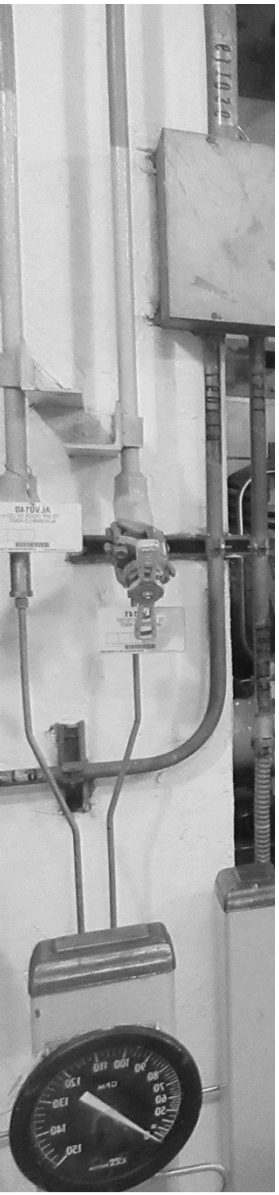

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xLPR: A Probabilistic Code for Fatigue and PWSCC Analysis of Welds in Nuclear Power Plants

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Plan

xLPR

> Goal
> Features

Fatigue

> Transient types
> Models

Examples

> Fatigue only problem
> Fatigue and PWSCC combined

Conclusion

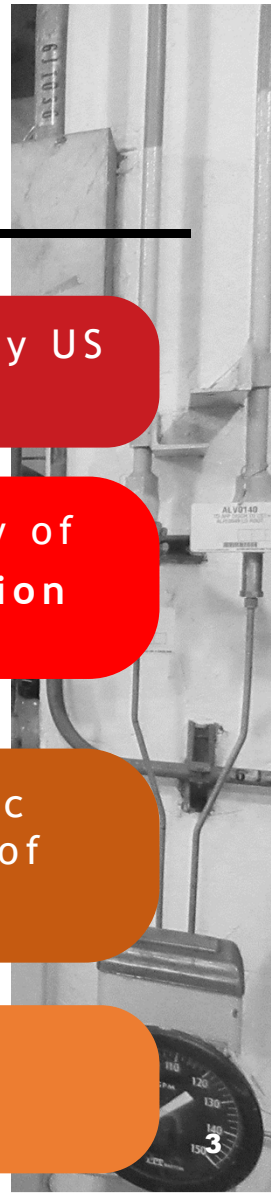
xLPR

> **Probabilistic Fracture Mechanics (PFM)** code developed conjointly by US NRC, EPRI and contractors through a Memorandum of Understanding.

> Experts use state-of-practice models to evaluate structural integrity of components subjected to **fatigue** and **primary water stress corrosion cracking (PWSCC)** degradation

> Probabilistic aspect modeled via Monte Carlo approach. Deterministic models follows cracks initiation and growth/ coalescence up to end of simulation or pipe rupture

> Additional features: leak rate detection, In-service-inspection (ISI), impact of seismic events, physical and chemical mitigation



Fatigue: Transient definition

Transients are grouped into 3 categories with the following inputs

Type I transient: duty cycle transients

> variation of temperature and/or pressure over transient time

Type I and II transient (thermal stratification)

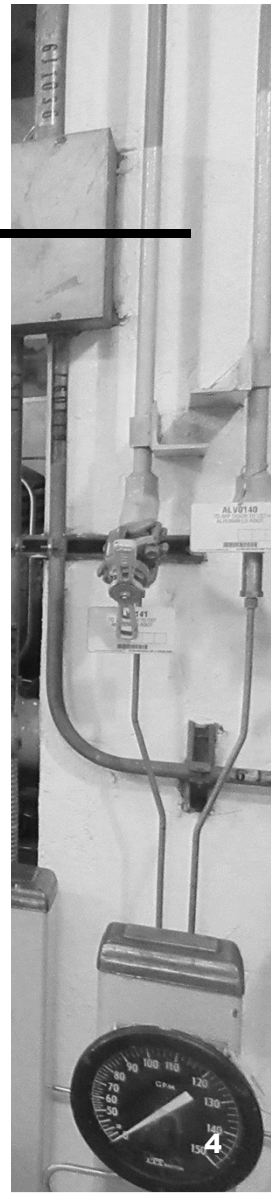
> Includes same variation as type I transient
> Bounds for additional membrane and/or bending stress added to normal operating stresses

Type III transient (other transients)

> Bounds for additional membrane and/or bending stresses
> Rise time

All Transients types inputs

> Start and end time
> Frequency
> Number of cycles



Fatigue Growth Models (1/2)

The total fatigue crack growth rate is estimated as the sum of each transient contribution

$$\frac{da_f}{dt} = \sum_{i=1}^{NTS} \frac{da_i}{dt}$$

where i represents the transient number and NTS the total number of transients

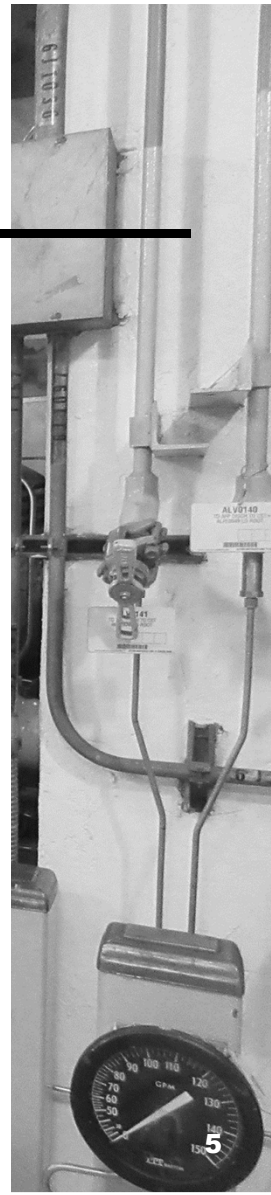
Each fatigue growth model considers growth on a per cycle basis. Time rate obtained from per cycle growth conversion

$$\frac{da_i}{dt} = \frac{1}{\Delta t}\left[\frac{da_i}{dN} . N_{cyc,i}\right]$$

where $N_{cyc,i}$ represents the number of cycle for transient i

Several models available depending on the material considered

- Austenitic stainless steel
- Nickel-based alloy
- Ferritic steel
- Custom Material



Fatigue Growth Models (2/2)

Austenitic Stainless Steel

$$\frac{da_i}{dN} = C_{ss}.f_{SS,alloy}.\tau_{limit}^{0.3}.F_{SS,R}.F_{SS,T}(\Delta K_i)^{n_{SS}}$$

C_{SS}: scaling constant (SS)
τ_i: rise time
n_{SS} : Paris law exponent (SS)
$f_{Ni,alloy}$: alloy factor (SS)
$F_{Ni,R}$: load ratio effect(SS)
$F_{Ni,T}$: temperature effect (SS)

Ferritic Steel*

$$\frac{da_i}{dN} = C_{env}\left(\frac{\Delta K_i}{(2.88 - R_i)^{n_R}}\right)^{n_{fer}}$$

C_{env} : ferritic scaling model
R_i : load ratio of transient component
n_R : sulfur dependent load ratio exponent
n_{fer} : ferritic Paris law exponent

*Environmentally Accelerated Cracking (EAC) can be modeled

Nickel-based Steel

$$\frac{da_i}{dN} = \left.\frac{da_i}{dN}\right|_{air} + A_{env}\left(\left.\frac{da_i}{dN}\right|_{air}\right)^{n_{env}} \tau_i^{1-n_{env}}$$

With $\left.\frac{da_i}{dN}\right|_{air} = C_{ni}.f_{Ni,alloy}.F_{Ni,T}(1 - 0.82R_i)^{-2.2}(\Delta K_i)^{n_{ni}}$

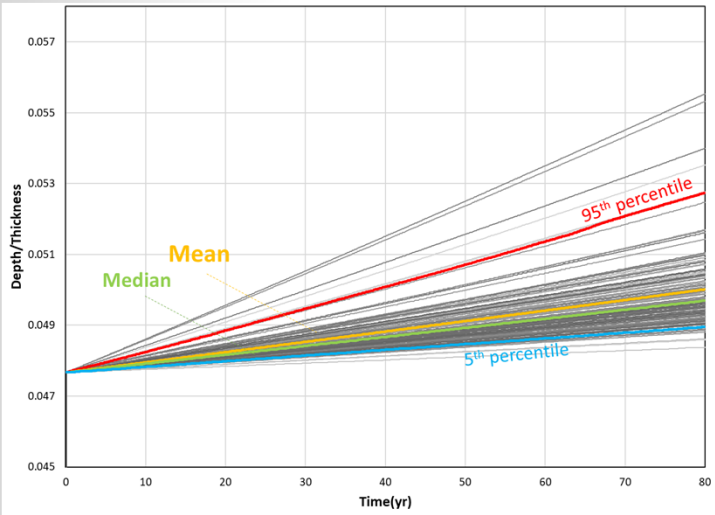
A_{env}: environment factor
τ_i: rise time
n: environment exponent
C_{Ni}: scaling constant (Nickel)
n_{Ni}: Paris law exponent (Nickel)
$f_{Ni,alloy}$: alloy factor (Ni)
$F_{Ni,T}$: Ni temperature effect
R_i: load ratio of transient component

Custom Made Material

$$\frac{da_i}{dN} = C\tau_i^p\left(\frac{\Delta K_i}{(1 - aR_i)^b}\right)^m$$

C: scaling model
τ_i: rise time
p: rise time exponent
a, b: model load ratios
m: Paris law exponent

Example 1: Fatigue Only



Starting with existing crack
Initiation by fatigue only too low

Very slow growth with starting shallow crack
Probability of leakage and Rupture still zero with 100K realizations

Depth variation over time plotted
Depth increased by a fraction of 1% at max through the thickness over 80 years

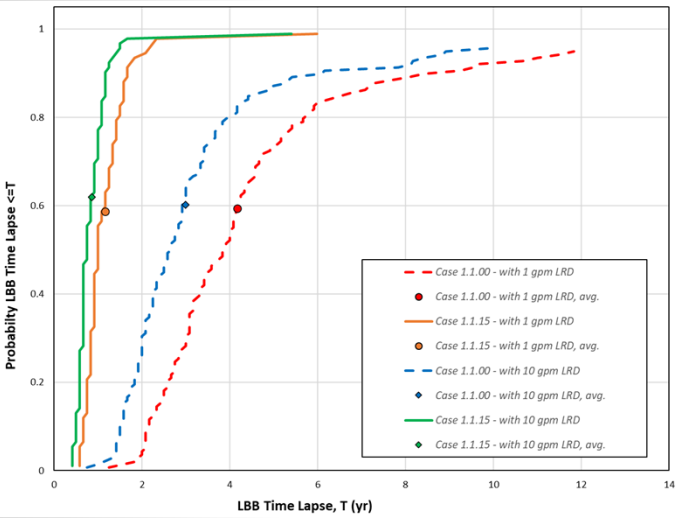
Fatigue only mechanism not an issue in the situations considered

Example 2: Fatigue and PWSCC

CDF of LBB time lapse

Shorter time between detectable leak and rupture

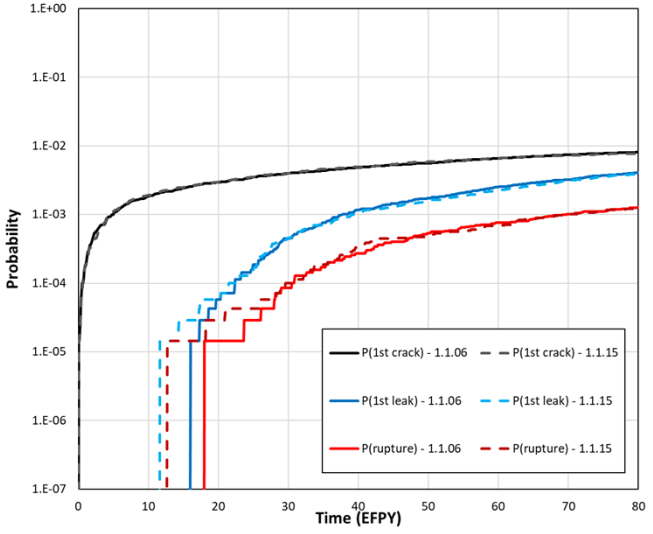
Fatigue accelerate the crack growth once deep or through wall



Probability of initiation, leak and rupture

Leak and rupture probabilities are higher early one

influence is reduced over time due to flattening of the curve



Fatigue has more impact in conjunction with PWSCC, but impact on risk remain low over time

Conclusion

- xLPR is a PFM code that can consider both PWSCC and Fatigue mechanisms
- Several fatigue models available to account for material specificities
- Fatigue growth has negligible impact by itself for the problems considered and small impact when coupled with PWSCC
- Future work may consider impact of fatigue coupled with other mechanisms, such as IGSCC and high temperature creep