Assessment of the cement sheaths structural integrity in oil wells

Maria Clara. L. Medeiros[1], Catarina. N. A. Fernandes[1], Thiago. B. Silva[1], William. W. M. Lira[1]

[1]*Laboratory of Scientific Computing and Visualization, Federal University of Alagoas*
Campus Ac. Simões. Av. Lourival Melo Mota, S/N, Tabuleiro do Martins, 57072-970, Maceió/AL, Brazil
maria.clara.cm7@gmail.com, catarina@lccv.ufal.br, thiago.barbosa@lccv.ufal.br, william@lccv.ufal.br

Abstract. This work proposes a study on the analytical modeling of the system composed of casing-cement-formation, considering displacements and stresses acting at the interfaces, to assess the structural integrity of the cement sheath in oil wells. The interaction of this system is also evaluated through numerical modeling, using the commercial software Abaqus, aiming to verify the results provided by the studied analytical model. In the process of oil well construction, the cementing phase is one of the most important and demands integrity analyses and risk assessment, as poorly executed cementing may result in increased financial costs and operational problems. Cement failure can be modeled using the traditional Mohr-Coulomb criterion, which provides the limiting stress for shear failure. In this context, a comparative case study is presented to illustrate the proposed investigations and verify the results obtained from the following methodology: a) implementation of a discrete analytical model that estimates the mechanical behavior of the system and evaluates the integrity of the cement sheath and b) discrete numerical modeling, evaluated by a static structural analysis, considering the effect of temperature. Through the comparative analysis of the results obtained, it is noted that the two strategies used (analytical and numerical) provide very similar results. Thus, the computational implementation of the analytical solution is an important tool to provide support to the design of oil wells, allowing rapid and precise analysis and prediction of the structural integrity of cement sheaths.

Keywords: Cement sheath, Structural integrity, Oil wells.

1 Introduction

The oil industry, from extraction to processing of products - oil and gas - for over a century of activity, stands out as one of the most profitable sectors in the global economy. Currently, the discovery of fields in deep and geologically complex areas exposes wells to high levels of pressure and temperature (HPHT) and requires special attention in managing the integrity of wells, from their construction and throughout their lifetime [1].

In oil exploration and production, an important stage during the well construction is the cementing operation. This operation involves filling the annular space between the casing and the geological formation with cement and is carried out to promote complete and permanent isolation of producing zones. In this context, one of the fundamental procedures to ensure the well's stability and durability is the effectiveness of this cementing operation, as the lack of cement integrity can compromise production and cause undesirable communication between the reservoir zones [2].

The predictability of compression and tension stresses on the cement sheath allows the modeling of the necessary mechanical properties of the cement slurry to prevent failures. Such mechanical failure can result in a loss of annular isolation due to the debonding of the cement and fracturing at the interface with the formation. In this context, it is important to highlight that the failure of sealing of the cement sheath is one of the critical factors that influence the wellhead casing pressure (WHCP). Therefore, maintaining the integrity of the sheath is essential to reduce WHCP and increase the safety of the system [3].

This article deals with the analysis of the integrity of cement sheaths in a system composed of casing-cement-formation, when subjected to stresses induced by mechanical and thermal phenomena. Thus, the study presented by Xu et al. [3] is used as a reference for the proposed model, which is developed based on Lamé's equations designed to map stresses, strains, and displacements of thick-walled cylinders, and numerically using the Finite Element Method. It is expected that the two proposed strategies will present similar results, enabling the structural analysis of cement sheath integrity using an analytical model.

2 Methodology

The proposed methodology is based on the following steps: a) definition of the mechanical model under study; b) implementation of a discrete analytical model that estimates the mechanical behavior of the system and assesses the integrity of the cement sheath; c) numerical modeling of the studied problem using a computational program that implements the Finite Element Method; d) verification of the results obtained in steps b) and c). Figure 1 illustrates a scheme of the methodology used.

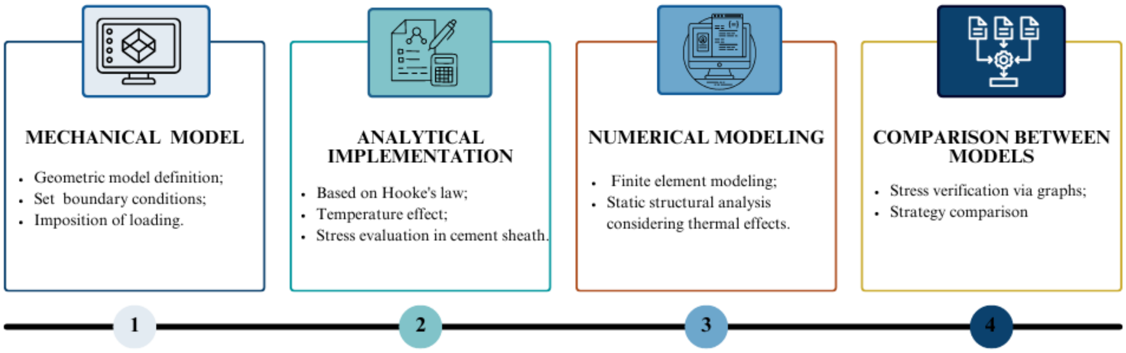


Figure 1. Steps of the proposed methodology

2.1 Mechanical Model

In an oil well, the cement functions as a barrier element, filling the annular space between the geological formation and the casing, forming a sheath. Once solidified, the casing-cement-formation system can be interpreted as a combined thick-walled cylinder. In this context, due to existing pressure and temperature differences, contact pressures are generated at the interfaces between these elements. The pressure at any radial point of the cement sheath can be calculated based on the displacement continuity condition at the interface, assuming the following assumptions related to the theory of linear elasticity: i) The casing, the cement sheath, and the formation are homogeneous and isotropic materials, ii) There is perfect bonding at the material interfaces, iii) The initial stress in the cement sheath is zero, iv) The temperature of the casing-cement-formation system varies uniformly along the radial direction, v) The combined cylinder is considered to be in a plane strain state. Figure 2 presents the conceptual scheme of the model.

2.2 Analytical application

The analytical strategy used to evaluate the existing stresses in the cement sheath is based on Hooke's law, considering the effect of temperature through the thermal expansion of materials. This strategy is described in greater detail in [3]. Strains are defined in terms of the radial and tangential components, according to the assumption of plane strain state for the combined cylinder (i.e., $\varepsilon z \approx 0$ or constant).

The radial and tangential stresses in the casing $(\sigma_{rs}, \sigma_{\theta s})$, cement sheath $(\sigma_{rc}, \sigma_{\theta c})$, and formation $(\sigma_{rf}, \sigma_{\theta f})$ are defined based on the thick-walled cylinder equations proposed by Lamé:

$$\begin{cases} \sigma_{rs} = \dfrac{p_i d_1^2}{d_2^2 - d_1^2}\left(1 - \dfrac{d_2^2}{d^2}\right) - \dfrac{p_{C1} d_2^2}{d_2^2 - d_1^2}\left(1 - \dfrac{d_1^2}{d^2}\right) \\ \sigma_{\theta s} = \dfrac{p_i d_1^2}{d_2^2 - d_1^2}\left(1 + \dfrac{d_2^2}{d^2}\right) - \dfrac{p_{C1} d_2^2}{d_2^2 - d_1^2}\left(1 + \dfrac{d_1^2}{d^2}\right) \end{cases} \tag{1}$$

$$\begin{cases} \sigma_{rc} = \dfrac{p_{C1} d_2^2}{d_3^2 - d_2^2}\left(1 - \dfrac{d_3^2}{d^2}\right) - \dfrac{p_{C2} d_3^2}{d_3^2 - d_2^2}\left(1 - \dfrac{d_2^2}{d^2}\right) \\ \sigma_{\theta c} = \dfrac{p_{C1} d_2^2}{d_3^2 - d_2^2}\left(1 + \dfrac{d_3^2}{d^2}\right) - \dfrac{p_{C2} d_3^2}{d_3^2 - d_2^2}\left(1 + \dfrac{d_2^2}{d^2}\right) \end{cases} \tag{2}$$

$$\begin{cases} \sigma_{rf} = \dfrac{p_{C2} d_3^2}{d_4^2 - d_3^2}\left(1 - \dfrac{d_4^2}{d^2}\right) - \dfrac{p_f d_4^2}{d_4^2 - d_3^2}\left(1 - \dfrac{d_3^2}{d^2}\right) \\ \sigma_{\theta f} = \dfrac{p_{C2} d_3^2}{d_4^2 - d_3^2}\left(1 + \dfrac{d_4^2}{d^2}\right) - \dfrac{p_f d_4^2}{d_4^2 - d_3^2}\left(1 + \dfrac{d_3^2}{d^2}\right) \end{cases} \tag{3}$$

The contact pressures on the inner and outer walls of the cement sheath (p_{C1} e p_{C2}), respectively, are obtained by imposing the displacement compatibility between both interfaces.

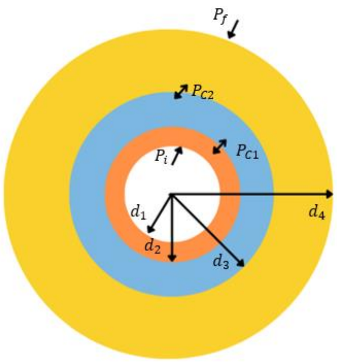


Figure 2. Conceptual scheme for the mechanical model

2.3 Numerical modeling and description of the scenario under study

The numerical strategy employed to evaluate the integrity of the cement sheath in oil wells is based on a scenario proposed by Xu et al. [3]. An axisymmetric casing-cement-formation model with the well axis is established, with the geometric and elastic parameters presented in Table 1. The thermomechanical analysis is carried out using the finite element software ABAQUS (2019), capable of performing finite element analyses on linear and nonlinear problems of various systems. For the computational simulation, 8-node quadratic quadrilateral elements with reduced integration (CPE8R) were adopted.

The integrity of the cement sheath is evaluated by a static structural analysis considering thermal effects. The proposed scenario considers an internal pressure in the casing (WHCP) of 70 MPa and the influence of the hole temperature, increasing 60ºC during production or testing of the well and decreasing -60ºC during the pumping of fracturing fluids, acting on the internal interface of the casing. For the numerical model, the temperature variation is also assumed even for the entire domain.

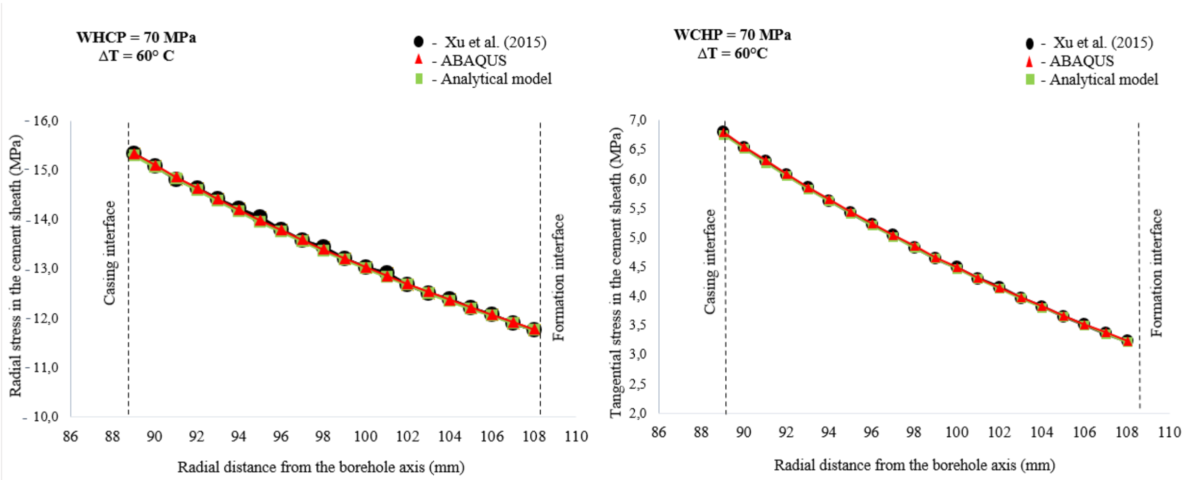
Table 1. Geometric and elastic parameters used in the study scenario

Parameter	Casing	Cement	Formation
Inner Radius (mm)	76.25	88.90	107.95
Outer Radius (mm)	88.90	107.95	1079.50
$\alpha(^{\circ}C^{-1})$	1.30E-05	1.00E-05	1.20E-05
E (GPa)	200	5.57	20
ν (-)	0.27	0.15	0.23

3 Results and discussions

A comparative study is carried out to verify the results obtained from thermoelastic modeling in ABAQUS, comparing these results with the analytical strategy used and with the reference values available in Xu et al. [3]. This comparison is expected to reveal significant similarities in the assessment of the structural integrity of cement sheaths in oil wells through both analytical application and discrete simulation.

Figure 2 illustrates the distribution of radial and tangential stresses acting on the cement sheath, evaluated for a WHCP of 70 MPa and a 60°C increase in the wellbore temperature. The results obtained from thermoelastic modeling in ABAQUS are compared with the analytical strategy used and the values presented by Xu et al [3]. Thus, it is observed that the stress results indicate good adherence between the studied models and the numerical solution. Additionally, it can be noted that the highest stresses occur at the casing-cement interface, as the studied pressure acts on the inner wall of the casing, and there is a tendency for it to decrease along the well's radial distance.

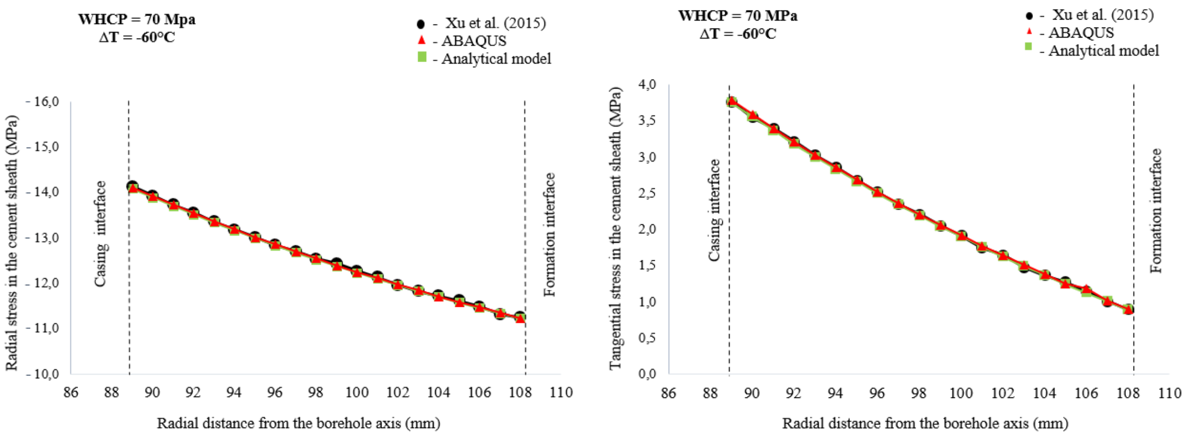


a) Radial stress b) Tangential stress

Figure 2. Stress distribution in the cement sheath along the borehole considering WHCP = 70 MPa and an increase of 60°C in the wellbore temperature

Figure 3 shows the distribution of radial and tangential stresses acting on the cement sheath, evaluated for the same WHCP but considering a decrease of 60°C in the wellbore temperature. Additionally, it is observed that the highest stress values continue to act at the cement-casing interface.

The results in Figures 2 and 3 show that the stresses calculated by the analytical and numerical models are very close, with relative errors less than 1% for radial stress and below 2% for tangential stress. These errors are smaller than those reported by Xu et al [3].



Radial stress b) Tangential stress

Figure 3. Stress distribution in the cement sheath along the borehole considering WHCP = 70 MPa and a decrease of 60°C in the wellbore temperature

4 Conclusions

In this study, the comparative analysis of the stress values acting on the cement sheath, using the presented methods, aims to evaluate the stress levels to which the cement sheath is subjected. The strategy ensures reliable results by comparing thermomechanical effects using analytical and numerical methods, demonstrating the adequacy of the equations used. Thus, the use of numerical models to verify analytical formulations is an important tool for oil well projects, allowing for quick analysis and prediction of the structural integrity of cement sheaths.

Acknowledgements. The authors would like to thank PETROBRAS for the financial and technical support related to the development of the research project "Desenvolvimento de Produtos Digitais para Gestão de Integridade de Estrutura de Poço" (ANP code 23599-4). The first author acknowledges the financial support related to the development of this research provided by the Institutional Program for Scientific Initiation Scholarships – PIBIC/UFAL (2023-2024).

References

[1] T. B. Silva, E. T. Lima Junior, C. O. Souza. Probabilistic Assessment of Cement Sheath Integrity in Oil and Gas Wells. In XLIV Ibero-Latin-American Congress on Computational Methods in Engineering – CILAMCE, Porto, Portugal. ABMEC, 2023.
[2] J. J. Freitas. Validação de uma Metodologia de Ensaio de Resistência ao Cisalhamento para Avaliação da Aderência de Interfaces Revestimento Metálico-Bainha de Cimento Aplicada a Poços de Petróleo. 141 p. Dissertação (Mestrado em Engenharia Mecânica) - Programa de Pós Graduação em Engenharia Mecânica, Universidade Federal do Rio Grande do Norte, Rio Grande do Norte, Brasil, 2007.
[3] H. Xu, Z. Zhang, T. Shi, and J. Xiong. Influence of the whcp on cement sheath stress and integrity in hthp gas well. Journal of Petroleum Science and Engineering, vol. 126, pp. 174–180, 2015.
[4] A. P. Boresi., R. J. Schmidt. *Advanced Mechanics of Materials.* John Wiley & Sons, Inc., 2003.
[5] E. Fjaer., R. M. Holt., P. Horsrud., A. M. Raaen, R. Risnes. *Petroleum Related Rock Mechanics*. Elsevier, 1992.