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RBDO AS A DECISION-MAKING TOOL IN THE TUBULAR DESIGN AGAINST COLLAPSE

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Abstract. During drilling and lifetime production of an oil well, the casing system is responsible for its hydraulic isolation and structural integrity, having a high associated cost in relation to the total amount of the well. The occurrence of failure events in casing tubes can result in large environmental damage and human losses. Its structural design must comprise the different load scenarios acting on the tubular, including internal and external pressures, besides axial, bending and torque efforts. Among the possible failure modes, the collapse of the tubulars, due to the action of external pressure, stands out. The casing design methodology currently adopted in the oil and gas industry is the Serviceability Limit State (SLS) verification proposed by API/TR 5C3 (2008), based on a model of four collapse regimes, depending on the slenderness of the tube. Its formulation does not deal with the uncertainties inherent to projects of this magnitude, which could improve the structural safety analysis of the tubular, without compromising its economicity. In this way, it is proposed to apply reliability-based design optimization (RBDO) techniques in confluence with an Ultimate Limit State (ULS) model in order to find optimal configurations for the design variables, taking into account the variability of some geometrical and mechanical parameters, due to the manufacturing process, considering required target safety levels.

Keywords: Casing, Collapse, Drilling, Optimization, Reliability

1 Introduction

Throughout the construction and operation of an oil well, the casing system is one of the major physical barriers contributing to the structural integrity and hydraulic isolation of the well. Among its structural functions, it can be cited the support of unconsolidated formations and equipment installed in the wellhead system. Regarding operational aspects, the casing system prevents loss of circulation in the drilling process and confines the production inside the well. The occurrence of failures in this system, if not controlled or mitigated, can lead to human injuries, as well as high environmental and financial losses.

The high cost associated with the casing phase - 15% to 20% of the total cost of an offshore well [1] - demands an appropriate choice of parameters and materials in its project. The demand for structurally safe casing designs at an acceptable cost has prompted the interest of the oil and gas industry for probabilistic analysis.

In this context, the theory of structural reliability proposes the description of design variables as random variables allied with the development of mathematical models to estimate the probability of failure. This kind of approach allows the safety assessment of a structure, either at the design stage or at later verification, under service conditions. The document [2] that standardizes the design of the casing system already includes probabilistic analysis suggestions, presented as informative annexes.

In general, engineering problems can admit several solutions, since different combinations of the variables involved lead to admissible answers, both from the mathematical and normative point of view. As example, in the design of casing tubulars, different arrangements of tube thickness and steel grade values meet specified design criteria, with different levels of structural safety stored in each solution. In the search for adequate solutions, it is possible to use parametric optimization techniques, which consists in defining an objective function that one wishes to minimize or maximize, given the constraints imposed by the problem under analysis, defined in terms of the design variables involved.

The combination of these two approaches gives rise to reliability based parametric optimization models, known by the acronym RBDO (Reliability Based Design Optimization), which aim to obtaining a set of design variable values that satisfies optimality conditions by meeting design values that attends an allowable probability of failure for the structure.

2 Tubular Collapse Resistance Model

The collapse phenomenon is characterized by the loss of stable geometry caused by scenarios where the external pressure (P_{ext}) to the tubular is greater than the internal pressure (P_{int}) and the ultimate resistance to external pressure (R_{ext}^{ult}) of the well [3]. This condition is briefly presented as follows:

$$P_{ext} > P_{int} + R_{ext}^{ult}. \tag{1}$$

The present work uses empirical formulations calibrated to design parameters presented in imperial units. However, for uniformity requirements and when necessary, they are given in SI units.

2.1 Ultimate Limit State (ULS) equation

According to the standard [2], the model developed by Klever and Tamano [4] is the one that best estimates the external pressure resistance of well casing tubes, whose formulation is presented as follows:

$$R_{ext}^{ult} = \frac{\left(R_{eu} + R_{yu}\right) - \sqrt{\left(R_{eu} - R_{yu}\right)^2 + 4 \cdot R_{eu} \cdot R_{yu} \cdot h_u}}{2 \cdot (1 - h_u)}. \tag{2}$$

Where R_{eu} is the ultimate elastic collapse pressure, R_{yu} is the ultimate flow collapse pressure and h_u is a reduction factor influenced by the imperfections of the tube production process. These terms are given by the equations presents below:

$$R_{eu} = k_{eu} \cdot \frac{2 \cdot E}{1 - v^2} \cdot \frac{1}{\left({D_\mu}/{t_\mu}\right) \cdot \left[\left({D_\mu}/{t_\mu}\right) - 1\right]^2}; \quad (3)$$

$$R_{yu} = 2 \cdot k_{yu} \cdot f_y \cdot \left({t_\mu}/{D_\mu}\right) \cdot \left(1 + {t_\mu}/{2 \cdot D_\mu}\right); \quad (4)$$

$$h_u = 0.127 \cdot o_v + 0.0039 \cdot e_c - 0.44 \cdot \left({r_s}/{f_y}\right) + h_n. \quad (5)$$

Where E, v, D_μ, t_μ, f_y, o_v, e_c, r_s and h_n are, respectively, steel's modulus of elasticity, steel's Poisson's ratio, the average outside diameter measured, the average wall thickness measured, the yield stress, the ovalization, the eccentricity, the residual stress and a form factor for the stress-strain curve of stell. While k_{eu} and k_{yu} are empirically calibrated coefficients.

This paper assumes, by standard [2] recommendations, that h_u equals to 0.2.

2.2 Design equation – Serviceability Limit State (SLS)

For the design practice, the standard [2] suggests a modified version of the ULS equation (2), as presented below:

$$R_{ext}^{API} = \frac{\left(k_e \cdot R_e + k_y \cdot R_y\right) - \sqrt{\left(k_e \cdot R_e - k_y \cdot R_y\right)^2 + 4 \cdot k_e \cdot R_e \cdot k_y \cdot R_y \cdot h_d}}{2 \cdot (1 - h_d)}. \quad (6)$$

Where k_e and k_y are penalty coefficients. The terms R_e and R_y are derived, respectively, from Eq. (3) and Eq. (4) by adopting nominal values for the diameter and thickness, and removing the empirical coefficients from the formulations. The term h_d is obtained from Eq. (5), by adopting mean values from a coherent sample series for ovality and eccentricity.

3 Reliability-Based Design Optimization

Reliability-based optimization (RBDO) seeks to find the optimal solution to a given problem by considering the uncertainties inherent in it and a predetermined security level known as the reliability index (β). Those uncertainties are modeled as random variables according to structural reliability theory and incorporated into the study. This paper uses a method called single loop that seeks to find the deterministic constraints equivalent to the uncertainties considered.

Thus, the transformation brought by Eq. (7) is applied to the random variables in order to create a feasible and reliable space of solutions to the RBDO problem [5].

$$x_{i,j} = \mu_i - \beta_j \cdot \sigma_i \cdot \left\{ \frac{\sigma_i \cdot \left[\frac{\partial G_j(\vec{X})}{\partial \tilde{x}_i}\right]}{\sqrt{\sum_i \left[\sigma_i \cdot \left(\frac{\partial G_j(\vec{X})}{\partial \tilde{x}_i}\right)\right]^2}} \right\}. \quad (7)$$

Where indexes i and j refer to random variables and performance constraints, respectively. The terms μ_i and σ_i are, respectively, the mean and the standard deviation of the i-th random variable, while β_j is the reliability index assigned to the j-th performance constraint. This transformation results in $x_{i,j}$ which is the conversion into deterministic space of the i-th random variable $\tilde{x}_i$ with respect to the j-th performance constraint $G_j(\vec{X})$ applied to the vector of variables $\vec{X}$, random or not. The transformed variables must be replaced in their respective performance constraints, obtaining deterministic constraints for a traditional optimization problem, which can be solved by a convenient method.

4 Case Study

Considering a load scenario where the differential pressure applied results is 82.74 MPa, it is desired to minimize the cross-section area of the casing tube. The nominal outside diameter, which is predefined accordingly to the diameter of the borehole, is adopted as 0.27305 m. Thus, the objective function is presented by Eq. (8), as follows:

$$A = \frac{\pi^2}{4} \cdot [D^2 - (D - 2 \cdot t)^2] \tag{8}$$

Where D and t are, respectively, the tube outside diameter and its wall thickness.

This paper aims to compare the results obtained by traditional optimization methods and reliability-based optimization, whose resistance constraints are presented, respectively, by Eq. (9) and Eq. (10).

$$R_{ext}^{API} \geq 82.74 \text{ MPa}; \tag{9}$$

$$M_{KT} \cdot R_{ext}^{ult} \geq 82.74 \text{ MPa}. \tag{10}$$

Where M_{KT} is the uncertainty related to the model developed by Klever and Tamano [4]. Moreover, regarding the RBDO problem, the target reliability index is 3.5.

In addition, the characterizations of the specimens and random variables considered in this paper are given by Table 1 and Table 2, respectively.

Table 1. Characterization of specimens

Specimen	Steel Grade	f_y
Tube 1	L80	551.58 MPa
Tube 2	P110	758.42 MPa

Table 2. Characterization of the random variables

Random variable	Mean/Nominal	COV	Distribution
D	1.0059	0.00181	Gaussian
t	1.0069	0.02590	Gaussian
f_{y-L80}	1.1000	0.05290	Gaussian
f_{y-P110}	1.1000	0.03600	Gaussian
M_{KT}	0.9991*	0.06700	Gaussian

Where COV is the coefficient of variation and the symbol “*” indicates that the information given already represents the mean of the parameter.

5 Results

The results obtained for the minimization of the cross-sectional area are presented in Table 3.

Table 3. Optimization results

Specimen	Optimization	D [m]	t [m]	D/t	F_s
Tube 1	Deterministic	0.27305	0.02512	10.87185	1.00
Tube 1	RBDO	0.27305	0.02795	9.77084	1.13
Tube 2	Deterministic	0.27305	0.02027	13.46926	1.00
Tube 2	RBDO	0.27305	0.02343	11.65279	1.22

For both tubes, the deterministic optimization resulted in a design resistance equivalent to the acting load, with no strength reserve to meet uncertainties or scenarios that were not accounted in the design phase. The reliability-based design optimization, however, resulted in a noticeable and expected increase of the tubulars wall thickness, making them more robust.

This can be observed through the safety factor (F_S), defined by the ratio between the design resistance of the adopted configuration, in serviceability limit state, and the assigned load scenario. Therefore, the design method that includes RBDO in its formulation resulted in design strengths 13% and 22% greater than the acting load for Tube 1 and Tube 2, respectively. This difference can be explained by the more dispersed behavior of the yield stress of steel grade L80, as well as by the physical phenomenon of collapse.

Finally, it is expected to contribute to the adoption of numerical models that take into account the Ultimate Limit State (ULS), as proposed by Klever and Tamano [4], resulting in more reliable evaluation of the real conditions faced by casing tubulars and reducing operating costs. Also, it is important to mention the need for the availability of production data series by the manufacturer, so that the uncertainties inherent to a specific product are properly incorporated into the design practice.

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