XLIII CILAMCE
21-25, November, 2022
FOZ DO IGUAÇU - PR - BRAZIL

Collapse strength of worn casing tubes from wear log inspection

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Abstract. Oil wells are drilled by depth intervals with different diameters, which usually get smaller when it gets deeper. When the bottom of a phase is reached by the drill bit, it needs to be cased, cemented, and tested. The inner wall of the casing string will always be subject to the drill string's intense contact and rotation. The friction will remove material from the casing tube, reducing its strength. The current deep wells with directional trajectories and severe tortuosity increase the casing wear making its assessment even more relevant for structural integrity purposes. This work proposes a methodology to estimate the collapse strength of worn casing tubes using inspection data of oil wells integrated with nonlinear Finite Element Analysis (FEA). The methodology starts by identifying wear grooves from an ultrasonic log (US) by applying a strategy from the literature. Then, an equivalent cross-section geometry is proposed, in which the identified wear grooves are inserted, emulating the most likely original geometry, since the inspected shape is deformed. Although inner radius and thickness data for many cross sections of the casing string also become available with the inspection, the boundary conditions are not known, e.g., pressure and temperature. Due to this, FEA performed with this scanned geometry will result in an unrealistic estimate of the tube strength. The 2D numeric simulation is performed in Abaqus with the equivalent geometry to estimate the residual strength of the worn casing tube. A nonlinear approach is necessary because the collapse of a tube is an instability problem. It is observed that the stress concentration in the groove wear zone reduces the resistance. The results show that the multiple wear grooves observed from the inspection can significantly reduce the strength of the tube. However, most works found in the literature are concerned with only one wear groove in their modeling, since the inspection data is not accurately interpreted. A case study is presented to demonstrate this contrast.

Keywords: well integrity, casing wear, finite element modeling.

1 Introduction

Since ancient times, structural engineering has been essential in the advancement of humanity. According to Martha [1], it was empirically present in the construction of great monuments, pyramids, temples, roads, bridges, and fortifications of ancient civilizations. From the beginning of theoretical formalization in the 17th century to the present day, the mastery of new construction techniques together with human creativity made possible civil and industrial constructions of high complexity. The beginning of the oil industry in the 19th century in the United States of America was also guided by empirical knowledge, including drilling activities and well structure management. Currently in Brazil, the challenge of oil exploration in extreme offshore environments demands structural engineering responses for the integrity of wells throughout their life cycle.
Casing tubes present in oil wells are always subject to wear resulting from intense contact with the drill string (Fig. 1). The well design considers this effect conservatively, to avoid critical situations. On the other hand, modern tools for the inspection of tubes in wells have made it possible to update the prediction made in the design stage. This allows a better assessment of the integrity of the tubes, helping decision-making process in well design and

monitoring.

The casing wear subject has been widely studied over the years. While many works are concerned with an accurate prediction of the wear intensity (Hall et al. [2]; Hall and Malloy [3]; Mittal et al. [4]; Binas et al. [5]; Ferreira et al. [6]), others have made efforts to improve the inspection interpretation of wear through modern logging tools (Sawaryn et al. [7], Chandrasekhar et al. [8], Aichinger et al. [9], Gouveia et al. [10]) and to develop residual strength models of the worn tube (Kuriyama et al. [11], Moreira et al. [12]).

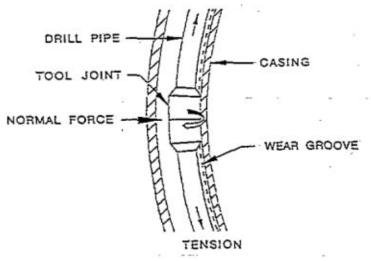


Figure 1. Tool joint wear on the internal casing wall

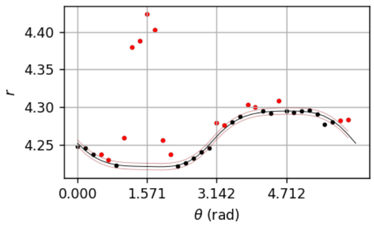
This work aims to evaluate the residual collapse resistance of worn casing tubes in oil wells, integrating an advanced interpretation of inspection data with a 2D nonlinear FEA. The results are compared with relevant models found in the literature. It is expected to contribute to improving the understanding of the collapse mechanism of worn tubes.

2 Casing wear inspection

The methodology discussed in Gouveia et al. (2022) is applied here to calculate the wear of casing cross-sections that were inspected with a US tool. Inner radius data is measured in 60, 72, 90, or even 120 equally spaced channels in a cross-section. Cross-section measurements are usually performed every 5, 10, or 15 cm in a depth interval. Once the wear grooves are identified, they can be incorporated into the FEA model to provide an accurate estimate of the residual collapse strength.

Figure 2 presents two critical cases of worn tubes found in the Volve dataset [18], in which major wear grooves were identified. The continuous black line represents the elliptical shape that best represents the tube inner wall before wear happens. The outliers from this shape are the wear points (red dots), where the red lines represent a statistical tolerance. In Case 1 one is centered in 1.571 rad, as shown in Figure 2.a). In Case 2, three groove points are observed closer to 2.618 rad, four grooves points closer to 4.189 rad, and other two small grooves are identified before 1.047 rad (Figure 2.b).

a)



b)

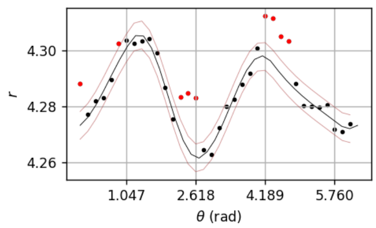


Figure 2. Inner radius data of: a) Case 1, a cross-section with a major wear groove, and, b) Case 2, a cross-section with two major wear grooves.

3 Worn tube strength analytical equations

Some analytical equations for strength of worn casing tubes have been proposed in the literature. In this work, two of them are selected to be compared with the numeric model, due to their relevance and usage in the industry. Kuriyama et al. (1992) was the first to propose a solution for the residual collapse strength of worn tubes. The model is the analytical solution of an eccentric tube, which is a simplification for the problem of the single wear groove in the tube cross-section. Moreira et al. (2015), after performing experimental collapse tests and 3D FEA simulations of worn tubes with a single groove, propose an empirical equation that best fits the results obtained. In both equations, the main parameter that degrades the collapse strength is the maximum groove depth. They do not consider the groove width or multiple grooves in a cross-section. In this work, it is proposed to consider these aspects, and verify its influence on the collapse resistance.

4 Finite Element Analysis

The adopted methodology to estimate the residual collapse resistance of worn tubes is based on nonlinear 2D FEA, because many tubes cross sections are thin or moderately-thick walled. This approach is applied using the Abaqus [13] software. In this section, the FEA modeling aspects are briefly explained, and then, the approach to integrate the inspection data with the numeric simulation is detailed.

4.1 Modeling aspects

The numerical model can simulate the collapse of tubes covering the entire range of usual transverse slenderness ratios found in specific casing catalogs. Therefore, this methodology can estimate collapse strengths for slender and robust cross-section specimens, whose failure mechanisms differ from each other. For thick tubes, the simulations can take place in a regime of small displacements and deformations, however, for tubes of medium and high slenderness, these estimates can be verified geometrically in a nonlinear framework.

The modeling presented in this work is analogous to collapse tests of casing tubes in hyperbaric chambers. The tubular is placed inside a chamber so that the portion to be collapsed is subjected to the action of the hydrostatic pressure loading exerted by a fluid. According to Moreira et al., this load is applied incrementally, monitoring the pressure levels over time by a supervisory system.

The elastoplastic constitutive model considered in the simulations is based on the formulation present in the ASME BPVC [12] code, taking the form of true stress versus true total strain curve. It should be noted that the Abaqus software requires a true stress-strain curve to be inserted for constitutive models, thus contemplating the updating of the instantaneous areas of the element under stress.

The chamber subjects the tubular to conditions that, in a simplified way, can be modeled in the plane strain state, since it is considered that there are no deformations outside the cross-sectional plane, that is, deformations in the longitudinal direction of the tube. This constraint limits the movement of coupling nodes to translation and rotation with respect to a reference point. According to Simulia [13], this kind of constraint can couple all nodes of the surface to the central point of the model. This mechanism allows these nodes to move freely, moving in the radial direction or rotating around the longitudinal axis.

Second-order (or biquadratic) CPE8 elements are applied in the simulations. Quadrilateral finite elements can provide adequate results for the study of structural elements in a plane strain state, subjected to compressive stresses, being subject to large displacements (KAWECKI and PODGÓRSKI [14]). In regions close to the wear grooves, which have irregular geometry, it is necessary to insert CPE6 triangular elements in the mesh, getting a better adaptation to the boundaries.

To solve the instability problem, the Riks method is used, also known as the numerical method of solution by arc length (SIMULIA, 2013). As exposed by Ma [15], this method is commonly used to predict unstable collapse in structures subjected to geometrically nonlinear regimes. The solution process is based on the gradual increase in load, which develops along the equilibrium path. At each increment, the balance of the system must be checked, until the maximum supported load is found. This load is proportional to the initially prescribed load that must be scaled. Thus, the load proportionality factor (LPF) can be defined as the ratio of P_c, the incremental pressure applied to the model when the tube fails, over P_0, the initial pressure adopted as unitary.

Intact tube geometries are used to validate the model by performing a convergence study and a comparison of the collapse pressures with the Klever and Tamano [16] equation (KT), which was selected by API TR 5C3 [17] as the most representative collapse equation, based on 2986 collapse tests gathered from several industry manufacturers. KT model uncertainty for this dataset, defined as the ratio of actual collapse pressure to the KT predicted strength, is estimated to be a normal distribution with 0.9991 mean and 0.0670 coefficient of variation. Figure 3a shows that the model achieves a stable response with 4 quadrilateral elements in the radial direction, i.e., splitting the thickness of the cross section in four elements. A dataset with both thick and thin casing tubes is adopted to compare the collapse pressure estimates with KT equation. It is expected that most of the conventional casing tubes fall in the range of external diameter (OD) over wall thickness (OD/wt) from 10 to 25. In Figure 3b and 3c a good agreement is observed between FEA and KT, being the maximum errors around +17% and -9%.

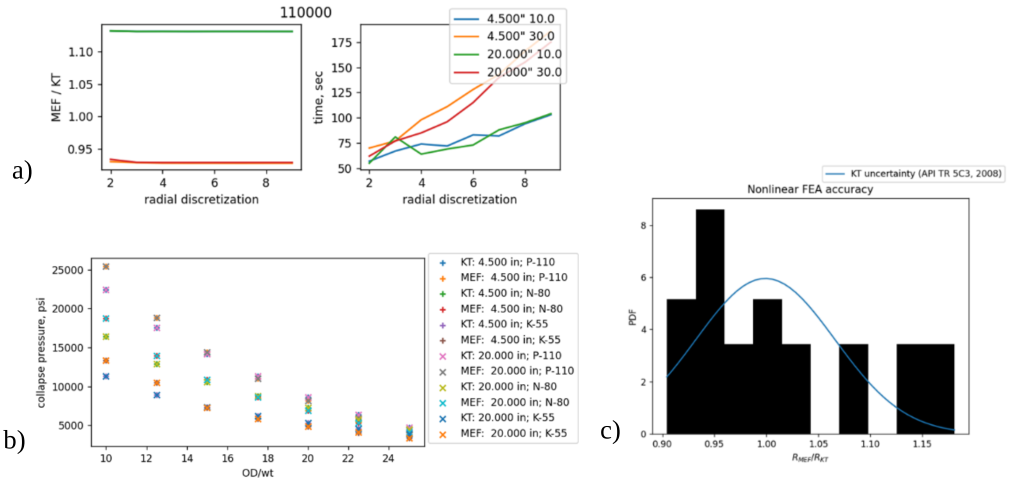


Figure 3. Validation of the nonlinear 2D FEA model using a convergency analysis (a) and a comparison with KT equation for intact tubes (b) and (c).

4.2 Integration of inspection data with FEA

The cross-section that has been scanned in the US inspection represents a portion of the tube that is already set in the well. Thus, it is deformed, and it is not possible to know the conditions of pressure and temperature it is subjected to. Our approach consists in adopting a probable original geometry for the tube before it has been set in the well. This original geometry can be retrieved by looking for the tube manufacturer data. For our study, we adopt the API TR 5C3 (2008) summary that provides average values for external diameter, wall thickness, ovality, and eccentricity of several manufacturers. Finally, the identified wear grooves are inserted in this estimate of the original geometry to be simulated in FEA. Figure 4 presents how the cross-sections of Case 1 and Case 2 remain after this strategy.

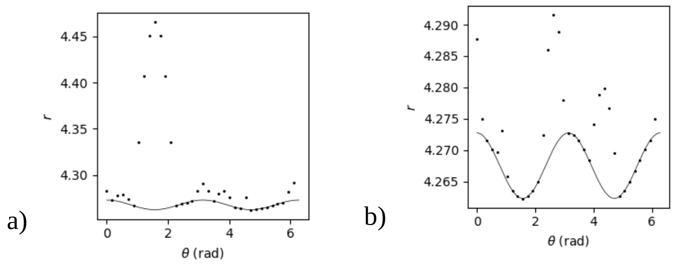


Figure 3. Validation of the nonlinear 2D FEA model using a convergency analysis (a) and a comparison with KT equation for intact tubes (b) and (c).

5 Results

Two studies are performed to demonstrate how important it is to consider a detailed evaluation of the worn tube by integrating the inspect data with the nonlinear FEA. First, a comparison of the maximum penetration observed in the wear log with the worn area is carried out. Secondly, the two case studies presented in previous section are simulated and compared with the analytical models.

5.1 Maximum penetration and worn area effects on tube residual strength

Random worn tube geometries are generated and simulated with FEA to allow a better understanding of the residual collapse strength with varying maximum wear penetration and worn area. Figure 5 presents a linear trend for both parameters. The maximum penetration seems to have a growing dispersion over the linear trend. The worn area presents a more constant dispersion over its range. It can be concluded that both parameters need to be considered in the residual collapse strength evaluation. However, current analytical models, as the discussed previously, consider only the maximum penetration rather than both of them.

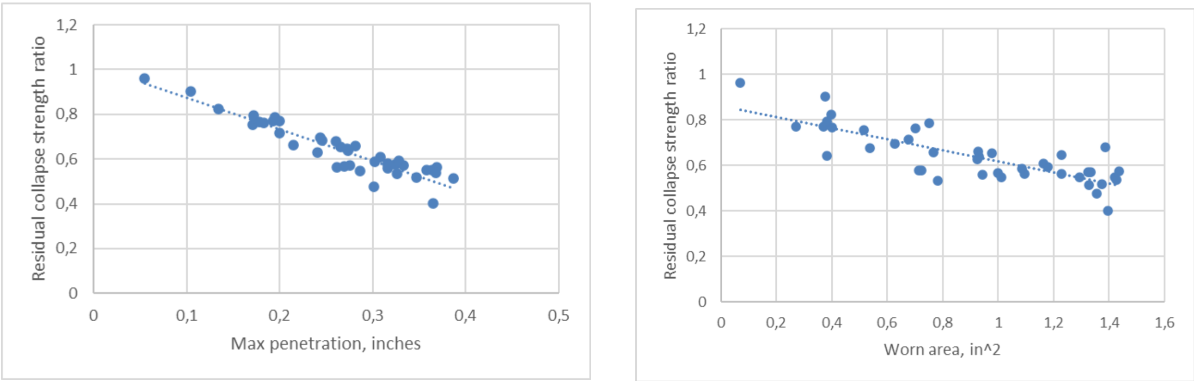


Figure 5. Residual collapse strength ratio (worn tube strength/original tube strength) behavior over maximum wear penetration and worn area for a P-110 casing tube.

5.2 Case study

The two case studies present in previous sections are analyzed to compare how the approach developed in this work differs from methodologies found in the literature. The unworn strengths of this cases are: KT=10785 psi and FEA=10812 psi. Table 1 presents the estimates for the residual collapse strength of the discussed strategies. In the Case 1, the results obtained are more conservative than the ones estimated by analytical equations. In Case 2, Moreira et al. provide the greatest derating in the collapse pressure.

Table 1. Coefficients in constitutive relations

	Model	Collapse pressure (psi)	Reduction
Case 1 (single wear groove)	Kuriyama et al.	7435 psi	31.1 %
Max wear: 37.3 %	Moreira et al.	6397 psi	40.7 %
Worn area: 4.38 %	FEA (present study)	6207 psi	42.4 %e
Case 2 (double wear groove)	Kuriyama et al.	10956 psi	-1.59 %
Max wear: 3.93 %	Moreira et al.	10206 psi	5.36 %
Worn area: 0.63 %	FEA (present study)	10440 psi	3.44 %

6 Conclusions and perspectives

The developed analysis carried out a robust integration of inspection data with the nonlinear FEA that have not been observed in other works in the literature. It the beginning of a investigation to better understand the collapse mechanism of worn casing tubes in oil wells. Future work should try to propose a factor that accounts for the maximum wear penetration and worn area.

Acknowledgements. The authors acknowledge the financial and technical support provided by Petróleo Brasileiro S.A. - PETROBRAS.

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