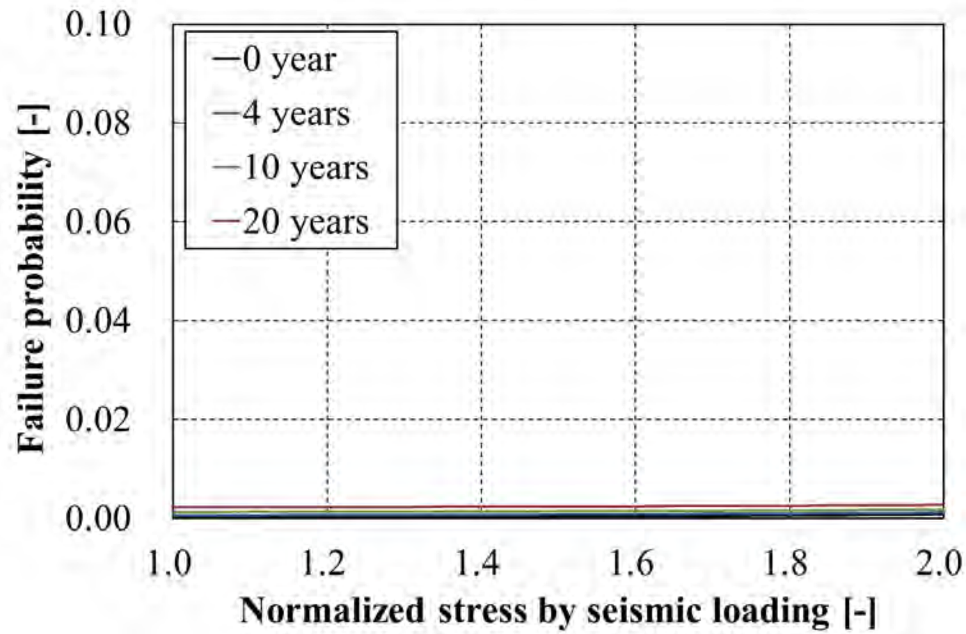
Failure criteria	(1) Crack penetration ($a/t = 0.99$) (2) Failure analysis based on EPFM* by JSME FFS code

*EPFM: Elastic Plastic Fracture Mechanics

Results

Probability of rupture or penetration for carbon steel pipes





Even though both inspection and mitigation measures are not implemented, failure probabilities only slightly increase with the time of operation.

Fatigue crack growth may have little effects on seismic fragilities of carbon steel pipes.

Case 2: Austenitic stainless steel

Overview of a pilot study Case 2

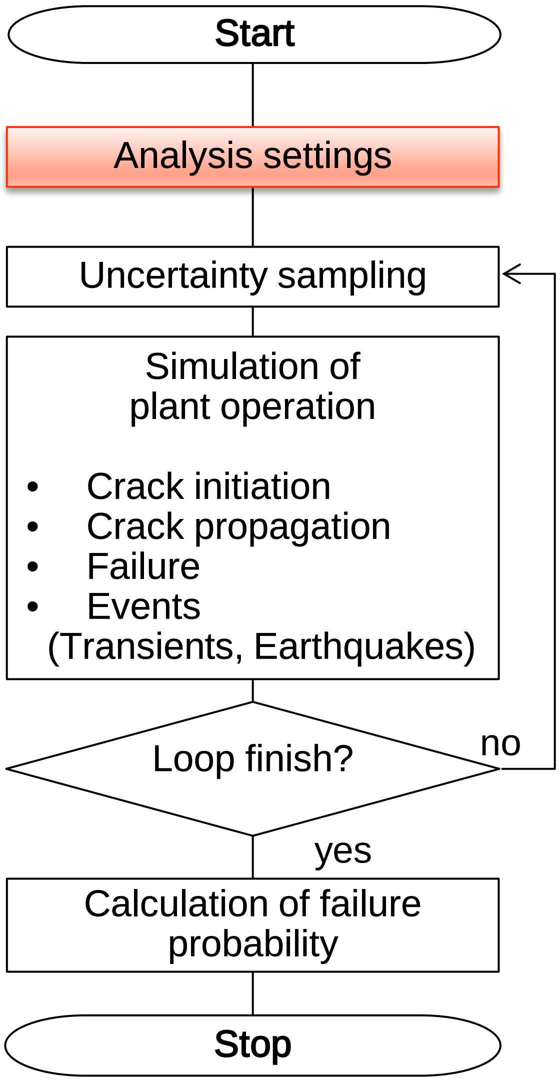
Case 2: Austenitic stainless steel pipe subjected to seismic loadings

We chose one of the simplified cases as a pilot study using PASCAL-SP code.

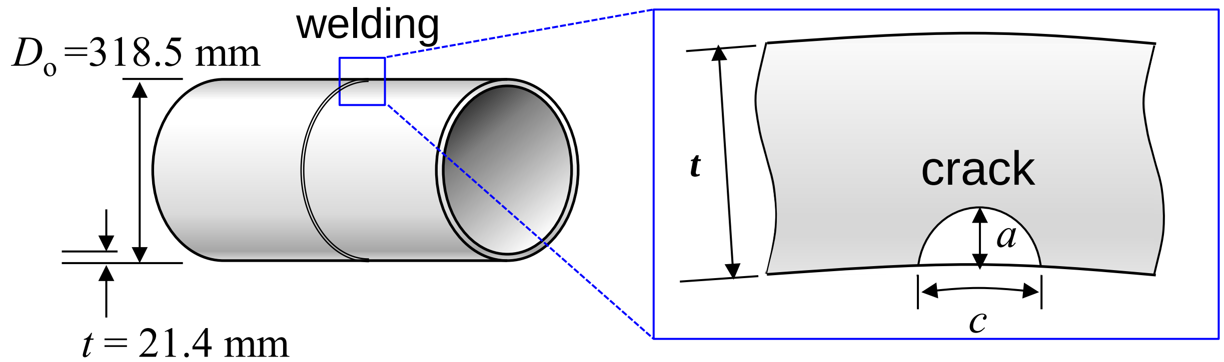
- All cracks were modeled as circumferential internal surface cracks.
- Crack growth by fatigue and Stress Corrosion Cracking (SCC) were considered with no mitigation and inspection.
- All cracks were subjected to identical operational loadings and strong seismic loadings.
- A simplified model for seismic loads at crack location was adopted.
- The absolute values of the failure probabilities have not been validated.

Analysis settings

Flowchart for PASCAL-SP code



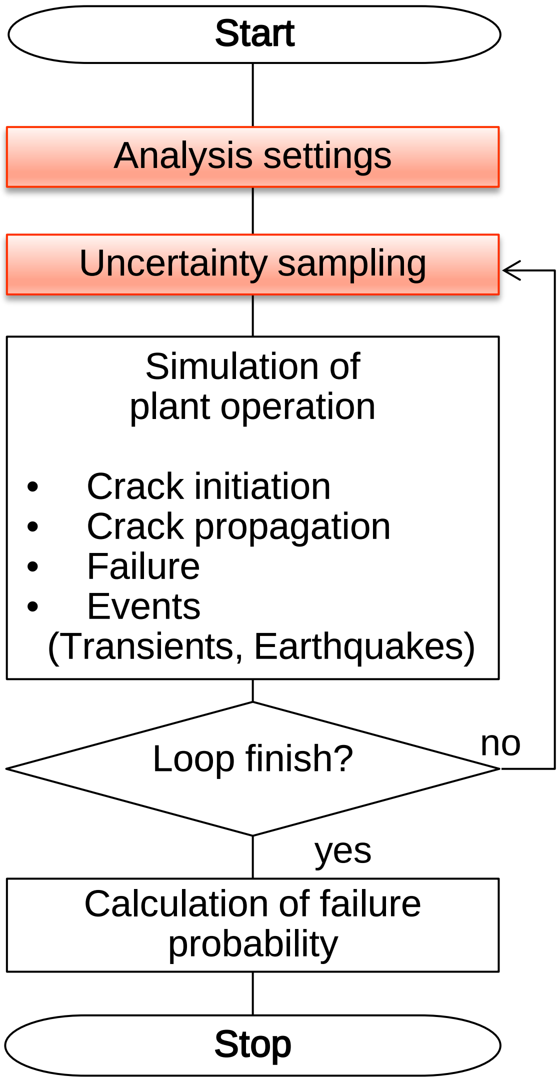
PFM analysis for circumferential surface cracks in Austenitic Stainless Steel pipes

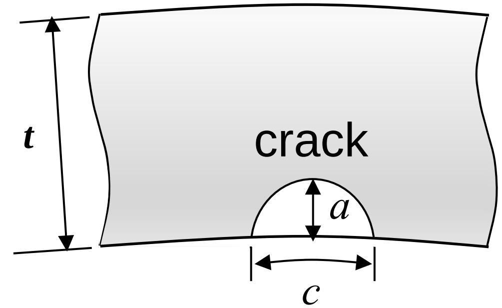


Piping system	Primary loop recirculation system in BWR (300A, Sch100)
Material	Austenitic stainless steel, Type 316L
Crack type	Circumferential internal surface crack
Crack initiation	SCC at Heat Affected Zone (HAZ) of welded joints
Method of K_I determination	(1) Surface crack: JSME FFS code (2) Through crack: D.J. Shim, 2014

Parameter uncertainty

Flowchart for PASCAL-SP code





Log-normal distribution

$$f(x) = \frac{C}{\sqrt{2\pi}\sigma x}\exp\left(-\frac{1}{2}\left(\frac{\ln(x/\mu)}{\sigma}\right)^2\right)$$

μ: mean,

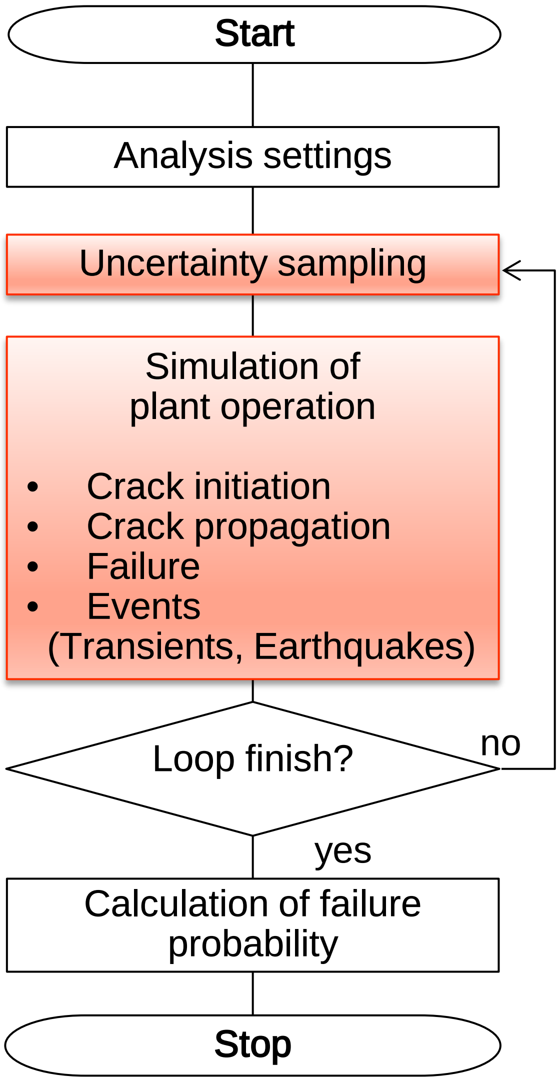
σ: standard deviation

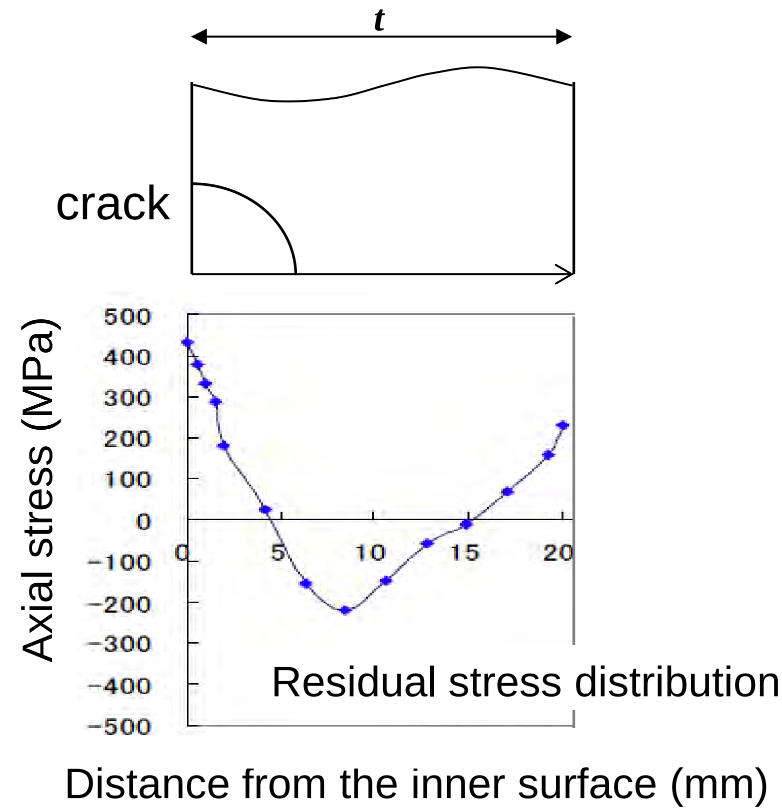
C : coefficient

Flow stress (288ºC)	Log-normal distribution where $\mu = 256.5$ MPa, $\sigma = 10.85$, $C = 1.0$
Crack initiation time *t* (*a* = 0.5 mm) (H. Machida, 2008)	Log-normal distribution where $\mu = 9.21$ year, $\sigma = 0.485$, $C = 1.0$
Half crack length c (H. Machida, 2008)	Exponential distribution $f(c) = \lambda\exp(-\lambda c)$ where $\lambda = 7\ \mathrm{mm}^{-1}$
Seismic load	Log-normal distribution where $\mu = 60\,N$ MPa, $\sigma = 0.2$, $C = 1.0$ $N = 1,2$, or 3

SCC growth analysis

Flowchart for PASCAL-SP code

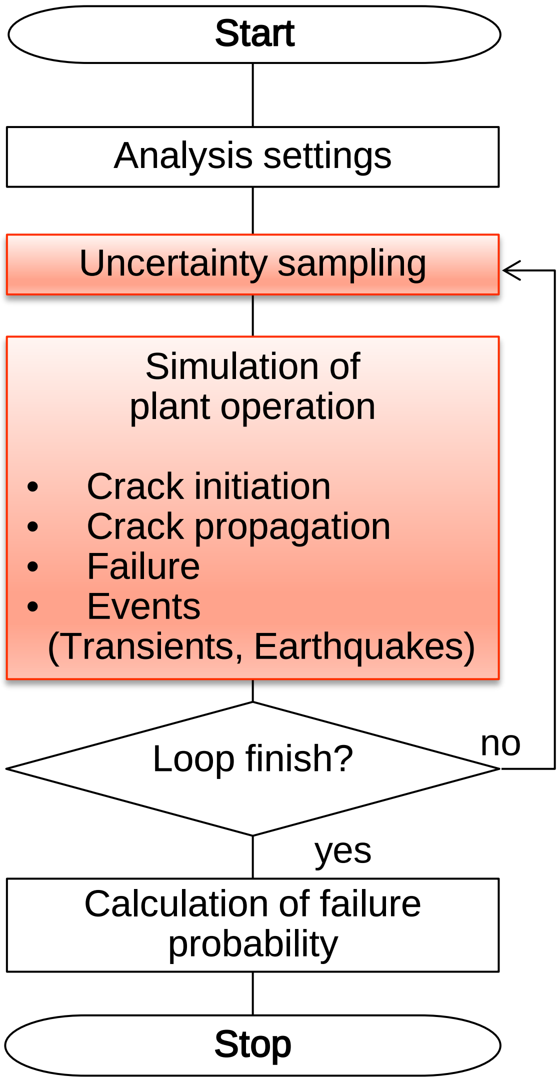




Membrane stress	34.3 MPa
SCC Growth rate (Y. Li, 2014)	Probabilistic model $$\frac{da}{dt} = CK^{2.161}$$ where C is a material property.

Fatigue crack growth analysis

Flowchart for PASCAL-SP code



Transient load (H. Machida, 2008)

Event ID	Frequency (times/year)	Membrane (MPa)		Bending (MPa)	
		Min.	Max.	Min.	Max.
1	40	1.6	34.2	0.0	0.0
2	85	1.6	63.0	0.0	2.5
3	85	16.0	70.0	0.0	3.2
4	85	16.0	47.0	0.0	134.4
5	85	8.3	31.0	0.0	130.2
6	85	1.6	8.3	0.0	4.2
7	300	63.7	70.1	0.0	0.0

Seismic loadings

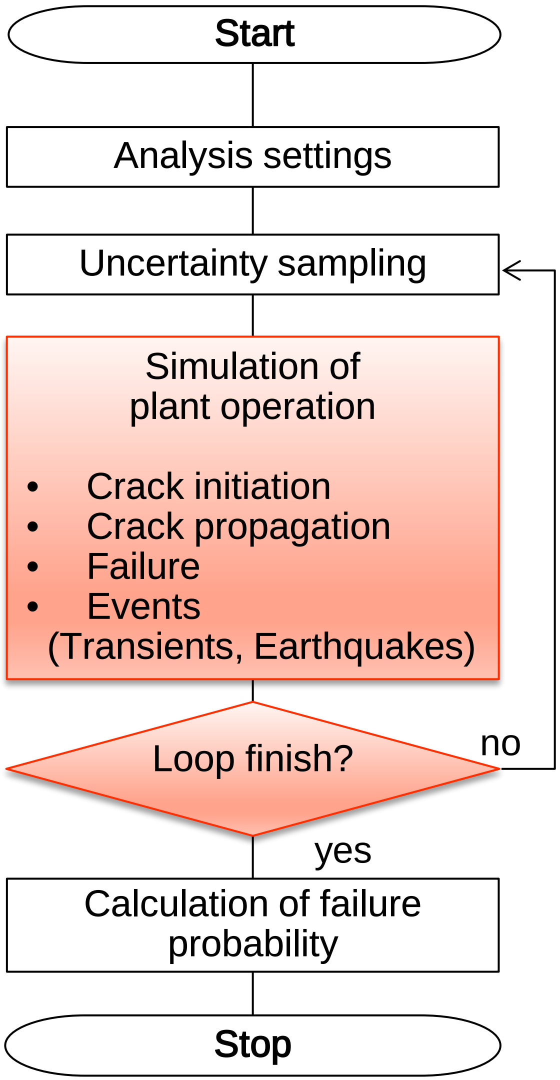
Bending stress	90 × N MPa where N is coefficients
Load cycle	100

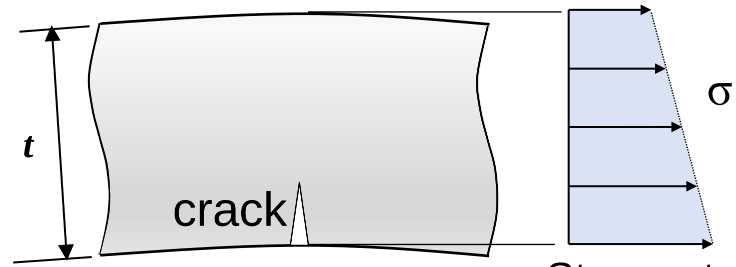
Fatigue crack growth

Growth rate for fatigue (Y. Li, 2014) (Yamaguchi, 2011)	Probabilistic model $$\frac{da}{dN} = C\Delta K^n$$ where C and n are material properties.

Failure evaluation

Flowchart for PASCAL-SP code





Stress at gross section
(Membrane and bending)

Seismic loadings

Bending stress	90 × N MPa where N is coefficients
Load cycle	100

Other mechanical loadings

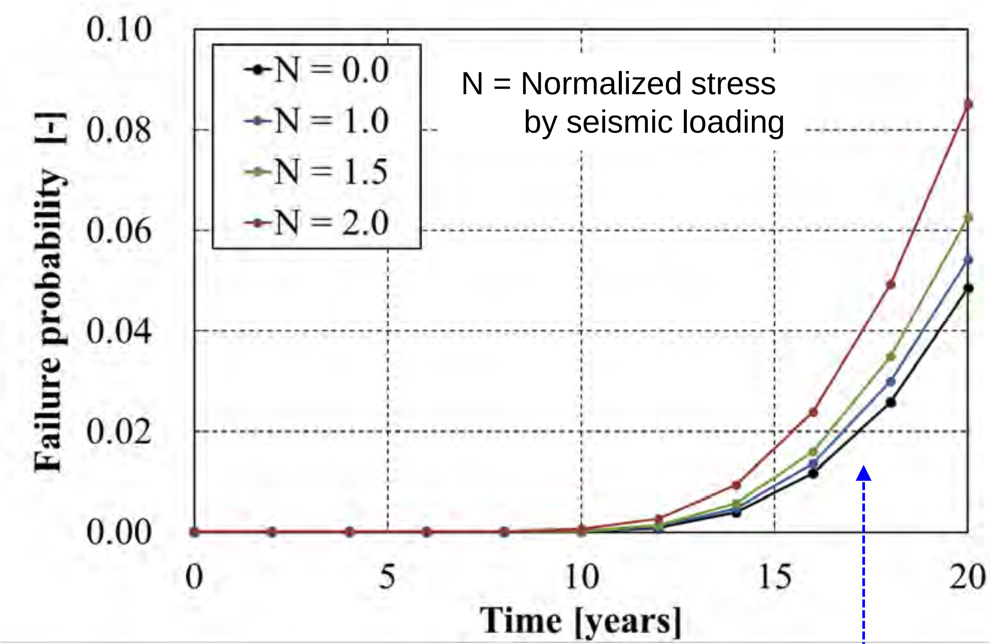
Membrane stress	33.5 MPa
Bending stress	41.8 MPa
Secondary stress	0.0 MPa

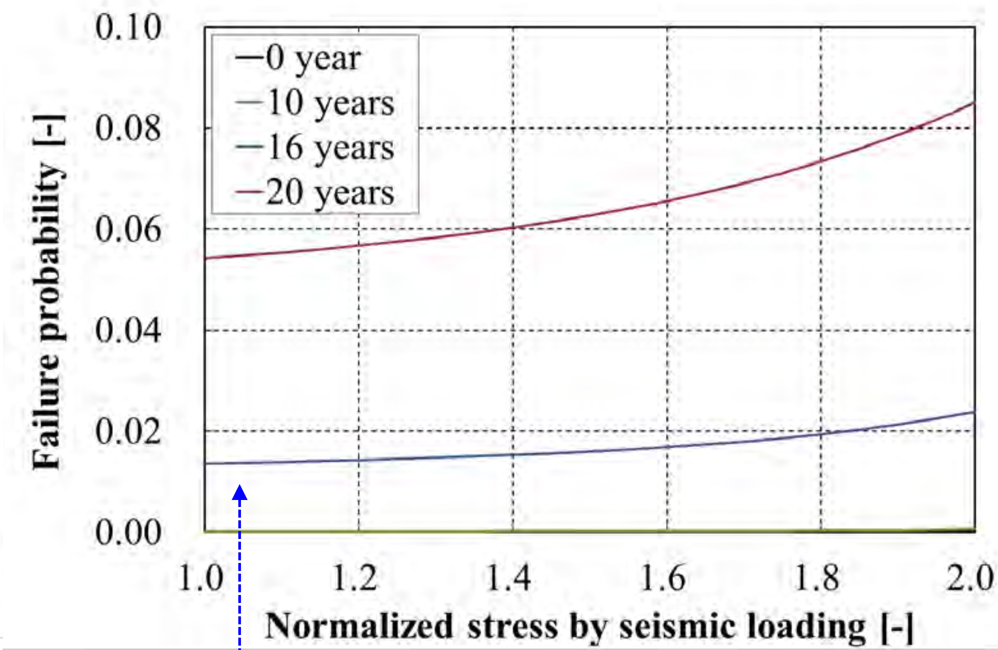
Failure evaluation

Failure criteria	(1) Crack penetration ($a/t = 0.99$) (2) Failure analysis based on EPFM* by JSME FFS code

Results

Probability of rupture or penetration for austenitic stainless steel pipes





Failure probabilities increase with crack growth by SCC.

SCC may affect the seismic fragilities of austenitic stainless steel pipes.
It is necessary to evaluate the seismic fragilities based on the appropriate inspection results.

Summary

We investigated the effects of crack initiation and propagation on the seismic fragilities of carbon steel and austenitic stainless steel piping systems.

Here is the summary of our pilot studies:

- Fatigue crack growth may have little effects on seismic fragilities of carbon steel pipes.
- SCC may affect the seismic fragilities of austenitic stainless steel pipes. It is necessary to evaluate the seismic fragilities based on the appropriate inspection results.

Appendix - Fatigue crack growth rate for ferritic steels

Probabilistic model of fatigue crack growth rate for ferritic steels $\left(da/dN \ [\mathrm{m/cycle}] \right)$

$R \le 0.25$	$\frac{da}{dN} = \begin{cases} 1.48 \times 10^{-14} \Delta K^{5.95} Q & \Delta K < 19.48 \ [\mathrm{MPa}\sqrt{\mathrm{m}}] \\ 2.13 \times 10^{-9} \Delta K^{1.95} Q & \Delta K \ge 19.48 \ [\mathrm{MPa}\sqrt{\mathrm{m}}] \end{cases}$ $Q = \exp(-0.408 + 0.542 C_F)$
$0.25 < R < 0.65$	$\frac{da}{dN} = \begin{cases} f_1 \Delta K^{5.95} Q & \Delta K < f_3 \\ f_2 \Delta K^{1.95} Q & \Delta K \ge f_3 \end{cases}$ $f_1 = 1.48 \times 10^{-14}(26.9R - 5.725)$ $f_2 = 2.13 \times 10^{-9}(3.75R + 0.06)$ $f_3 = \left(\frac{f_2}{f_1}\right)^{0.25}$ $Q = \exp[(0.1025R - 0.433625 + (0.6875R + 0.370125) C_F]$
$R \le 0.25$	$\frac{da}{dN} = \begin{cases} 1.74 \times 10^{-13} \Delta K^{5.95} Q & \Delta K < 13.23 \ [\mathrm{MPa}\sqrt{\mathrm{m}}] \\ 5.33 \times 10^{-9} \Delta K^{1.95} Q & \Delta K \ge 13.23 \ [\mathrm{MPa}\sqrt{\mathrm{m}}] \end{cases}$ $Q = \exp(-0.367 + 0.817 C_F)$

Probabilistic model of fatigue crack growth rate for Austenitic stainless steel

(da/dN [m/cycle])

$$\frac{da}{dN} = \frac{C \cdot t_r^{0.5} \cdot \Delta K^{3.0}}{(1-R)^{2.12}}$$

$$t_r = 1000 \text{ [sec]}$$

$$f(C) = \frac{1}{\sqrt{2\pi}\sigma C} \exp\left(-\frac{1}{2}\left(\frac{\ln(C/\mu)}{\sigma}\right)^2\right)$$

$$\mu = 2.86 \times 10^{-12}、\ \sigma = 0.525$$

Appendix - Fatigue crack growth rate for austenitic stainless steels

Probabilistic model of fatigue crack growth rate for Austenitic stainless steel

(da/dt [m/s])

HAZ	$\frac{da}{dt} = \begin{cases} C \times K^{2.161} & (2.0 \times 10^{-12} \leq da/dt \leq 9.2 \times 10^{-10}) \\ 2.0 \times 10^{-12} & (da/dt < 2.0 \times 10^{-12}) \\ 9.2 \times 10^{-10} & (da/dt < 9.2 \times 10^{-10}) \end{cases}$ $f(C) = \frac{1}{\sqrt{2\pi}\sigma C} \exp\left(-\frac{1}{2}\left(\frac{\ln(C/\mu)}{\sigma}\right)^2\right)$ $\mu = 9.22 \times 10^{-14}$、$\sigma = 0.309$
Weld	$\frac{da}{dt} = \begin{cases} C \times K^{2.161} & (2.0 \times 10^{-12} \leq da/dt \leq 2.1 \times 10^{-10}) \\ 2.0 \times 10^{-12} & (da/dt < 2.0 \times 10^{-12}) \\ 2.1 \times 10^{-10} & (da/dt < 2.1 \times 10^{-10}) \end{cases}$ $f(C) = \frac{1}{\sqrt{2\pi}\sigma C} \exp\left(-\frac{1}{2}\left(\frac{\ln(C/\mu)}{\sigma}\right)^2\right)$ $\mu = 1.02 \times 10^{-14}$、$\sigma = 1.18$