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FATIGUE LIFE PREDICTION OF A BUTTRESS CASING CONNECTION EXPOSED TO LARGE TEMPERATURE VARIATIONS

C. Teodoriu, G. Falcone

Texas A&M University
3116 TAMU
College Station, TX, 77843, USA
e-mail: catalin.teodoriu@pe.tamu.edu, gioia.falcone@pe.tamu.edu

ABSTRACT

When the thermal stresses induced in a geothermal well's casing string exceed the yield strength of the casing material, the fatigue behavior of the latter can be defined as low cycle fatigue (LCF). The connection threads in the casing body amplify the local stress distribution and lower LCF resistance.
A theoretical approach is presented to evaluate LCF resistance and compared with preliminary results from experiments on a large diameter buttress connection. The latter is commonly used in geothermal well completions. This paper shows that, under extreme loads, the LCF resistance of the buttress thread connection can be as low as 10 cycles.

INTRODUCTION

Over the operating life of a well, its casing string is generally subject to external loads that can be considered as static or quasi-static. Current industry design standards consider the casing string to be statically loaded, yet it can be subject to variable loads due to changes in temperature or internal pressure in geothermal operations. As casing movement is restricted by the presence of a cement sheath, temperature variations induce thermal stresses in the casing string, which may become greater than the material's yield strength. Thus, the fatigue behavior of the casing material during a well's operational life can be classified as LCF. The presence of geometrical variations in the casing body such as the connection threads will amplify the local stress distribution, and reduce the casing's LCF resistance.
The diameter of the last casing string in a geothermal well, often termed the production casing, is commonly 9-5/8 inches (Teodoriu, 2005). Such a large diameter pipe requires a correspondingly larger surface casing and a 13-3/8 inches diameter is commonplace in the USA and Japan (Bohm, 2000; Jotaki, 2000; Williamson, 2001). In Europe, most of the wells drilled to depths deeper than 4000 m are completed with surface casing diameters of 18-5/8 inches or greater (Tanzer, 2001).
The large diameter of production casings is a consequence of the amount of fluids (and associated heat) to be pumped from geothermal wells.
The surface casings of deep geothermal wells are exposed to significant temperature variations during drilling, which may affect their subsequent integrity.
The following theoretical and experimental work focuses on the fatigue resistance of an 18-5/8 inch diameter casing with Buttress thread connections.

THEORETICAL BACKGROUND

Local Stress/Strain Concept (LSSC) uses the local stress state to determine the fatigue resistance of materials. LSSC allows the evaluation of LCF resistance of components having notches (which act as stress concentration zones) using the experimental results of uniaxial small scale specimens. Casing connections are known to have stress concentration zones due to thread geometry. Classic fatigue estimation requires intensive full scale testing. Figure 1 shows the number of points used to determine the stress versus number of cycles to failure curve (S-N curve) for drill pipes. The application of the local stress concept reduces the time and cost needed for a traditional statistical evaluation using full scale specimens.

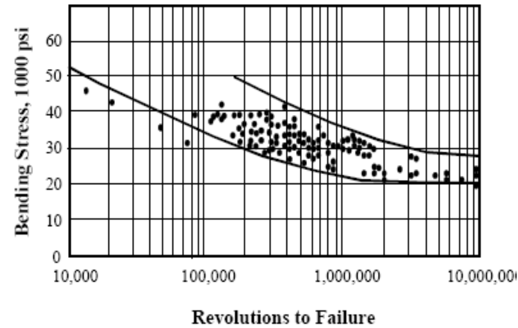

Fig.1. S-N curve for grade D drill pipe, (Warren et al. 2000)

Two input data are required for the application of the LSSC: the experimental determination of the stress/strain curve (σ/ε curve) and an evaluation of the local stress distribution.

The stress/strain curve is measured using pure uniaxial load, with constant deformation cycles. The results can be represented as a stress/strain diagram or a Wöhler diagram (Teodoriu, 2005). The stress vs. strain dependency can be written using the Ramberg-Osgood correlation (Ulmanu, 2001):

$$\varepsilon_a = \varepsilon_{a,e} + \varepsilon_{a,p} = \frac{\sigma_a}{E} + \left(\frac{\sigma_a}{K'}\right)^{1/n'} \quad (1)$$

where:

ε_a - amplitude of total strain;

$\varepsilon_{a,e}$,- elastic strain amplitude;

$\varepsilon_{a,p}$ - plastic strain;

σ_a - total stress amplitude;

E - Young’s modulus;

K' - cyclic hardening coefficient;

n' - cyclic hardening exponent;

K', n', E - to be experimentally determined.

The Wöhler-type diagram (Teodoriu, 2005, Ulmanu, 2001) can be drawn using the following equation:

$$\varepsilon_a = \varepsilon_{a,e} + \varepsilon_{a,p} = \frac{\sigma_f'}{E} \cdot (2 \cdot N)^b + \varepsilon_f' \cdot (2 \cdot N)^c \quad (2)$$

where:

σ'_f is fatigue strength coefficient;
ε'_f - fatigue ductility coefficient;
b - fatigue strength exponent
c - fatigue ductility exponent
2N – number of cycles to failure (N – semicycles).

The experimental determination of σ_f‘, ε_f‘, b and c is required because the stress-strain curve differs from static to cyclic loading. The b and c parameters are material constants experimentally determined, or estimated based on casing material characteristics determined by tensile test. When the external load variation is slow, the static stress/strain load may be used without introducing large errors. For example, Figure 2 shows a comparison between static and cyclic stress-strain curve for 42 CrMo4 steel.

Fatigue determination using the local stress/strain method is based on the cyclic behavior of materials, on the relationship between external loads and local generated stress, and on the evaluation of the stress/strain curve. The result is represented as a Wöhler diagram or stress/strain curve for a technical crack having a length of 0.5 to 1.0 mm.

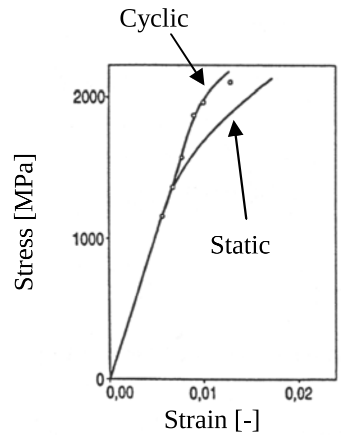

Fig.2. Comparison of static and cyclic stress/strain diagrams for 42CrMo4/SAE 4142, hardened (Teodoriu, 2005)

The relationship between local and average stresses and strains is given by the Neubert equation (Ulmanu, 2001):

$$K_t^2 = K_{t\sigma} \cdot K_{t\varepsilon} = \frac{\sigma_a}{S} \cdot \frac{\varepsilon_a}{e} \quad (3)$$

where:
K_t - total intensity factor;
K_{ts} - intensity factor for stress;
K_{te} - intensity factor for strain;
σ_a, ε_a - local stress and local strain;
S, e - average stress and average strain.

Using the notation e = S/E, the following equation for the elastic domain can be written:

$$\sigma_a \cdot \varepsilon_a \cdot E = (K_t \cdot S)^2 \quad (4)$$

where E is Young’s modulus.

The left hand term ($\sigma_\alpha \varepsilon_\alpha E$) represents a damage parameter that, for different loads, describes the corresponding damage. According to Smith et al (Ulmanu, 2001), the damage parameter (noted as P_{SWT}) can be calculated as follows:

$$P_{SWT} = \sqrt{\sigma_a \cdot \varepsilon_a \cdot E} \quad (5)$$

The so-called modified Wöhler curve of P_{SWT} can be determined using the following equation:

$$P_{SWT} = \sqrt{\sigma_f'^2 \cdot (2 \cdot N)^{2b} + \sigma_f' \cdot \varepsilon_f' \cdot E \cdot (2 \cdot N)^{b+c}} \quad (6)$$

By solving equations 2 and 4, it is possible to determine the local stress and strain for a given load.

By replacing them in equation 5, the parameter P_{SWT} can be determined and the number of semi cycles, N, can be calculated using equation 6.
The influence of the average tension on the damage process must also be considered. The following equation can be used to this aim:

$$\sigma_0 = a_M \cdot (\sigma_m + \sigma_a) \qquad (7)$$

where:
a_M - correlation coefficient, calculated as:

$$a_M = (M+1)^2 - 1$$

σ_m - average stress;
σ_a - stress amplitude;
M - factor depending on material characteristics.

For specific notch geometries, the stress concentration factor can be calculated using empirical formulae.
The equivalent notch of a casing connection thread can be modeled by using the so-called V- or U-type notch. For the U-type notch (see Figure 3), the German standard DIN 471 (1990) provides the following formula (assuming a bending stress state):

$$K_t = 1{,}14 + 1{,}08 \cdot \sqrt{\frac{t}{r}} = 1{,}14 + 1{,}08 \cdot \sqrt{\frac{1{,}57}{0{,}2}} = 4{,}17$$

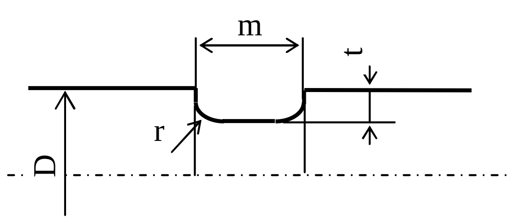

Fig.3. Typical U-type notch that mimics a threaded connection, DIN 471 (1990)

For standard threaded connections (nut and bolt) the stress concentration factor is considered to be between 4 and 10, according to (Buch, 1988).

NUMERICAL INVESTIGATIONS

The Finite Element Method (FEM) was used to better understand the stress state in the threaded connection. The first goal was to estimate the stress concentration factors within the complete and incomplete thread turns. Changes in material properties due to high temperature were not initially considered, as it was assumed that the stress concentration factor is a function of the geometry only.
A 2D model was used, as presented in Figure 4, as it provided fast and reliable results. A commercial FEM environment was used for this simulation.

The stress concentration factor is defined as the maximum stress that occurs in the connection (commonly at the thread root) vs. the average stress in the casing body.

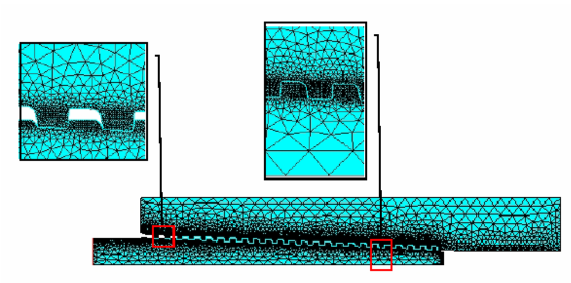

Fig.4. Geometry and mesh of a 2D finite element model of an 18-5/8 inch diameter casing connection.

Based on the FEM analysis, it was found that, for a buttress connection, the stress concentration factor, K_T, differs from tension to compression. This variation can be explained by the more aggressive bending on the thread turn for the tensile load.
The different way in which the connection responds to the loads was evaluated using a 3D model, as presented in Figure 5. The deformation of the thread turns under a tension load is different from that under a compression load. The following results were obtained: $K_t = 3{,}51$ for tension, $K_t = 2{,}73$ for compression. (

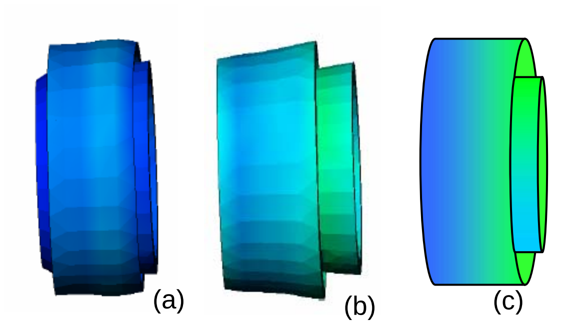

Fig.5. The qualitative representation of the deformation of a compression loaded (a), tension loaded (b) threaded connection compared to the non-deformed status (c)

Figure 6 shows thread turns under compression and tension loads, with high resulting stresses at the thread root (shown in red). In reality, the incomplete thread turns present sharp edges and therefore higher stress concentration factors may be expected.

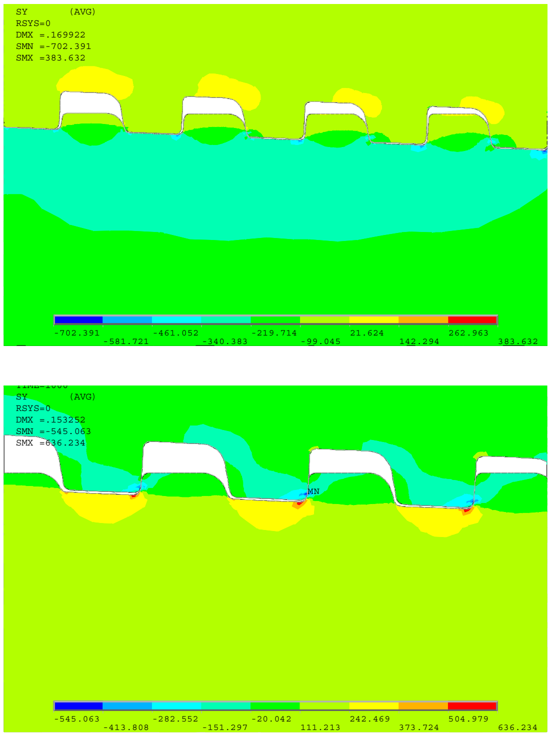

Fig.6. Stress distribution at the thread root for the compression (top) and tension (bottom) load cases, as simulated with FEM.

THERMAL INDUCED FATIGUE

To determine the influence of temperature on casing fatigue, the following assumptions were made:

- The casing cannot move in the cement sheath.
- There are no radial constraints.
- The induced average stresses remain in the elastic domain.

The induced thermal stresses are given by the following equation:

$$S_0 = \alpha \cdot E \cdot \Delta t \qquad (8)$$

where:
S_0 – thermal induced stress
α - expansion coefficient,
E - Young's modulus,
Δt - differential temperature to which casing is exposed.

Material properties such as the yield strength change with temperature. This leads to the fact that, at elevated temperatures, the resistance of a casing is lower than at ambient temperature. Figure 7 shows the yield strength variation with temperature for different OCTG grades (Lari, 1997).
Table 1 shows the temperature variation that induces thermal stresses equal to material yield strength for commonly used grades of steel pipe. The values presented in Table 1 were calculated using equation (8) and the following values for steel expansion coefficient, α, and steel young modulus, E:
α = 12.5E-06 1/^{0}C, E = 2.05E05 MPa

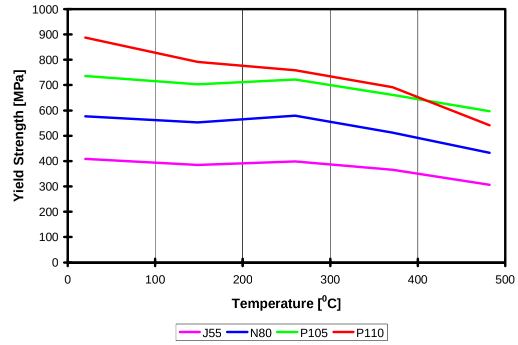

Fig. 7. Yield Strength of different OCTG grades as a function of temperature, after Lari (1997)

Table 1. Temperature induced stresses in steel pipe

Grade	J55	N80	P105	P110
Temp in ^{0}C	157	222	286	310
Yield strength (temperature corected) in MPa	392	553	712	771

DISCUSSIONS

As shown in Table 1, any high-enthalpy geothermal well will cause plastic deformation even to casing strings made of high-grade steel. It is also important to note that, for low-enthalpy geothermal wells with temperatures below 120^{0}C, a J55 steel-grade pipe is adequate. In this case, the well depth and the required collapse resistance are the parameters that will dictate the appropriate selection of steel grade.
Figure 8 shows the modified Wöhler curve obtained from the LSSC theoretical model. The y-axis represents the maximum differential temperature to which the casing is subjected. Table 2 shows the parameters used for the casing fatigue estimations. All parameter are shown in equation 6.

Table 2. Parameters used for casing fatigue calculations

Parameter	Notation	Value
Constant	b	-0,079
Constant	c	-0,869
Young's Modulus	E	182000 MPa
Maximum strain	ε_f	1,78
Tension strength	σ_f	720 MPa

Figure 8 shows that, for extreme temperature variations, the fatigue resistance of the connections is as low as 10 cycles. It took 12 cycles to reach fracture with the full-scale experimental tests, corresponding to a stress concentration factor of 4.17.

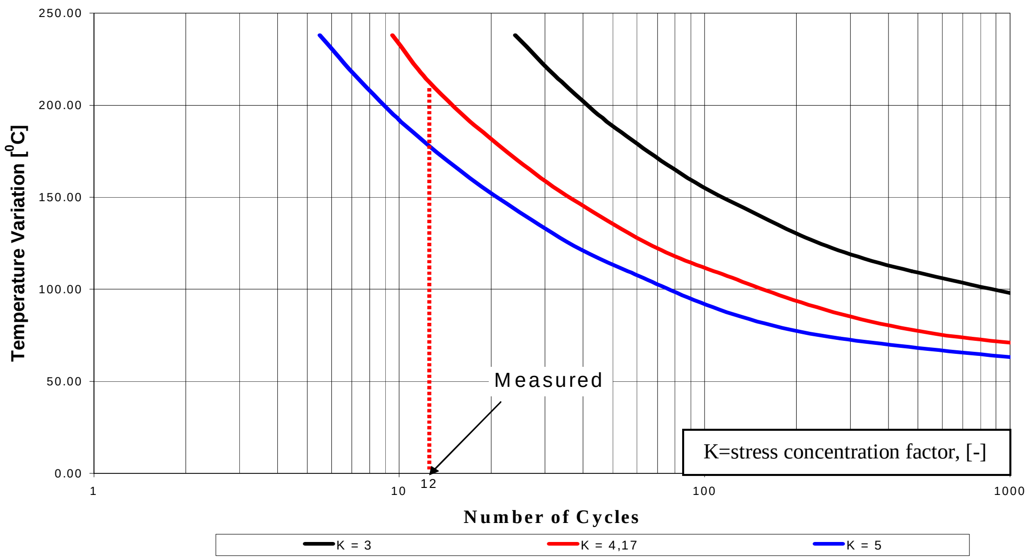

Fig.8. Temperature versus cycle curve for a 18 5/8" Buttress connection, grade N80

The stress concentration factor varies from one type of connection to another, as it is a function of connection geometry and its manufacturing process. The fracture obtained during the experimental investigations was located at the zone of imperfect thread turns, suggesting that more attention must be paid during the thread manufacturing process.

For high-enthalpy geothermal well producers with temperatures of produced fluid between 100 and 250^{0}C the fatigue resistance of the tested N80 Buttress connections varies between 10 and 110 cycles. This information should be considered for the planning process to evaluate the minimum project life time as well as optimizing the well operations. The thread geometry, especially the incomplete thread turns finishing affects strongly the value of stress concentration factor. For example a lower stress concentration factor will increase the life time of the casing over 1000 cycles, as shown in Figure 7.

CONCLUSIONS

This paper presented the theoretical and experimental work carried out to evaluate LCF resistance of an 18-5/8 inch diameter casing with Buttress thread connections (typically used in geothermal well completions).

The results showed that, under extreme loads, the LCF resistance of the buttress thread connection can be as low as 10 cycles.

More full-scale experimental work is required to extend the validity of the results obtained with this study to other types of threaded connections.

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