Prognostics for Small Bore Piping Undergoing Fatigue Degradation

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Abstract –**Prognostics of Small Bore Piping (SBP) degrading due to fatigue deals with estimating its remnant useful life (RUL). This manuscript elaborates the RUL prediction procedure for SBP. Physics-based model is utilized to estimate the RUL, and the uncertainty in the different parameters of the Paris law are quantified and propagated. According to Paris law, crack growth per cycle is proportional to Stress Intensity Factor (SIF) which in turn depends upon initial crack size (ICS) and stress range. ICS is generally estimated using the Non-Destructive Examination techniques while the stress acting at the interface of SBP and the mainline piping is determined using Fluid Structure Interaction (FSI) performed using ANSYS software to couple CFD and FEA analysis. Finally, the predicted RUL is employed to estimate reliability and frame inspection interval for SBP which shall ensure mitigation of hydrocarbon leak at the process facilities.**

Keywords - **Prognostics, Remaining Useful Life, Small Bore Piping**

I. INTRODUCTION

The root cause for Hydrocarbon Leak from process piping is due to degradation mechanisms such as vibration induced fatigue (VIF), acoustic induced fatigue (AIF), pitting corrosion, corrosion under insultation, erosion etc. A research study performed by DNV [1], clearly highlights that amongst the degradation mechanisms causing failure of process piping, fatigue (high cycle) is the prominent cause of process piping failure in petroleum and maritime sector as shown in Fig. 1.

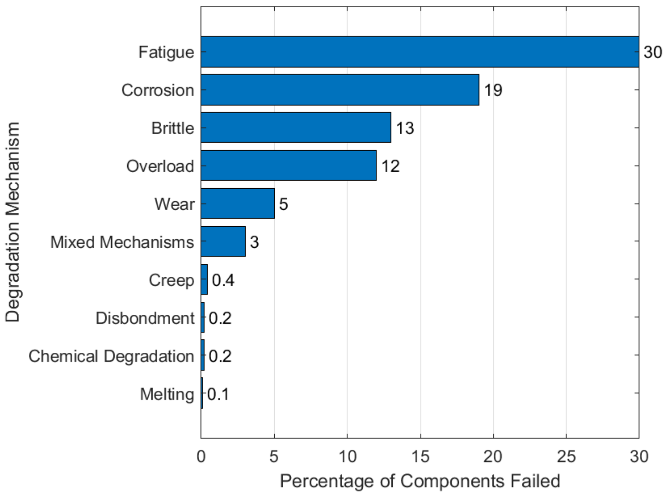

Fig. 1. Dominant Degradation Mechanisms for Process Piping [1]

In recent years, development of virtual sensors, coupled with cheap data storage, and advancement in AI, has enabled Condition Based Maintenance (CBM) as the most promising maintenance strategy for SBP. Prognostics which deals with estimating the remnant useful life (RUL) of SBP is one of the vital steps in CBM. The main rationale behind prognostic models is their ability to estimate the future health of the piping system and thus generate warnings if the system is prone to failure. This ensures timely inspection and maintenance of the piping system before these assets lead to a hydrocarbon leak, thus augmenting safety and mitigating downtime [2]. A spate amount of modelling approaches are adopted by researchers to execute fatigue damage prognostics of process piping [3]. However, the two approaches that stand out are physics-based approaches (PBAs) and data driven models. In particular for process piping deteriorating due to fatigue, the former modeling approach is used to predict RUL, due to large availability of such models (such as Paris Law, Elbers' model). Nevertheless, certain physical phenomenon does not have a PBA. Consequently, for such scenarios researchers rely upon DDMs for carrying out prognostics.

The paper is structured as follows. Firstly, a brief discussion about fatigue damage prognosis is performed in Section II. A case study is then presented in Section III, with a suitable conclusion in last Section of the paper.

II. FATIGUE DAMAGE PROGNOSIS

One of the primary sources of hydrocarbon leak in the Petroleum and Maritime sector is the small-bore piping (SBP). The primary failure mode of SBP is high cycle fatigue which can be prevented by performing optimal inspection and maintenance which relies upon accurate estimation of the remaining useful life (RUL). The three common models use for RUL prediction of an engineering system are survival model, degradation model and similarity models as shown in Fig. 2. The selection of the model for analysis depends upon the quantity of information at hand. For example, if data from failure is available then survival model's are best for predicting RUL. On the contrary, if data between a healthy and a failure state is available and the safety threshold is also known, then a degradation model is employed for RUL estimation. The latter model generally estimates the count of cycles that process piping can be subjected to. Furthermore, it is customary to

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identify various sources of uncertainty in the assumed failure model and quantify them by using a suitable probability distribution and associated parameters.

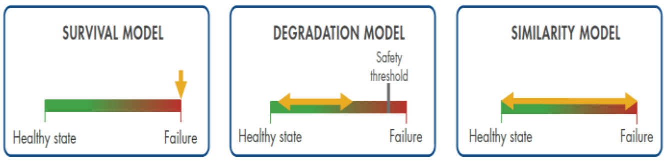

Fig. 2. RUL Estimator Models [4]

Paris law due to its simplicity is assumed to be the underlying degradation model which shall be used for estimating RUL. The details about the usage of Paris law for calculation of RUL can be found in [5, 6] and after performing simple integral analysis and rearrangement of terms Paris law can be rewritten as

$$N = \frac{a_N^{1-\frac{m}{2}} - a_i^{1-\frac{m}{2}}}{C\left(1-\frac{m}{2}\right)\left(\Delta\sigma\, Y\, \sqrt{\pi}\right)^m}$$

Where N is cycle count needed for a crack of initial size (a_i) to grow to final crack size (a_N), C and m are material parameters, Y is geometric parameter and $\Delta\sigma$ is nominal stress range. If RUL is to be estimated deterministically, then all the above-mentioned parameters are treated as fixed values, while for probabilistic RUL estimation, some of the parameters (such as remote stress strange, material parameters, initial crack size) are treated as random variables. Afterwards, uncertainty propagation is performed either using semi-probabilistic crack growth models (such as Markov chains) or full probabilistic crack growth models which employs Monte Carlo Simulation (MCS) to predict the RUL, which must be reported not as a point estimate but with the associated confidence bounds [7]. In the forthcoming section, both deterministic and probabilistic RUL assessment of small bore piping shall be presented.

III. ILLUSTRATIVE CASE STUDY

A. General

For this case study, the piping material is AISI Type 304 Stainless Steel (SUS 304) having yield strength of 215MPa. A detailed computationl fluid dynamics (CFD) analysis along with structural Finite Element Analysis (FEA) is performed in order to predict the stress on the weld toe, as shown in Fig. 3.

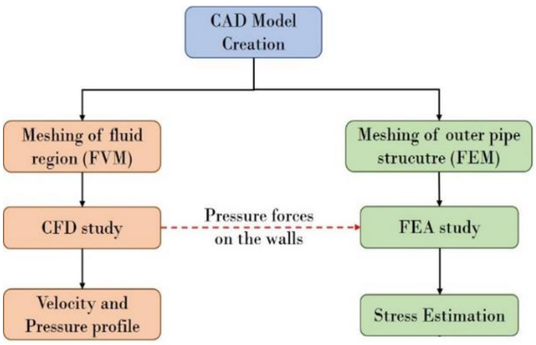

Fig. 3. Methodology for Stress Estimation

B. Stress Estimation

Fluid Structure Interaction (FSI) is performed using ANSYS software to couple CFD and FEA analysis. ANSYS CFX is used for the CFD part while ANSYS Mechanical is used for the FEA part. The CAD model shown in Fig. 4a is prepared according to set dimensions. The outer diameter and inner diameter of main pipe are 273mm and 254.6mm respectively while the outer diameter and inner diameter of the small-bore pipe are 60.3mm and 52.3mm respectively. In order to represent the fluid flow inside the pipe CAD model is divided into the fluid region. Likewise, the model is divided into the solid region in order to represent the solid body of the pipe as indicated in Fig. 4b. The internal volume is meshed using Finite Volume Method (FVM) as shown in the Fig. 5a. while Fig. 5b depicts the distribution of the mesh at the SBPP and main pipe interface. Fig. 5c illustrates the inflation layer distribution and other relevant details of meshing.

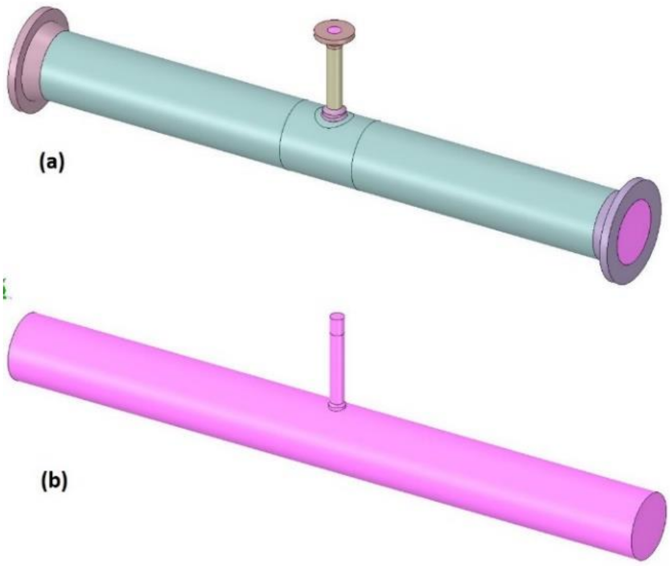

Fig. 4. CAD Model showing a) Pipe and Fluid Region, b) Complete Fluid Region

For structural part of the analysis a separate mesh is generated using a Finite Element Method as depicted in Fig. 6a. Fig. 6b depicts the element distribution on the mainline piping and SBP. Mesh sensitivity analysis was performed in order to select the mesh size for both CFD and FEA.

The CFD analysis was performed in ANSYS CFX software. The analysis was kept simplistic, as the inlet velocity of the fluid was kept constant at 15m/s and the outlet pressure or downstream pressure (DS) was kept constant at 15bar. Air (compressible) is used as the fluid. The output of the CFD results include velocity, density, pressure and other fluid variables. Among these variables the fluid pressure on the pipe internal walls is transmitted to FEA, in order to approximate the structural stress as shown in Fig. 7. Fig. 7a and Fig 7.b respectively show the stress distribution at inner and outer surface of SBP and mainline piping interface for a DS pressure of 15 bar. Higher stress is observed on the intrados as compared to extrados of the pipe. The calculated stress is used to estimate the RUL which is discussed next.

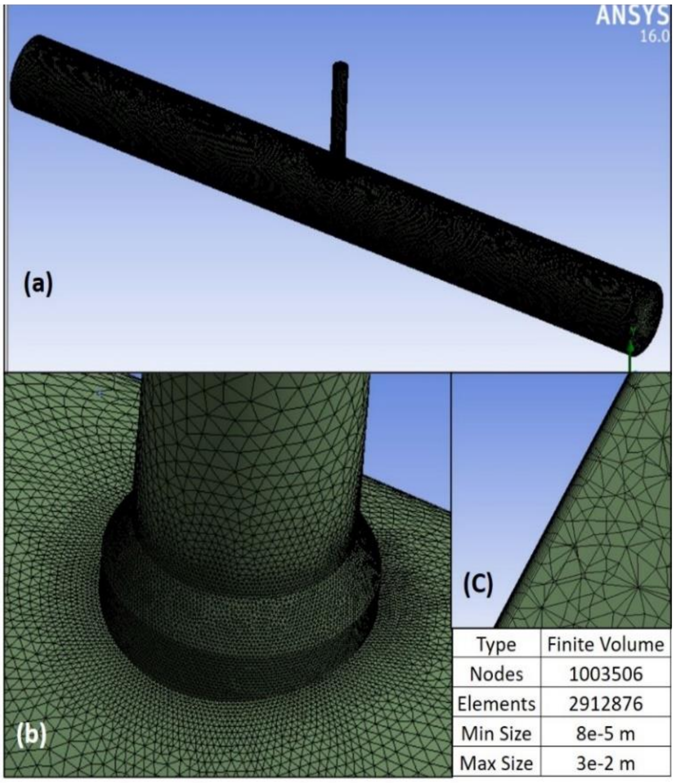

Fig. 5. Mesh Distribution and Mesh Details for CFD Analysis

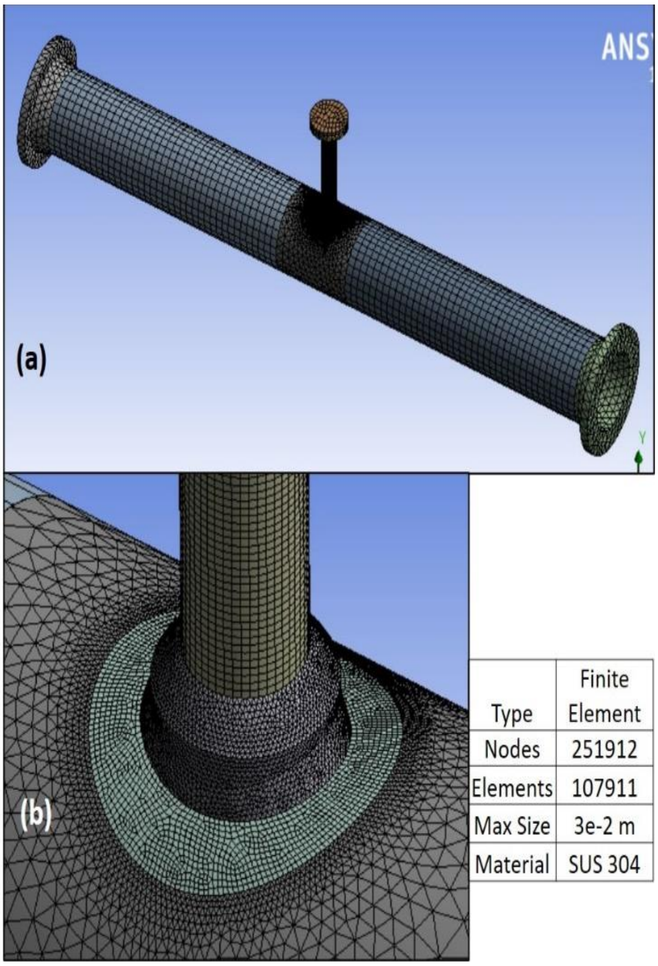

Fig. 6. Mesh Distribution and Mesh Details for FE Analysis

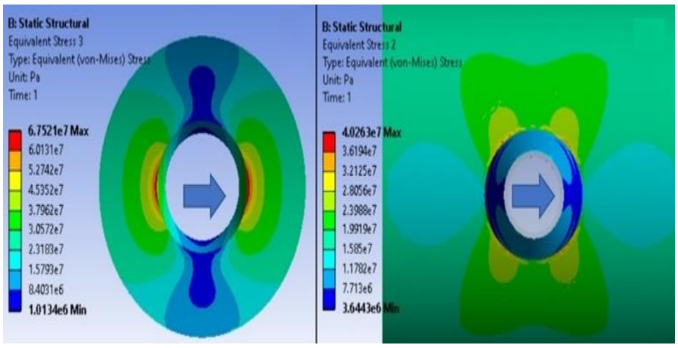

Fig. 7. Stress Distribution at Inner and Outer Diameter of the SBP and Mainline Pipe

B. Deterministic RUL Assessment

As discussed previously, while performing deterministic RUL assessment different parameters of Paris law are treated fixed. Amongst various parameters, a_i is most sensitive to the RUL prediction. Although, advanced approaches such as Equivalent Initial Flaw Size (EIFS) have been used in the past to estimate the value of a_i. However, in practice, the detection limit of Ultrasonic testing which equals to 1.5 mm is treated as the value of a_i [8]. Furthermore, the value of nominal stress range is approximated using CFD-FEA analysis as explained in previous section. Value of a_c is equal to the thickness of the mainline piping which in our case is equal to 9.27mm. The value of rest of the attributes is shown in Table 1. The deterministic RUL assessment is performed according to the methodology provided in BS-7910 and Paris law forms the basis for crack growth estimation. It can be seen from Fig. 13, that RUL of the process piping equals to 91540 cycles.

TABLE I

PARAMETERS FOR DETERMINISTIC RUL PREDICTION

Parameter Name	Parameter Symbol	Parameter Value
Initial crack size	a_i(mm)	1.5
Material parameter	C	5.21e-13
Material parameter	m	3.5
Nominal stress range	$\Delta\sigma$ (MPa)	67
Critical crack size	a_c(mm)	9.27
Geometric function	Y	0.952

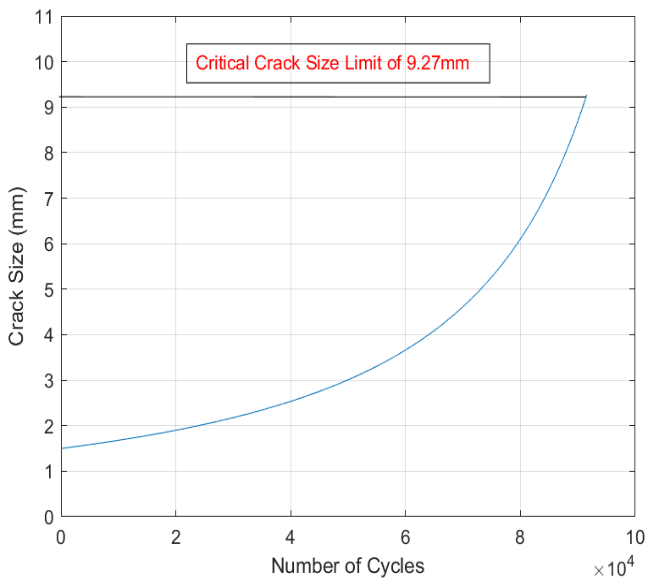

Fig. 8. Deterministically obtained RUL

D. Probabilistic RUL Estimate

During the stochastic RUL estimation, the different uncertainty sources are considered. Paris model parameters are treated as random, and this randomness is represented by using appropriate probability distribution and associated parameters (depicted in Table 2). IN this case study uncertainty is considered only in parameters, a_i, C and stress range, while other parameters are treated constant. Furthermore, the uncertainty in Paris model is accounted by a modelling error ε_r represented by a 5% Gaussian white noise [9].

Table II

UNCERTAINTY QUANTIFICATION OF RUL ESTIMATION

Uncertainty Source	Random Variable	Parameter Value
Initial crack size	a_0 (mm)	LogNormal (1.5, 0.05)
Material parameter	C	LogNormal (5.21e-13, 2e-13)
Material parameter	m	3.5
Remote stress range	$\Delta\sigma$ (MPa)	LogNormal (67, 5)
Critical crack size	a_c(mm)	15
Geometric function	Y	0.952

Once the uncertainty in various parameters have been quantified, it is then propagated by employing Monte Carlo Simulation (MCS) to predict the RUL. For this study, 10000 samples are generated to arrive at probability density function of RUL as shown in Fig. 9. The mean the RUL is 54,795 cycles, and 95% confidence interval (CI) is [20234 and 121172] cycles. The associated, cumulative density function and reliability function plots are shown in Fig. 10. The estimated RUL can be used for inspection and maintenance planning. DNV (2010) [10] suggests that the first inspection should be performed after one-third of the lower bound of the predicted RUL. Using the aforementioned logic the first inspection should be after 6744 cycles.

Another method of obtaining inspection interval could be using the reliability curve shown in Fig. 10. For high safety class and a fatigue limit state the target reliability level for the SBP is 0.99999 and the corresponding number of cycles is 7000 [11]. Thus, both the approaches lead to approximately same number of cycles after which first inspection must be done. Such a proactive strategy would avert unwanted piping failure arising because of fatigue.

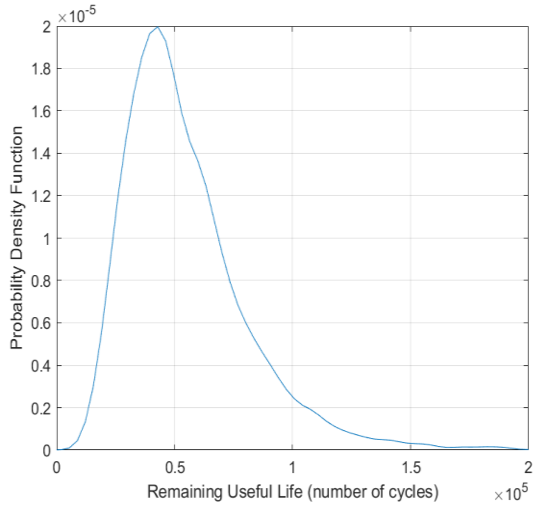

Fig. 9. Probability Density Function of RUL of process piping (10000 samples)

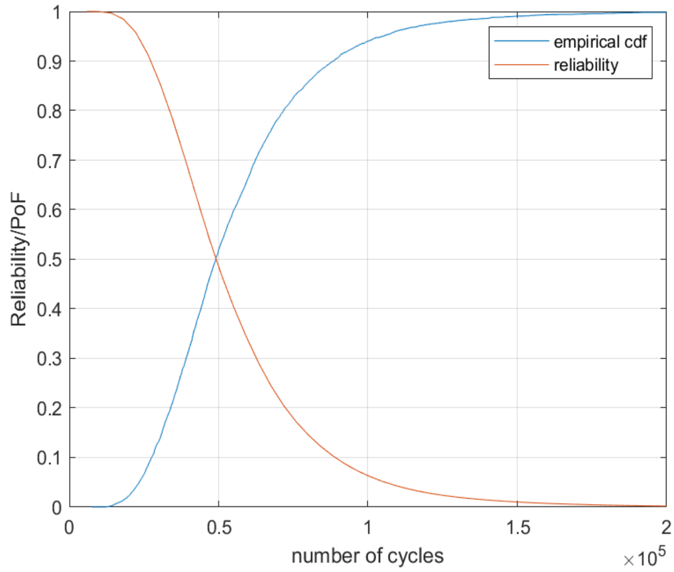

Fig. 10. Cumulative Density Function and Associated Reliability of process piping (10000 samples)

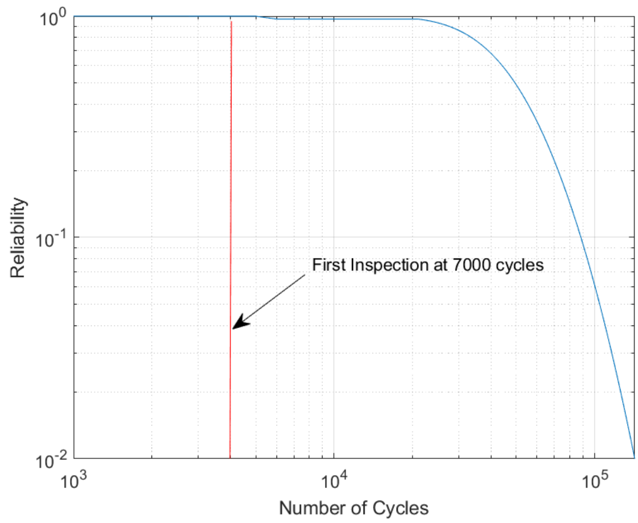

Fig. 11. Inspection interval obtained from reliability curve

IV. CONCLUSION

Fatigue damage prognosis of offshore piping deals with accurately estimating its remaining useful life (RUL). In this manuscript, the procedure for execution of RUL assessment was elaborated. Uncertainty quantification and propagation were identified as the two important steps, for estimating RUL accurately. Paris model was used as the crack propagation law. The stress acting on the junction of small-bore piping and mainline piping were obtained using CFD and FEA in ANSYS. At first deterministic RUL was estimated to be 91540 cycles. Thereafter, various parameters of the Paris model (such as initial crack size, Stress) were treated as uncertain and as a part of uncertainty quantification suitable probability distribution and associated parameters were assigned. Afterwards, using Monte Carlo Simulation, RUL was estimated probabilistically. The mean value of RUL was 54,795 cycles while the lower and upper bounds were estimated to be 20,234 and 121,172 cycles respectively. Finally, inspection interval for process piping was estimated to be 6,744 cycles by employing method proposed in DNV standard and 7,000 cycles by considering a target reliability of 0.99999 corresponding to fatigue limit state and high safety class.

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