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Procedia Engineering 213 (2018) 708–719

Procedia Engineering

www.elsevier.com/locate/procedia

7th International Conference on Fatigue Design, Fatigue Design 2017, 29-30 November 2017, Senlis, France

Uncertainties Propagation within Offshore Flexible Pipes Risers Design

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Abstract

Flexible riser systems offer operators a robust method of producing oil and gas fields in harsh environments. Systems are currently designed using a mixture of local and international standards such that they can withstand conditions with a sufficient margin of safety. Flexible pipes have been installed for water depth exceeding 2500m. The application of reliability methods to determine the design of offshore systems such as jackets and ship hulls is well developed and has a long and successful track record. Flexible risers are subjected to the same random environmental loads. While probabilistic methods have been explored, they have yet to be applied in any meaningful manner to the fatigue limit state.

How to account in the most robust manner for uncertainties within the loading has become critical for deriving cost effective and robust design rules for flexible risers. Especially the layer of the flexible riser bearing the tensile load, named tensile armours, is critical in the design in many of the deep-water developments. In this paper, multiple structures designed for west of Africa and the North Sea are investigated through a reliability method. Typical Uncertainties within the global riser motions, the local stress computations and in the stress-life curve resistance are accounted for. Demonstration is made that for the same uncertainties the variables influencing the reliability of the structure differ. Finally, the comparison with actual international design rules is made through the value of the safety factor applied on the design life.

Peer-review under responsibility of the scientific committee of the 7th International Conference on Fatigue Design.

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Peer-review under responsibility of the scientific committee of the 7th International Conference on Fatigue Design.
10.1016/j.proeng.2018.02.067

Keywords: offshore structures ; flexible pipe riser ; fatigue ; structural reliability analysis ; design optmization

1. Introduction

Flexible riser systems are a robust method of producing oil and gas fields in a range of locations. Often, these locations are most economically developed using a floating production vessel with flexible risers linked to the subsea infrastructure. Many applications are in locations which experience harsh environments and high seas like West-of-Shetland, South Atlantic or Offshore Canada. Designing flexible riser systems to withstand these conditions with a sufficient margin of safety while still making them economically viable remains a challenge.

Flexible riser systems are currently designed using a mixture of local and international standards [1, 2]. Once an initial geometry has been determined, fatigue dynamic analysis using proprietary finite element analysis codes and models (e.g. [3]) is performed. An agreed, between operator and manufacturer, deterministic load case matrix over the scatter diagram is used. For this specific failure mode, uncertainties in the resistance side are accounted for using validated fatigue curves established based on international standards such as ASTM E739-10 [4]. The low frequency, wave induced, fatigue limit state may govern the design of flexible pipe for harsh environments or accidental loading conditions (e.g. flooded annulus). The current design rules allow room for optimization as illustrated in [5] where lower safety factor where demonstrated to contain a sufficient safety margin. These methodologies follow an approach developed for steel riser under medium frequency vortex induces vibrations [6]. These methodologies may also be used to understand the impact of uncertainties during fatigue reassessment for life extension where some historic information on the loading is available [7].

To allow optimization for all types of flexible pipes (production, water injection or export line) in a multitude of sea environments and floating units, the design should assess how the uncertainties propagate throughout the design models. Indeed, the fatigue behavior of the flexible structure varies greatly within the different configurations. This is covered within the physical model, however the current understanding of the impact of the inputs dispersion, on the fatigue predictions is limited. Specifically, the influence of loading uncertainties and not only resistance dispersion, which is characterized experimentally in the fatigue curves, should be further investigated. Furthermore, the pipeline design shall be based on potential failure consequence. This is covered by the safety class that depends on the location of the flexible pipe and the fluid transported by the flexible pipeline. Full structural reliability methods are not the objective as the design process should be kept as efficient as possible, they are however a mean to derive optimized design criteria.

Specifically, this paper is organized as follows. In Section 2, constituents of the unbonded flexible pipe are introduced followed by the current deterministic design methodology related to fatigue limit state. Section 3 presents the structural reliability analysis used in this paper and the safety philosophy on which it is based. We are then in position to apply the methodology on two project cases in the North Sea and West of Africa and evaluate the impact of the flexible configuration on the propagation of uncertainties (Section 4).

Nomenclature

d	Deterministic damage
D	Damage random variable
C	Curvature of the flexible riser
i	Index of the bin in the rainflow-counting algorithm
T	Tension of the flexible riser
σ_a	Alternate stress
σ_m	Mean stress
$\boldsymbol{X}$	Vector of random variables

2. Flexible pipe design

2.1. Unbonded flexible pipe

Flexible pipes are used in oil industry for fluid transportation between seabed and the offshore floating unit. Applications of a flexible pipe can be either for a production line, water injection line, gas injection line, and export line. The flexible pipe is composed of different layers where each one fulfills a specific function. An example is given in Fig 1.

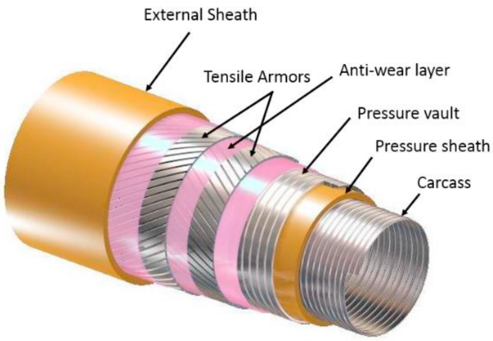

Fig. 1. Illustration of layers in an unbonded flexible pipe.

The function of each layer of a flexible pipe structure in Fig. 1, from the internal to the external layer, are the following.

- The carcass provides collapse resistance to external pressure.
- The pressure sheath contains fluid within the pipe bore[†] and provides the fluid transportation capacity.
- The pressure vault provides internal pressure resistance.
- The tensile armors provide tensile strength to support axial loads; and are composed of two or four layers with opposite laying angles to equilibrate torsion torque.
- The anti-wear layer prevents friction between armor layers.
- The external sheath prevents ingress of seawater to the annulus[‡].

The pipe could be a bonded or un-bonded structure. For an unbonded structure, layers can slide relatively which is not the case for bonded structure. In the current paper, only un-bonded pipes are addressed. The design of a flexible pipe is subjected to the multiple checks of failure modes governed through API 17J [1] and API 17B [2]. Among these failure modes, the fatigue of the tensile armors belongs to the most critical ones. In the following section, a brief description of the design check of this failure mode is presented.

2.2. Current deterministic fatigue design limit state

The flexible pipe links the offshore floating unit and the equipment on the seabed. The whole system works within offshore environment and is subjected to the movements generated by waves and currents through the floating vessel response. This cyclic loading leads to cyclic stresses within the tensile armors. The fatigue design process is summarized in Fig. 2. Due to different scales in the configuration a two-scale approach is used. Indeed the

[†] The term bore indicate the area inside the pressure sheath.
[‡] The term annulus indicates the area between the pressure and external sheathes.

pipe length can exceed 2000 meters whereas the armor pitch is circa 1 meter. The accurate model of offshore flexible risers' behavior should account for its complex internal structure, the interaction between layers including friction, the variable nature of the loads along the pipe, the interactions with structures used to limit the pipe curvature.

The cyclic motions and loads (tension and curvature) are computed through a global analysis, where the pipe is modelled with equivalent beams. Finite element software (like DeepLines, Orcaflex or Flexcom) determine tensions and curvatures of the pipe in dynamic simulations, including wave, current and vessel motions effects. The flexible pipe is considered as a homogeneous pipe specified by its geometric configuration and mechanical properties (bending stiffness, weight density …). The result is obtained in the form of time dependent signal of tension T and curvature C at some critical zones of the pipe.

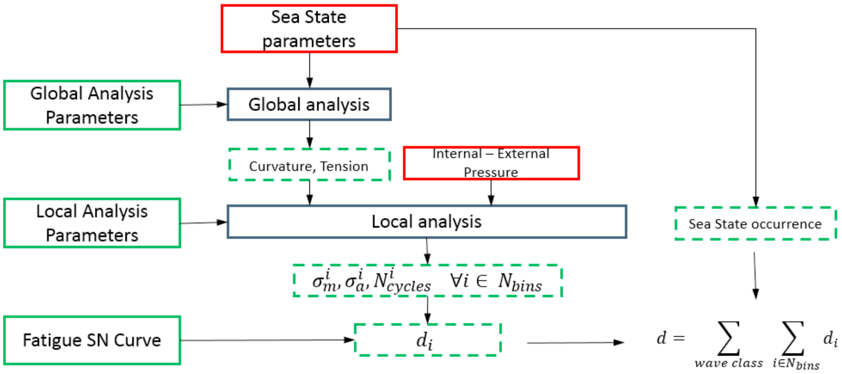

Fig. 2. Deterministic fatigue design workflow.

The local analysis [3] uses tension and curvature as input and results stress values within the tensile armors. In contrast with the global analysis, the local analysis considers the detailed structure of each layer of the pipe. To evaluate the cumulated damage, the Miner's rule is used [10]. For each wave class from the scatter diagram, the individual damage d_i is calculated in function of the cyclic stress specific values (mean and alternate values) associated with the number of cycles, and the fatigue resistance of the material stress-life curve. Concerning the fatigue stress-life curve, fatigue tests on tensile armors are carried out following ASTM E739 – 10 [5] for each material grade. The damage is computed with the 2.3% probability of failure curve. To account for the annulus condition, two kinds of fatigue stress-life (S-N) curves may be used: fatigue in air and corrosion fatigue one. The first kind corresponds to a dry condition of the annulus, whereas the second corresponds to the presence of condensed or seawater in the annulus.

The cumulated damage d is the sum over all the bins of the rainflow-counting methodology and over all sea states. The occurrence of the sea state accounts for the design life, usually 20 years. The cumulated damage is multiplied by a global safety factor SF and compared with 1. The tensile armors are considered to fulfill the fatigue limit state requirement if the design equation $SF * d \leq 1$ is enforced.

3. Reliability approach to flexible pipe design

3.1. Safety philosophy

As per today, flexible pipes are designed according to API 17J [1], which allows for structural reliability analysis. However, as little indications are given on the referential for the target reliability, this paper adopts the safety philosophy framework of another international standard DNV-OS-F201 [8]. This safety philosophy is structured around a quality assurance and safety class methodology. Quality assurance requires that gross errors (e.g. human errors) shall be controlled by requirement to the organization of the study and verification of the design, during all relevant phases. The safety class methodology implicates that flexible pipe systems are classified into safety classes based on failure consequences, normally given by the content of the flexible and its location. For each safety class, a target probability of failure is assigned in Table 2.5 of [8]. This probability of failure should be understood as an annual probability of failure, typically the last year of operation. This paper focuses on making use of the safety class methodology for the flexible pipe structure.

The basic approach of the limit state design method, common to API 17J [1] and DNV-OS-F201 [8], consists in recognizing the different failure modes related to each functional requirement and associating each failure mode to a specific limit state beyond which the structure no longer satisfies the functional requirements. Consequently, each limit state is related to a relevant failure mode and anticipated consequence of failure. For each layer of the pipe, for each limit state based on the structural capacity, the design criteria are defined including the safety margins. Here we address the fatigue limit state for tensile armors. As detailed in Section 2.2, the fatigue design criterion is a combination of characteristic values (choice of loading conditions, fatigue curve) and a global safety factor and reads

$$SF * d \leq 1$$

where d is the cumulated damage for the design life.

The final objective of a risk based design approach is to derive design criteria that allows for the correct safety margin according to the safety class. Structural reliability analysis allows to quantify the impact of uncertainties in the design on the probability of failure. In offshore structure, a reference document for structure reliability analysis is the DNV Classification Notes 30.6 [9]. This paper takes advantage of the same framework. The probability of failure is the probability that the fatigue limit state is exceeded during the last year of the design life,

$$P_f = Prob\left(D_{design\ life}(\boldsymbol{X}) > X_{fail}\right) - Prob\left(D_{design\ life-1}(\boldsymbol{X}) > X_{fail}\right)$$

where $\boldsymbol{X}$ is the input random vector, X_{fail} is the random variable characterizing the Miner rules limit state, $D_{design\ life}$ the random variable accumulate damage at the design life and $D_{design\ life-1}$ the random variable accumulate damage one year prior to the design life.

3.2. Implemented workflow – methodology

As mentioned in Section 2.2, the damage of tensile armors is evaluated through global analysis and local analysis steps. The uncertainties in the model appear of course at both the global and local levels. To assess dispersion on the damage, uncertainties propagation methods [11] are used. A non-intrusive method [12] that does not require modification of the deterministic model is implemented. In fact, the deterministic model is considered as a parametric model where each realization of input generates one realization of the output (damage). A "probabilistic layer" is added. This layer generates, depending on the algorithm, a set of realizations of input, executes the parametric model to calculate the corresponding realizations of output and assesses the uncertainties of the damage from these realizations. Fig. 3 is an updated workflow of the damage evaluation, where the damage becomes a random variable $D(\boldsymbol{X})$ of the random vector $\boldsymbol{X}$. In Fig. 3 the uncertainties of the random vector $\boldsymbol{X}$ are separated in three blocks, orange for global level, green for the local level and blue for the material resistance. The probabilistic model is detailed in Section 3.3.

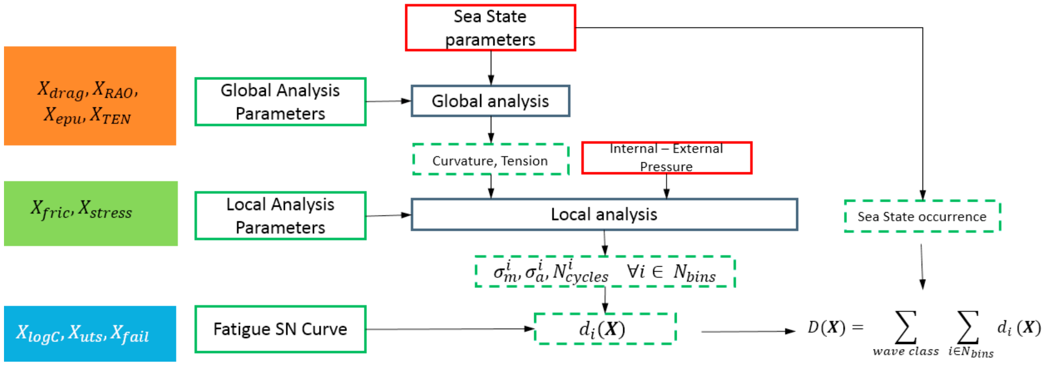

Fig. 3. Probabilistic fatigue workflow and associated uncertainties.

Assessing the dispersion of the output, and consequently the probability of failure, requires the execution of the deterministic models a large number of times (between hundreds and millions depending on the analysis methodology). If the deterministic model is time consuming, which is the case for this fatigue analysis, the computation time to assess uncertainties is crippling. One possible way to reduce the calculation time is to use a meta-model [13]. The main idea is to replace the original parametric model by an approximated one (Fig. 4). The calibration of the meta-model requires also the execution of the deterministic model several times but it is expected that this number of executions is moderate. Furthermore, with an adaptive design of experiment the calibration step is optimized with respect to the range of uncertainties of the probabilistic model $\boldsymbol{X}$.

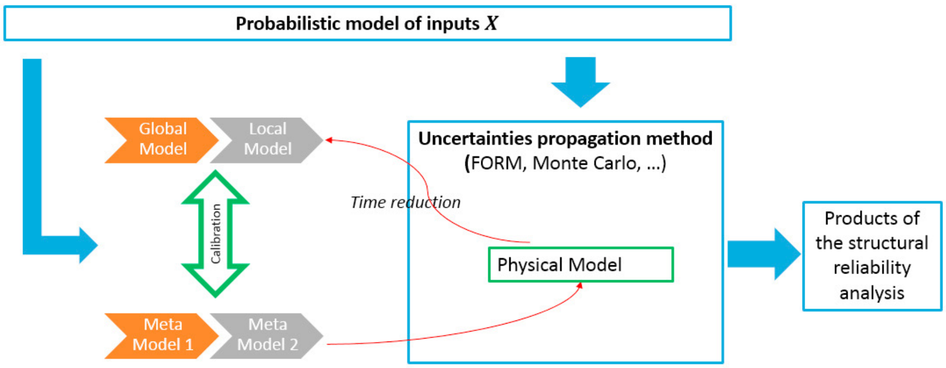

Fig. 4. Uncertainties propagation using meta-models: the physical model within the structural reliability approach is a set of meta models calibrated against the fatigue workflow of Fig. 2.

In the current analysis, two kriging surrogate models are used. One replaces the global analysis and one replaces local analysis (Fig. 4). The main idea of splitting into two meta-models is to reduce the number of executions of the deterministic model required to build the meta-model. To be more specific, meta-model 1 is a set of meta-models where each one is established for one load case (wave class). In this analysis, once the meta-models are built, First Order Reliability Method (FORM) method [11] is used to evaluated the probability of failure P_f defined in Section 3.1.

Due to the slope of the stress-life curve, any error on the stress is amplified in the damage computation. Therefore, the global meta model 1 cannot be validated independently of the local meta model 2. For the validation of the meta-models, we propose to compare the value of damage obtained by using both meta-models and the one obtained through the global and local analysis. The comparison has been performed on selected design points, i.e. the most probable failure point, as an output of the FORM analysis. Indeed, the accuracy in the calculation of the probability of failure by using meta-models depends on the accuracy of the approximated limit state function around the design point. These design points are not used for the calibration of the meta-models.

3.3. Global and local sources of uncertainties

In the fatigue workflow, among the vast amount of input parameters, a selected number are considered as stochastic variables. In the choice of the uncertainties in the probabilistic workflow, a specific focus is put on the uncertainties that can be further assessed or managed by a flexible pipe manufacturer (e.g. manufacturing, model uncertainty quantification). The inputs whose uncertainties have potentially significant impact on the damage are chosen as uncertain input. These uncertainties appear at all level of the multi-scale approach to fatigue design. It is expected that the input modelling could evolve when more information on input and more sensitivity analysis results are available. However, this evolution is beyond the scope of this paper.

By using Miner's rule [10], the damage is evaluated by "injecting" the mean and alternate stresses with the associated number of cycles into the stress-life curve. Therefore, uncertainties of the damage are generated by the uncertainties of the stresses, the fatigue curve and the Miner's rule limit state. Concerning the uncertainties on the Miner's rule, the result presented in [10] is used in the current analysis. The uncertainties on stress-life curve are assessed based on the test samples. Uncertainties on stresses are due to the whole mechanical calculation process that is divided in global and local analyses, as mentioned in Section 2.2.

Generally, the uncertainties of local and global analyses come from their uncertain input and from the software(s) approximation. It is not always easy to model uncertainties on input, or the software error. Indeed, these require specific uncertainty quantification protocol that exceed the current validation tests. The probabilistic laws modelling the uncertainties of inputs and the software error could come from literature, such as the Miner's rule, or from data, such as the stress-life curve, or by expert judgement when no data is available. It should be noticed that the accuracy of the probabilistic approach depends strongly on the accuracy of the input parameters modelling. The toughest challenge in this study does not lie with the structural reliability workflow, but with the input parameters modelling when data is not always available. In the current analysis, several scenarios concerning the uncertain inputs are considered. For each of the three blocks defined in Fig 3 the following random variables are considered.

Global analysis

- X_{drag} accounts for uncertainties on drag coefficient that is a coefficient modelling mechanical interaction between the pipe and the seawater. The value recommended in [14] is considered.
- X_{RAO} accounts for uncertainties on the movement of the vessel. The value recommended in [14] is considered.
- X_{epu} accounts for uncertainties on the mechanical behaviour of Bend Stiffener Polyurethane material. In fact, the Bend Stiffener is used to increase the stiffness in the area with important bending moment.
- X_{ten} accounts for uncertainties on the curvatures and tensions released from global analysis that come from other sources than the three variables X_{drag}, X_{RAO}, and X_{epu}.

Local analysis

- X_{fric} accounts for uncertainties on friction coefficient between armour layers used in local analysis software.
- X_{Stress} accounts for uncertainties on the mean and alternate stresses issued from local analysis software that come from other sources than the above variables. The most important contribution to X_{stress} is likely to be the uncertainties on the software calculation of the local analysis.

Armour layer fatigue strength and Miner's rule

- X_{logC} and X_{uts} accounts for uncertainties on the fatigue resistance curve. They are based on proprietary physical tests.
- X_{fail} accounts for the uncertainties on the Miner's rule and the associated fatigue model [10].

The probabilistic model $\boldsymbol{X} = [X_{drag}, X_{RAO}, X_{epu}, X_{ten}, X_{fric}, X_{stress}, X_{logC}, X_{uts}]$ is detailed in Table 1. The random variables come as a multiple factor of the nominal value following the distributions proposed in Table1, the value 1 corresponds to the nominal value and 1.2 for example corresponds to an increase of 20% of its nominal value. The random variables X_{logC} and X_{uts} are material and environment specific but do not vary between the three scenarios. The difference between these three scenarios is on the modelling of the uncertainties in the loading computation ($X_{ten,}$ $X_{fric,}$ X_{Stress}) are as follows:

- In the first scenario, a dispersion around the local stress evaluation is considered simultaneously with a bias on the friction coefficient.
- In the second scenario, to avoid the double dipping on the local model, the uncertainties in the stress computation are removed, and an uncertainty on the global model is considered.
- In the third scenario, in the local computation, an important bias is included. This means that the nominal computation for the stress in the local analysis is conservative. The uncertainty in the friction is included in the evaluation of the local stress. The dispersion on the global evaluation is maintained.

Table 1. Three scenarios considered for the probabilistic law of input random variables.

Scenario	X_{drag}	X_{RAO}	X_{epu}	X_{ten}	X_{fric}	X_{Stress}	X_{logC}	X_{fail}	X_{uts}
1	Normal (1,0.2)	LogNormal (1,0.1)	Normal (1,0.07)	1	Normal (0.8,0.2)	Normal (1,0.1)	Normal (.,.)	LogNormal (1.0.3)	Normal (.,.)
2	Normal (1,0.2)	LogNormal (1,0.1)	Normal (1,0.07)	Normal (1,0.1)	Normal (0.8,0.2)	1	Normal (.,.)	LogNormal (1.0.3)	Normal (.,.)
3	Normal (1,0.2)	LogNormal (1,0.1)	Normal (1,0.07)	Normal (1,0.1)	1	Normal (0.65,0.15)	Normal (.,.)	LogNormal (1.0.3)	Normal (.,.)

Within Table 1, the uncertainties related to the loading are not specified to serve as a reference. Merely, these scenarios are specifically to investigate which uncertainties, within the design models, should be quantified accurately to allow for further robust optimization of the design.

4. Project application and associated sensitivity analysis

The methodology presented previously is applied in this Section for two specific cases whose information is presented in Table 2. The difference between a Lazy wave and Pliant wave configurations is presented in Fig. 6. Concerning the fatigue curve, the tensile armour layers in project A work in dry environment, thus an in-air fatigue curve is considered (intact external sheath). In project B, the tensile armour layers work in an environment with the presence of the seawater (damaged external sheath) where a corrosion fatigue curve is considered. The water depth and geographical area vary between the two projects leading to different wave and current solicitations.

Table 2. Information related to projects A and B.

Information	Project A	Project B
Geographical area	Africa	Nord sea
Configuration	Lazy wave	Pliant wave
Water depth	1450m	395m
Application	8.11" Water Injection	7.4" Gas Export/Import
SN Curve	Fatigue in air curve	Corrosion fatigue curve
Deterministic damage for service life	0.08	0.03

Service life required	20 years	1 year

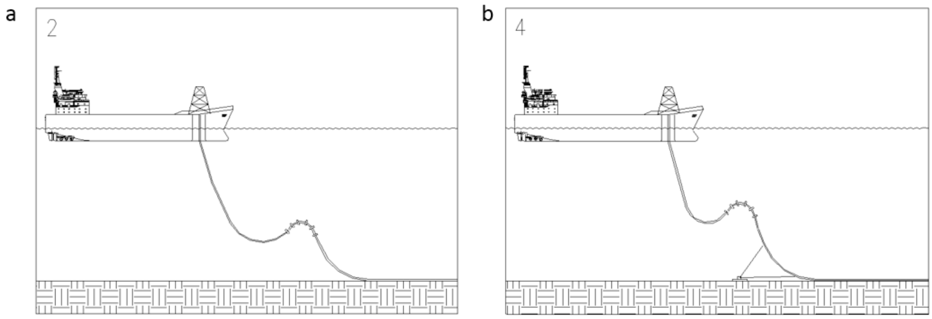

Fig. 5. (a) Lazy wave configuration; (b) Pliant wave configuration

4.1. Project A: Water Injection West of Africa – Lazy wave configuration

The line is an 8.11 inches (internal diameter) water injection riser. The consequence of a failure and loss of containment from of the line is moderate (compared to the one of a gas application). Therefore, the line is considered belonging to normal safety class with the associated target probability of failure 10^{-4} per year according to DNV-OS-F201 [8]. For each scenario considered in Table 1, the safety factor (reliably-based safety factor) that results from the target probability of failure 10^{-4} is determined. The associated impact factors (associated with FORM method) are calculated. The larger the impact factor, the more significant its impact on the probability of failure.

The reliability based safety factors and impact factors are presented respectively in Table 3 and in Fig. 6. It can be observed that the reliability based safety factor depends significantly on the choice of the input model (scenario). In this case, the international design rule seems to be more severe than the reliability approach. Concerning the sensitivity analysis, the impact of uncertainties on load (calculated stresses) is relatively equivalent to the one of uncertainties on material fatigue resistance.

Table 3. Comparison between international design rule safety factor and reliability based safety factor: Project A: Water Injection West of Africa.

	International design rule safety factor [1]	Reliability based safety factor meeting [8] requirement
Scenario 1	10	7.3
Scenario 2	10	5.1
Scenario 3	10	3.2

The reliability based safety factor in Table 3 is the one applied on the deterministic damage which gives a design service life equivalent to the reliability based service life. The reliability based service life being the service life which gives the correct probability of failure (as per [8]) within the last year of operation, with the flexible pipe design of this project. This measure is used instead of the probability of failure to compare the conservatism in the current deterministic design depending on the chosen probabilistic scenario. In Table 3, the decrease of the calibrated reliability based safety factor implies that the flexible pipe design (with the safety factor from [1]) would see its annual probability of failure decrease further below the required probability of failure.

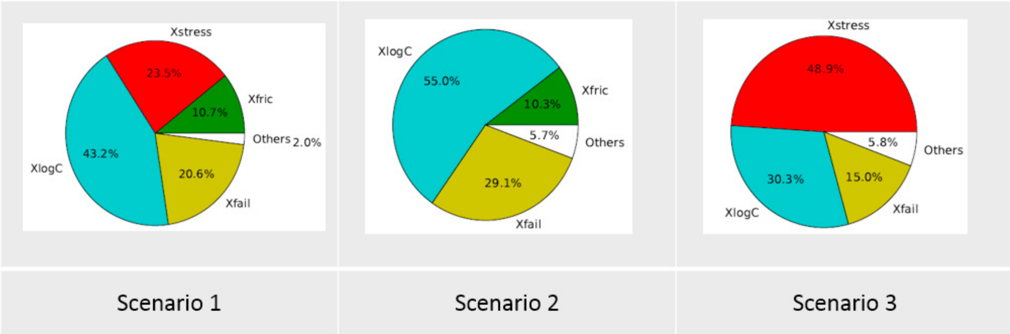

Fig. 6. Impact factors associated with FORM method: project A Water Injection West of Africa. Importance factors for a probability of failure of 10^{-4} per year.

4.2. Project B: North sea Gas Export – Pliant Wave configuration.

The line is a 7.4 inches gas application. Therefore, the line is considered belonging to high safety class with the associated target probability of failure 10^{-5} per year. The same calculation process as in the case of project A is performed. The reliability base safety factors and impact factors are presented respectively in Table 4 and in Fig. 7. Like the case of project A, the reliability based safety factor depends strongly on the choice of the input statistical scenario. The international design rule seems also to be more severe. The impact of load in this case is more important than the one of uncertainties on material fatigue resistance.

Table 4. Comparison between international design rule safety factor and reliability based safety factor: project B North Sea Gas Export.

	International design rule safety factor [1]	Reliability based safety factor meeting [8] requirement
Scenario 1	10	8.0
Scenario 2	10	3.6
Scenario 3	10	< 2.0

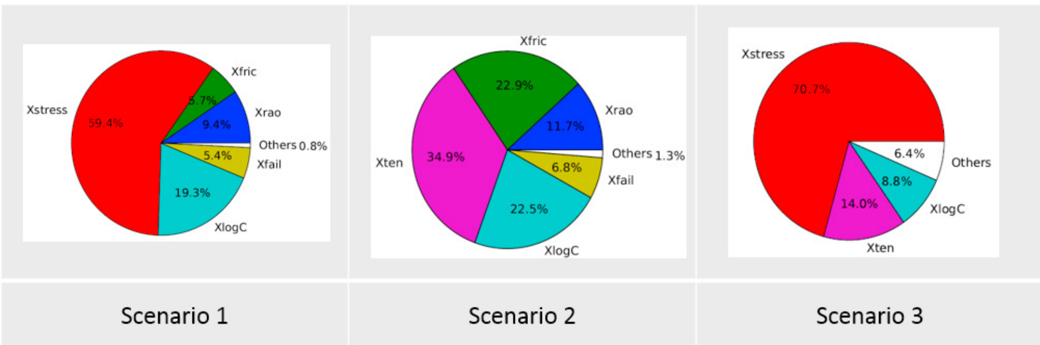

Fig. 7. Impact factors associated with FORM method: Project B North Sea Gas Export– Pliant Wave configuration. Importance factors for a probability of failure of 10^{-5} per year.

4.3. Comparison of sensitivity analysis

From the results obtained in Section 4.1 and 4.2, the following observations can be drawn.

- By considering the same uncertainties on input (same scenario), the reliability safety factors and the impact of each input are relatively different between project A and B. This can be explained by the differences related to each project (wave solicitation, water depth, …) detailed in Table 2. Furthermore, the difference of the considered safety class (target probability of failure) implies that the risers are not solicited in the same regime.
- The impact of the uncertainties on fatigue stress-life curve is more important in project A than in project B. This can be explained by the fact that the air fatigue curve (project A) has a flatter slope than the corrosion fatigue (project B). Indeed, with a flat SN curve, a small variation of stresses will generate a more significant variation of the damage.
- Passing the dispersion (coefficient of variation of 10 %) from the local stress to the global tension curvature (change between scenario 1 and 2) decreases the safety factor required.
- For both projects, when the bias in the local stress evaluation is accounted for (Scenario 3) the global reliability based safety factor is the smallest. Therefore, this bias adds in the current deterministic framework an important safety margin.
- Even if the two projects are with different configurations and fatigue curves, the influence between the three probabilistic models' scenario is the same on the global safety factor.
- The influence of the limit state (uncertainties on Miner's rule), even with a significant coefficient of variation of 30% has a moderate influence in the Project A and a negligible influence in Project B.

4. Conclusion and perspectives

In this paper, the low frequency wave induced fatigue of flexible pipe has been investigated through an uncertainties propagation method. The final objective of this study is to allow for an optimized design with respect to fatigue of unbonded flexible pipes with a sufficient margin of safety, as per offshore operators and international standards requirements. This design aspect extends to fatigue reassessment and monitoring, in a life of field context. As a first step, this paper focuses on the impact of the choice of the uncertainties within the physical model, as well as the difference in the flexible riser configuration.

A robust non-intrusive reliability methodology is introduced in this paper, making use of kriging surrogate models. Compared to previous work on reliability in fatigue of flexible risers, this paper focused on the investigation on the sensitivities of the probabilistic model at the global and local scales. Specifically, the influence of multiple model uncertainties is investigated. Based on two flexible riser configurations and three scenarios for uncertainties, where only the loading side changes, it is demonstrated that the safety margin in the current design criteria (i.e. in deterministic approach) is overestimated (typically with a factor from 1.2 to 5 times). Furthermore, the influence of the same probabilistic model depends on the riser configuration.

The common dominant parameters are fatigue stress-life curve parameters and local analysis parameters. As the probabilistic model on stress-life curve is already based on extensive physical tests, as a first perspective, the uncertainty on local analysis should be further investigated (tests, data collection, …). The uncertainties in the occurrences of the different load cases are not modified in this work, this may increase the influence of global uncertainties compared to the local one. Nevertheless, this would only increase the influence of the loading random variables on the probability of failure. Therefore, even in a life of field context where only the loading can be monitored, this study also demonstrates that monitoring the loading is sufficient to have a more detailed assessment of the fatigue state.

The second perspective is that to account for the different influences of uncertainties on the limit state, a design by the partial safety factor method may be required. The partial safety factor format separates the influence of uncertainties and variability originating from different causes. They are applied as factors on specified characteristic values of these load and resistances variables, thereby allowing for further optimization.

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