Investigation of the Fatigue Cracking and Leakage Rate potential of U-Bend Tube Bundles subjected to Flow-Induced Vibrations

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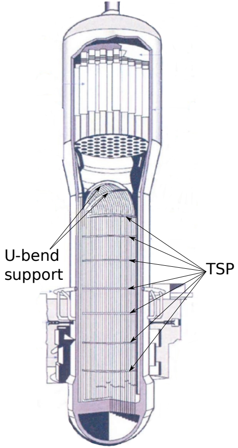
Outline

SG Mechanical Problems

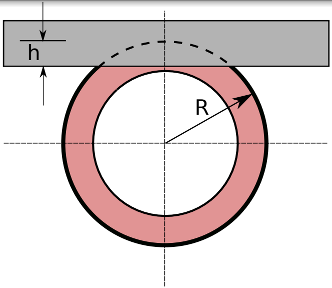
- SG Problems
  - Many failures due to corrosion
  - FIV related failures
    - Fretting Wear at Supports
    - Cracking
    - Tube-to-Tube Impact
- SG Support Functional architecture
  - Hydraulically invisible
  - Ensure stability
  - Clearance
    - Affects fretting wear
    - Should be kept small

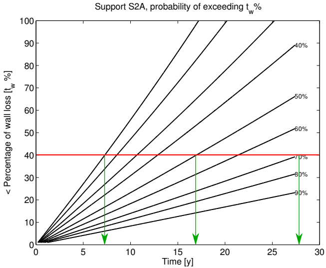


Clearance Enlargement

Cause:

- Tube Degradation
  - Fretting wear damage
  - Should be accounted for at the design stage
- Support Degradation
  - Tube support plate corrosion
  - Loss of support effectiveness
  - May affect stability
  - May accelerate wear at other supports

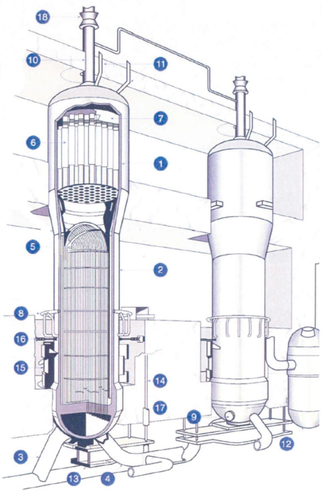




Background

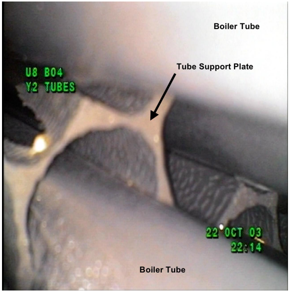
Tube/support Example : Bruce Boilers

- 7 Tube support plates (TSPs)
- 3 U-bend supports.
- TSPs are 25.4 mm thick carbon steel plates.



Bruce Unit 8

- FAC damage to the tube support plate
- Minor to complete loss of ligaments (H07)
- Loss of tube support $\Longrightarrow$ risk of instability



Counter measures:

- 2 pairs of flat bars in the U-bend
- 1 Comb support at H07

Objectives

The main objective is to independently evaluate the integrity of steam generator tubes as plants age and degradation proceeds. Special attention will be paid to the consequence of support loss in the straight portion of the tube in terms of fatigue cracking rate of the tube bundle.

Outline

Elements of Investigation

- Structural Modelling (FEA)
  - Tube
  - Loose supports (impact+friction)
- Fluid Excitation Modelling
  - Turbulence
  - Fluidelastic
- Tube Cracking and Leakage

Structural Modelling (FEA)

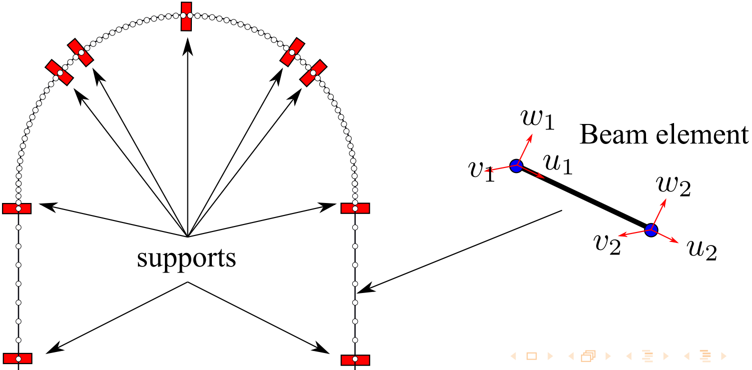
$$[M]\left\{\ddot{w}\right\} + [C]\left\{\dot{w}\right\} + [K]\left\{w\right\} = \left\{f_T\right\} + \left\{f_a\right\} + \left\{f_{fei}\right\} + \left\{f_c)\right\}$$

$\{f_c)\}$ Contact Forces

$\{f_T\}$ Turbulence Forces

$\{f_a\}$ Add Mass Effect

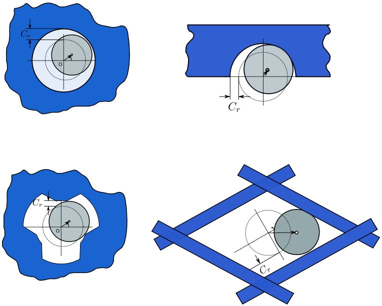
$\{f_{fei}\}$ Fluidelastic Forces



Support Types

Support Types

- Drilled-Hole Support
- Scallop-Bar Support
- Broached-Hole Support
- Lattice-Bar Support

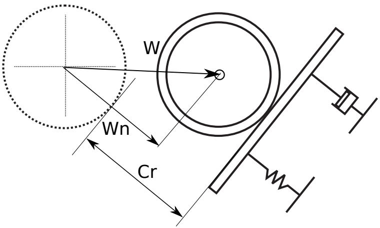


Forces due to support contact

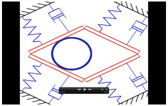
Tube support contact by adding massless bars attached to:

- Contact Stiffness
- Contact damper

$$\delta_{ni} = y_{ni} - C_{ri}$$
$$F_{ci} = F_{si} + F_{di}$$
$$F_{si} = -\left(K_{ci}\delta_{ni}\right)\hat{e}_{ni}$$
$$F_{di} = -sign\left(\dot{\delta}_{ni}\right)\left(1.5\alpha\left|F_{si}\right|\right)\hat{e}_{ni}$$



(g)



FSIL

Fluid Excitation

Turbulence

- Random excitation
- Small amplitude response ($< 2\%$ tube diameter)
- Determines the long-term wear
- Turbulence Bounding Spectrum $\Longrightarrow$ Equivalent Random Distributed force

Fluidelastic Forces (FEI)

- FEI under the spotlight for the last 40 years.
- Extensive research provided a progressive understanding:
  - Empirical Models.
  - Semi-Analytical.

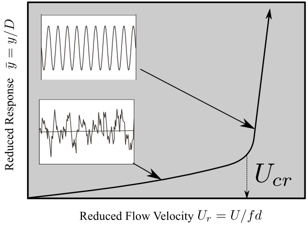
Fluidelastic Instability (FEI)

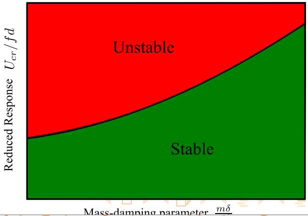
- Self exciting mechanism
- Critical flow velocity

Reduced critical velocity $U_{cr} = \frac{U_c}{fd}$

Mass-damping parameter $MDP = \frac{m\delta}{\rho d^2}$

- U_c = Critical flow velocity
- f = Tube frequency
- m =Tube mass per unit length
- δ = Logarithmic decrement
- ρ = Flow density



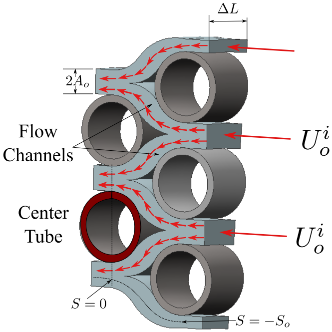


Fluidelastic Instability Force Model

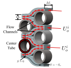
Based on the original model of Weaver et al.

- Flow-cell
- 1-D flow
- Flow perturbation

$$A(s,t) = A_0 + a(s,t)$$
$$U(s,t) = U_0 + u(s,t)$$
$$P(s,t) = P_0 + p(s,t)$$

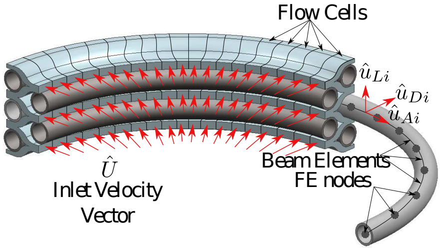


- Time Lag
- $F_L(t) = \int_{s_a}^{s_s} [P_{i1} - P_{i2}] \cos\beta \partial s$
- $F_D(t) = \int_{s_a}^{s_s} [P_{i1} - P_{i2}] \sin\beta \partial s$

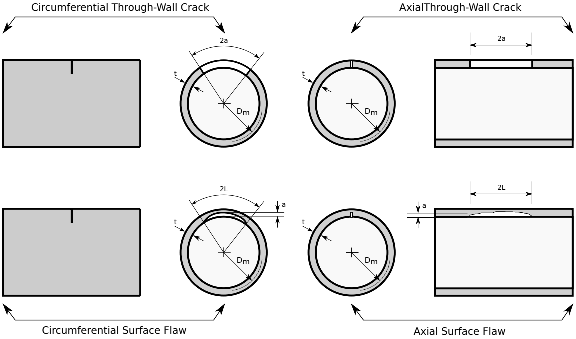


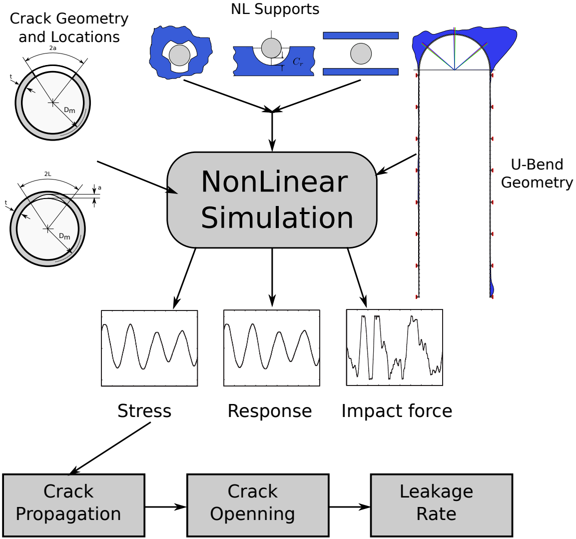
U-bend Fluid Force Model

- Flow is divided into a number of layers
- Each layer is associated with a tube finite element.
- Layer = two flow channels.
- For layer i we have U_{oi} and ρ_{oi}.
- The flow is defined by
  - $\hat{u}_{Li}$ Lift
  - $\hat{u}_{Di}$ Drag



Tube Cracking and Leakage




Crack Geometry
and Locations
2a
t
Dm
2L
a
NL Supports
C_r
U-Bend
Geometry
NonLinear
Simulation
Stress
Response
Impact force
Crack
Propagation
Crack
Openning
Leakage
Rate

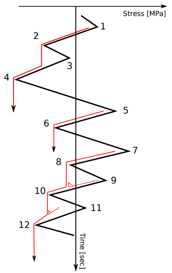
Fatigue Crack Growth

Inconel 600 Crack Growth Model (Kozluk 1989)

$$\frac{da}{dN} = \frac{2.39}{E^2\sqrt{1-R}}\left[\Delta K - \left(25.9 \times 10^{-6} E\right) \times \left(e^{-0.66R}\right)\right]^2$$

Calculate Crack Growth Rate

- Determine Stress Cycles
  - Rainflow counting
- Determine Crack Length vs. Time
  - Block Method



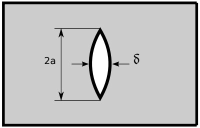
Crack Opening Displacement (COD)

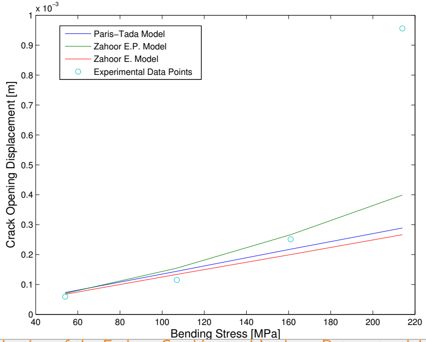
GE/EPRI Method

Zahoor (1989)

$$\delta = \delta_{elastic} + \delta_{plastic}$$

Paris-Tada Model NUREG





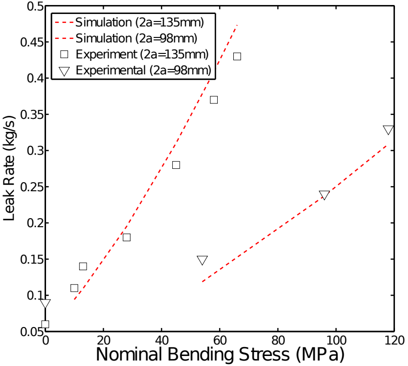
Leak Rate Modelling

Leak Rate Modelling

- Flow through Non-Circular Ducts
- Single Phase Approx (Upper Bound, Friedel, 1990)
- Equilibrium Expansion (Lower Bound, Feburie, 1993)

* ANL Model

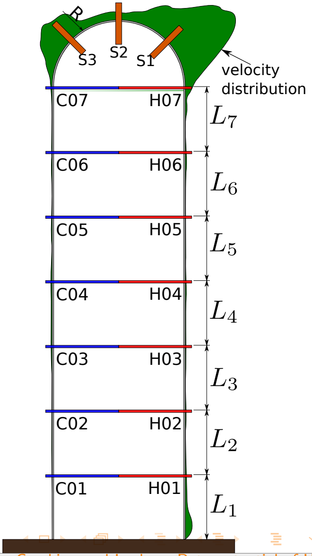
*French LB Model



Outline

Tube Configuration

- Bundle: Parallel triangle P/D=1.6
- Flow Distribution
  - External flow density: variable
  - External flow velocity: variable
- Support config
  - 3 scallop bars (S1,S2,S3)
  - 14 broached holes C01:C07 and H01-H07
- Tube:
  - Diameter 13 mm
  - Thickness 1.2 mm



Models

Simulations were conducted using INDAP code

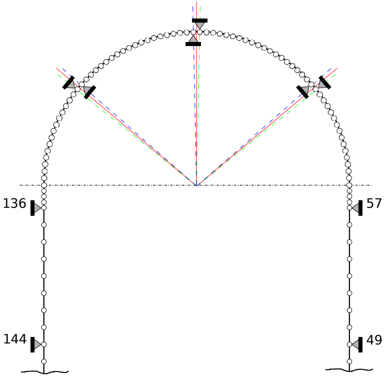
- Linear Models
  - Natural frequencies
  - Mode shapes
  - Determine the stability threshold
- Nonlinear Models
  - Response
  - Impact force
  - Work rates

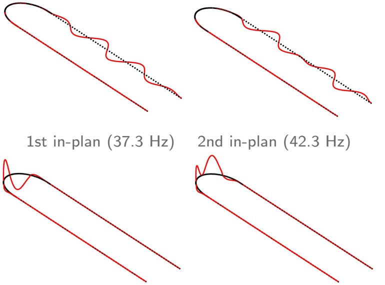
Three Configurations

- Configuration 1 (original)
- Configuration 2 (total loss)
- Configuration 3 (remedies)

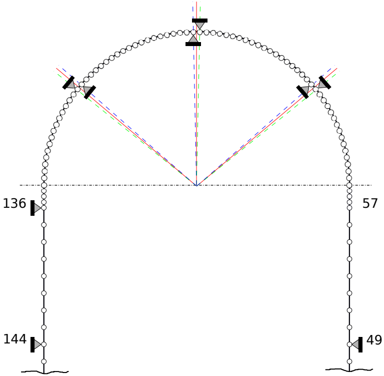
Outline

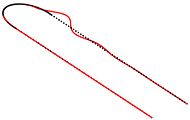
Linear - Configuration 1





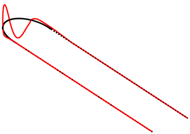
Linear - Configuration 2



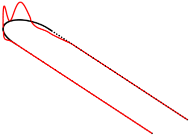


1st in-plan (28.3 Hz)

2nd in-plan (37.3 Hz)



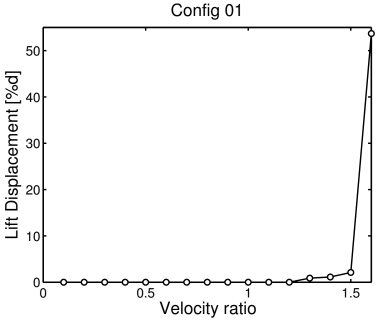
1st out-of-plan (55.5 Hz)

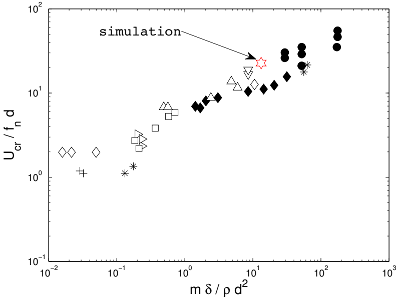


2nd out-of-plan (80.3 Hz)

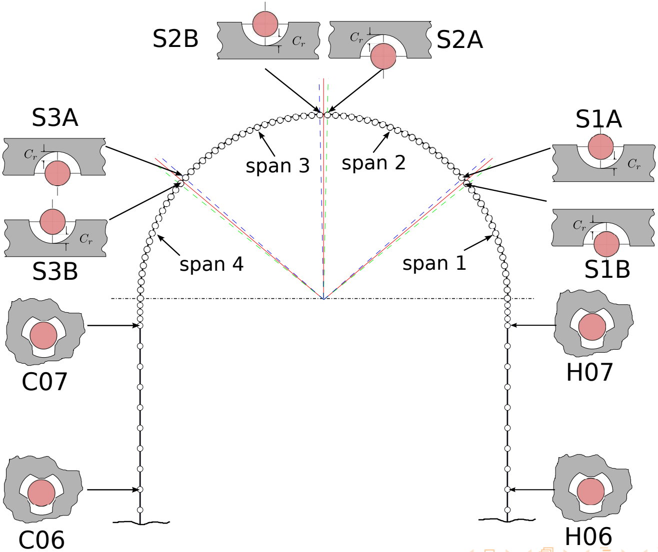
Stability Threshold

$$velocity\ \ ratio = \frac{Flow\ \ Velocity}{Rate\ \ Velocity}$$

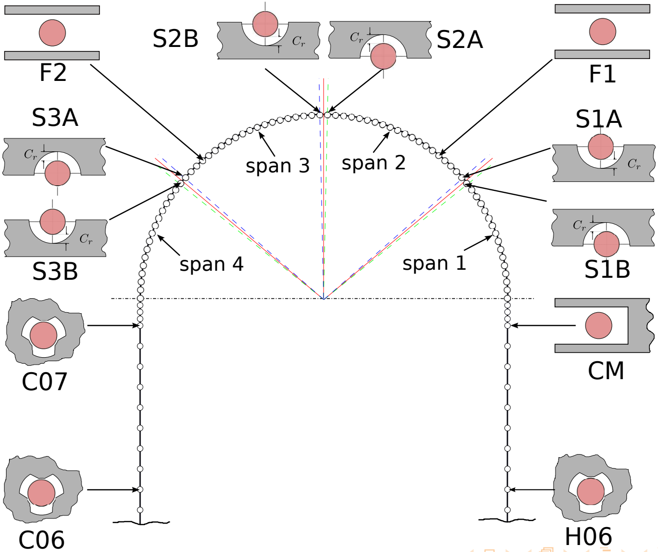




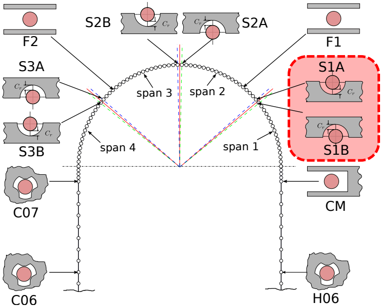
NL Configurations



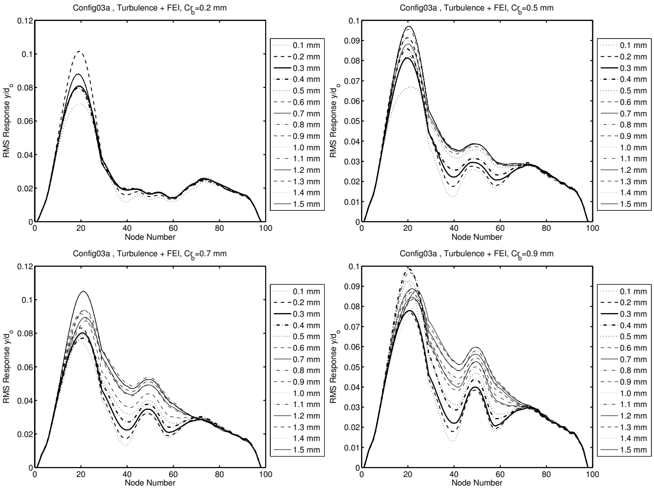
NL Configurations cont.



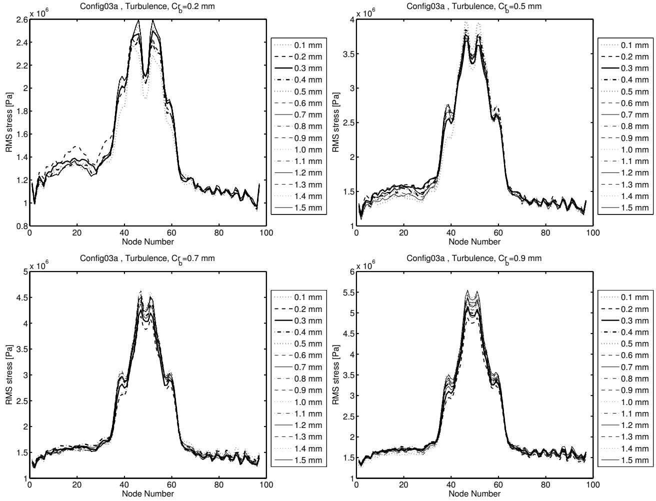
Effect of Scallop bar S1



RMS Tube Displacement



RMS Bending Stresses

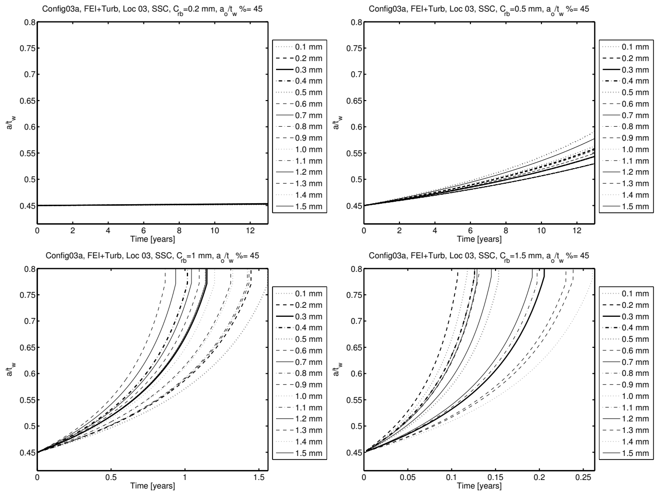


SCC Crack Configuration

Crack ratio (a/t)	Crack size (a) [mm]	Aspect ratio (2L/a)	Crack angle [deg]
45%	0.54	5.76	30
50%	0.60	5.18	30
55%	0.66	4.71	30
60%	0.72	4.32	30
65%	0.78	3.99	30
70%	0.84	3.70	30
75%	0.90	3.46	30

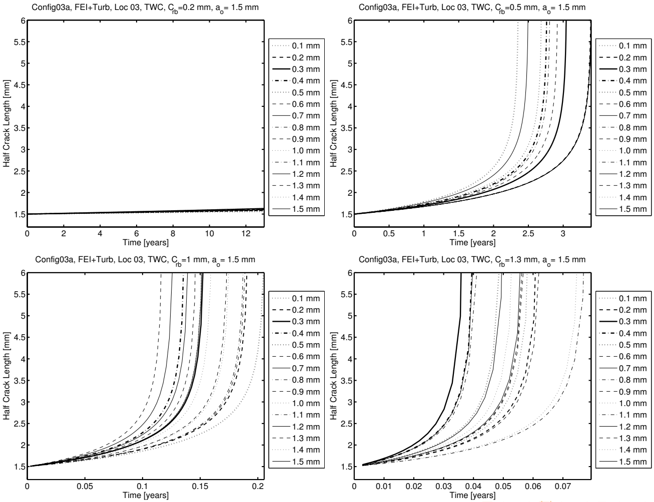
SCC Crack Growth Predictions

Configuration 03a, $a/t_w = 45\%, \theta = 30°$



TWC Crack Growth Predictions

Configuration 03a, $a_0 = 1.5$ mm

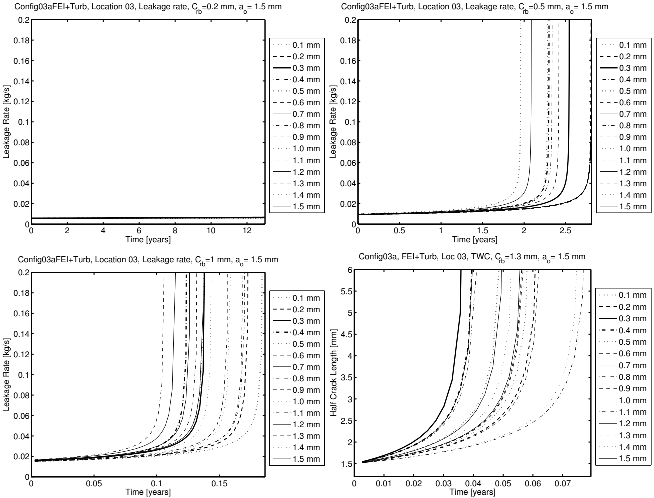


TWC Leakage Conditions

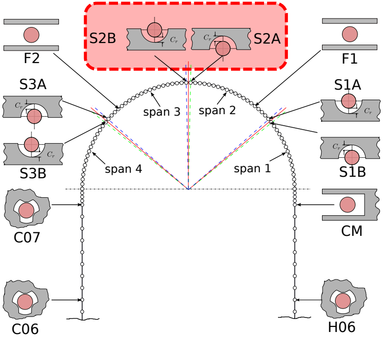
- Internal pressure $P_i = 9.31$ MPa.
- External pressure $P_o = 4.43$ MPa.
- Internal temperature $T_i = 303.2°$C.
- External temperature $T_o = 243.0°$C.
- Two-phase mixture model.

TWC Leakage Rate Predictions

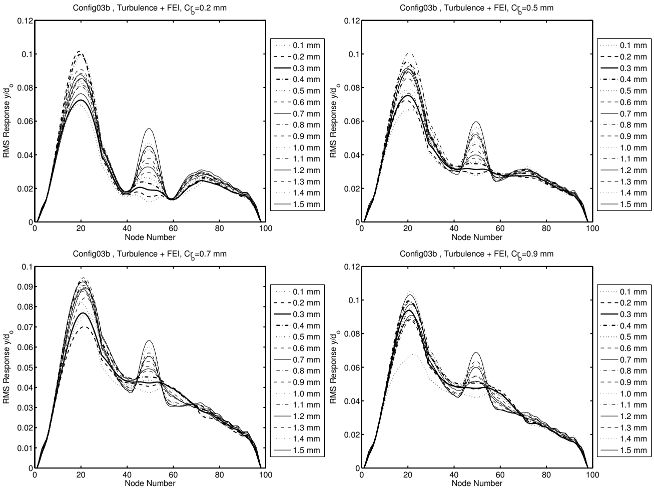
Configuration 03a



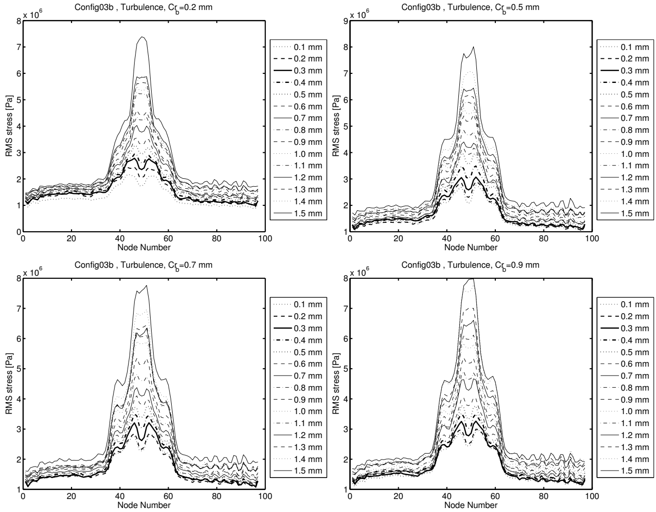
Effect of Scallop bar S2



RMS Tube Displacement

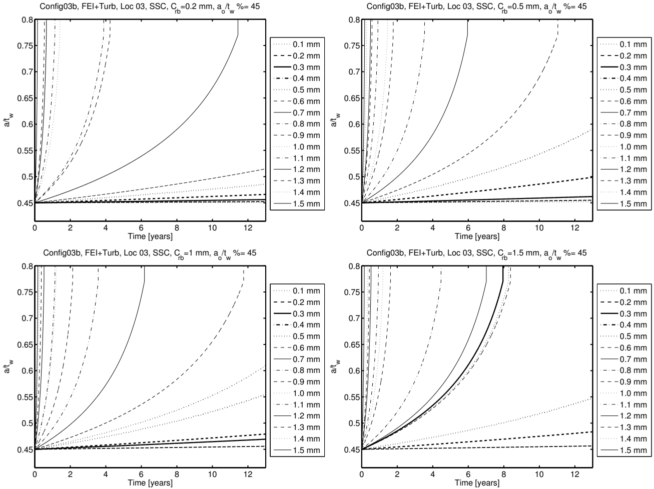


RMS Bending Stresses



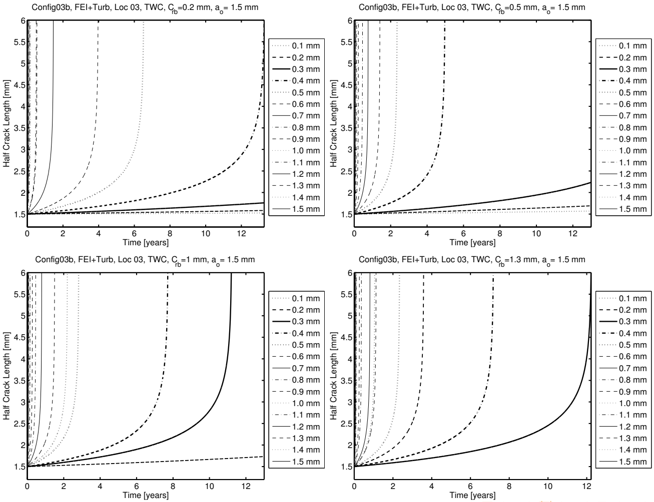
SCC Crack Growth Predictions

Configuration 03b, $a/t_w = 45\%, \theta = 30°$



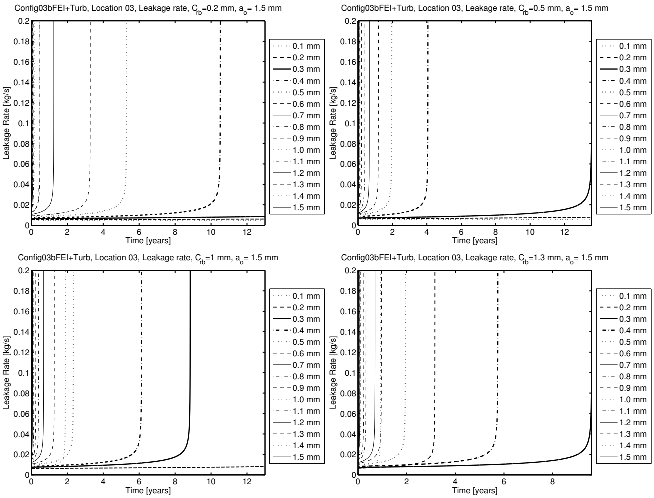
TWC Crack Growth Predictions

Configuration 03b, $a_0 = 1.5$ mm



TWC Leakage Rate Predictions

Configuration 03b

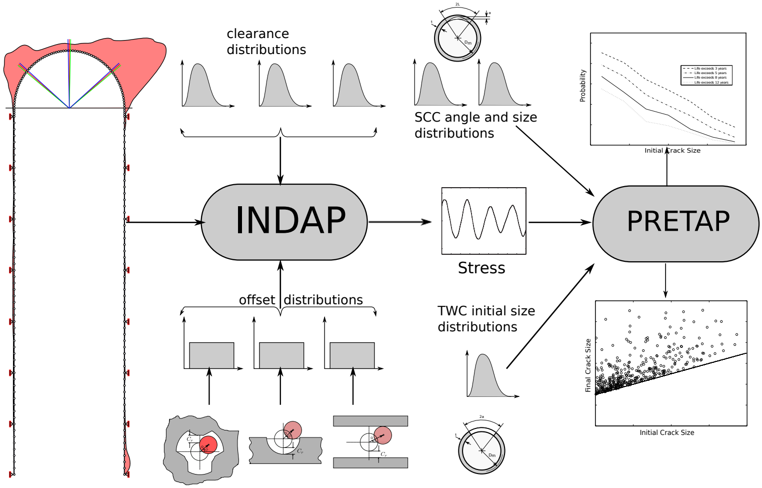


Probabilistic Evaluation

- The deterministic simulation is useful in providing a basic understanding of the effect of the clearance
- Controlling clearance value is difficult
- Almost impossible to keep tubes centred
- There is very complex interaction of supports
- Investigate all possible combinations a very large number of simulations is required

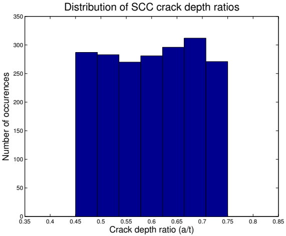
The solution is to employ a probabilistic techniques

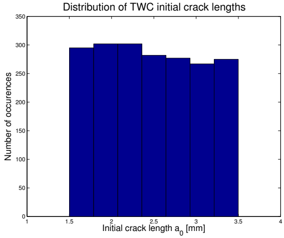
Probabilistic Evaluation



Input Distributions

Variable	Distribution	μ	Range
SCC, a_0/t_w	Uniform	0.60	$0.45 - 0.75$
SCC, $2L/a$	Uniform	7.5	$3 - 12$
TWC, a_0	Uniform	2.5 mm	$1.5 - 3.5$ mm

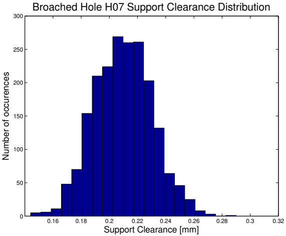


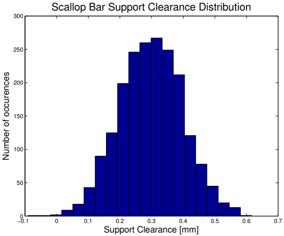


Support Clearance Distribution

Support	Distribution	μ	σ
H01 - H06	Gaussian	0.25 — 4.15 mm*	0.1 mm
C01 - C07	Gaussian	0.25 — 0.55 mm*	0.1 mm
Flat bars	Gaussian	0.21 mm	0.02 mm
S1-S3	Gaussian	0.3 mm	0.1 mm

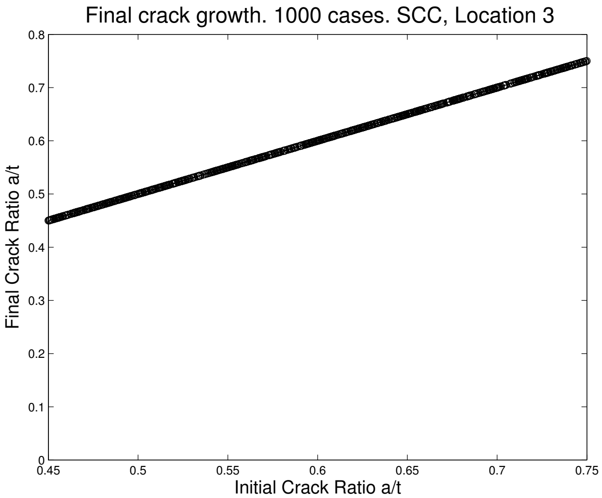
* Clearance linearly varied along leg



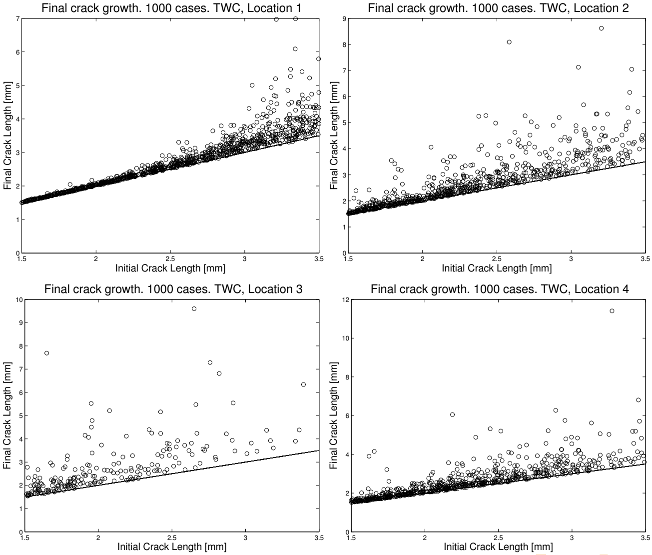


SCC Results

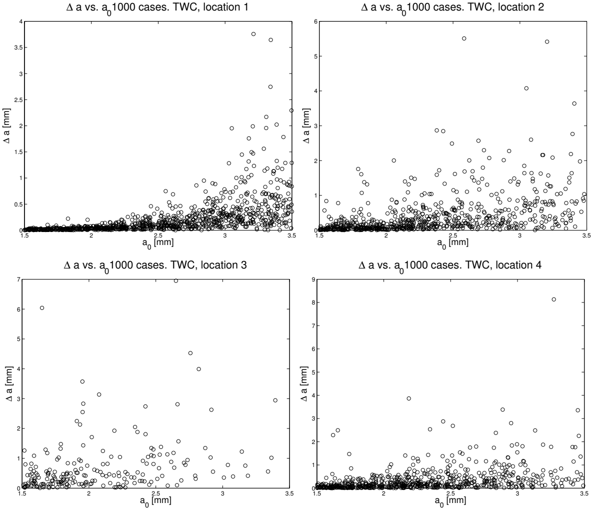
Location 3.



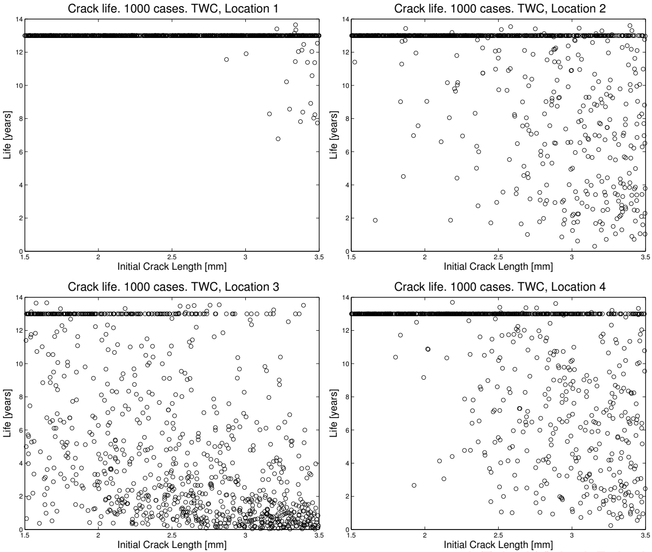
TWC - Final Crack Length



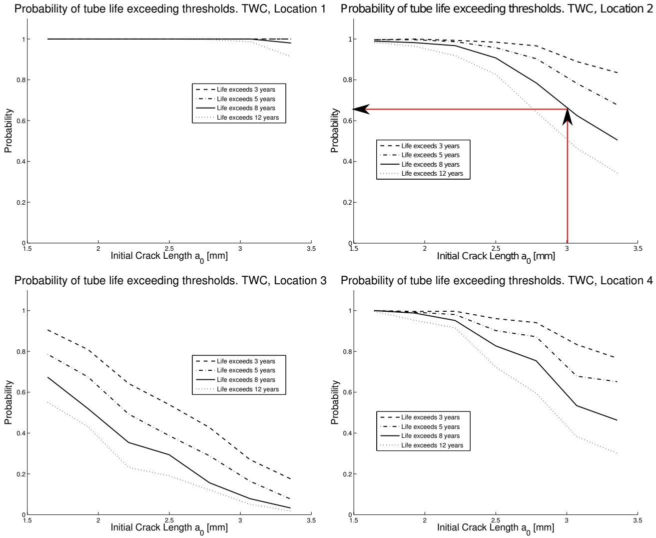
TWC - Crack Growth *vs.* Initial Crack



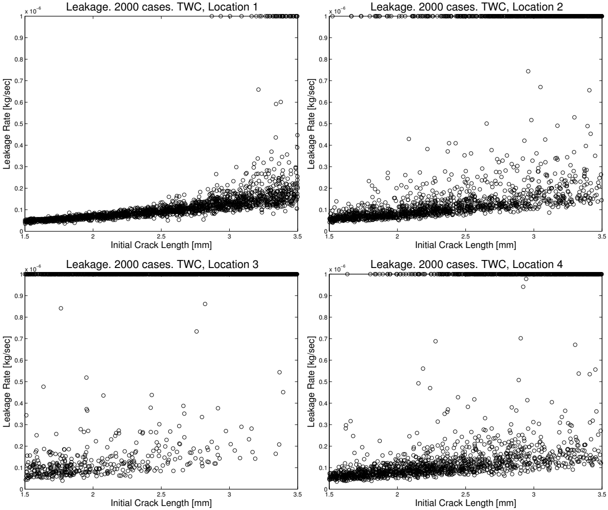
TWC - Tube Crack Life



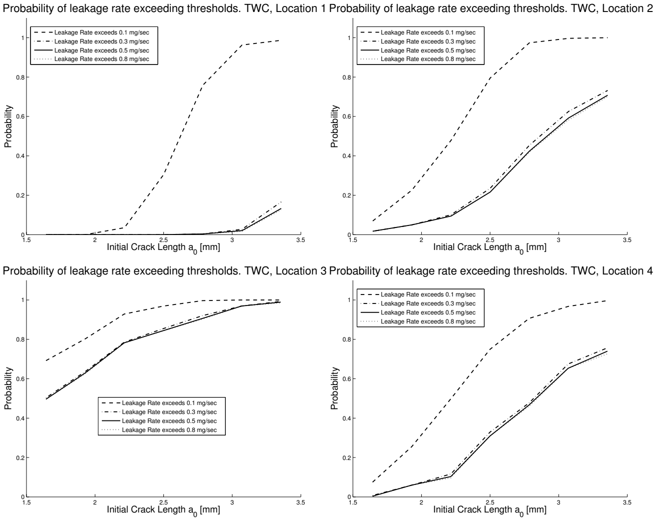
TWC - Tube Crack Life Probabilities



TWC - Leakage Rate *vs.* Initial Crack



TWC - Tube Leakage Rate Probabilities



Summary

Both deterministic and probabilistic evaluation were conducted

- Clearance is an important factor that affects life.
- SCC - no risk
- TWC - no risk if If the support clearance in the U-Bend region $\leq$ 0.2 mm
- Degradation of Scallop Bars 1 or 3 did not result in a dramatic effect.
- Degradation of the scallop bars at the apex of the U-Bend proves to be critical for the system.
- The variability of combination of the clearances is very important - Probabilistic evaluation would be more realistic

Questions and Comments