XLVI CILAMCE
VITÓRIA - ES - BRAZIL - 2025
XLVI IBERO-LATIN AMERICAN CONGRESS ON COMPUTATIONAL METHODS IN ENGINEERING

Predicting Remaining Useful Life of Well Tubulars

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Abstract. This work proposes a reliability-based framework to estimate the Remaining Useful Life (RUL) of well tubulars throughout the lifecycle of oil and gas wells. The RUL estimation is supported by a probabilistic analysis that accounts for uncertainties in geometrical and material properties, based on failure modes defined in the API/TR 5C3 standard. The framework is applicable to both design and monitoring phases, incorporating degradation mechanisms such as corrosion. The methodology integrates a mechanical model to calculate safety factors and failure probabilities associated with internal and external pressures and axial forces, as defined by API/TR 5C3. Structural reliability methods combined with Monte Carlo simulation are used to propagate uncertainties and to update failure probabilities over time. The framework enables the estimation of key integrity indicators, such as the failure rate and Mean Time to Failure (MTTF), essential for RUL assessment. A case study is presented, utilizing statistical data on mechanical properties, and degradation effects. The proposed methodology allows for integrity assessment under both serviceability and survival load conditions, incorporating advanced features such as the effect of corrosion in several loading scenarios. By capturing the variability of mechanical and geometrical parameters over time, the approach provides a robust basis for evaluating the mechanical condition and failure probability of casing and tubing strings. These results support more informed decision-making in RUL analysis and contribute to the improvement of well design and monitoring strategies

Keywords: Remaining Useful Life, Structural reliability methods, Failure rate, Mean Time to Failure, Casing design

1 Introduction

The design of oil and gas wells is a complex process requiring technical solutions to ensure safe and efficient operation throughout their lifecycle [1]. It involves selecting and installing steel casing and cementing materials along the wellbore to preserve structural integrity, control pressure, and prevent leaks or contamination. A well-designed casing system protects against mechanical damage and environmental risks while ensuring operational performance. At this stage, it is critical to verify that all components are designed to withstand the maximum expected loads over the well's service life [2]. Well integrity is maintained through well barriers, protective layers that prevent, control, or mitigate unwanted events [3,4]. Barriers may be physical, technical, human, or organizational; here, focus is given to the physical barrier provided by the casing system.

Reliability-based integrity analysis is essential to prevent or mitigate risks during installation and maintenance. It accounts for uncertainties in material properties, environmental loads, and operational conditions. Existing studies address the probabilistic response of well structures [5-7] and statistical models for failure prediction and Remaining Useful Life (RUL) estimation [8-12] Factors influencing RUL include material

degradation, changing reservoir conditions, and effects such as corrosion, which can lead to metal loss and increased risk of extreme events. Studies have examined collapse strength of corroded tubulars [13], corrosion-related failure probabilities in pipelines [14], and late-life integrity management [15].

Despite advances in well integrity assessment, there is a lack of studies on the RUL of tubulars considering both degradation and extreme scenarios such as Worst Case Discharge (WCD). This work addresses this gap by combining statistical characterization of geometry, material, and load parameters with API/TR 5C3-defined failure modes to estimate tubular failure rates over the well's lifecycle.

1.1 Reliability analysis

The reliability analysis can be defined as the ability of a component to perform a required function, under certain environmental and operational conditions, during a specified time interval [16]. Reliability aims to evaluate the failure rate of the desired component. In this regard, while in survival analysis the survival function, $S(t)$, is generally used, in reliability engineering the reliability function $R(t)$ is defined, which indicates the probability that the component be working at a time t:

$$R(t) = P(T \geq) = \int_t^{\infty} f(t)dt. \tag{1}$$

Therefore, the failure time T must be greater than the analysis time t. Its kernel contains $f(t)$, the probability density function (pdf), as follows:

$$f(t) = \lim_{\Delta t \to 0} \frac{P(t \leq T < t + \Delta t)}{\Delta t}. \tag{2}$$

The cumulative distribution function $F(t)$ defines the probability that a given item will fail by time t, which is the complement of $R(t)$,

$$F(t) = 1 - R(t) = P(T < t) = \int_0^t f(t)dt. \tag{3}$$

The failure rate is defined as

$$h(t) = \lim_{\Delta t \to 0} \frac{P(t \leq T < t + \Delta t | T \geq t)}{\Delta t} = \frac{f(t)}{R(t)} \tag{4}$$

1.2 Weibull distribution for RUL estimation

The Weibull distribution is a widely used criterion in reliability engineering as it can represent decreasing, constant and increasing failure rates by using two parameters, η and β. The first, $\eta > 0$, is a scale parameter, while the second, $\beta > 0$, is the shape parameter. These two parameters and the pdf $f(t)$ are following described:

$$f(t) = \frac{\beta}{\eta}\left(\frac{t}{\eta}\right)^{\beta-1} e^{\left(-\frac{t}{\eta}\right)^{\beta}}. \tag{5}$$

The reliability function takes the form:

$$R(t) = 1 - F(t) = e^{\left(-\frac{t}{\eta}\right)^{\beta}} \tag{6}$$

and the failure rate can be defined as follows:

$$h(t) = \frac{f(t)}{R(t)} = \frac{\beta}{\eta}\left(\frac{t}{\eta}\right)^{\beta-1}. \tag{7}$$

Finally, the mean time to failure (MTTF) can be written, in terms of the Gamma function Γ:

$$MTTF = \int_0^{\infty} f(t)\, t\, dt = \eta\Gamma\left(\frac{1}{\beta} + 1\right). \tag{8}$$

2 Proposed Methodology

The methodology proposed in this work is based on Monte Carlo simulations to create realizations of the model and predict the remaining useful life (RUL) of tubulars. The data from these realizations is used to estimate reliability data. Fig. 1 presents the proposed methodology flowchart, which all steps, including mechanical model, reliability assessment and RUL data, to estimate failure rate.

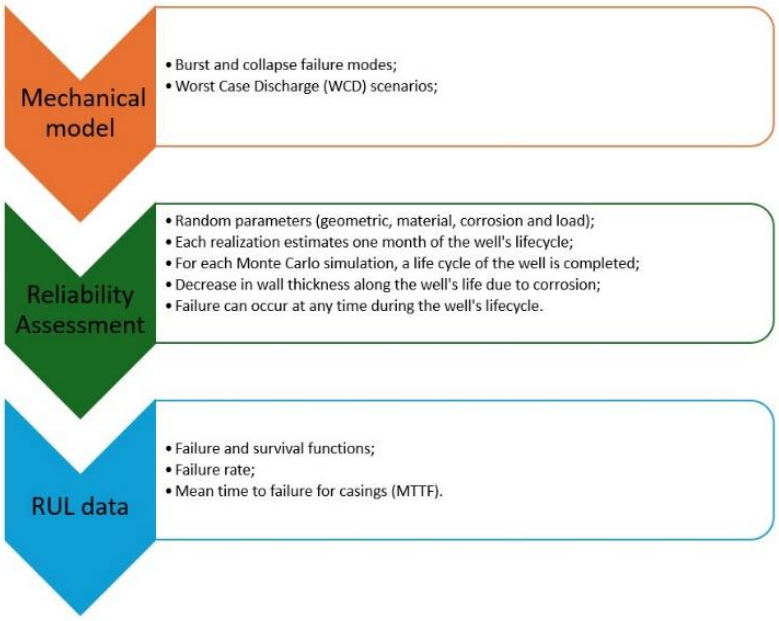


Figure 1. Proposed methodology flowchart

The structure of the Monte Carlo simulations is presented in Fig. 2. In total, 50,000 simulations are performed month by month over the well's lifetime. The simulation procedure is stopped at the first failure and is then evaluated the next month. Thus, the failure rate can be quantified throughout the service life.

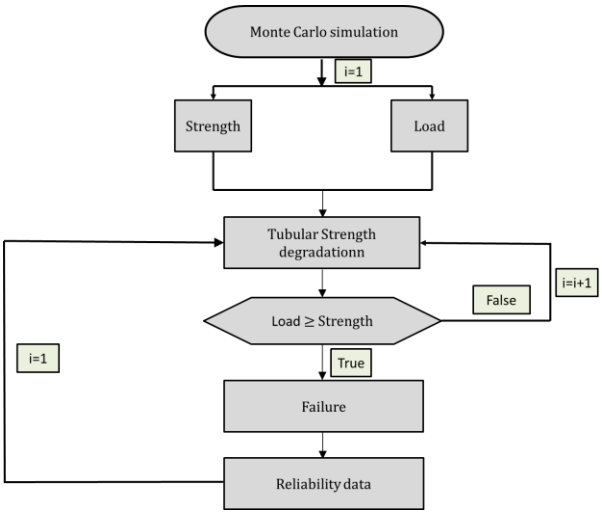


Figure 2. Flowchart of the Monte Carlo simulation for each month

2.1 Case Study

The proposed methodology is verified in an oil production well under a water depth of 804 m (Fig. 3), whose schematics is presented in Fig. 3. For service loading scenarios, the API/TR 5C3 [17] equations for Service Limit State (SLS) are used, based on the tubular elastic limit. For survival loads, the normative equations for Ultimate Limit State (ULS) are adopted, which aim to estimate the ultimate resistance of the tubulars. For the proposed methodology, the uncertainties inherent to resistance are presented according to the statistical characterization presented in the Annex F of API/TR 5C3 [17].

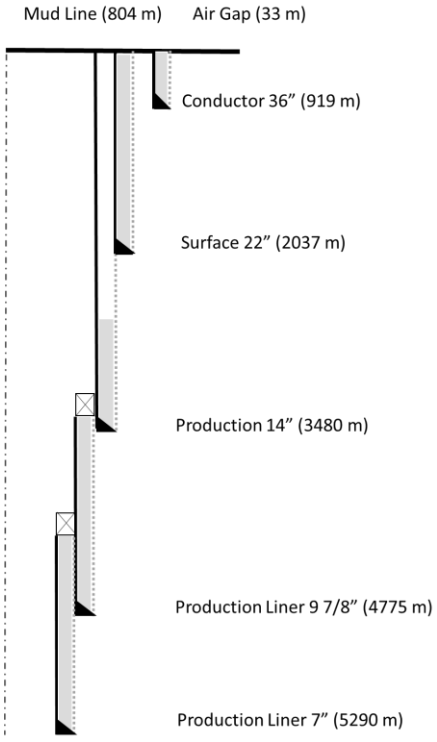


Figure 3. Wellbore schematic diagram

The casing properties are presented in Table 1, regarding tubular parameters, mud weight, as well as borehole parameters. It is important to mention that the case study assesses the production liner (Phase 4). Table 1 details each casing of the well regarding tubular parameters, as fluid density and True Vertical Depth (TVD).

Table 1. Casing parameters

Phase	**Name**	**Type**	**OD (in)**	**Grade**	**TVD (m)**	**Fluid density (ppg)**
1	Conductor	Casing	36	X-80	919	8.55
2	Surface	Casing	22	X-60	2037	8.55
3	Production	Casing	14	X-80	3480	12.30
4	Production	Liner	9 ¼"	C-110HC	4775	12.30
5	Production	Liner	7"	TN 110 Cr 13S	5290	13.50

Table 2 presents mechanical and geometric properties used in the analysis. The random casing properties can be found at API/TR 5C3 [17]

Table 2. Deterministic parameters used in the case study considering the production liner.

Parameter	**Casing**
Wall thickness (in.)	0.453
Young's Modulus, E (GPa)	300
Poisson Ratio, v	0.30

Finally, the limit state equation is presented in Eq. 9, based on Klever and Tamano [18] and Klever and Stewart [19] equations. The failure function for the external resistance pressure is defined considering the parameters in Table 3.

$$G\left(D, t, f_y, ov^*, ec^*, rs^*, mu_{KT}^*\right) = R_{prob} - \Delta P \tag{9}$$

where ΔP is the differential pressure regarding the loads presented in Table 4 and the WCD influx scenario, Table 2. R_{prob} is tubular resistant, based on Klever-Tamano [18] (collapse) and Klever-Stewart [19] (burst) models, and the random variables in API/TR 5C3 [17].

The case study estimates the RUL parameters of a 20-year lifetime offshore production well. Statistical information about tubular geometry, material and degradation effects are taken into account. The simulation covers two operational phases: drilling for the first 2 months and production for the following 238 months. In the drilling stage, the WCD is considered, whereas in the production stage, the critical loads for burst, pressure test, and for collapse, full evacuation, were considered. The limit state equation presented in Eq. 9 is considered. In Fig. 4a, the failure rate in logarithmic scale is presented. After the first months, an increase in failure probability is expected, as corrosion reduces the wall thickness of the tubulars, thereby weakening their strength, Fig. 4b. Consequently, the survival function declines, and the failure function increases over time (Fig. 5). This degradation in strength leads to a higher failure rate throughout the well's lifecycle, potentially compromising its Remaining Useful Life (RUL). Notably, an exponential increase in the failure rate, during the production stage, is observed starting at 165 months. The MTTF of this casing is estimated in 301 months.

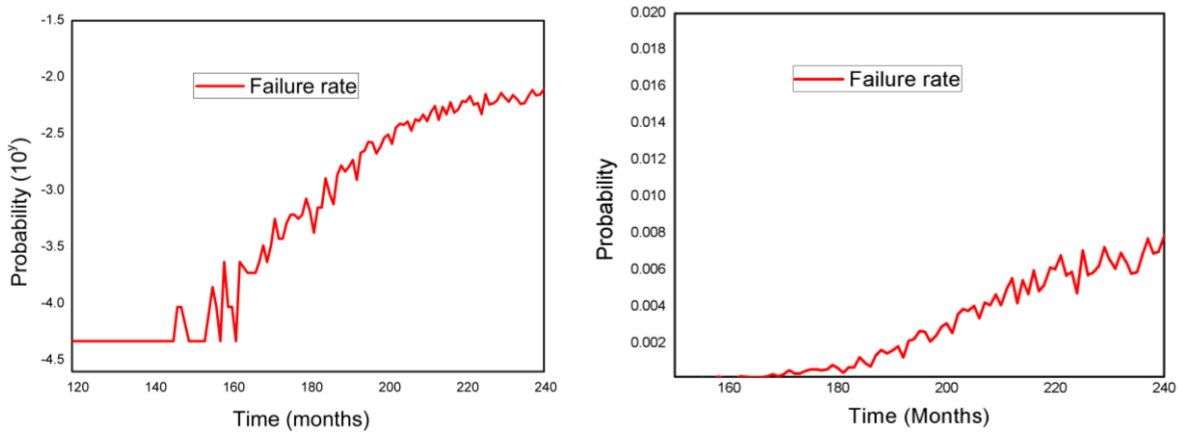


Figure 4. Failure rate of the well analyzed considering the entire 20-year lifetime (a) and final years (b).

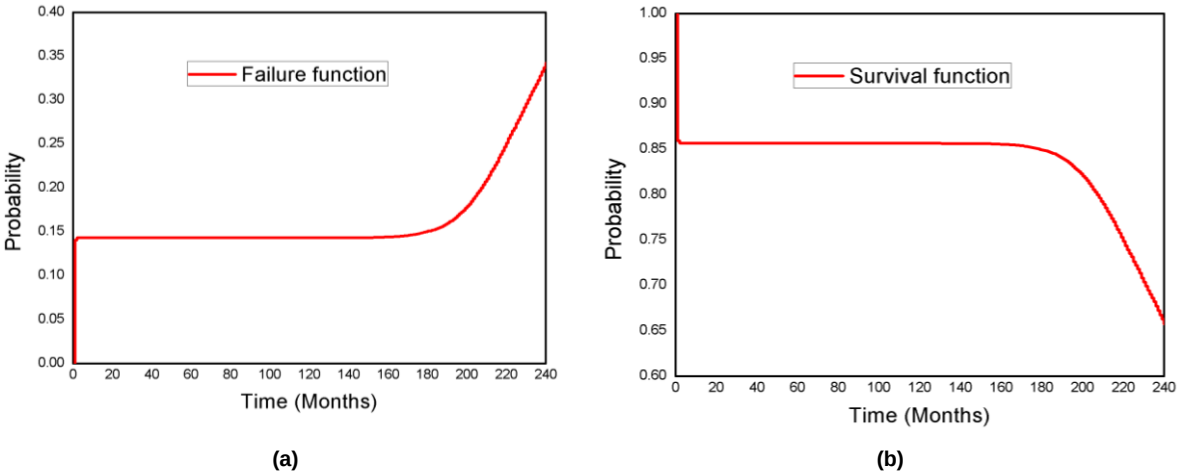


Figure 5. Failure function (a) and survival function (b) considering the well analyzed.

3 Conclusions

The methodology assesses the integrity of well tubulars in both burst and collapse load scenarios, enabling advanced features such as the consideration of wear degradation and corrosion. Klever and Tamano [18] and Klever-Stewart [19] equations were utilized in the resistance criterion, Eq.9. WCD scenarios are applied during the drilling phase, whereas hydrostatic loads are considered in both the drilling and production phases. The critical loads were chosen to estimate RUL parameters of the well. Accounting for the variability inherent to mechanical and geometrical variables throughout the service life of casing and tubing strings allows evaluating their mechanical condition and failure probability over time. These findings contribute to the decision-making process in RUL analysis, enhancing well design and monitoring practices.

Acknowledgements. The authors would like to acknowledge LCCV/UFAL for the technical support provided and to CENPES/PETROBRAS for their technical and financial support.

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