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Influence of casing decentralization on the thermo-poroelastic integrity assessment of cement sheaths in oil wells

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Abstract. This study preliminarily investigates the influence of casing decentralization on the structural integrity of the cement sheath in oil wells under thermo-poroelastic conditions. The cement sheath, located between two casings or the casing and surrounding rock formation, performs essential functions, including ensuring casing support, providing hydraulic isolation between producing zones, and maintaining the structural stability of the well. Traditionally, its design is based on thermoelastic models with circular cross-sections and concentric geometry. However, geometric imperfections, such as casing decentralization, can significantly modify stress distribution and compromise the structural integrity of the cement sheath. In addition, the porous behavior of hardened cement, often disregarded, can meaningfully influence its mechanical response. In this context, the methodology comprises: (i) definition of the numerical model; (ii) establishment of material properties and boundary conditions; (iii) verification of the eccentric model; (iv) definition of the case studies; and (v) structural integrity assessment. The results show that decentralization intensifies circumferential stresses in the region of reduced thickness, increasing susceptibility to failure. The inclusion of thermo-poroelastic behavior, although reducing absolute stress levels, amplifies the effects of eccentricity. Thus, this study integrates both factors, providing initial insights for safer and more realistic designs in the oil and gas industry.

Keywords: Casing decentralization, Cement sheath, Structural integrity, Thermo-poroelasticity, Numerical modeling

1 Introduction

The cement sheath is an essential element for the structural integrity of oil wells, serving to provide hydraulic isolation between permeable zones, support the casings, and mitigate mechanical failures as well as undesirable fluid migration. Maintaining its structural integrity is essential for both operational safety and the economic viability of well operations. When compromised, it may lead to the loss of zonal isolation, enabling communication between geological formations and increasing environmental and operational risks. Moreover, such damage often necessitates costly remedial interventions, with a direct impact on the sustainability of the operation [1].

Classical cement sheath design models often assume idealized concentric geometries and disregard the porous behavior of hardened cement [2]. While such simplifications are common, they do not adequately represent actual well conditions. Casing decentralization, for instance, is a recurring condition resulting from factors such as the limited use of centralizers and drilling in unconsolidated formations, which compromises annular symmetry and can generate stress concentrations in the cement sheath [3]. These concentrations have a greater impact on tangential stresses, which are more sensitive to geometry [4]. Furthermore, once hardened, cement behaves as a porous medium, and the presence of fluids within its pores influences stress distribution and its sealing capacity [5]. In this context, approaches that account for porous behavior, such as poroelasticity, become relevant for more accurately representing the system's structural response.

Previous studies have addressed geometric and poroelastic effects separately. Grainger [6] and De Andrade and Sangesland [7] employed thermoelastic models to assess structural failures associated with decentralization

and geometric imperfections. In contrast, Joulin et al. [8] and Lins [2] adopted thermo-poroelastic models but assumed concentric geometries. Liu et al. [4] analyzed casing eccentricity using analytical solutions, considering pressure variations during fracturing. De Andrade et al. [9] experimentally demonstrated the loss of hydraulic isolation associated with decentralization and thermal variations. This highlights the lack of approaches that simultaneously integrate geometric and poroelastic effects in the analysis of cement sheath structural integrity.

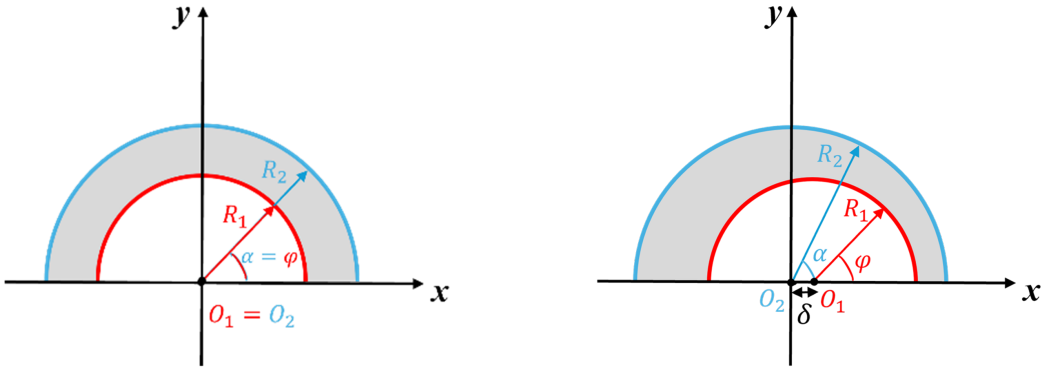
Given these limitations, it becomes necessary to investigate how casing decentralization, combined with the porous behavior of hardened cement, affects the structural integrity of the sheath. Casing decentralization tends to intensify circumferential stresses in the sheath, while the presence of fluid-filled pores alters the internal stress distribution, potentially mitigating or amplifying these effects. In this context, the aim is to assess the extent to which thermoelastic models underestimate the risks to cement sheath structural integrity in decentralized configurations when compared with thermo-poroelastic models, which more realistically account for the porous behavior of cement. This work proposes a comparative analysis between these approaches, intending to investigate the isolated and combined impacts of decentralization and thermo-poroelasticity on the structural integrity of the cement sheath in oil wells.

2 Methodology

The adopted methodology is structured into five main stages. The following sections describe the stages undertaken.

2.1 Definition of the numerical model

In this study, a two-dimensional plane strain model is adopted, representing the cement sheath as a hollow cylinder, with the aim of assessing the effects of geometric decentralization on its structural integrity. The simulations are carried out using the Abaqus® software [10], considering two geometric configurations: one with the sheath centered, Fig. 1(a), and another decentered, Fig. 1(b). The decentralization is described in terms of eccentricity (δ), defined as the distance between the casing center and the wellbore center.



(a) centralized configuration (b) decentralized configuration

Figura 1. Cross-sectional geometry of (a) concentric and (b) eccentric casing configurations, illustrating radii R_1 and R_2, centers o_1 and o_2, and angles α and φ

Two constitutive approaches are adopted: in the first, the cement sheath is modeled as a thermoelastic material; in the second, based on the methodology proposed by Lins [2], its thermo-poroelastic behavior is considered. The strategy adopted in this approach was validated in Lins's dissertation [2], which also provides a tutorial for performing this type of modeling. In this configuration, constant pore pressure is assumed and applied as a boundary condition.

Considering the symmetry of loading and geometry, half of the cross-section is modeled, with vertical constraints at the base. Temperature is assumed to be steady-state and applied as a prescribed field. In addition, an internal pressure P_i is applied to the inner surface, and an external pressure P_o to the outer surface of the sheath. The mechanical response is evaluated as static, disregarding dynamic effects.

The discretization follows the same refinement adopted by Liu et al. [4] for the cement sheath, to maintain compatibility with the reference model. Finite elements compatible with the material behavior are employed:

CPE8R elements, with biquadratic interpolation and reduced integration, for the thermoelastic case; and CPE8RP elements, with biquadratic interpolation for displacements and bilinear interpolation for pore pressure, also with reduced integration, for the thermo-poroelastic case. The final mesh consists of 72 elements in the tangential direction and 10 in the radial direction (Fig. 2).

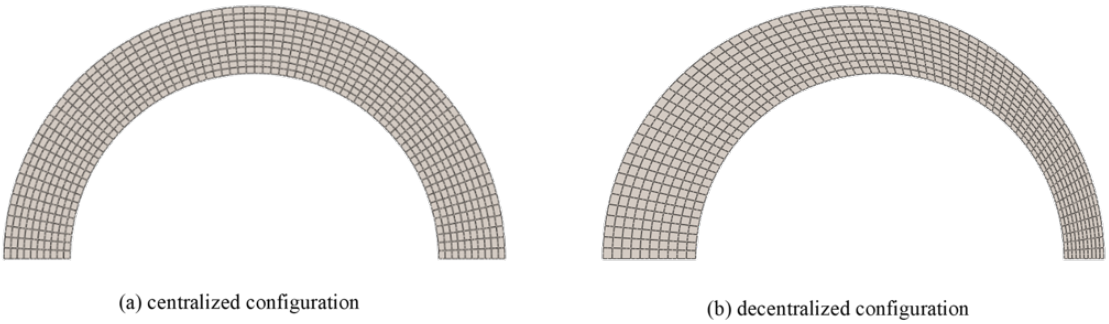


Figura 2. Finite element mesh configuration

2.2 Assignment of physical properties and boundary conditions

The definition of the geometric and elastic properties of the cement sheath is based on the study by Liu et al. [4]. For the thermo-poroelastic approach, the thermal and porous parameters were incorporated based on the data presented by Joulin et al. [8].

The eccentricity adopted to represent casing decentralization is 0.01 m, as also suggested by Liu et al. [4]. As boundary conditions, an internal interface pressure of 30 MPa and an external interface pressure of 50 MPa are applied to the cement sheath. For the analyses, the loading condition proposed by Joulin et al. [8] is adopted, representative of the production start-up event, characterized by a pore pressure of 44.3 MPa and a well temperature of 121 °C.

The physical, geometric, thermal, and porous properties used in the modeling are summarized in Table 1.

Tabela 1. Properties of the cement sheath of the evaluated well section

Parameter	Cement
Outer Diameter (m)	0.189
Inner Diameter (mm)	0.139
Elastic Modulus (GPa)	25
Poisson Ratio (-)	0.3
Biot Coefficient (-)	0.75
Thermal Expansion Coefficient ($^{\circ}\mathrm{C}^{-1}$)	9.00×10^{-6}
Cohesion, c (MPa)	35
Friction Angle, ϕ (°)	15

2.3 Numerical verification of the decentralized model

In order to ensure the reliability of the adopted numerical approach, the model presented by Liu et al. [4], in which only the cement sheath is represented, is initially reproduced. This step aims to validate the model that will be employed in the subsequent analyses.

The same elastic parameters listed in Table 1 are used, as well as the boundary conditions and loadings described in the previous sections. The comparison is carried out in terms of the circumferential stress distribution along the inner interface of the sheath, a parameter that is particularly sensitive to eccentricity.

2.4 Definition of case studies

In order to investigate the effects of casing decentralization and thermo-poroelasticity on the stress distribution in the cement sheath, this study establishes four scenarios, combining two modeling approaches (thermoelastic and thermo-poroelastic) and two geometric configurations (centralized and decentralized). This framework allows for the isolated and combined evaluation of the influence of thermo-poroelasticity and casing eccentricity on the structural integrity of the cement sheath.

The scenarios considered are: (i) thermoelastic model with centralized casing; (ii) thermoelastic model with decentralized casing; (iii) thermo-poroelastic model with centralized casing; and (iv) thermo-poroelastic model with decentralized casing.

All cases employ the same finite element mesh and are subjected to identical thermal and mechanical loadings, ensuring the comparability of results.

These four cases form the basis of the analyses presented in the results and discussion section, allowing for a critical assessment of the combined effects of decentralization and thermo-poroelasticity on the structural integrity of the cement sheath.

2.5 Assessment of the structural integrity of the cement sheath

The structural integrity of the cement sheath is assessed based on the analysis of circumferential stress and the application of the Mogi–Coulomb shear criterion. Circumferential stress is considered because it is the component most sensitive to casing decentralization, as eccentric displacements exert little influence on radial stress but can significantly intensify tangential stresses in the sheath. Additionally, the Mogi–Coulomb criterion is adopted, which extends the classical Mohr–Coulomb model by including the contribution of the intermediate principal stress (σ_2), enabling a more accurate assessment of shear strength under triaxial stress conditions. The linear form of the failure envelope is expressed as:

$$\tau_{\text{oct}} = a + b\sigma_{m,2}, \tag{1}$$

where τ_{oct} represents the octahedral shear stress at failure, and $\sigma_{m,2}$ is the mean of the maximum and minimum principal stresses, defined as:

$$\sigma_{m,2} = \frac{\sigma_1 + \sigma_3}{2}. \tag{2}$$

The coefficients a and b are calculated based on the cohesive strength (c) and the internal friction angle (ϕ), according to:

$$a = \frac{2\sqrt{2}}{3} c \cos\phi \qquad b = \frac{2\sqrt{2}}{3} \sin\phi. \tag{3}$$

The function f_{MG}, used to estimate the structural condition of the sheath, is defined by:

$$f_{MG} = a + b\sigma_{m,2} - \frac{1}{3}\sqrt{(\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_3 - \sigma_1)^2}. \tag{4}$$

Positive values of f_{MG} indicate that the sheath is in a safe structural condition, while negative values signal a potential shear failure.

3 Results and discussions

The results of the numerical model verification are first presented. Comparison with the data from Liu et al. [4] demonstrated strong agreement, with relative errors under 4% at most points (Fig. 3). These results validate the accuracy of the developed model and supports its application in the subsequent analyses.

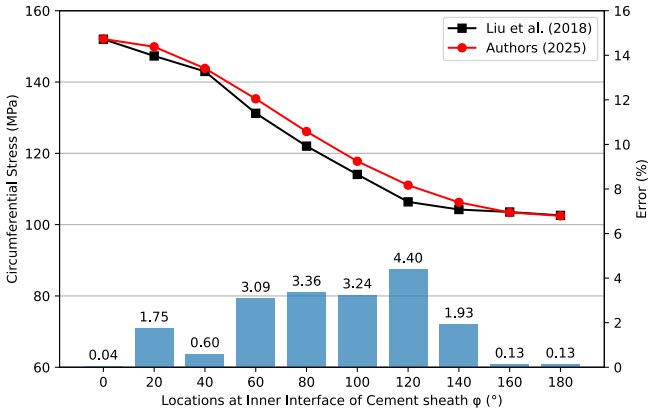
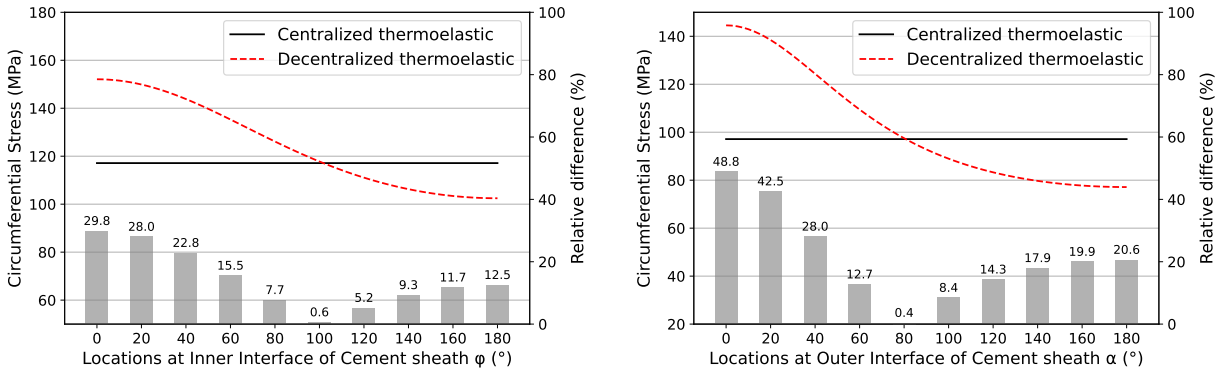


Figura 3. Comparison between numerical results: circumferential stress on the inner interface of the cement sheath

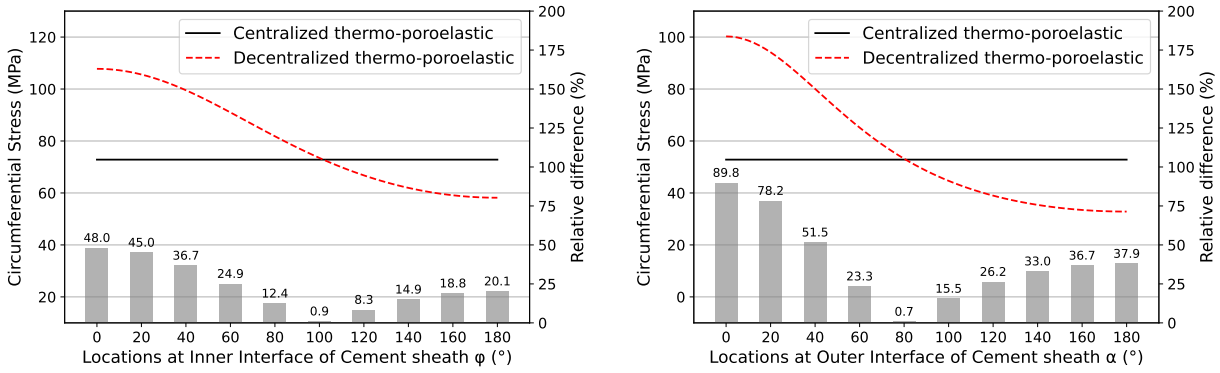
Figures 4 and 5 present a comparative assessment of the effective circumferential stress in the cement sheath, considering the thermoelastic (Fig. 4) and thermo-poroelastic (Fig. 5) constitutive models. Each figure contrasts the ideal (centralized) and eccentric (decentralized) geometric configurations. Subfigures (a) and (b) depict, respectively, the stress distribution at the inner and outer interfaces of the sheath, along with the relative percentage difference between the centered and decentralized cases, thereby quantifying the influence of eccentricity.



(a) Inner interface of the cement sheath

(b) Outer interface of the cement sheath

Figura 4. Comparison between numerical results for the thermoelastic behavior: Circumferential stress in the cement sheath.



(a) Inner interface of the cement sheath

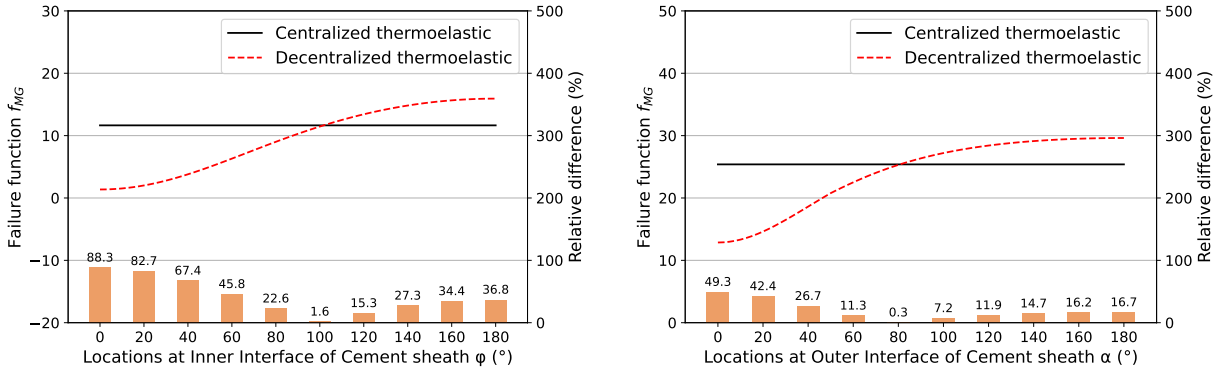
(b) Outer interface of the cement sheath

Figura 5. Comparison between numerical results for the thermo-poroelastic behavior: Circumferential stress in the cement sheath.

In particular, the introduction of thermo-poroelastic behavior in Fig. 5 produces a dual effect. On one hand,

the absolute levels of effective circumferential stress decrease compared to the thermoelastic case, as the pore pressure supports part of the total load, alleviating the stress borne by the cement sheath's solid matrix. On the other hand, the impact of eccentricity becomes markedly more significant: the relative difference between the decentralized and centralized configurations reaches approximately 48% at the inner interface and nearly 90% at the outer interface. Thus, while eccentricity already modifies the stress distribution in the thermoelastic regime, this effect is substantially amplified when pore pressure is accounted for.

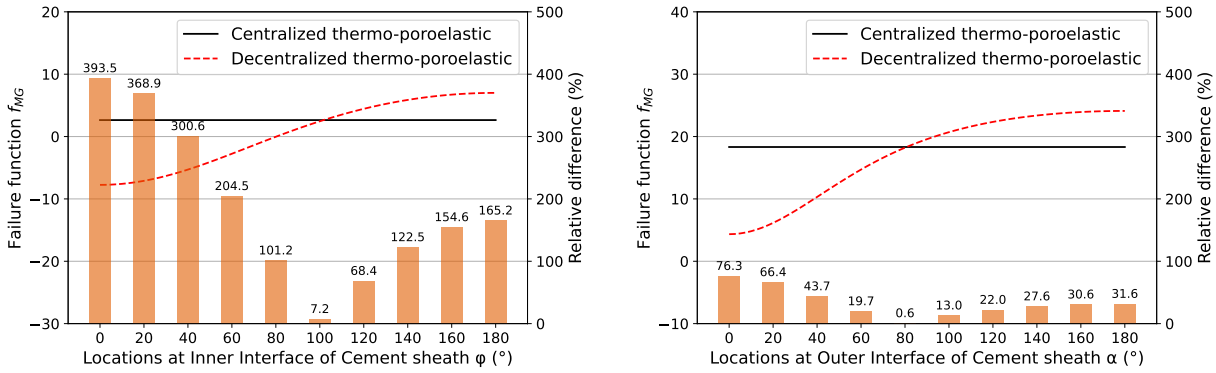
Figures 6 and 7 illustrate the results of the failure function (f_{MG}) for thermoelastic and thermo-poroelastic behaviors, respectively, comparing centralized and decentralized configurations at the inner (a) and outer (b) interfaces. In the centered arrangement, f_{MG} remains essentially constant along the circumferential angle. In contrast, under eccentric conditions, f_{MG} exhibits angular variation, reaching its minimum in the region of reduced thickness indicating a higher susceptibility to structural failure.



(a) Inner interface of the cement sheath

(b) Outer interface of the cement sheath

Figura 6. Failure function (f_{MG}) for thermoelastic behavior.



(a) Inner interface of the cement sheath

(b) Outer interface of the cement sheath

Figura 7. Failure function (f_{MG}) for thermo-poroelastic behavior.

In Fig. 6, the thermoelastic assessment based on f_{MG} indicates the absence of failure ($f_{\mathrm{MG}} > 0$) at both interfaces. The region of minimum sheath thickness ($\phi, \alpha = 0°$) exhibits the lowest safety margin, particularly at the inner interface, where the relative difference between the centralized and decentralized models reaches its maximum. Thus, although eccentricity does not induce failure under these conditions, it significantly reduces the safety margin on the thin side of the cement sheath, making it the most vulnerable point to additional pressure or temperature increments.

Regarding the thermo-poroelastic results in Fig. 7, f_{MG} remains positive for the centered model. However, in the decentralized configuration, the sheath's inner interface exhibits $f_{\mathrm{MG}} < 0$ over a certain angular range, indicating a loss of structural integrity in the corresponding region.

Therefore, for the geometry and loading conditions considered, structural failure was predicted only when eccentricity and porous behavior acted simultaneously, highlighting the importance of accounting for both effects when their concurrent occurrence is plausible.

Finally, it is noteworthy that, although thermo-poroelastic modeling leads to lower effective stress levels, this does not inherently imply greater structural safety. The reduction in principal effective stresses can, in fact,

bring the stress state closer to the strength limit (Mogi–Coulomb criterion), thereby decreasing the safety margin—particularly in the region of minimum thickness under eccentric conditions.

4 Conclusions

This study aimed to evaluate the influence of casing eccentricity on the stress distribution and structural integrity of the cement sheath, in conjunction with thermo-poroelastic effects. The results demonstrated that the geometric configuration plays a decisive role, with eccentricity intensifying the concentration of circumferential stresses in the sector of minimum sheath thickness.

The introduction of thermo-poroelastic behavior reduced the absolute levels of effective circumferential stress compared to the thermoelastic model, owing to the contribution of pore pressure. However, this reduction did not translate into improved structural safety. On the contrary, the combined effect of decentralization and porous behavior significantly amplified the impact of eccentricity, resulting in negative values of the failure function at the inner interface in the region of minimum thickness, indicating loss of structural integrity.

These results highlight the importance of incorporating porous behavior into structural integrity analyses of the cement sheath, particularly when casing eccentricity is a plausible scenario. Neglecting the combined effects of eccentricity and poroelasticity may lead to an underestimation of structural risks, ultimately compromising operational safety over the well's service life.

For future work, it is recommended to extend the simulations to models that incorporate both the casing and the surrounding rock formation, as well as to conduct parametric studies assessing the influence of eccentricity and the Biot coefficient on the results. Such advances could contribute to improved design practices and a more accurate assessment of structural integrity in oil wells.

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