Influence of Creep and Plastic Behaviour on Thermal Fatigue of High-Temperature Geothermal Casings

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ABSTRACT

This study examines the combined influence of plasticity and creep on the thermal fatigue behavior of casing materials used in high-temperature geothermal wells. Through advanced numerical simulations and calibrated material models, the research systematically evaluates how creep-induced stress relaxation and plastic deformation interact during repeated thermal cycling, particularly under the extreme conditions typical of super-hot geothermal environments (>350 °C). Results demonstrate that while plastic deformation contributes to cumulative damage, creep plays a decisive role in casing integrity-especially during cooling phases, where it can significantly accelerate damage evolution and reduce fatigue life. The findings highlight that neglecting creep effects can lead to substantial overestimation of casing durability. To address these challenges, the study implements a Thermo-Plastic-Creep constitutive model and an energy-based damage criterion, enabling more accurate prediction of casing performance under realistic operational scenarios. This work underscores the necessity of incorporating both plastic and creep behavior into the design and analysis of geothermal casings. The adoption of advanced material models and strain-based design methodologies is essential to ensure the long-term reliability and safety of wells operating in super-high-temperature regimes.

1. INTRODUCTION

Super-hot geothermal wells, operating at temperatures exceeding 350 °C, present a substantial opportunity for increased energy yield compared to conventional geothermal systems (200–300 °C). However, these extreme thermal environments introduce significant engineering challenges, particularly concerning the mechanical performance and long-term integrity of casing materials (Gruben et al. 2022). Traditional well designs and standard casing materials, as demonstrated in projects such as the Icelandic Deep Drilling Project, have proven inadequate for withstanding the complex thermo-mechanical loads encountered in super-hot geothermal wells (Kruszewski and Wittig, 2018, Kaldal et al. 2019).

A critical aspect of well integrity under these conditions is the pronounced influence of creep-a time-dependent deformation mechanism that becomes increasingly significant at elevated temperatures and over long service periods (Hoang et al. 2021, Gruben et al. 2022, Suryanarayana et al. 2016). Creep affects multiple failure modes, including burst, tensile failure, and both axial and radial buckling, and its impact can be either beneficial (e.g., stress relaxation during start-up) or detrimental (e.g., increased risk of tearing during operation), depending on the stage of the casing's lifecycle. Despite foundational work on strain-based design approaches for tubulars (e.g., Holliday, 1969) and more recent industry guidelines (e.g., Canadian Industry Recommended Practice, 2012), current standards such as NZS 2403 (2015) offer limited quantitative direction for post-yield and creep-informed design, especially for temperatures above 200 °C.

In this context, the interplay between creep, plasticity, and thermal fatigue must be rigorously addressed to ensure the structural integrity of casings subjected to cyclic thermal loading. Experimental investigations have shown that, at 500 °C, the creep rates of common carbon steels, titanium, and nickel alloys used in casings increase by two to three orders of magnitude compared to 350 °C, with nickel alloys exhibiting superior resistance to creep at lower temperatures. To capture these effects, advanced material models-such as the calibrated Norton creep law-are essential for accurate prediction of long-term casing performance.

To enhance the reliability and flexibility of casing design for super-hot geothermal wells, a Thermo-

Plastic-Creep material model has been implemented within a strain-based design framework using the specialized software CASINTEG (Hoang et al. 2021). This approach incorporates temperature-dependent elastic, plastic, and creep properties, and is further complemented by an energy-based damage criterion that extends the Cockroft-Latham model for ultra-low-cycle fatigue (ULCF), allowing for practical assessment of thermal fatigue life under cyclic loading[1]. The adoption of such models enables a more robust post-yield design methodology, addressing the limitations of traditional working stress design and supporting the deployment of geothermal wells in increasingly demanding environments.

2. PLASTIC AND CREEP BEHAVIOUR OF CASING

2.1 Plasticity of Carbon Steel Casings

Carbon steel grades such as API K55, L80, T95, and P110 are widely used for well casings due to their favorable combination of strength and ductility. Under tensile loading at room temperature, these steels exhibit classic ductile behavior, characterized by a distinct yield point followed by significant plastic deformation. For instance, API K55 typically demonstrates a yield strength ($R_{p0.2}$) of 397–444 MPa, an ultimate tensile strength of 714–738 MPa, and an elongation at necking (A_{gt}) of 11–13.5%.

However, as temperature increases, both the yield and ultimate tensile strengths of these steels decrease markedly, and ductility is significantly reduced. Figure 1 shows typical stress strain curves of K55 obtained at different testing temperatures (Grube et al. 2021). At 500°C, API K55 exhibits a yield strength of only 281–314 MPa and a tensile strength of 332–407 MPa, with elongation at necking dropping to 3.6–5.2%. This reduction in mechanical properties at elevated temperatures is primarily due to thermally activated dislocation movement and microstructural changes such as grain growth and carbide precipitation.

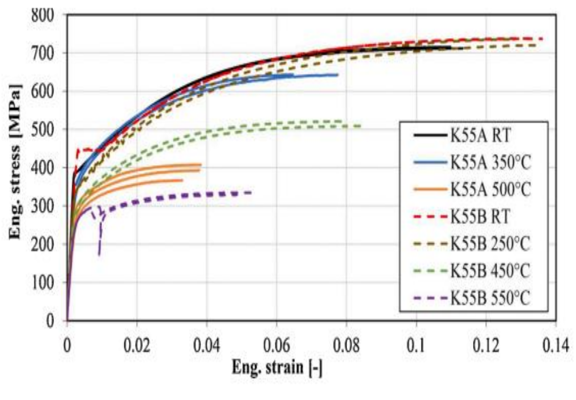

Figure 1: Engineering stress-strain curves from all tensile tests on the K55 materials (Gruben et al. 2021)

Figure 2 shows the loss in yield strength in carbon steel casing materials as temperature increases, reinforcing the need for careful material selection and derating in high-temperature geothermal applications. The close agreement between experimental data in the work by Gruben et al. (2021) and NZS 2403 code values also supports the use of these factors in engineering practice for casing design at elevated temperatures.

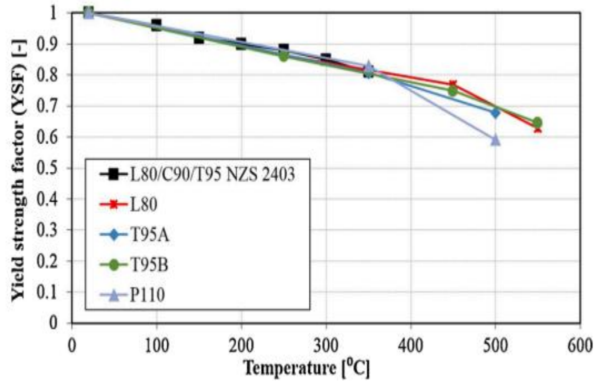

Figure 2: Yield strength factor (YSF) for different carbon steel grades (Gruben et al. 2021).

In geothermal and other high-temperature wells, plastic deformation becomes a critical design consideration. Thermal cycling and elevated in-situ stresses can induce permanent plastic strains, particularly as the material's yield strength diminishes with temperature. This increases the risk of casing fracture and loss of well integrity if the applied stresses exceed the reduced strength of the material. Therefore, a strain-based design approach is increasingly necessary for wells operating at super-hot temperatures.

Plastic deformation becomes particularly relevant in geothermal and high-temperature wells. Thermal cycling and high in-situ stresses can induce permanent plastic strains, potentially leading to casing fracture if the material's strength is exceeded. The reduction in yield and tensile strength at elevated temperatures means less stress is needed to cause plastic deformation, increasing the risk of well integrity issues.

2.2 Creep Behaviour

Creep, defined as the time-dependent plastic deformation of materials under constant load, is a major concern for carbon steel casings in wells operating above 350°C. At these temperatures, the rate of creep deformation accelerates significantly, affecting the long-term structural integrity of the casing.

Figure 3, adapted from Gruben et al. (2022), presents the experimentally measured true secondary creep strain rates as a function of true stress for the tested casing materials. The figure clearly shows the exponential increase in creep rate with both stress and temperature. For example, the steady-state (secondary) creep rate of carbon steels such as API K55, T95, and P110 increases by two to three orders of magnitude as the temperature rises from 350°C to 500°C.

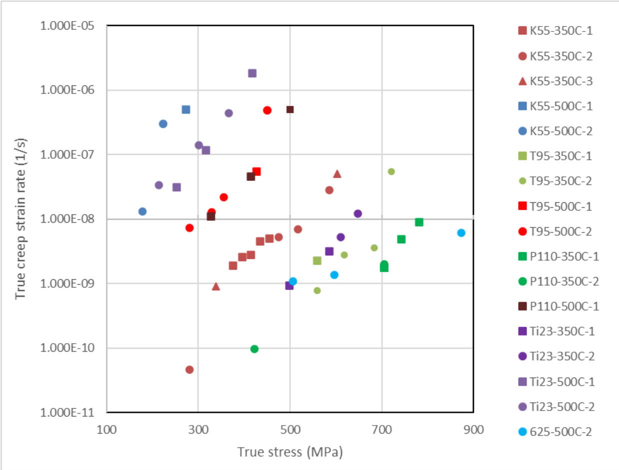

Figure 3: Experimental rue secondary creep strain-rate as function of true stress for the tested materials. (Gruben et al. 2022)

For more comprehensive data and analysis, readers are referred to Gruben et al. (2022). The authors further emphasize that while creep-induced stress relaxation can be beneficial in certain operational phases (such as reducing the risk of buckling during thermal expansion), excessive or long-term creep may lead to detrimental effects, such as tearing during other operational phases. The results from these authors highlight the need for careful material selection and advanced design methodologies in high-temperature geothermal wells to ensure the long-term integrity of the well.

3. CONSITUTIVE MODEL OF CASING MATERIAL

The constitutive material model was developed and implemented in CASINTEG (Hoang et al. 2021). to account for temperature effect, plasticity and creep behaviour of casing. The main ingredients of the model are a yield criterion, isotropic thermal expansion, associated flow rule with a nonlinear isotropic strain-hardening rule, and Norton-like creep law. More details can be found in the work by Hoang et al. (2021). However, the main constitutive equations are described below for the sake of clarity.

3.1. Plasticity and Creep

The strain tensor $\boldsymbol{\varepsilon}$ is assumed to be additionally decomposed into thermal, elastic and plastic and creep part parts:

$$\boldsymbol{\varepsilon} = \boldsymbol{\varepsilon}_{\boldsymbol{\tau}} + \boldsymbol{\varepsilon}_{\mathbf{e}} + \boldsymbol{\varepsilon}_{\mathbf{p}} + \boldsymbol{\varepsilon}_{\mathbf{c}} \qquad (1)$$

where $\boldsymbol{\varepsilon}_{\boldsymbol{\tau}}$, $\boldsymbol{\varepsilon}_{\mathbf{e}}$, $\boldsymbol{\varepsilon}_{\mathbf{p}}$ and $\boldsymbol{\varepsilon}_{\mathbf{c}}$ are respectively the thermal, elastic, plastic and creep strain tensors. The relation between the Cauchy stress tensor and strain is defined as:

$$\boldsymbol{\sigma} = \mathrm{C}:\boldsymbol{\varepsilon}_{\mathbf{e}} = \mathrm{C}:\left(\boldsymbol{\varepsilon} - \boldsymbol{\varepsilon}_{\mathbf{e}} - \boldsymbol{\varepsilon}_{\mathbf{p}} - \boldsymbol{\varepsilon}_{\mathbf{c}}\right) \qquad (2)$$

Where is $\mathbf{C}$ is the fourth-order tensor of elastic constants.

Assuming isotropic thermal expansion, thermal strain tensor can be calculated by:

$$\boldsymbol{\varepsilon}_{\boldsymbol{\tau}} = \alpha \Delta\tau \mathbf{I} \qquad (3)$$

in which α is the coefficient of thermal expansion, $\Delta\tau$ is the temperature change, and $\mathbf{I}$ the unit tensor. The plasticity is modelled using von-Mises yield criterion with isotropic strain hardening. The yield function f which defines the elastic domain in stress space, is expressed as:

$$f = f(\boldsymbol{\sigma}) - \sigma_Y = \sigma_{VM} - \sigma_Y \leq 0 \qquad (4)$$

in which σ_{VM} is the equivalent von-Mises stress and σ_Y is the follow stress. The latter is modelled with the Hollomon hardening power constitutive law as follows:

$$\sigma_Y = \sigma_0 + A\overline{\varepsilon_p}^{\,n} \qquad (5)$$

where $\overline{\varepsilon_p}$ is the equivalent plastic strain, while σ_0 , A and n are material parameters defining the temperature dependent yield stress and strain hardening, respectively.

For creep modelling, only the secondary creep is accounted for in the model and the Norton creep law is used to express the logarithmic (secondary) creep strain rate $\dot{\overline{\varepsilon_c}}$ as follows:

$$\dot{\overline{\varepsilon_c}} = K\left(\frac{\sigma_{VM}}{\sigma_0}\right)^m \qquad (6)$$

In Eq. 6, K and m are material parameters defining the temperature dependency of secondary creep behaviour. It is to note that owing to stress normalization, m is dimensionless while K is only time dependent parameter.
The plasticity and creep model parameters are calibrated using the tests from Gaute et al. (2021, 2022) and summarized in Table 1 for the API K55 grade.

Table 1: Material parameters for API K55 grade.

Temp	Young's modulus	σ_o	A	n	K	m	W_d
[°C]	[°C]	[MPa]	[MPa]	[-]	[MPa]	[-]	[MPa]
RT	210	380	1473	0.52	0.0	0.0	668
350	176	288	1205	0.39	6.68E-7	7.48	680
500	134	213	520	0.29	3.85E-4	8.56	287

3.1. Damage

In order to account for the accumulation of damage under thermal cycling, a damage model is implemented in Casinteg for casing material. The Cockroft-Latham based damage model, and the incremental damage ΔD is written as follows:

$$\Delta D = \frac{(\Delta\overline{\varepsilon_p} + \Delta\overline{\varepsilon_c}).\max\langle\sigma_I, 0\rangle}{W_d} \qquad (7)$$

Where $\Delta\overline{\varepsilon_p}$ and $\Delta\overline{\varepsilon_c}$ are respectively the incremental values of equivalent plastic strain and creep strain. σ_I is the first principal stress from the stress tensor, while W_d is the damage parameter, depending on materials and temperature. Whether or not the creep is contributing to plastic damage evolution remains unclear. However, users have the possibility to include or exclude $\overline{\varepsilon_c}$ from Eq. (7), in order to investigate the influence of creep strain on the casing damage under thermal cycling. Due to the lack of data, the damage parameter W_d is calibrated from the tensile stress-strain curves of K55 for different temperatures and summarized in Table 1.

4. NUMERICAL MODELLING

To investigate the effects of plasticity and creep on the thermal fatigue of casing, FEA models of a 12m long well segment, consisting of casing, cement and formation multi-layers, were established in CASINTEG, see Figure 4a for illustration. The casing string is 12mm thick, while the cement sheath thickness is determined by the casing geometry and drill bit geometry. Three and five elements through thickness were used to model the casing and cement, as illustrated in Figure 4b. The rock radius is 10m, sufficiently large to model the far field condition. The established model geometry is summarized in Table 2.

Table 2: Model geometry.

Outer diameter (OD)	Casing OD (inch)	Drill bit OD (inch)	Rock OD (m)
Casing	9" 5/8	12" 1/4	10

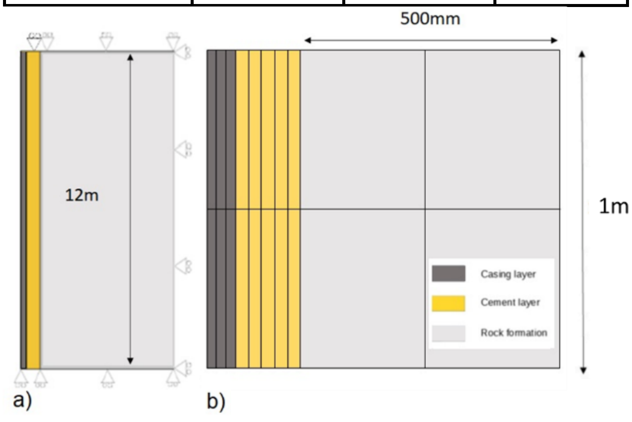

Figure 4. a) Casing segment models (12m long) and b) Illustration of meshed model

The cement and rock materials are modelled using a thermo-elastic model, while casing is modelled by the constitutive equations in Section 3. Typical thermo-mechanical properties of casing, cement, and rock materials can be found in Table 3. The bottom and top of the whole model were constrained in the axial displacement, except for the production casing string. The radial displacement of the end rock was constrained, see Figure 4a for illustration. The initial temperature in the whole model was set homogeneously at 50°C. Cyclic temperature loads are applied to the inner surface of the casing, with one thermal cycle defined as follows: ramping from 50°C to 400°C over one day, maintaining 400°C for 60 days, then cooling down to 50°C and holding it constant for 10 days, as shown in Figure 5.

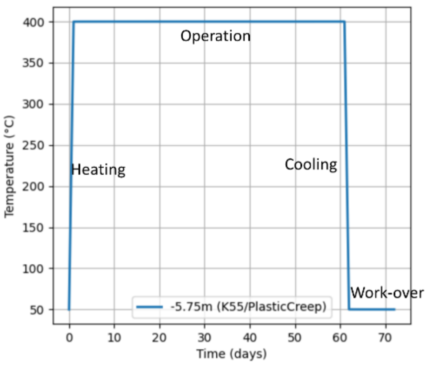

Figure 5. One cycle temperature loading in the wellbore (on the casing inner surface).

Table 3: Material parameters.

Materials	Casing steel	Cement	Rock
Young modulus (GPa)	217	10	50
Poisson's ratio	0.30	0.15	0.3
Thermal Expansion (10-6/K)	12	10	5.4
Density (kg/cm3)	7800	1900	2650
Specific heat (J/kg/K)	400	880	840
Thermal Conductivity (W/m/K)	50.4	0.81	2.0

5. NUMERICAL RESULTS

Figure 6 shows the temperature distribution in the well segment at different times during the simulation. It can be observed that the temperature in the cement reaches a steady state after approximately 30 days of heating. During cooling, the temperature in the cement follows the temperature change in the casing quite rapidly. However, the temperature in the rock (at the 1m radius) remains largely unaffected by the temperature fluctuations in the wellbore after 1 day cooling.

5.1. Influence of materials models used for modelling the casing

To investigate the effects of material models used for casing design, simulations were performed considering three cases: thermo-elastic behavior, thermo-plastic behavior, and thermo-plastic behavior with creep. Figure 7 shows the plot of axial stress as a function of simulated time for these cases. As observed, considering only elastic behavior results in a significant overshoot in the actual stress in the casing. It is crucial to account for thermo-plastic behavior during the warm-up phase to enable strain-based casing design. On the other hand, creep behavior leads to stress relaxation in the casing during operation, which is beneficial for casing integrity. However, the plastic and creep behaviour results in high tensile stress in the casing upon cooling. This high tensile stress is a primary driver for tensile failure in high-temperature geothermal casings during cool-down. The results highlight that the casing's creep behavior cannot be neglected in the reliable design of geothermal wells, especially under super-high-temperature conditions.

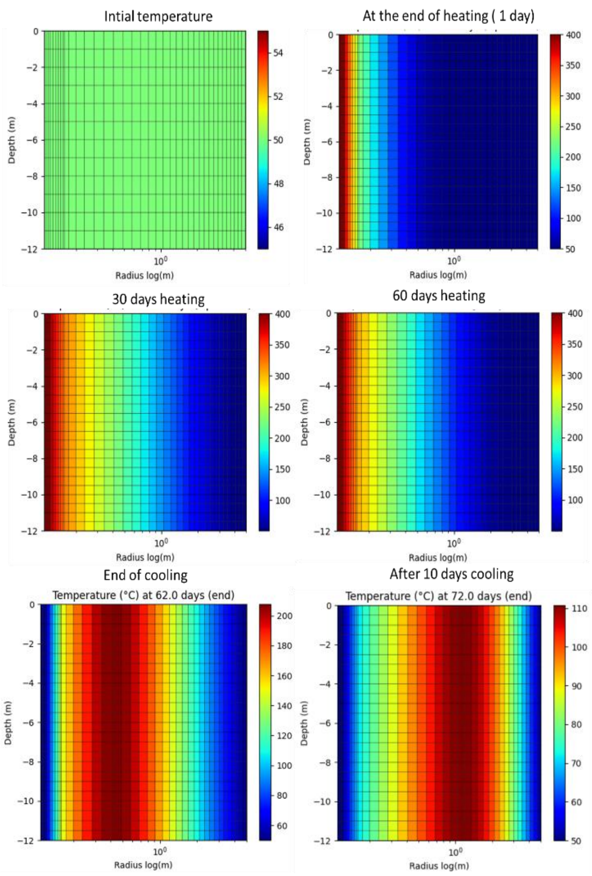

Figure 6. Temperature fields in the model at different times.

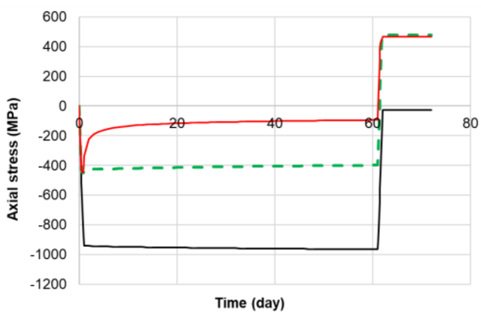

Figure 7. Influence of used material models on the stress prediction for casing.

Figure 8a shows the effects of creep behavior on the plastic strain evolution in the casing. As observed, creep behavior results in lower plastic deformation during heating but higher plastic deformation during cooling. The latter leads to higher damage in the casing when using the Plastic-creep model, as seen in Figure 8b. During heating, the stress state in the casing is negative, and the plastic deformation in this phase does not contribute to damage evolution, according to Eq. (7). As a result, damage in the casing is zero for both the Plastic-creep model and the Plastic model during heating. However, during cooling, tensile (positive) stress is developed in the casing, and the plastic deformation in this phase contributes to damage evolution. This explains the higher damage evolution in the casing with the Plastic-creep model during thermal cyclic loading, as seen in Figure 8b.

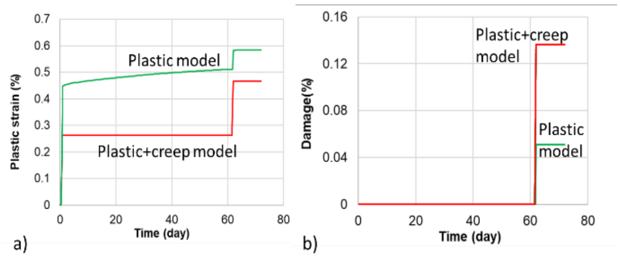

Figure 8. Influence of Plastic and Creep material models on a) Plastic strain and b) Damage prediction in the casing.

Under this thermal cyclic loading, the Plastic model predicts a lifetime of approximately 2000 cycles, while the Plastic-Creep model predicts around 670 cycles for K55 casing under investigation. It is important to note that the predicted thermal fatigue lifetime applies only to the smooth casing string. The actual casing string includes threaded couplings, which result in significantly higher plastic deformation due to stress concentration at the threaded joints. Therefore, the actual fatigue lifetime of the casing string could be much lower. For more reliable predictions of thermal fatigue, it is essential to consider the stress concentration factor due to joint geometry. While this is not the focus of the present study, the current results suggest that it is crucial to account for the creep behavior of the casing when modeling thermal fatigue in geothermal wells.

5.2. Effects of cooling temperature

Different locations in the well may experience different temperatures when cooling down (shut-in) for work-over. In order to investigate these effects of, simulations are run with different temperature cycling loading as shown in Figure 9. In these simulations, the Plastic-Creep model is used for the casing.

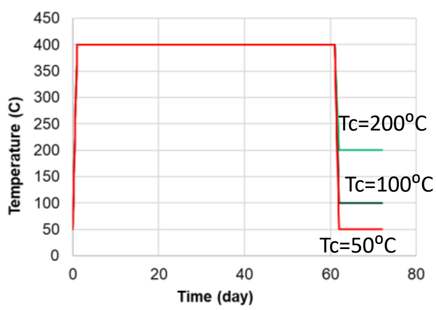

Figure 9. Temperature cycling with different cooling temperatures Tc.

Figure 10 shows the axial stress in the casing for the three corresponding cooling temperatures. As expected, higher temperatures result in less axial stress in tension during the cooling phase. However, for the K55 casing under investigation, only a slight reduction in stress is observed as the cooling temperature increases.

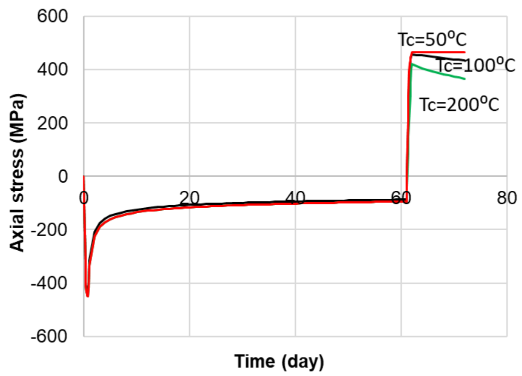

Figure 10. Axial stress in the casing for three cooling temperatures Tc.

However, the cooling temperature has a more pronounced effect on plastic strain and, consequently, on the damage evolution in the casing. As shown in Figure 11, cooling the well to 200°C results in a damage evolution of about 0.03% per cycle, which is five times lower than the damage observed in the casing when cooling to 50°C. This indicates that the casing is safer in locations experiencing less cooling.

It is also interesting to observe that plastic deformation does not develop in the casing when the temperature is held constant after cooling. However, damage increases due to the contribution of creep deformation at high temperatures. The increase in damage after cooling is more significant with higher cooling temperatures. When cooling to 50°C, no damage evolution is observed after cooling, as no creep deformation is expected in the casing material at such a low temperature.

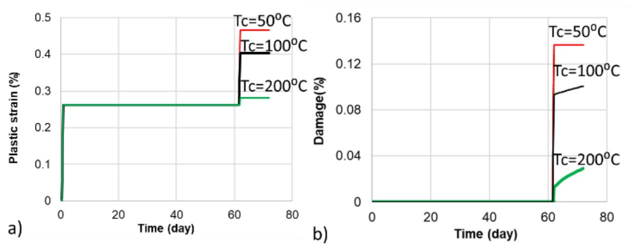

Figure 11. Influence of cooling temperature Tc on a) Plastic strain and b) Damage prediction in the casing.

6. CONCLUDING REMARKS

The integrity and long-term performance of casing materials in high-temperature geothermal wells are fundamental to the safe and efficient operation of these energy systems. This study provides a numerical assessment of how both plasticity and creep behaviour influence the thermal fatigue life of geothermal casings subjected to severe cyclic thermal loading.

The results demonstrate that creep-induced stress relaxation can be advantageous during certain operational phases, such as thermal expansion, by reducing peak stresses and mitigating buckling risks. However, during cyclic loading-particularly in the cooling phases-creep becomes a dominant factor in damage evolution, significantly accelerating fatigue and reducing the predicted service life of the casing. Numerical simulations reveal that models incorporating both plasticity and creep (Plastic-Creep models) predict substantially shorter fatigue lives compared to models considering plasticity alone, underscoring the importance of accounting for time-dependent deformation mechanisms in design.

The findings also highlight that plastic deformation, while contributing to cumulative damage, is not the sole driver of casing failure under thermal cycling. Instead, the interaction between plasticity and creep-especially during rapid temperature fluctuations-determines the rate and extent of damage accumulation. Furthermore, the study shows that the extent of cooling during shut-in or work-over operations has a pronounced impact on damage evolution: lower cooling temperatures result in higher tensile stresses and greater damage per cycle, while maintaining higher minimum temperatures during cooling can significantly extend casing life.

While the present study highlights the importance of integrating both plastic and creep behaviour for robust casing design in super-hot geothermal wells, future work is still needed to improve model reliability. For instance, casing systems with threaded couplings are subject to additional stress concentrations, leading to greater local deformation and potentially much shorter operational lifespans. Additionally, advancements in cement modelling, particularly incorporating cement hydration phenomena, are crucial for more accurately representing well downhole conditions. These improvements will be essential for developing robust design methodologies that ensure the long-term integrity and safety of geothermal wells operating in extreme environments.

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