PROSIDING SNTTM XXI 2023
Volume 21, Tahun 2023, 5 Oktober 2023
e-ISSN 2623-0313
p-ISSN 3032-1972

Uncertainty analysis of stress cycle and force-moment frequency effect on corroded armor and carcass layer of flexible pipe in Indonesian deepwater

Ekha Panji Syuryana[1,a], **Bagus Budiwantoro**[2,b], **Mardiyati**[3], **Muhammad Agus Kariem**[2]
[1]Doctoral Study Program, Mechanical Engineering Dept. Faculty of Mechanical & Aerospace Engineering, ITB
[2]Mechanical Engineering Dept. Faculty of Mechanical & Aerospace Engineering, ITB
[3]Material Engineering Dept. Faculty of Mechanical & Aerospace Engineering, ITB
Ganesa Rd. No.10, Bandung, West Java, Indonesia 40132.

[a]epanji.syuryana@gmail.com, [b]budiwan56@gmail.com

ABSTRACT

Flexible pipes are required for deepwater oil and gas exploitation. Its application has many challenges due to operation conditions and the environment. Indonesian deepwater ranges approximately from -400 to -1800 meter depth. The depth potentially deteriorated the pipe in any form of damage mechanism. For example, polymer layer cracking, armor bird caging, deformation of the armor layer, erosion on the surface of the carcass, and other forms. Those defects in flexible pipes are driving factors to high-risk failure probabilities. Flexible pipe material development for deepwater applications also required methodology for integrity analysis. Considered factor for assessment based on corroded metallic layer degradation criteria. Due to operation, the uncertainty of wave current and flow direction crosses the cylinder body of the flexible pipe. Selection and comparison of its specified minimum yield strength to stress cycle in the range from 3 MPa to 278 MPa. Further calculation of force-moment condition in three orientations of pitch, yaw and roll to estimate the remaining performance of the flexible pipe.

Keywords: Deepwater, flexible pipe, carcass, armor, corroded

Received 30 September 2023; **Presented** 5 October 2023; **Publication** 27 May 2024

INTRODUCTION

Flexible pipe systems with the rapid development of pipeline engineering technology, flexible pipes have been widely used in the oil and gas industry, both onshore and offshore. For example, from Bai's et in [1] its pipe can be used as any type of riser, jumper line, flow line, export line, loading/unloading pipe, umbilical's, kill and choke line. They are considered to be an efficient solution in terms of technical as well as economic performance due to their easy and fast laying procedure, durability, and recoverability. Based on the type of material, flexible pipe is divided into two categories, namely metal based and composite based, also divided into two class of un-bonded and bonded technology which are covered by applicable codes and standards such as API RP 15 and 17 series.

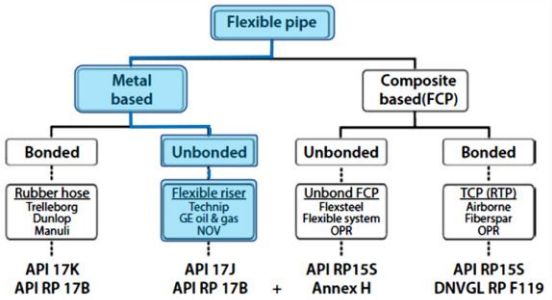

Figure 1 Flexible Pipe Classification [1]

This paper as preliminary research scope and related field database analysis for uncertainty analysis of stress cycle and force-moment frequency effect on a deepwater flexible pipe. In the operation condition and gas transportation process. Seawater movement and current contact to the tubular body of flexible pipe give force to move the riser and pipeline.

In the flexible pipe, the polymer layer has function for protecting the annulus of CRA (corrosion resistance alloy) material from gas permeation from internal bore fluid flow to armor steel layer. Its layer requirement and specification based on (API 17J, 2016): Extruded Material, Minimum thickness 1 mm, Minimum diameter 40 mm, Design range temperature, Fluids permeability minimum for CH_4, CO_2, H_2S, Methanol, H_2O. (ISO 2556), Blistering resistance (API 17 TR1). The layer is illustrated in **Figure 2** below.

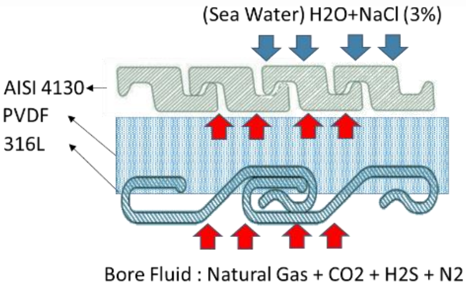

Figure 2 Three-Layered 316L-PVDF-4130 Steel of Typical Flexible Pipe

RESEARCH METHODOLOGY

Methodology for mapping an uncertainty model in scope of flexible pipe force effect by external environment, material properties and electrochemical contact analysis following the chart shown in **Figure 3** below.

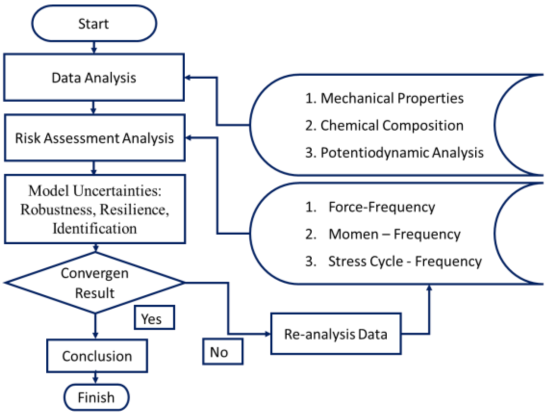

Figure 3 Uncertainties factor and numerical step in flexible pipe design

DATA ANALYSIS

Indonesian deepwater field oil and gas exploitation and transport using any kind of platform type. Based on data shown in **Error! Reference source not found.** the depth of those area operated by three type of floating production facility, there are floating production offloading unit (FPSO), floating production unit (FPU) and tendon leg platform (TLP). Two of Indonesia project for deepwater (DW) exploitation was area DW1 deepwater development with -975 to -1800 meters, DW2 -900 meters, DW3 deepwater development with -100 to -460 meters and the new area for next development area DW4 is -800 meters depth [2] In DW1 gas pipeline use 16 and 20-inch diameter and 8-inch for condensate, In DW3 field export gas pipeline use 14-inch diameter in [3].

Figure 4 Water Depth (DW) in Several Indonesia Deep Water Fields

Flexible pipe application in deepwater environment have a configuration type such as simple catenary, lazy wave, pliant wave, step wave, step S and lazy S. Lazy wave catenary riser configuration as shown in Figure 5. The position of critical point from flexible pipe configuration at hang off location, touchdown point, and any bending condition such in Sag bend, Arch bend, drag section and also at touchdown point bend. Internal condition in straight and curved pipe potentially have flow induced pulsation (FLIP). From Cabrera's in [4] and Chatjigeorgiou's in [5] riser in bend or straight condition assumed as beam cross section to figure different effect in bend and straight pipe by the forces and moments in flexible pipe section.

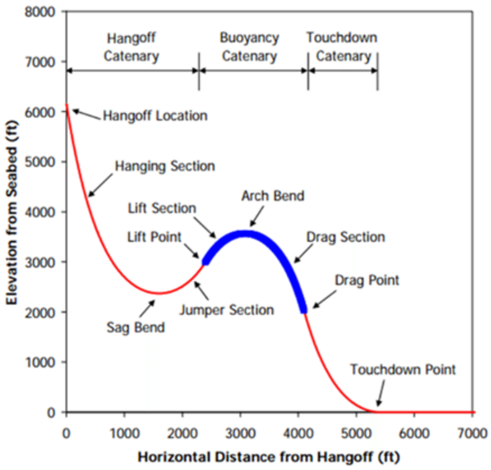

Figure 5 Lazy-wave catenary riser and critical position in riser [6]

Illustration for movement condition of FPU (floating production unit) or other sea surface structure shown in following **Figure 6**.

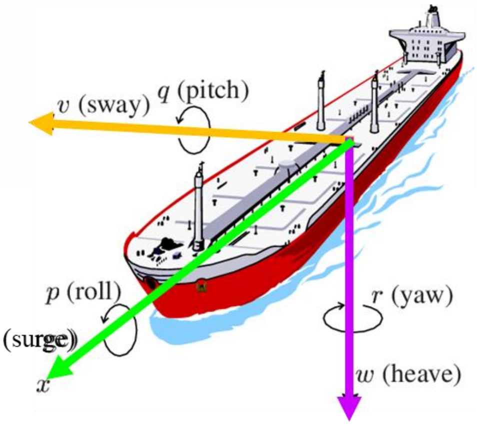

Figure 6 Movement orientation of floating production unit. [13]

Environment condition based on sample measuring from flexible riser structure in study field have value of Force (N) to Frequency (Hz) in three orientation FZ (grey), FY (orange), FX (blue). The force value and frequency for FZ (grey) and FY (orange) shown in **Figure 7** have similarity level, the highest force 52000 N in 100 Hz. For orientation FX (blue) have lowest for or in negative direction 200 Hz with force -12000 N. In scope of analysis and simulation the force and frequency data required for simulation input parameter to give bending force to specimen in FEA model. This data gives 3 orientations of bending effect to specimen in FEA model.

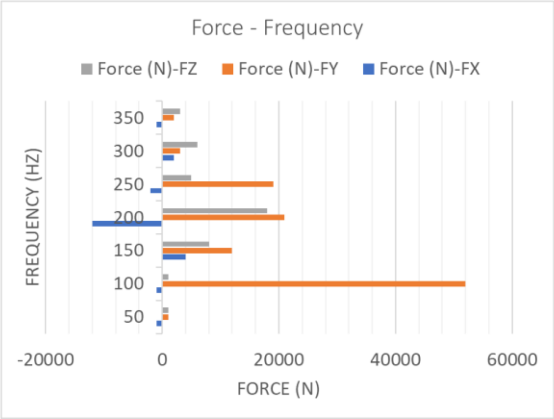

Figure 7 Applied Force and Frequency Orientation

Environment condition based on sample measuring from flexible riser structure in study field have value of Moment (Nm) to Frequency (Hz) correlation to moment orientation of MZ (grey), MY (orange) and MX (blue). The highest moment in orientation MZ (grey) and frequency 250 Hz is 8300 N. In MY (orange) direction moment have value 3000 N, and in MX (blue) have highest negative value -4000 N and frequency 100 Hz as shown in Figure 8 below.

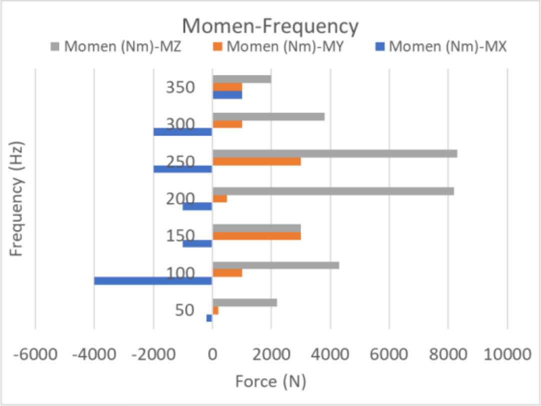

Figure 8 Applied Momen and Frequency Orientation

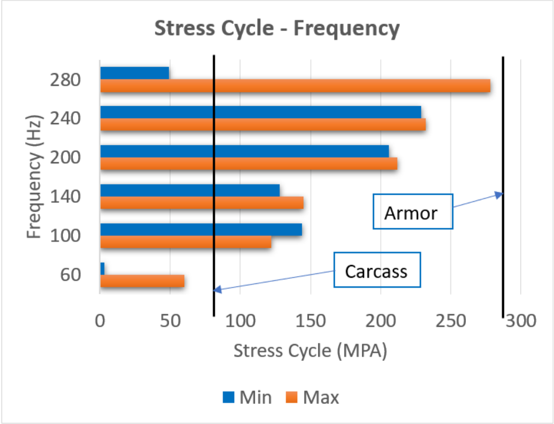

Figure 9 Stress Cycle and Frequency compare to material SMYS

Fatigue Life Calculation

Fatigue calculation for tubular geometry like flexible pipe in deepwater application affected by hydrodynamic condition from seawater environment. Parameter for calculation vortex induced vibration to flexible pipe is reduced velocity of wave and current, natural frequency of span, and total outside diameter of flexible pipe. Bai’s in [7] using chart shown in Figure 10 and formula shown in (1) below.

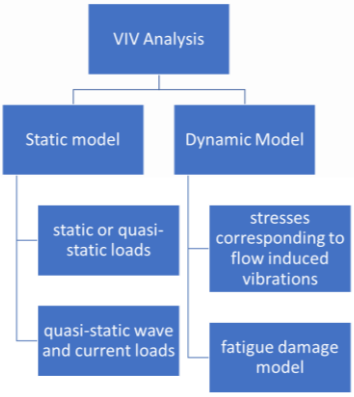

Figure 10 Hydrodynamic effect in VIV analysis [7]

Where, V_R is reduction velocity parameter, U_c is current velocity normal to pipe, U_w is wave velocity normal to pipe, f_0 is natural frequency of the span for given vibration mode, and D is total outside diameter of the pipe including coating.

$$V_R = \frac{U_c + U_w}{f_0 \cdot D} \quad (1)$$

$$m_e = m_{str} + m_c + m_a + m_{con} \quad (2)$$

Where, m_e is effective mass, m_{str} is structural mass including coating, m_a is added mass which combined with following formula shown in Eq. 3 with D is pipe diameter, ρ is seawater density, C_a is added mass coefficient and m_{con} is mass of fluids content. For Eq. 4. ζ_T is total modal damping ratio at a given vibration.

$$m_a = \frac{\pi}{4} D^2 \cdot \rho \cdot C_a \quad (3)$$

$$K_s = \frac{4 \cdot \pi \cdot m_e \cdot \zeta_T}{\rho \cdot D^2} \quad (4)$$

Based on field sample and condition data minimum stress cycle 3 MPa to maximum stress 278 MPa in range of frequency 250 to 300 Hz as shown in **Error! Reference source not found.** below. Bai's in [1] data for flexible pipe layer material have combination strength and capabilities such as for steel wire grade strength from 750 – 1400 MPa.

Fatigue Life Assessment

Safety requirement in flexible pipe application required high fatigue capabilities from each layered of flexible pipe material. In subsea and deepwater environment with different characteristic of force and pressure from seawater it pipes materials also affecting by internal pressure of bore fluids. For considering the horizontal force, Huang's in [8] using predicted formula by calculate viscous drag and inertia for is generally expressed in following Eq. 5.

$$f_H = f_D + f_I = \frac{1}{2} C_D \rho D u_x |u_x| + C_M \rho \frac{\pi D^2}{4} \dot{u}_x \quad (5)$$

Where, h is Water depth, a is Cartesian Coordinate, f_H is horizontal component, f_D is viscous drag, u_x is water particle velocity, f_I is inertia force, $\dot{u}_x$ is water particle's acceleration, CD is drag coefficient, ρ is sea water density, D is cylinder diameter, C_M is inertia force coefficient.

Risk Assessment

According Syuryana's et all, [9] if any hazard identification and flexible pipe segmentation has been successfully identified based on dynamic segmentation, further work to conduct a failure probability assessment. The characteristics of segments of the pipeline and the surrounding area are used to derive an actual estimate of the risk for each segment. Probability of Failure (PoF) is estimated as the frequency of failure along each segment over a year's time (or over some other relevant period). The PoF value is estimated as the failure frequency of various types of degradation mechanisms operating in the piping system. All component failures must be included in the PoF assessment. According to Muhlbauer's 2015 methodology5, each damage mechanism must have three aspects that are measured independently as follows:

1) Exposure (attack) – The type and aggressiveness of the environmental or process exposure that can trigger failure. Exposure has units of events per mile-year or mils per year metal loss.
2) Mitigation (defense or protection) – The type and effectiveness of any mitigation measures designed to prevent or reduce exposure.
3) Resistance (resistance of the material) – the ability of a material (eg pipelines) to retain its mechanical properties against exposure in the event of a mitigation failure.

Several assumptions for PoF calculation are used to get the value of final PoF. The QRBI approach is taken by calculating the three aspects of exposure, mitigation, and resistance. Table 2 below summarized the PoF value for each flexible pipe segment.

Table 1 PoF Value of Risk in Pipe Segment

Segment	Damage Mechanism	PoF Value* (Failure per year)
Riser	Above Water Level Riser Internal Corrosion	1.21 x 10^{-3}
	Above Water Level Riser External Corrosion (Marine Atmospheric)	1.54 x 10^{-3}
	Below Water Level Riser Internal Corrosion	1.21 x 10^{-3}
	Below Water Level Riser External Corrosion	2.63 x 10^{-3}
Flow Line	Carcass Internal Corrosion	3.28 x 10^{-3}
	Sand Erosion	7.19 x 10^{-4}
Touch Down Point	Deep Sea Debris Impact	2.66 x 10^{-5}
	Sand Erosion	2.26 x 10^{-3}
*Assumption based value		

Corrosion Testing and Analysis

According Budiwantoro's et all, [10] Based on potentiodynamic test result shown in Figure 11 corrosion resistant of carbon steel and stainless-steel material required a treatment to increase the resistance due to saline solution of NaCl environment simulation. Optional corrosion prevention for carbon steel required a cathodic protection or coating to mitigate the higher corrosion rate. For corrosion resistant alloy compare to original, mechanical polished and electrochemical polished surface condition. Significant corrosion rate between three surface condition of stainless steel during potentiodynamic test. Electrochemical polished shown best performance of corrosion resistivity. In flexible pipe layer this material has an inner layer carcass, design requirement for this layer have resistance to CO_2 and H_2S which dissolved in natural gas. Carbon steel material function in flexible pipe material using for middle to outer layer divided functions into tensile and torsion resistance to give safety condition to handle the pressure of fluids and environment (sea water) force.

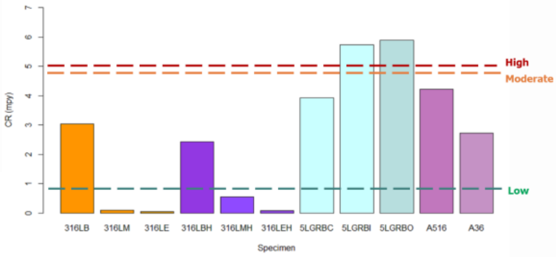

Figure 11 Corrosion rate (CR) comparative for API 5L Gr. B, A516, A36 carbon steel and 316L stainless steel based on potentiodynamic test results.

Specimen material notes in Figure 11 remaining 316LB for original base material test in 0.9 wt.% NaCl, 316LM mechanical polished and 316LE electropolished, 316LBH for original base material test in 3.5 wt.% NaCl, 316LMH for mechanical polished, 316LEH for electropolished. Carbon steel material code 5LGRBC for original non-contact with two-phase fluids test in 3.5 wt.% NaCl, 5LGRBI for contact material with two phase fluids, and 5LGRBO for external side pipe material, A516 and A36 for original material.

Conceptual for Uncertainty Analysis

External and internal factors affecting the integrity condition of flexible pipe mapping to a variable as developed by Pelz's in [11], (X_1 , Y_1 , X_2 , Y_2 ... , X_n , Y_n). Data analysis from potentiodynamic as a decreasing factor to material thickness and also affecting strength. As consideration from fatigue, a couple of data from force, moment and stress cycle as main factor with sub calculation to their different orientation. Risk as probability of failure also calculated as an uncertainty key factor, but its value and range refer to specific standard related in this field. Environtmental factor such as water pressure, viscous drag, current velocity considered as factor multivariable and predictable based on secondary field data.

CONCLUSIONS

Seawater as an environment of flexible pipe application has many characteristics in flow and force can affected to flexible pipe tubular structure as reciprocating force in any direction as bending moment, vortex-induced vibration and also from internal fluids pressure. The preliminary research purpose in this scope of analysis has multidisciplinary knowledge to identify the material fatigue and corrosion characteristics in the three-layered combination of flexible pipe prototypes in the first development phase. The uncertainty of the stress cycle, moment, and force should be considered as a limit of the SMYS of the carcass and armor compared to a higher potential value of approximately 270 Mpa at a frequency of 280 Hz. Compared to armor strength, which is 278 MPa, carcass strength is approximately 84 MPa. Carcass corrosion rate ranges from 0.5436 mpy to 2.4236 mpy based on potentiodynamic test data.

REFERENCES

[1] Q. Bai, Y. Bai, and W. Ruan, *Flexible Pipes*. John Wiley & Sons, 2018.

[2] Asiaflex, “Asiaflex.” (www.mprc.gov.my/properties/asiflex-products-sdn-bhd.).

[3] “Ruang Energi.” (www.ruangenergi.com/chevron).

[4] J. M. Cabrera-Miranda and J. K. Paik, “Two-phase flow induced vibrations in a marine riser conveying a fluid with rectangular pulse train mass,” *Ocean Eng.*, vol. 174, no. September 2018, pp. 71–83, 2019, doi: 10.1016/j.oceaneng.2019.01.044.

[5] I. K. Chatjigeorgiou, “Hydroelastic response of marine risers subjected to internal slug-flow,” *Appl. Ocean Res.*, vol. 62, pp. 1–17, 2017, doi: 10.1016/j.apor.2016.11.008.

[6] Gcaptain, “fpso-gulf-mexico.” https://gcaptain.com/shell-orders-fpso-gulf-mexico/.

[7] Y. Bai and Q. Bai, *Subsea pipeline and riser*, vol. 35, no. 17. 2005.

[8] W. Huang, X. Wu, J. Liu, and X. Bai, *Dynamics of Deepwater Riser*. Springer Singapore, 2022.

[9] E. P. Syuryana, I. Puja, B. Hanifan, and M. Maulana, “Risk Assessment and Integrity Analysis of Flexible Subsea Pipeline in Indonesia,” 2022, doi: 10.4108/eai.31-3-2022.2320948.

[10] B. Budiwantoro *et al.*, “Potentiodynamic Test for Pipeline and Static Mechanical Carbon Steel Material for Asset Integrity Assessment PT X,” Bandung, 2022.

[11] P. F. Pelz and M. E. Pfetsch, *Mastering Uncertainty in Mechanical Engineering*.

[12] www.researchgate.net/publication/3943583_Control_of_nonlinear_mechanical_systems/figures?lo=1