Analysis of Oil Well Casing Connections Subjected to Non-axisymmetric Loads

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Abstract: Oilfield casings employ threaded connections which are designed to provide both structural and sealing integrity under installation and service loads. This paper presents a finite element methodology for analyzing casing connections subjected to non-axisymmetric loads. The analysis approach can be used for assessing connection structural integrity, sealability and fatigue life.

Keywords: Casing, Curvature Loads, Fatigue, Non-axisymmetric Loads, Premium Connection, Sealing, Strength.

1. Introduction

There are two types of oil wells: the primary production wells used for conventional low temperature production and the thermal wells widely used for the production of heavy oils. Figure 1 shows a typical thermal SAGD (Steam Assisted Gravity Drainage) process which is composed of a producing well and a steam injecting well. As shown in the figure, the SAGD wells are designed with an upper vertical or slant section, a build section with a given well curvature and a horizontal section extending through the reservoir zone. Wells are usually completed with casing strings cemented to the formation (in the upper and build sections) and slotted (or perforated) liners through the reservoir layer.

A casing string consists of many casing joints (usually 10 m long) joined by threaded connections. The oil country tubular goods (OCTG) connections can be classified into three groups: API round, API oversized buttress, and proprietary premium connections. The API round connection uses round threads which provide the structural function, but do not provide the sealability function. The API buttress connection provides the structural function and some degree of sealability by the combination of the action of a thread compound and the helical leak path of the buttress thread section. The premium connection uses the buttress threads for the structural function and a metal-to-metal profile for sealability. Many premium connections also include the metal-to-metal shoulder next to the profile region for additional sealability. Figure 2 shows a typical premium connection with profiles of the buttress threads, metal-to-metal seal and metal-to-metal shoulders on the pin and coupling.

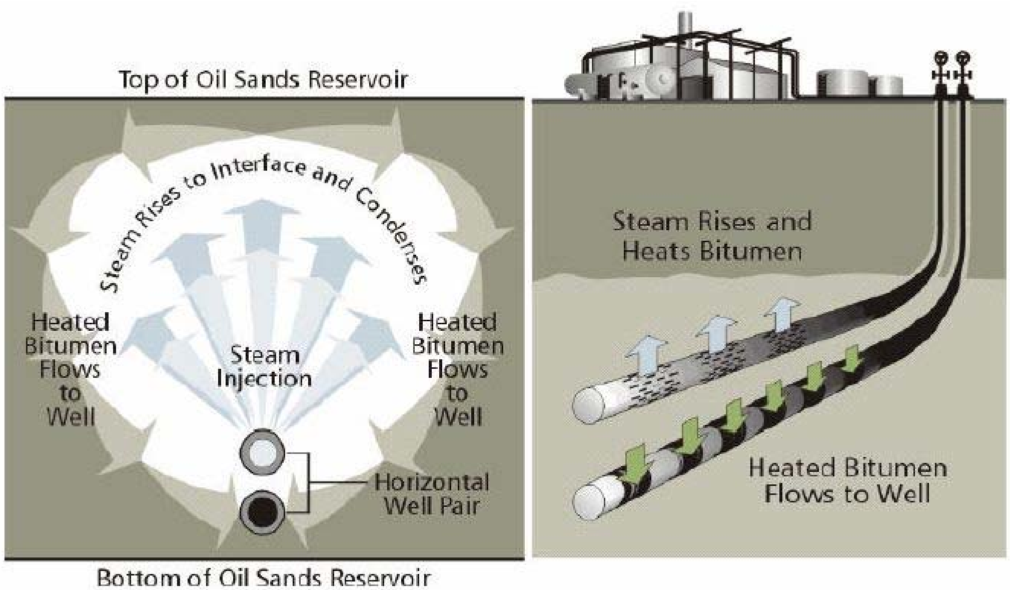

Figure 1. Casing strings used in producing well and steam injection well for the SAGD (Steam Assisted Gravity Drainage) Process (used with permission from Suncor Canada).

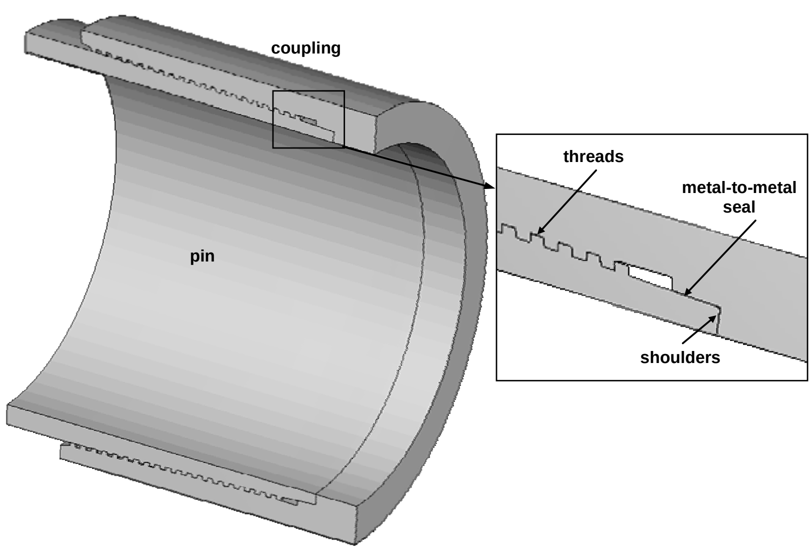

Figure 2. Schematic of a typical premium connection (half coupling shown).

The threaded connections are viewed to be one of the most critical components of an oil well in terms of achieving minimal risk of casing string failure. Ensuring adequate structural and leakage integrity of the connections over the full service life of a well can pose a significant challenge, especially for thermal wells where inelastic material response will often govern the casing and connection performance. Full-scale testing has shown that most premium connections can provide a higher degree of seal integrity as compared to API buttress connections. Therefore, the use of premium connections is typically preferred for the production casings in the thermal wells, where the effective connection sealability is very important to the integrity of wells. Because of the critical and challenging role that premium connections serve in thermal well applications, this paper will focus on the analytical study of premium connections.

Extensive analytical and experimental studies have been conducted by various investigators on the structural and sealing performance of premium connections. However, it is noted that most of the existing analytical studies focused on the connection performance under axisymmetric loading conditions. This paper presents an analytical methodology for analyzing premium connections subjected to non-axisymmetric loads. The analysis models discussed in this paper can be used for assessing three key functions of premium connections in thermal wells: connection structural integrity, sealability and fatigue life.

2. Background

Casing strings are designed to sustain installation and service loads with sufficient structural capacities and leakage resistance. The installation loads include the following:

- axial tension and compression resulting from hanging weight and buoyancy effects; and
- curvature loading due to well curvature in the build section.

The service loads usually include the following:

- axial compression and tension resulting from formation compaction or expansion;
- bending and shear resulting from casing buckling and lateral formation movement; and
- for thermal wells, the thermal strain resulting from the temperature variations that occur over the life of the well.

The casing and connection design is typically based on elastic design criteria and some safety factor for the installation loads. The service loads are usually displacement controlled; therefore, a strain-based design criterion should be used. The structural strength of a premium connection can be established where material failure occurs at one of several critical locations. The potential structural failure modes include the rupture of pin threads near the coupling face, strain localization in the coupling groove area, and shear band failure of pin or coupling shoulders.

Connection leakage or failure can lead to serious economic and safety consequences to the industry. Leakage in a premium connection can usually be related to insufficient contact stress in critical seal regions. In some cases, sealability can be impaired by insufficient shoulder contact.

Connection evaluation programs usually consist of a combination of finite element analysis (FEA) and physical testing. In some cases, the physical tests are conducted on a limited number of specimens to verify the FEA results. In an FEA model for premium connections, the structural integrity is evaluated by examining the stress/strain levels in the critical areas. In the strain-based design cases, where the strains at critical areas usually exceed the elastic limit, the strain levels in these critical areas are examined. In the finite element analysis, the sealing capacity for a premium connection is determined by the metal-to-metal contact stress over the seal and shoulder regions.

There has been extensive finite element analysis work and research done on the assessment of casing connections. However, most of the analysis work has been limited to the connection performance under axisymmetric loading, such as make-up, torque, internal/external pressure and axial tension/compression loads. Until now, little has been published on the casing connection performance under non-axisymmetric loading. Nevertheless, several field observations have shown that connection failures due to non-axisymmetric loads, such as casing buckling and formation shear movement, do occur, particularly in cold and thermal horizontal wells. Therefore, it is becoming increasingly important to develop analytical models that can be used for assessing the effect of non-axisymmetric loads in these applications. Note that due to the level of geometric detail required to assess these types of analyses, it is virtually impossible to model a connection using full three-dimensional solid elements.

This paper presents a methodology for analyzing premium connections subjected to non-axisymmetric loads. The analysis model can be used for structural and sealability assessments of various connection types. The presented methodology can also be used for assessing connection fatigue life, such as in situations where the casing/connection is forced to pass through the build curvature sections during installation operations.

3. Finite Element Model

The modelling and analysis described in this paper were performed using ABAQUS Standard 6.6.1.

3.1 Modelling of Connection Structures

Figure 3 shows a schematic representation of the finite element model for a premium connection and a section of the pipe body. Due to the symmetry of deformation about the connection centre under the imposed loading (except for the case of shear deformation), only half of the coupling was modelled. At the coupling centre plane (A-A), symmetric boundary conditions were assumed.

The connection was modelled using axisymmetric solid elements with non-linear, asymmetric deformation. As noted in the ABAQUS documentation, these elements are intended for the non-linear analysis of structures which are initially axisymmetric, but which undergo non-linear, non-axisymmetric deformation. Contact between the pin and coupling elements was modelled using slide-lines.

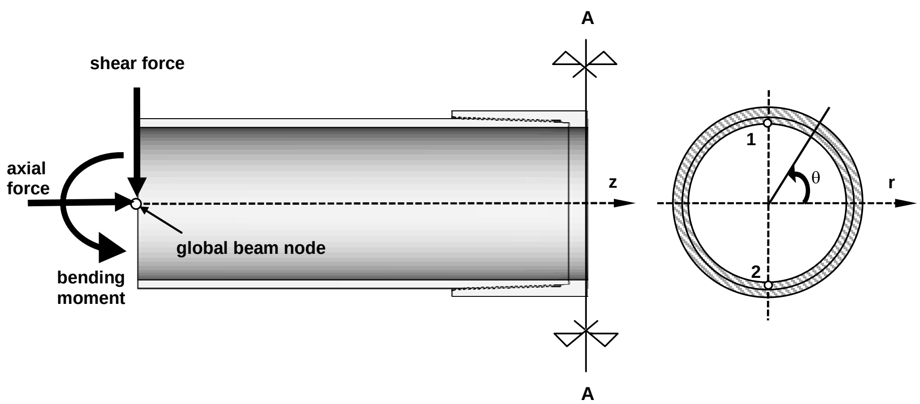

Figure 3. Schematic of finite element model.

3.2 Non-linear Asymmetric Elements

ABAQUS Standard includes a library of solid elements whose geometry is initially axisymmetric and that allows for non-linear analysis wherein bending can occur about the plane $\theta = \pi / 2$ in the (r, z, θ) cylindrical coordinate system of the model (Figure 3). The geometric model is defined in the *r-z* plane only. The displacements, *u*, are the usual isoparametric interpolations with respect to *r* and *z*, augmented by Fourier expansions with respect to θ. A general interpolation scheme for the displacement using Fourier terms with respect to θ is as follows:

$$u_\alpha = \sum_{m=1}^{M} H^m(g,h)\{u_\alpha^{m0} + \sum_{P=1}^{P}(\cos p\theta \ u_{\alpha c}^{mp} + \sin p\theta \ u_{\alpha s}^{mp})\}, \qquad (\alpha = r, z, \theta) \qquad (1)$$

where *g* and *h* are isoparametric coordinates in the original *r-z* plane; H^m are polynomial interpolation functions; and u_α^{mo}, $u_{\alpha c}^{mp}$, and $u_{\alpha s}^{mp}$ are solution amplitude values. *M* is the number of terms used for interpolation with respect to *g*, *h*; and *P* is the number of terms used in the Fourier interpolation with respect to θ. Purely axisymmetric deformation results when $P=0$.

The integration scheme used in these elements is a product of integration with respect to element coordinates in surfaces that were originally in the *r-z* plane and integration with respect to θ. For the former, the same scheme is used as in the corresponding purely axisymmetric elements. For integration with respect to θ, the trapezoidal rule is used with the number of integration points set to $2(P+1)$.

For the analyses presented in this report, only one Fourier mode was used in the model. A sensitivity study of Fourier modes indicated that under small to moderate curvature loading, the results developed with one Fourier mode were reasonably accurate in terms of the prediction of seal contact stress and connection deformation.

3.3 Modelling of Casing Materials

Casing connection materials are usually modelled using an elastic-plastic-thermal constitutive law. The initial yield stress at room temperature was assumed to be 581 MPa. The Young's modulus was assumed to be 200,000 MPa. Figure 4 presents the engineering stress versus engineering strain relationships at elevated temperatures for L-80 casing material based on a previous coupon test at C-FER (Humphreys et al., 1991).

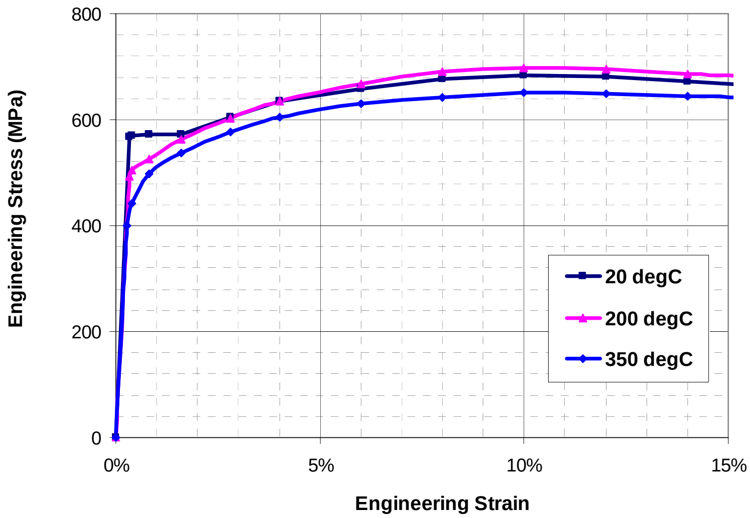

Figure 4. Stress-strain relationship for L-80 material.

3.4 Modelling of Load Steps

The analyses were performed in three load steps:

1. Make-up of connection;
2. Application of internal/external pressure (optional); and
3. Application of external loads.

The connection make-up was modelled based on interference fit in the thread, seal and shoulder regions. The interference within the threads and seal were based on geometric tolerances derived from drawings and measurements of the thread profile obtained by gauging procedures. The shoulder interference is usually defined by the torque-turn relationship of the connection during make-up.

External loads were imposed at the end cross-section of pipe body. The end cross-section was tied to a "global beam node" using three constraint equations for the three degrees of freedom: the lateral and axial displacements and rotation of the cross-section. Both the axisymmetric and non-axisymmetric external loads can be applied at the "global beam node" (see Figure 3).

4. Stress Analysis of Connections under Curvature Loading

The first analysis example presented is a stress analysis of a premium connection under pure bending. This analysis has been used by C-FER Technologies to validate the model against physical test data obtained by bending a pipe-connection specimen in the laboratory.

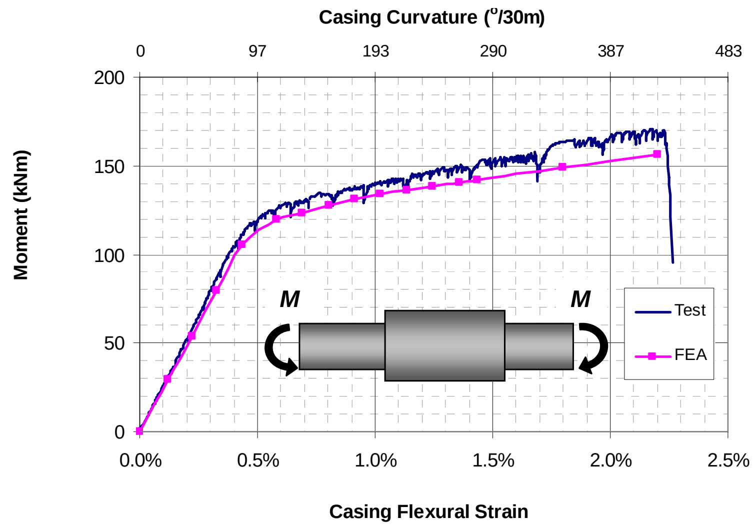

Figure 5. Moment-strain relationship for a premium connection from physical test and FEA prediction.

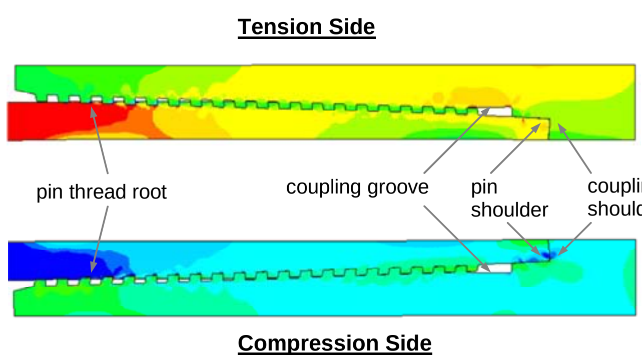

Figure 6. Longitudinal strain contour in a premium connection under bending showing the critical locations for material failure (RED as tension; and BLUE as compression).

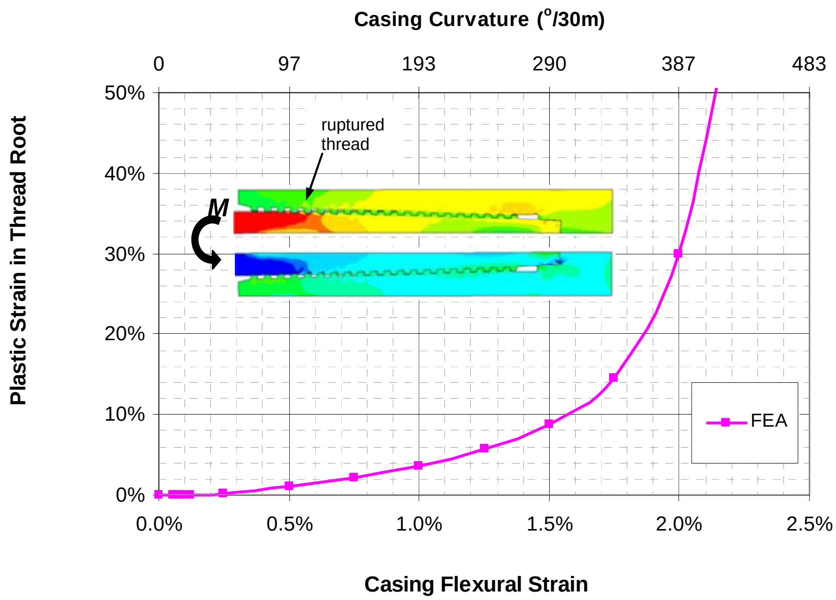

Figure 7. FEA prediction of plastic strain in the ruptured thread.

In one test, a 177.8-mm 34.2 kg/m L-80 premium connection was subjected to controlled bending loads to determine the critical casing pipe-body strain at which the connection fails. Figure 5 shows the relationship between the bending moment and the casing pipe-body flexural strain (i.e. casing curvature) obtained from the laboratory test. Note that the laboratory test suggested that the connection failed due to thread rupture at a casing pipe-body flexural strain of 2.2%.

A finite element analysis was also performed to simulate the test condition. As shown in Figure 5, the analysis results of moment versus flexural strain relationship match closely with the data obtained from the laboratory test.

Figure 6 presents the longitudinal strain contour for the premium connection under a casing curvature of 100º/30 m, which is a realistic curvature for casing connections to be subjected to in a cold or thermal heavy oil well over its life. The critical locations of material failure, as identified by the analysis, include the thread roots, dope relief groove, and the pin and coupling shoulders. These areas are also critical from a fatigue assessment perspective (e.g. if the connection and pipe body are rotated over a curved section). As shown in the figure, the thread root experiences the highest stress concentration and becomes the most critical location for the structural failure of a connection. This confirms the observations made by examining the connection subjected to bending in the laboratory test. Figure 7 presents the analytical prediction of the plastic strain in the critical thread root area on the tension side of the bent connection. As the casing and connection are bent, the plastic strain initially develops gradually. However, at about 1.5% casing pipe-body flexural strain, the rate of the plastic strain starts to increase significantly. This analysis demonstrates that major plastic deformation happens prior to the connection rupture, which occurs at about 2.2% casing pipe-body flexural strain according to the test. The analysis suggests that micro-cracks could be present in the threads long before connection failure would be observed in a test. Based on this analysis, it is suggested that the casing pipe-body strain limit be defined as the critical point when the rate of the local plastic strain has suddenly increased; in this case, this limit would be at about 1.5% casing flexural strain.

5. Sealability Assessment of Connections under Curvature Loading

The analysis model presented in this paper can also be used to assess the sealability of premium connections under non-axisymmetric loading.

The sealing capacity for a premium connection is determined by the metal-to-metal contact stress over the seal region. Figure 8 shows the contact stress distribution over the seal region as determined by finite element analysis. As a necessary requirement, the seal contact stress must be higher than the oil/gas pressure in order to maintain sealability. In a more generalized assessment approach, the sealing capacity of a premium connection can be represented by the "Seal Contact Intensity"(f_s), which is an integration of the seal contact stress (σ_c) over the effective seal length (L_{ES}):

$$f_s = \int_{L_{ES}} \sigma_c dx \qquad (2)$$

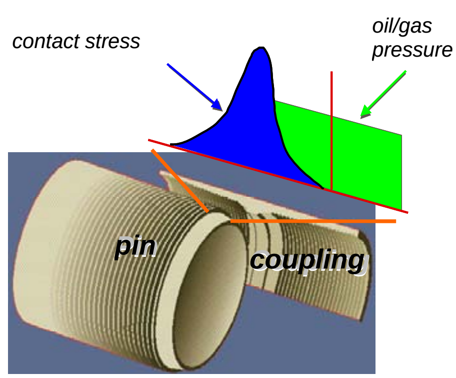

Figure 8. Illustration of seal contact stress in a premium connection.

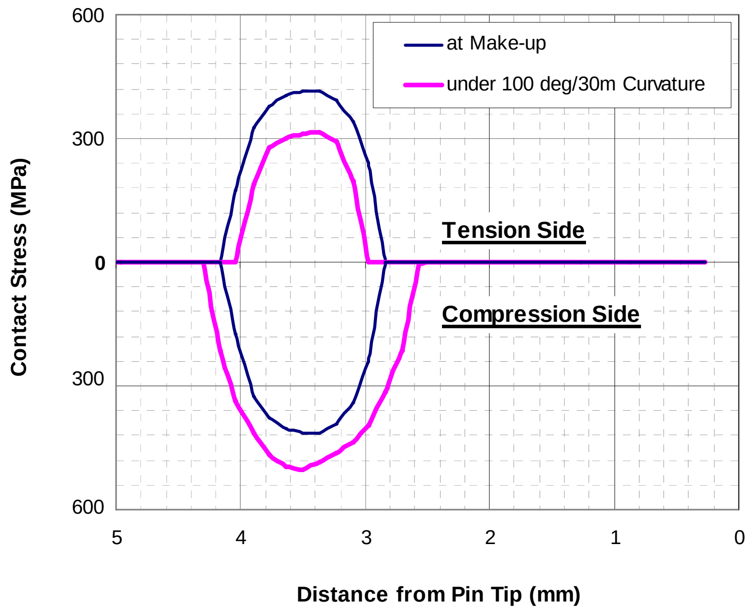

Figure 9. Contact stress distributions over the seal length at make-up and under bending.

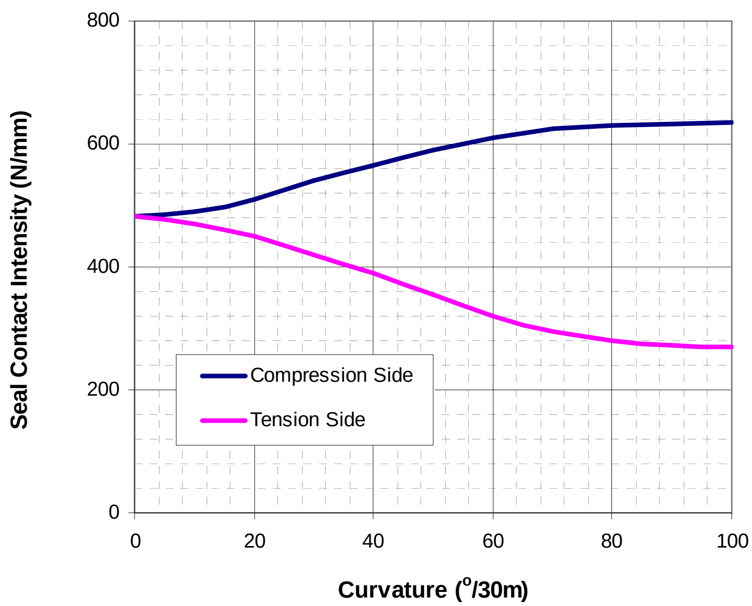

Figure 10. Seal contact intensities versus casing curvature.

The limit for acceptable seal contact intensity was established by physical tests. The program involved testing numerous premium connections and benchmarking their seepage rates with the corresponding finite element prediction of the seal contact intensities.

The analysis example presented in the preceding stress analysis is used here to demonstrate the model capability for assessment of connection sealability under non-axisymmetric loading.

Figure 9 presents the contact stress between the pin and coupling over the metal-to-metal seal length on both the tension and compression sides of a bent connection. The presented analysis results correspond to the connection make-up and 100º/30 m imposed curvature conditions. As shown in the figure, the contact stress distribution is axisymmetric at make-up. As a curvature loading is imposed, both the contact stress and contact length increase on the compression side, but decrease on the tension side. Figure 10 presents the analysis results of seal contact intensities on both the tension and compression sides of a bent connection. The seal contact intensities start at the same value of 482 N/mm due to the axisymmetric distribution of contact stresses at connection make-up. As a curvature loading is imposed, the seal contact intensity increases to 634 N/mm on the compression side, but decreases to 270 N/mm on the tension side. The lower value of the seal contact intensity on the tension side is often used for the sealability assessment of a connection. This example demonstrates that the curvature loading will impose a weaker sealing condition on the tension side of a bent connection. This example illustrates the importance of assessing the effect of curvature loading on the sealing performance of premium connections in cold and thermal heavy oil applications.

6. Fatigue Life Assessment for Casing Installation Rotation

During installation and/or cementing operations in horizontal wells, casing strings are often rotated. It is important to evaluate the ability and limits of selected connections to withstand cyclic loading during these operations. The curvature within the build section of a well will introduce bending strains that can cause plastic load cycling within a premium connection as the casing string is rotated. The torque applied to the casing at surface could also impact the make-up condition of the connections (e.g. the specified make-up torque may be exceeded), adversely impacting their structural and leakage integrity.

As shown in Figure 6, the critical areas in a premium connection from a fatigue damage perspective include the thread roots, dope relief groove, and the pin and coupling shoulders. Note that a multi-axial stress state typically exists at these locations under connection make-up and bending load conditions. With large seal and shoulder interferences at make-up, it is reasonable to expect the pin/coupling material to yield and plastic strains to develop at some of these locations within the connections. Therefore, traditional stress-based fatigue criteria, which are generally used in low stress situations, are no longer applicable, and it is necessary to adopt a strain-based criterion for the connection fatigue assessments. One of the well-known methods for the plastic fatigue assessment is the modified version of the Morrow approach (Dowling, 1998), which takes the following form:

$$\bar{\varepsilon}_a = \frac{\sigma'_f}{E}\left(1-\frac{\bar{\sigma}_m}{\sigma'_f}\right)\left(2N_f\right)^b + \varepsilon'_f\left(2N_f\right)^c \quad (3)$$

where $\bar{\varepsilon}_a$ is the equivalent strain; $2Nf$ is the number of full cycles; and σ'_f, ε'_f, b, c, E and $\bar{\sigma}_m$ are material parameters. Figure 11 presents the L-80 material fatigue life relationship between the number of cycles and allowable strain based on this modified method.

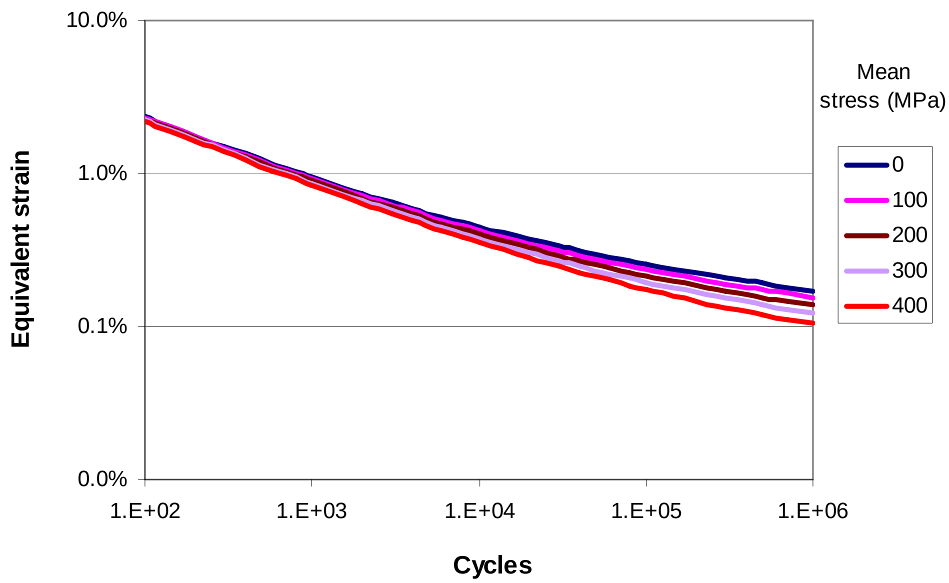

Figure 11. Relationship of equivalent strain, mean stress and cycles for L-80 material based on modified Morrow approach.

To demonstrate the application of this approach, a premium connection is analyzed with an imposed curvature of 9º/30 m (a realistic curvature for the build region of a SAGD horizontal well). The analysis considers two different make-up conditions corresponding to 100% and 120% drilling make-up torques. The analysis results of equivalent strain and mean stress are used in the modified Morrow equation to determine the fatigue life at selected critical locations. As shown in Figure 12 for the assessment results, the pin shoulder is the most critical location, with the fatigue lives of 12,000 and 7,800 cycles corresponding to 100% and 120% drilling make-up torques, respectively.

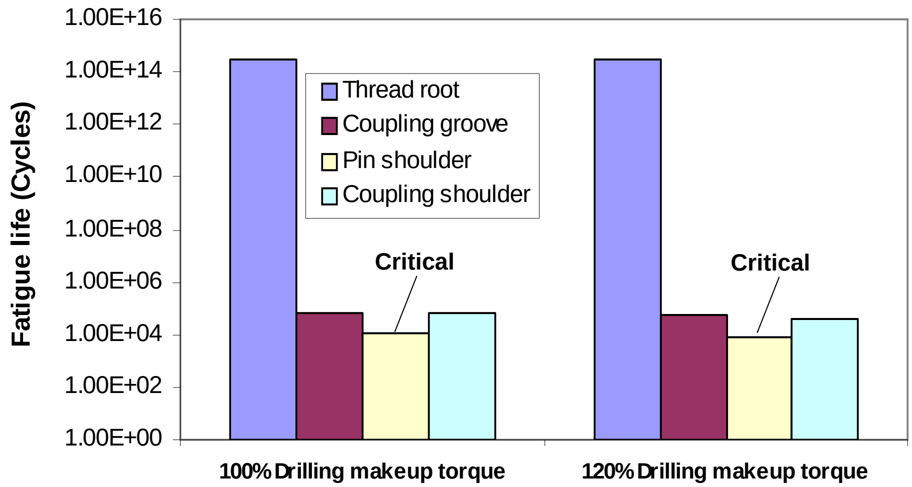

Figure 12. Fatigue life prediction for a premium connection in casing-rotation application.

7. Summary and Conclusions

This paper presents a finite element methodology for analyzing casing connections subjected to non-axisymmetric loads and describes the potential impact of these load conditions in cold and thermal heavy oil wells. The ABAQUS proprietary axisymmetric-asymmetric solid elements are shown to be viable and efficient element types well-suited for modelling the complex and interesting aspects of material non-linearity, large deformation and contact interactions.

The analysis model described in this paper was validated by simulating a physical test of a premium connection under bending. In addition, this paper demonstrates that the analysis models can be used for assessing connection structural integrity, sealability and fatigue life. These types of assessments can help industry to optimize casing/connection design and therefore minimize well failure in the demanding conditions of horizontal wells in cold and thermal heavy oil applications.

8. Acknowledgements

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9. References

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