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DETERMINING FITNESS FOR SERVICE OF SCRS AND FLOWLINES WITH PROBABILISTIC TOOLS

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ABSTRACT

Inspection of deepwater risers for flaws or pits using ILI tools can be challenging. Some lines are designed as "non-piggable", and it is not unusual for an inspection to be incomplete because of physical constraints. As with any measurement, there will be a degree of error. While deterministic conclusions cannot be reached based on such incomplete data sets, probabilistic methods can be used effectively to make judgments about fitness for service.

Commonly, different sections along a riser or flowline experience different fatigue spectra and extreme loads. Applying the loads from the sections with the highest loading to all flaws/pits can be too conservative. It is useful to employ statistical methods to assess the probability that a large defect occurs in a region with critical loads. These methods are especially useful when ILI data are incomplete or when estimates of damage must be made based on lines in similar corrosion environments.

Properties and parameters other than inspection findings have an element of uncertainty. Fracture toughness, yield stress, and fatigue crack growth rates will be known in terms of mean and standard deviation. Soil properties may be known in terms of upper and lower bound. Likewise, there will be a range of uncertainty about service history and chemical environment. In such cases where fitness for service is based on the interaction of multiple random variables, Monte Carlo methods are appropriate for determining if the probability of failure is sufficiently low to tolerate. In the case of deepwater risers and flowlines where failure could result in loss of containment of hydrocarbons, permissible failure rates are on the order of 1E-5 to 1E-6 per year.

This paper examines a riser and a flowline case study. For each case, a fitness for service analysis is conducted using a Monte Carlo simulation to evaluate the probability of failure based on incomplete ILI data and statistical characterization of other pertinent parameters. The results are compared against the conclusions of deterministic analysis.

Keywords: Corrosion, Pitting, Fitness for Service, SCR, Riser, Fatigue

INTRODUCTION

In the simplest sense, production risers are pipes connecting a floating platform with the seabed, and serve as conduits transporting unprocessed production fluid from the subsea wellhead to the vessel. However, subsea riser design is far from simple. In fact it is one of the most challenging parts of any deepwater field development. The dynamic operational and environmental loads experienced by the risers make them fatigue critical structures. With internal contents that are often corrosive and external seawater, the fatigue risks can be compounded if corrosion control is lost, even temporarily.

Marine production risers represent a special design challenge for fitness for service evaluations because they may see high stress, fatigue loading, as well as a corrosive environment. Some risers are designed to perform beyond yield during extreme storms. For example, in SCRs that hang from a platform that experiences large heave motions during storms can be stressed beyond yield by displacement controlled bending loads in the touchdown zone. The same riser will collect challenging fatigue load cycles. Fatigue loading can come from a number of sources including vessel motions, vortex induced vibration, and slugging. The production fluid from the reservoir can include CO_2, H_2S, and water along with the oil and gas which can accelerate fatigue crack growth.

As more operational experience is gained by the industry, it is becoming clear that maintaining control over corrosion through-out the life of subsea systems can be exceedingly difficult. When the internal chemistry drifts out of control, pitting corrosion can result. Even low levels of localized corrosion and pitting which do not infringe on the pressure capacity may be critical when they occur at fatigue hot spots. When such pitting is identified by in-line inspection (ILI), the operator is faced with the task of evaluating the impact of the damage on the capacity of the riser to sustain fatigue loading and tolerate randomly occurring extreme loads in a chemical environment that may accelerate fatigue crack growth rates.

A key part of managing riser and flowline integrity is inspection. For subsea risers and flowline where internal corrosion is a risk, the inspection must be done by ILI tools: i.e. MFL or UT devices on pigs. Unfortunately, not all riser and flowline systems are designed to be piggable. For some lines the original design intent may have called for the system to be piggable, but because of damage, modification, or operational issues, the system may end up being unpiggable. In these circumstances evaluation of the fitness becomes even more difficult.

Fitness for service encompasses both fitness with respect to strength, and fitness with respect to fatigue and fracture. In this paper the focus is on the fatigue and fracture aspects of FFS evaluation. While traditional deterministic fitness for service analysis is adequately covered in such codes as API-RP-579 [2] and BS7910 [1], ,the collection of issues unique to risers requires special treatment. For a number of reasons, a probabilistic assessment may make more sense than the deterministic assessment. API-RP-579 [2] does discuss and endorse use of the probabilistic approach, but by and large leaves the details of the methodology to the engineer.

In the traditional deterministic FFS process the measured flaw is magnified by the maximum expected measurement error and the fatigue crack growth is checked with worst case load and material properties and loading. Then a safety factor on life is applied. API-579 [2] does allow the engineer to use nominal properties and apply partial factors of safety which are based on a table of generic variances.

A probabilistic approach will start with the determination of a maximum allowable probability of failure that will depend upon the consequences of that failure. Guidance for selecting appropriate probabilities of failure is found in BS7910 [1] and DNV-OS-F101 [5]. For production flowlines and risers where the failure of the riser does not imply failure of the host vessel, a target probability of 7E-5 is in agreement with BS7910 [1], while DNV-OS-F101 [5] calls for a probability of failure of between 1E-5 and 1E-6. Note that while failure of a flowline may result in the release of some hydrocarbons, the flow can be shut at the well head tree when the damage is discovered and loss of contents would be limited to the fluid in the pipe. For riser components near the platform the probability of failure per year should be limited to 1E-6.

NOMENCLATURE

COV - Coefficient Of Variation (standard deviation divided by the mean)
CDF – Cumulative Distribution Function
CTOD – Crack Tip Opening Displacement
ECA – Engineering CriticalAssessment
EPFM – Elasto-Plastic Fracture Mechanics
FAD – Failure Assessment Diagram
FEA – Finite Element Analysis
FCG – Fatigue Crack Growth
FFS – Fitness For Service
FOS – Factor of Safety
GoM – Gulf of Mexico
ILI – In Line Inspection
IM – Integrity Management
KPI – Key Performance Indicator
MFL – Magnetic Flux Leakage
PSF – Partial Safety Factor
RSM – Reference Stress Method
SCF – Stress Concentration Factor
SCR – Steel Catenary Riser
UT – Ultrasonic Testing
VIV – Vortex Induced Vibration

PROCESS OF FFS ASSESSMENT

In the absence of an industry accepted method for assessing the fatigue and fracture performance of a structure containing corrosion pits, it is common practice to treat pits as planar flaws. In the methodology outlined, corrosion pits are assessed as crack-like defects. The reason for this approach is that it is conservative and there is no better alternative. The SN approach requires application of an appropriate SCF which requires knowledge of the radius at the base of the pit. This information is generally not available. Also, SN data in corrosive environments are more difficult to obtain than FCG data. The degree of conservatism inherent in assessing corrosion pits as crack-like defects is quantified in [8].

Treating pits and volumetric metal loss anomalies as though they are planar flaws is an acceptable assumption where the flaws are narrow and groove-like or where the root radius is sharp. Where the ILI tools cannot verify that the root radius is not sharp and cannot verify that cracks are not present, this conservative approach may be appropriate because of the criticality of the structure.

In evaluating the capability of the fatigue loaded riser or flowline pipes, the FFS procedures use fatigue crack growth (FCG) methods from [1] or [2]. These are implementations of Elasto-Plastic Fracture Mechanics (EPFM). Starting from an initial defect sized from ILI data, a crack is grown using FCG rate curves appropriate to the internal pipe environment. Eventually the crack will grow to failure, either by fracture, plastic collapse or by penetrating the pipe wall. So, in essence the assessment involves determining life by a three step process:

- Determine the initial crack size;
- Growth the crack in fatigue;
- Indicate when failure occurs.

To assess crack growth, an adaptation of the Paris law is used to account for the change in crack growth rate over the range of ΔK. See equation (1). This essentially says that the da/dn curve can be described by a series linear segments in log/log space. Typically an FCG curve for corrosive environments will depart substantially from those developed from in-air testing. Expressing the FCG curve in this fashion allows for the adaptation of the curve to the data.

$$\frac{da}{dn} = A_i \Delta K^{\,m_i} \tag{1}$$

Where:

da/dn = the crack growth per load cycle

A_i = the intercept of the i[th] segment of the crack growth curve in log space;

ΔK = the stress intensity range for the load cycle

m_i = the slope of the i[th] segment of the crack growth curve in log space

The stress intensity solutions for an internal surface crack on a cylinder are taken from API579 [2]. The reader should note the following dependencies:

$$\Delta K = f(a, \Delta\sigma, t, c, D) \tag{2}$$

Where:

a = crack depth

$\Delta\sigma$ = stress range

t = wall thickness

D = outer diameter

c = half the crack length

As the crack is analytically grown, the software checks to see if a flaw of that size would fail under the extreme load; i.e. it checks to see if the limiting flaw size has been reached. The limiting flaw is found from the failure assessment diagram (FAD) where the stress intensity ratio (K_r) is plotted vs. the load ratio (L_r). See equations (3) and (4). Typical FADs are shown in Figure 1 for the BS7910 [1] level 2A and level 2B assessments. Level 2B requires knowledge of the material stress strain curve. As the diagram shows, an increase in load ratio decreases the allowable stress intensity ratio.

$$K_r = \frac{K}{K_{mat}} \tag{3}$$

$$L_r = \frac{\sigma_{ref}}{\sigma_y} \tag{4}$$

Where,

K = stress intensity

K_{mat} = nominal material stress intensity limit

σ_{ref} = the reference stress

σ_y = yield stress

Reference Stress

Both API-RP-579 [2] and BS7910 [1] are reference stress based procedures. The "limit load", which determines the section capacity of a loaded structure, is a critical parameter to determine the failure criteria. The Reference Stress Method (RSM), which depends on evaluation of the limit load of the structure, is also used by the Nuclear Electric's R6 procedures [6] to assess the integrity of structures with and without defects. A simple relation exists between the reference stress, the yield stress of the material, total applied load on the structure and the collapse load of the structure where the loading is from a single force. This relationship is given by:

$$\sigma_{ref} = \frac{P\sigma_y}{P_L(a, \sigma_y)}, \tag{5}$$

where,

P = the applied load,

P_L = the limit load for a given yield stress and crack size, and

a = the crack size.

It should be noted that there is a complex interaction between a number of variables in the FFS solution. The FAD represents interaction of flaw size, material toughness, reference stress and yield stress to name a few. These interactions must be accounted for in the probabilistic assessment.

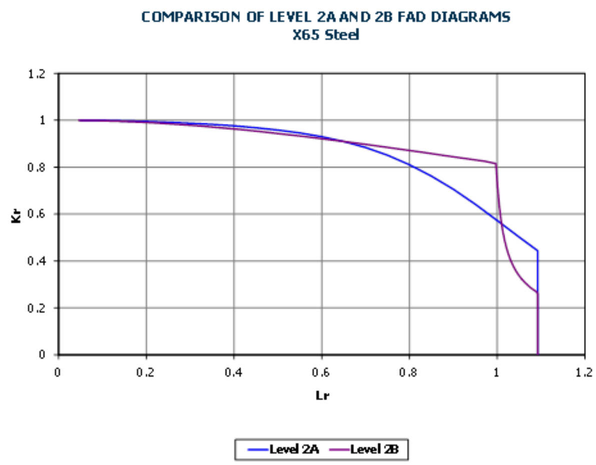

Figure 1 – Examples of FAD Diagrams for FFS Process.

ANALYSIS METHODOLOGY

The most generally useful tool in FFS probabilistic assessment is the Monte Carlo simulation. It relies on repeated random sampling of the key variables. In this method, the variability of the key inputs is defined in the underlying distribution type and the parameters that define the distribution. These inputs then become the random variables in the Monte Carlo simulation.

The selected values of the random variables are input to the FCG engine which computes life for each trial. The value of this type of approach stems from the fact that the proper linkage of the effects of the random variables is taken care of by the FCG engine. In these examples the proprietary program 2HFlaw is used as the FCG engine. 2HFlaw implements the ECA procedures of API-RP-579 [2], for crack growth, fracture and plastic collapse. The combined process is implemented in software. The flow of the software is shown in Figure 2.

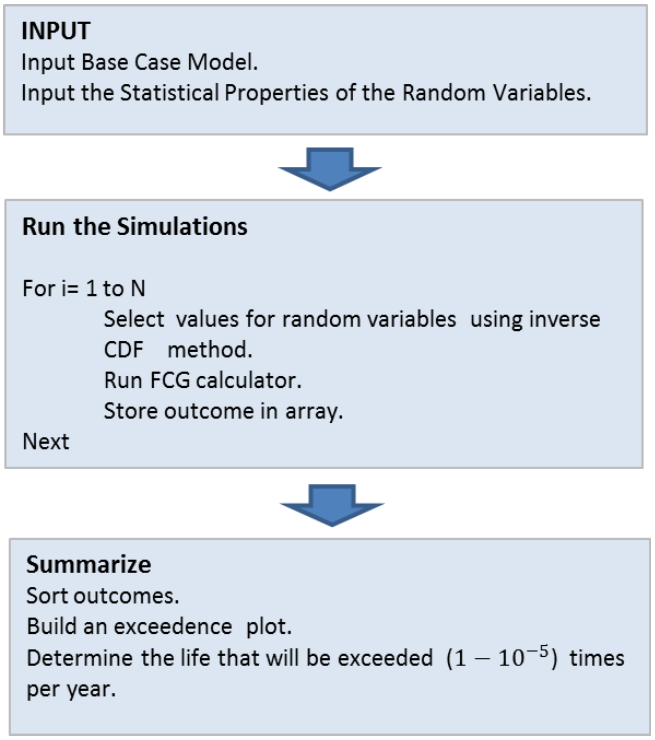

Figure 2 – Flow Chart

Selection of Random Variable Values

The inverse transformation method is used to select the values of the random variables for each trial. It provides the most direct route for generating a random sample from a distribution. In this method, the inverse of the cumulative probability density function (CDF) is generated based on the underlying probability distribution, given the parameters that define the distribution. Since the CDF ranges from 0 to 1, the inverse exists over the domain 0 to 1. To select the value, a random number between 0 and one is chosen and the inverse CDF gives a value for the trial. The process is repeated for each random variable.

FCG Assessment

The process of assessment involves calculating how long it will take an initial defect to grow to the point when the section will fail in service. In order to determine this, classical FCG methods are used. In this case the methods of API-RP-579 [2] are used.

When the probabilistic analysis path is chosen, the statistics of the parameters influencing crack growth and ultimate failure are accounted for as well as the probability that the initial flaw exists in the critical region. As such we look at a list of parameters; each with an associated mean, standard deviation and probability distribution function. A list of the key engineering parameters driving the outcome of the FFS assessment is given in Table 1.

These are addressed in the following section. Note that key inputs to the analysis are not necessarily a simple variable in an equation. For instance the load histogram is usually a matrix that includes bending and tension. In order to address its variability a scale factor is applied to it and that factor is handled as one of the random variables in the Monte Carlo analysis.

Symbol	Engineering Parameter	Distribution
Kmat	Fracture Toughness	Gaussian
YS	Yield strength	Gaussian
YS/TS	Yield/Tensile ratio	Gaussian
a_0	Initial crack depth	Gaussian
c/a	Initial aspect ratio	Weibull
SCF	Misalignment SCF	Gaussian
t	Wall thickness	Gaussian
F1	Factor on End of Life loading	Gaussian
F2	Factor on fatigue load histogram	Gaussian
AA2	Log(FCG curve intercept 2)	Gaussian
AA3	Log(FCG curve intercept 3)	Gaussian

Table 1 - List of Random Variables

This paper provides a methodology for making an assessment of an SCR with corrosion pitting through the use of an illustrative case study. The basis for the method is given as the process is delineated. While the basic process follows that outlined in ECA and FFS codes, key elements unique to the riser and flowline problems are addressed in a detail not available in the most commonly used codes. The methodology outlined assumes a steel riser.

The case studies are not based on any particular existing installation. Rather they constructed based on a number of real world examples chosen to be representative of behavior of risers and flowlines in deep water. It is important for the reader to understand that the methodology presented fundamentally requires that site specific data be available.

KEY PARAMETERS WHICH DRIVE THE FFS ASSESSMENT

Fracture Toughness

There is a high degree of scatter in fracture toughness data. The actual toughness in a given situation can be considerably higher than the lower-bound curve predicts. The data are treated statistically rather than deterministically because the steel does not have a single value of toughness at a particular temperature. Rather, the material has a toughness distribution. The values used in this assessment are typical values found in qualification of high quality riser pipe welds and are based on 20 samples. However, the reader is cautioned that data used in such assessment should be case specific.

It is common for the steel in flowlines and risers installed in recent years to exhibit high toughness. Even at welds in thick pipe, toughness will maintain upper shelf values over the range of operating temperatures. Based on the assumption of toughness being upper shelf, a normal distribution is used. The material fracture tough in these examples is taken from CTOD testing and converted to K with the relation defined in equation (6).

$$K_{\delta C} = \sqrt{\frac{m_{CTOD} \cdot \sigma_f \cdot \delta_{crit} \cdot E_y}{1-\nu^2}} \quad (6)$$

where:

δ_{crit} is CTOD
$K_{\delta C}$ is fracture toughness
m_{CTOD} is the constraint factor
σ_f is the material flow strength
E_y is Young's modulus
υ is Poisson's ratio

Material Strength
Yield Stress (YS) and tensile strength (TS) will factor into the load ratio Lr and the ratio between the two will affect the shape of the FAD diagram. The data used in this assessment are typical of high quality riser pipe. The sample set used contained 90 samples. The reader is cautioned that data used in such assessment should be case specific.

Initial Defect Size
Although the initial crack depth and aspect ratio will come from inspection, measurement error will introduce a statistical aspect. Two scenarios are considered.

1 – ILI is run on the line being evaluated and measured defects and their locations are defined.
2 – The line being evaluate cannot be pigged. However, a sister line has been inspected and a histogram of defect sizes is available. In this case a 4D table is developed showing the rate of occurrence per meter in terms of:

a	crack depth
2c/a	aspect ratio
ϕ	clock position
W	presence of a weld

The aspect ratio 2c/a can be described by a Weibull distribution. The CDF for a Weibull distribution is given by:

$$F(x) = 1 - e^{-\left(\frac{x}{\lambda}\right)^k} \quad (7)$$

A CDF illustrating pit width variance is shown in Figure 3 for pits in the range of 4 mm deep. Note that half the pits are less than 7 mm wide, but some are as wide as 60 mm.

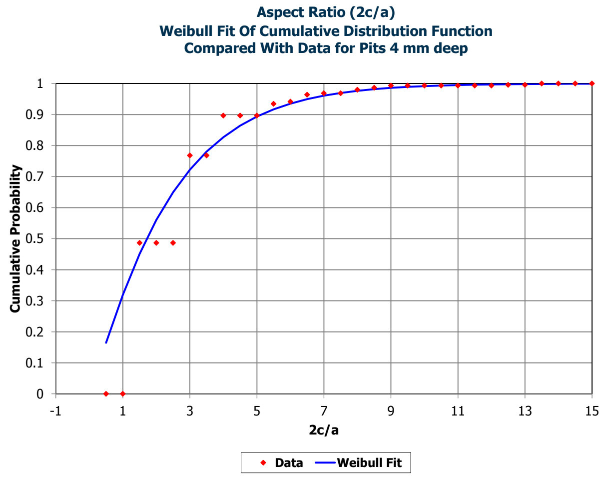

Figure 3 - Typical Distribution for Aspect Ratio for Pitting

Misalignment SCF
Because of pipe tolerances and imperfect alignment during welding each joint will be affected by a stress concentration facture due to misalignment of the pipe wall. This will magnify the stress and affect the growth rate of the crack. The SCF from misalignment found from design is assumed to represent a 2 standard deviation variation from the mean SCF which is half; i.e. for more background on this subject, see [7].

$$SCF_{mean} = 1 + \frac{(SCF_{design} - 1)}{2} \quad (8)$$

Wall Thickness
Typically the ILI will give the wall thickness with good accuracy. However, where ILI is taken from a sister line, the variance in wall thickness can be accounted for statistically. In these cases, the ILI generally will produce thousands of readings making the assessment easy.

End of Life Load
In the deterministic FFS process, the life is considered to be ended when the crack has grown large enough that the pipe can no longer survive the application of the design load, also known as the end of life load.

For the riser this load will correspond to the an environmental event like a hurricane. A cumulative distribution function for significant wave height (Hs) is constructed. Stress response in the touchdown zone is found from the seastate analysis conducted during riser design phase which establishes the correspondence of Hs with stress. From these two data sets a cumulative distribution of maximum stress per year is built. From the inverse of the CDF the values of the random variable F1 are derived. The underlying distribution would be Weibull. Note that in this example the end of life riser load is taken to be the 100 year hurricane. Since the structure design life is 20 years. This is an inherently conservative assumption. The variance in this value is the variance seen in multiple realizations of the 100 year random sea hurricane and can be treated as Gaussian.

For the flowline, the maximum loading (end of life load) is caused by the maximum temperature and pressure combination. These are limited by the reservoir and are known accurately by measurement. While the method can easily address the variability, in the case of the flowline the variability is small and inconsequential.

Fatigue Load Histogram

For circumferential flaws in risers the fatigue load histogram reflects the riser stress response to environmental loads like waves and currents. Typically riser analysis is conducted using carefully conservative assumptions that generate a good estimate of fatigue demand. In the probabilistic analysis the most likely response histogram is used. In the scheme used, it is scaled by a factor F2 which represents potential variation. See Table 1. Two standard deviations of excursion of F2 will scale the most probable histogram into the design histogram. Because the histograms used are based on measured data, the F2 factor is taken to be small. It is provided in the software for cases where variability in long term loading is more significant.

FCG Curves

Figure 4 illustrates a characteristic fatigue crack growth plot where a corrosive species is present. Data are shown for the in-air response as well as for the response in a sour environment. The sour response is characterized by a jump in the rate of growth at about 155 Nmm$^{3/2}$. The key influences on the crack growth are the point at which the jump in growth rate occurs and the magnitude of the jump. In order to capture those in the assessment, the intercept of Segment 2 and Segment 3 are treated as random variables AA2 and AA3. The crack growth function is defined by a series of segments in the log-log space. The equations of each segment follow the Paris equation;

$$\frac{da}{dn} = A_i \Delta K^{\,m_i} \quad (1)$$

$$AA_i = \log(A_i) \quad (9)$$

Note that by choosing these random variables, it becomes necessary to re-compute the intersection between the segments for each trial in the process per the following equations.

Segment 1

$$\log\left(\frac{da}{dn}\right) = m_1 \log(\Delta K) + \log(A_1) \quad (10)$$

Segment 2

$$\log\left(\frac{da}{dn}\right) = m_2 \log(\Delta K) + \log(A_2) \quad (11)$$

At the intersection

$$m_1 \log(\Delta K) + \log(A_1) = m_2 \log(\Delta K) + \log(A_2) \quad (12)$$

Solve for log(ΔK)

$$\log(\Delta K) = \frac{(\log(A_2) - \log(A_1))}{(m_1 - m_2)} \quad (13)$$

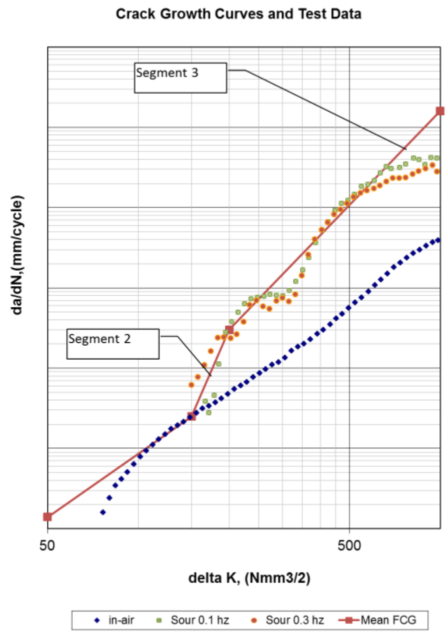

Figure 4 – Characteristic Fatigue Crack Growth in Corrosive Environment

EXAMPLE RISER SYSTEM DESCRIPTION

The example case considered is not an actual installed riser. Rather the properties and loads are realistic, based on experience with many deepwater risers in the GoM. A 12 inch production oil SCR supported by a semi-submersible is considered. The key parameters are given in Table 2

The system is subject to sweet CO_2 service. Tests indicate that the internal chemistry results in crack growth rates are greater than those in air. Crack growth curves used are shown in Figure 5. Load conditions examined are shown in Table 3.

Level 2A ECA is conducted, first deterministically, then probabilistically. The objective is to determine what level of corrosion pitting the SCR is capable of tolerating and still be able to tolerate a 100 year hurricane. In this example only circumferential flaws are addressed.

Parameter	Value
Nominal OD (mm)	323.8
Nominal WT (mm)	42.0
Nominal ID (mm)	239.85
Steel Grade	X70, de-rated to X65 in high temperature
Minimum yield strength, hot (MPa)	448
Minimum yield strength, cold (MPa)	482
Ultimate tensile strength, hot (MPa)	530
Ultimate tensile strength, cold (MPa)	565
Elastic modulus at room temp (MPa)	207,000
Poisson's ratio	0.3

Table 2 - Physical Data for SCR

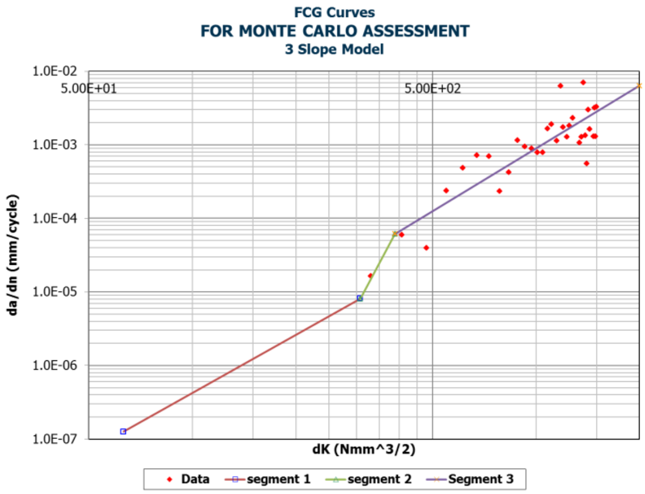

Figure 5 – Fatigue Crack Growth for Riser

Flaw Orientation	Extreme Loads		Long Term Loads
	TDP	Top	TDP/Top
Circumferential	100yr Hurricane	10yr Winter Storm	Fatigue Seastate Loading, VIV
	Ambient Pressure	Design Pressure	Operational Internal Pressure

Table 3 - Extreme and Long Term Loads

Rainflow counting is used to generate the long-term load histograms from time domain first and second order fatigue analysis. Additionally stress cycles are added from VIV analysis.

EXAMPLE FLOWLINE SYSTEM DESCRIPTION

The case considered is a realistic amalgam of various systems seen in the GoM. A 12 inch production oil flowline designed for high pressure and temperature is considered. The physical parameters are given in Table 4.

The system is subject to sweet CO_2 service. Tests indicate that the internal chemistry results in crack growth rates greater than those in air. Crack growth curves used are shown in Figure 5. The flowline experiences controlled buckling at a sleeper when at operating temperature. Cyclic fatigue loading occurs due to fluctuations in operating temperature and pressure. The stress cycle from shutdown to steady state is 80% of yield stress. In evaluating stress intensity, the crack face pressure is applied in both the K and reference stress solutions. See [10] for methodology for application of crack face pressure to in the reference stress solution.

Level 2A ECA is conducted, first deterministically, then probabilistically. The objective is to determine what level of corrosion pitting the flowline is capable of tolerating and still be able to tolerate a design pressure and maximum bending loads. In this example only circumferential flaws are addressed.

Parameter	Value
Nominal OD (mm)	323.8
Nominal WT (mm)	36.0
Steel Grade	X70, de-rated to X65 in high temperature
Minimum yield strength, hot (MPa)	448
Minimum yield strength, cold (MPa)	482
Ultimate tensile strength, hot (MPa)	530
Ultimate tensile strength, cold (MPa)	565
Elastic modulus at room temp (MPa)	207,000
Poisson’s ratio	0.3

Table 4 - Physical Data for Flowline

ANALYSIS SCENARIOS

Two analysis scenarios are considered. In the first, analysis is conducted on a riser where complete ILI inspection data are available. In the second, a non-piggable flowline is considered where the ILI data from a sister line are available.

Riser

For the riser the critical flaw is identified in the ILI and the life of the riser is evaluated by growing this flaw. The analysis is conducted to determine whether the probability of failing before 20 years is greater than 10^{-5} per year. This implies that the allowable probability of failing within the 20 year period is $2x10^{-4}$. The statistics of the random variables are given in Table 5. The data comes from real projects in the GoM. The treatment of some of those variables merits further discussion.

a_0 – The initial flaw depth is given by the ILI but the variance on the value is due to the potential for error in the measurement. The standard deviation is a measure of that error.

F1 – The extreme load is caused by the potential for hurricane. A cumulative distribution function for significant wave height (Hs) is constructed. Stress response in the touchdown zone is found from the seastate analysis conducted during riser design phase. From these two data sets a cumulative distribution of max stress per year is built. From the inverse of the CDF the values of the random variable F1 are derived.

Random Variable	Mean	Standard Deviation
Kmat (MPa*m^(1/2))	469	49
YS (MPa)	496	15.5
YS/TS	0.842	0.011
a_0 (mm)	As measured	0.2
SCF	1.05	0.025
t (mm)	42.0	0.88
F1	1	0.01
F2	1	0.02
AA2	-25.20	0.25
AA3	-11.64	0.25
	λ	k
2c/a	2.393	1.095

Table 5 - Statistical Parameters Used in Riser Assessment

In the case of the riser, the flaw size is known, so the questions answered by the probabilistic study are straight forward.

- Given the initial flaw, what is the probability of failure in 20 years?
- Given the initial flaw what is the life corresponding to a probability of failure of $2x10^{-4}$? This answer is compared against the life obtained using a deterministic approach.

Flowline

The random variables used in the flowline analysis are shown in Table 6. The data comes from real projects in the GoM. The treatment of some of those variables merits further discussion. The material and SCF data from the riser is applied to the flowline. The flowline is 6000 m long, but only one zone 24 m long has high stresses. ILI data from a sister line are expected to be statistically relevant. The ILI data are used to find the expected deepest pit in a 24m section. This is done by dividing the 6000 m into 250 sections 24 m long and tabulating the maximum pit depth in each segment. The mean and standard deviation of that variable is found. The variability found from one such study is shown in Figure 6 and that data is applied for this example.

The Monte Carlo assessment answers the question is whether the probability of failure is less than 2E-4 for a 20 year life. For comparison, a deterministic analysis is conducted using the mean+2 standard deviation flaw seen in the sister line to find the expected life.

Random Variable	Mean	Standard Deviation
Kmat (MPa*m^(1/2))	469	49
YS (MPa)	496	15.5
YS/TS	0.842	0.011
a_0 (mm)	4.37	0.62
SCF	1.05	0.025
t (mm)	36.0	0.68
F1	1	0.01
F2	1	0.02
AA2	-25.20	0.25
AA3	-11.64	0.25
	λ	k
2c/a	2.393	1.095

Table 6 - Statistical Parameters Used in Flowline Assessment

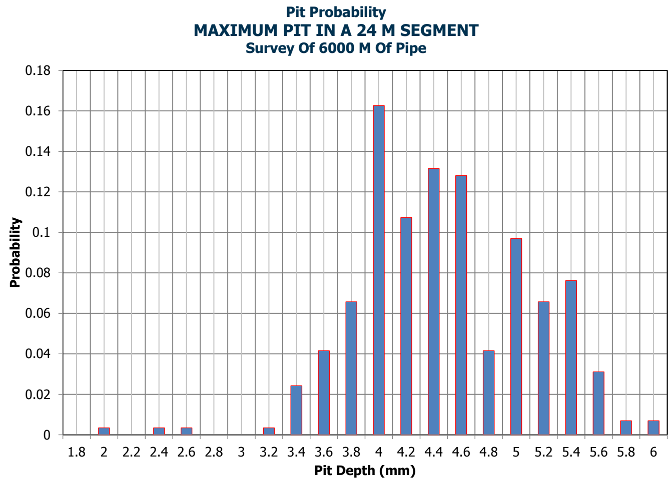

Figure 6 – Probability of Maximum Pit Size in 24m

RESULTS

Riser: Factor of Safety Determined Through Probabilistic Tools

In the traditional deterministic approach the values of the key parameters represent the maximum expected value. In practice this is the value two standard deviations beyond the mean. Additionally a factor of safety is applied to life. In the current exercise, the deterministic analysis is run iteratively to generate a locus of points representing allowable initial flaw sizes. This process is repeated using a range of safety factors from 1 to 5. Points on this line represent flaws that will fail after the factored design life; i.e. after 20 years to 100 years.. An example of the allowable initial flaw size for a 20yr design life with a FOS of 2 is shown in Figure 7.

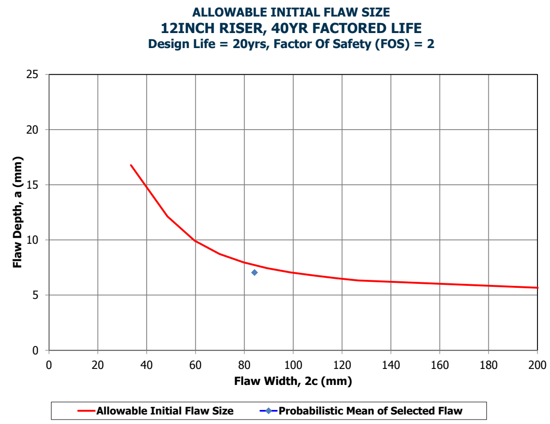

Figure 7 – Allowable Initial Flaw Size, 40yr Factored Life, Factor of Safety = 2

To compare the deterministic approach to the probabilistic approach, flaw sizes corresponding to points on the allowable initial curves are put into the probabilistic process as though they represent a measured flaw + 2 standard deviations of measurement error. Then 10^5 realizations are executed and the probability of failure in 20 years is found. The results are summarized in Table 7. They indicate that a FOS of 2 on life is consistent with the attaining an annual probability of failure of 1E-5. The CDF tails are shown in Figure 8 and Figure 9 for FOS of 2 and 3, while the CDF tails for the remaining FOS values are shown in the appendix. The smoothness of the tail of the distribution is visual indication of the adequacy of the number of realizations.

Mean Initial Flaw Size		Mean +/- 2σ on All Parameters (Worse of +/-)			Number of Occurrences (FCG Life < 20yrs) per 1e5 Runs
a	2c	Unfactored Life	FOS on Life for Mean Flaw Size	Factored Life	
mm	mm	yrs	-	yrs	-
7.94	142.52	20	1	20	361
7.04	84.18	40	2	20	27
6.40	63.79	60	3	20	2
6.26	49.84	80	4	20	1
3.82	68.56	100	5	20	0

Table 7 – Factor of Safety versus Probability of Failure

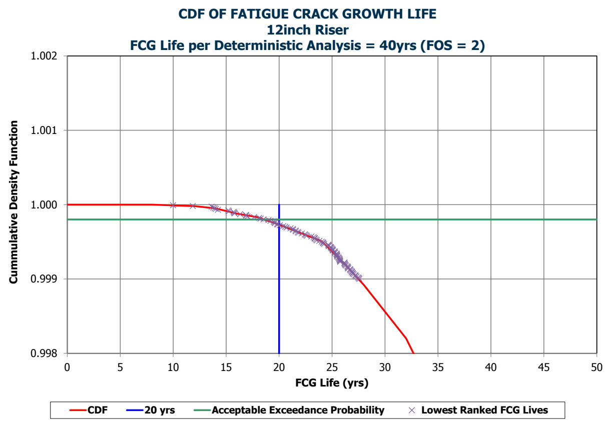

Figure 8 – CDF Tail of FCG Life for 12inch Riser, Initial Flaw Size with 40yr Deterministic FCG Life

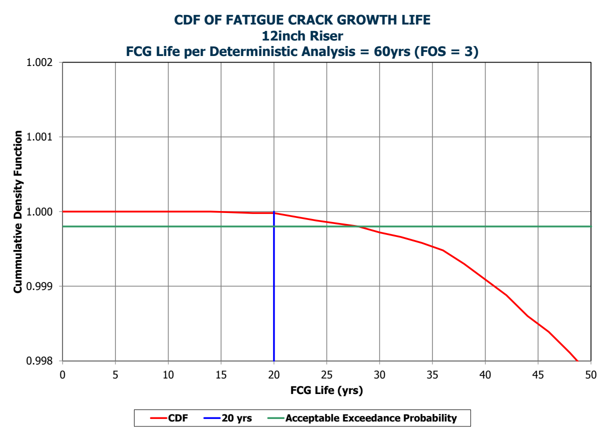

Figure 9 – CDF Tail of FCG Life for 12inch Riser, Initial Flaw Size with 60yr Deterministic FCG Life
Flowline

Probabilistic analysis is conducted for the flowline and compared with deterministic analysis. In this case the Deterministic life with a factor of 2.6 would equate to the probabilistic life. These results are summarized on Table 8. The tail of the CDF of the Monte Carlo results is shown in Figure 9.

Mean Initial Flaw Depth from Sister Flowline		Deterministic	Probabilistic	Ratio of Det. FCG Life to Prob. FCG Life
Mean Depth (a)	σ of Depth (a)	FCG Life with Mean +/- 2σ on All Parameters (Worse of +/-)	FCG Life with respect to Acceptable Probability of Exceedance of [1 - (2x10^{-4})]	
mm	mm	yrs	yrs	-
4.30	0.62	57	22	2.6

Table 8 – Factor of Safety versus Probability of Failure

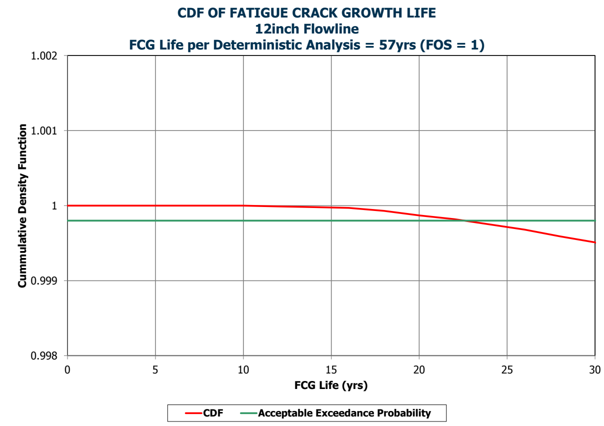

Figure 10 – CDF Tail of FCG Life for 12inch Flowline, Initial Flaw Size with 57yr Deterministic FCG Life

DISCUSSION

In any discussion of the use of probabilistic methods for evaluation of structural integrity, questions inevitably arise about the availability of the underlying data. This is only right since the method is only as good as the data. In the case of the fitness for service of subsea risers in flowlines with respect to fatigue loading, the engineer has the advantage that the structures are so costly and so critical that in the design phase significant material testing is conducted. Likewise, modern systems are highly instrumented and there is usually a very complete record of the service history, especially in terms of pressure, temperature and storm loading. Although crack growth rates in corrosive service may not be available from the published literature, the opportunity to conduct the testing is available.

Although we would always hope that direct inspection data are also available, the example given shows that reasonable answers can be obtained if the statistics of the problem can be described.

CONCLUSIONS

A methodology is described for using Monte Carlo methods to conduct Fitness for Service assessments in situations where pitting has damaged fatigue critical risers and flowlines. The method is illustrated with two case studies populated with realistic data. The results show that these methods can be useful in providing a basis for determination of fitness without resort to arbitrary factors of safety. In the case examined, it is shown that using deterministic analysis with worst case parameters together with the often used factor of safety of 5 on life results in conservative conclusions. The results for these examples indicate that a factor between 2.0 and 3.0 would be more appropriate where the target annual probability of failure is 1E-5.

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APPENDIX

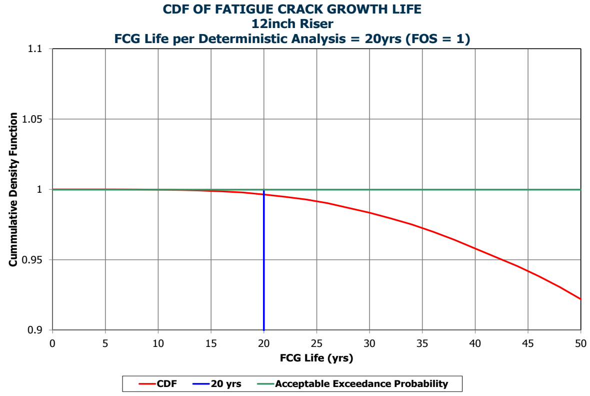

Figure A.1 - CDF Tail of FCG Life for 12inch Riser, Initial Flaw Size with 20yr Deterministic FCG Life

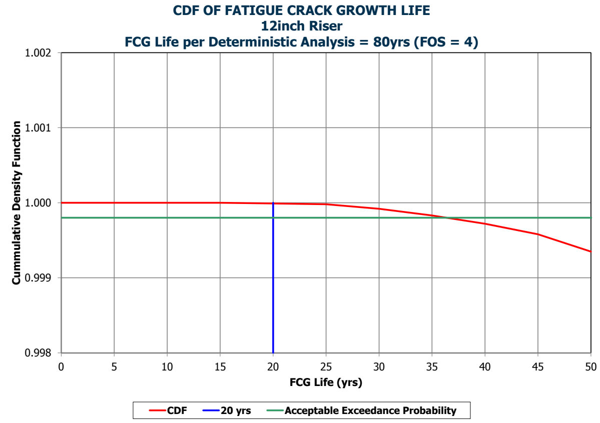

Figure A.2 - CDF Tail of FCG Life for 12inch Riser, Initial Flaw Size with 80yr Deterministic FCG Life

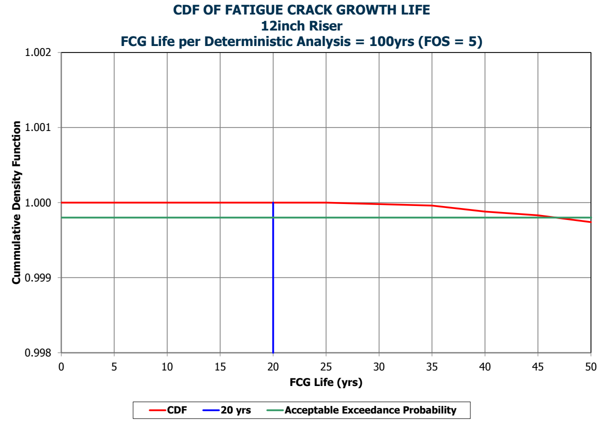

Figure A.3 - CDF Tail of FCG Life for 12inch Riser, Initial Flaw Size with 100yr Deterministic FCG Life