Analysis of Casing Deformations in Thermal Wells

Jueren Xie and Yu Liu

C-FER Technologies, Edmonton, Alberta, Canada

Abstract: *Thermal technologies are widely used for the heavy oil recovery. The thermal processes usually consist of some variation of Cyclic Steam Stimulation (CSS), steam flood or Steam Assisted Gravity Drainage (SAGD). These thermal recovery applications have experienced numerous well casing failures around the world, often resulting in loss of wellbore integrity, lost production and added costs. The primary casing failure mechanisms include casing connection leakage and/or parting due to excessive casing strain and wellbore serviceability difficulties due to large casing deformation associated with casing buckling and shear.*

Due to high operation temperatures (e.g. 220 to 350°C), casing deformations often exceed the elastic limit of typical thermal well casing materials. Therefore, a strain-based design concept and advanced finite element analysis are often used to consider the allowable casing strain capacity beyond yield and the associated non-linear material and structural responses. This paper presents analysis models, developed using Abaqus, for analyzing casing deformations resulting from thermal loading, buckling and formation shear movement. It is demonstrated that the analysis results of casing deformations can constitute a more advanced and sound basis for thermal well casing designs which minimize the potential for thermal wellbore casing failures.

Keywords: *Casing, Connection, Thermal Well, Thermal Cycle Loading, Buckling, Formation Shear, Plasticity, Strain-based Design, Axisymmetric-Asymmetric Elements, Beam Elements, Slide-line Contact Elements, Pipe-in-Pipe Contact Elements*

1. Introduction

Thermal technologies are widely used for heavy oil recovery worldwide. The thermal recovery of viscous heavy oil and bitumen is often achieved by some variation of Cyclic Steam Stimulation (CSS), steam flood or Steam Assisted Gravity Drainage (SAGD). A thermal cycle in CSS consists of four basic phases: high pressure, high temperature steam injection; a soak period, where the well is shut-in to allow for the injected steam to penetrate the reservoir and decrease the oil viscosity; flow-back, where the elevated reservoir pressure is sufficient to produce the hot oil, condensed steam and gases to surface; and pumping to lift the produced fluids to surface as the reservoir cools. SAGD is a more stable, gentle process where steam is continuously injected into one horizontal well, and condensed steam and mobilized fluids are produced from a second well (Xie, 2000). This method usually requires lower injection pressures and temperatures and fewer pressure/temperature cycles than CSS. The CSS process has been applied to a variety of well configurations including vertical, directional and horizontal as shown in Figure 1. SAGD applications are typically limited to pairs of parallel horizontal wells with the dedicated injector situated just above the dedicated producing well (Figure 2).

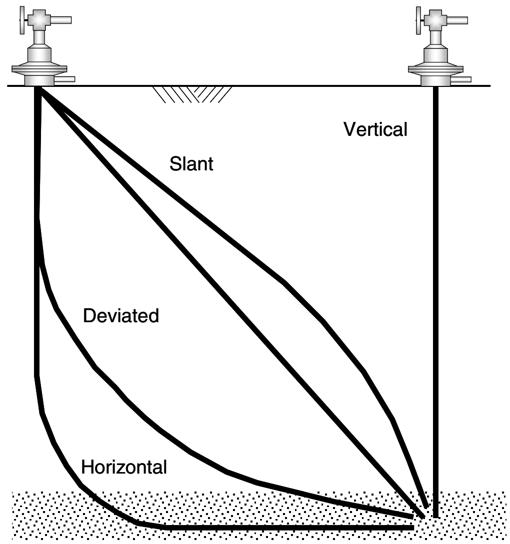


Figure 1. Straight and directional wells.

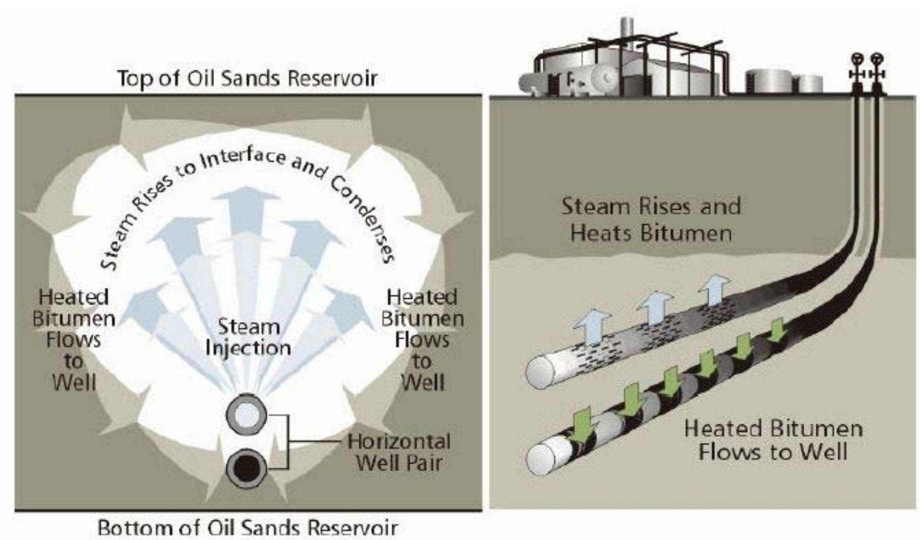


Figure 2. Casing strings used in producing well and steam injection well for the SAGD (Steam Assisted Gravity Drainage) process.

Thermal well production poses serious challenges to well casing designs. In addition to the installation loads, such as hanging/buoyancy forces and bending resulting from well curvature, a casing must support the thermal strains resulting from large temperature variations and formation movements induced by thermal effects and well production. In many field operations, the temperature cycles impose cyclic compressive casing stress during heating and tensile stress during cooling. When “ultra-high temperature” is used (for example, peak temperatures over 300°C, depending on casing grade), the casing can potentially yield under tensile stress during cool-down, leading to possible failure modes of low cycle material fatigue, connection leakage and connection parting. In addition to the cyclic stress-temperature response, several field observations have suggested that casings can be subjected to curvature loads, such as casing buckling due to thermal compressive stress and shear deformation due to formation shear movement (Xie, 2000).

Thermal well casing designs often require advanced finite element analyses to consider the effects of temperature and stress on material properties and the plastic, non-linear response of the materials. The casing constitutive model must consider the elastic-plastic response of the material, temperature dependence and time dependence. This paper presents modeling and analysis considerations using the finite element program Abaqus to aid the thermal wellbore designer by simulating thermal well casing responses for various load conditions and casing design options. In addition, this paper presents finite element models for analyzing casing buckling and curvature response to formation shear movements.

2. Casing Failure Mechanisms and Design Considerations

Excessive casing deformations leading to failure of steam stimulation wells have been documented in literature (IOL Report, 1977; CNRL Report, 2000; Fu, 2006). The majority of these casing failures are noted to be the result of casing connection parting due to material failure in the stress concentration areas in casing connections. Some well failures occurred at the interface between the producing zone and the overlying shales and have been attributed to shear movement along what is assumed to be a very low friction boundary between the two formations (Xie, 2000). One theory to account for these failures is that the production-induced heat caused thermal expansion of the formations, resulting in a formation shear movement.

Figure 3 shows a multi-sensor caliper survey (Xie, 2000) of a CSS well which displays deformations consistent with multi-wave buckling and shear displacement (lateral displacements have been magnified for illustrative purposes). The shear displacement of the casing has a resulting wellbore curvature or “dogleg severity” exceeding 1000°/30 m. This high local curvature translates to a flexural strain on the outside diameter of the casing of over 5%, which is sufficient to fail a casing connection.

Traditional methods for casing structural design use the stress-based design concept which limits the casing stress to the elastic state. However, in many design cases for thermal well casings, the magnitudes of casing strains resulting from thermal loading, casing buckling and formation movement exceed the elastic strain limit, making the conventional stress-based design method inappropriate for these applications.

Today's well design practices acknowledge that limited plastic strain is acceptable for casings provided that the driving forces are displacement-controlled. The thermal strain and formation movements are controlled and bounded by the magnitude of the well temperature and the lithology and operating conditions of the application. The allowable casing strain is often defined by wellbore serviceability limits or failure criteria and the structural integrity of casing connections. It is important to note that the casing strain limit does not directly correlate with the requirement for connection sealability; that is, a connection may leak even if it is not loaded.

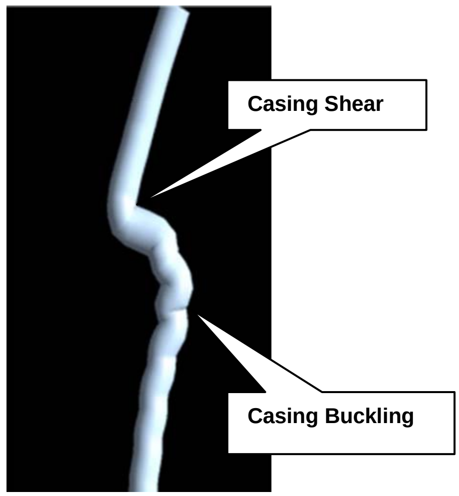


Figure 3. Multi-sensor caliper survey of casing buckling and shear in a cyclic steam stimulation well.

Based on the understanding of casing failure mechanisms, the casing design objectives proposed for thermal wells are as follows:

- Structural integrity to withstand the following:
  - **a.** thermal strain and internal/external pressures from the fluids and lithology;
  - **b.** casing buckling deformation caused by thermal compressive loading in cement void intervals; and
  - **c.** formation shear movement in the overburden and reservoir intervals.
- Connection sealability to withstand thermal loading, casing buckling and formation shear movements.

Note that the three structural integrity design objectives are examined in this paper while connection sealiability is not, in part because it is dependent on proprietary casing connection designs and there are several such designs available.

3. Analysis of Casing under Thermal Cycle Loading

3.1 Description of Loads

One of the key features in thermal wells is the large temperature change subjected to the well during normal operations. During steam injection periods, the temperature increases along the wellbore from as low as initial reservoir values of 10 to 25°C to peak temperatures of 220 to 275°C for SAGD wells, and 330 to 350°C for CSS wells. Assuming that the cement and formation provide sufficient axial constraint to axial movement, the temperature-induced thermal expansion of casing material will introduce significant axial compressive loading to the casing string. In the late part of a thermal cycle or during well servicing, when temperature decreases from the production peak value, the axial compressive force in casings may reverse to tensile force if the temperature drops sufficiently.

3.2 Analysis Models for Casing Material Response to Thermal Loading

Analysis of cyclic plastic/creep casing deformation in thermal wells requires a sophisticated finite element material model to account for the kinematic strain hardening deformation, or the Bauschinger effect, stress-relaxation and creep strain. Several researchers (Ellyin, 1995; Xia, 1997; Kaiser, 2005) have studied the mechanical properties of casing materials under cyclic loading conditions numerically and experimentally. It is generally acknowledged that the modified Mroz plasticity theory (Mroz, 1967) would be a better suited approach for modeling casing material response to plastic cyclic loading for thermal wellbore casing materials. However, the numerical attempts revealed a number of modeling issues that need to be resolved, especially when the problems involved cyclic plasticity and creep behavior of materials. These investigations indicated that, due to limitations of constitutive modeling, it is impractical to rely strictly on numerical analyses for casing cyclic plasticity deformation assessments.

A more simplistic and practical approach would be to assess casing design based on analyses of casing material response under monotonic or single cycle load conditions. Such analyses can be performed using established constitutive models available in many finite element programs, including Abaqus. Such simplified models should represent the stress-strain behavior in the casing materials in both elastic and plastic regions and across the entire spectrum of operating temperature of the analysis. It is therefore essential that the elastic-plastic constitutive model be defined as temperature and strain-rate dependent. Physical tests demonstrated that casing material yield strength usually decreases with temperature, and tensile strength may increase with temperature at the beginning of heating but decrease with further heating (Humphreys et al., 1991). Proper consideration of the strain-rate dependence of the material is necessary in order to simulate the stress relaxation phase of a thermal cycle.

3.3 Analysis Example

Consider a Western Canada SAGD well completion design that has a peak temperature of 275°C and an internal pressure of 2 MPa. The proposed design uses an L80 production casing, which is common for these applications. Finite element analysis is performed to determine the casing stress-strain response over the thermal cycle. This involves heating the casing from 10°C to

275°C and cooling back to 10°C. Figure 4 presents the relationship between the casing stress, plastic strain and temperature over the thermal cycle. The casing mechanical response to the thermal cycle consists of four loading stages:

1. During initial heating, the confined (cemented) casing material is compressed elastically until the elastic limit is reached in compression at approximately 196°C;
2. Further heating leads to plastic deformation (in this example, up to approximately 0.092%) due to the constrained thermal expansion;
3. As the casing is held constant at high temperature (275°C), stress relaxation occurs due to the development of creep strain; and
4. When the confined casing is cooled (from 275°C to 10°C), the axial load gradually changes from compression to tension.

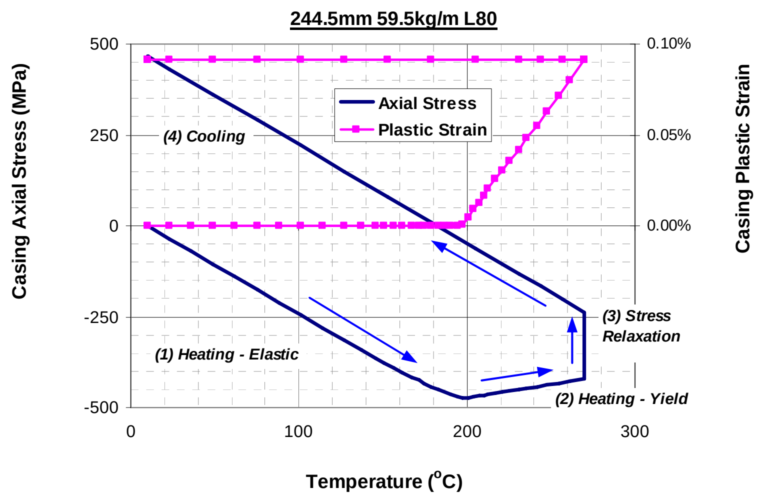


Figure 4. Stress and plastic strain over a thermal cycle for L80 casing material.

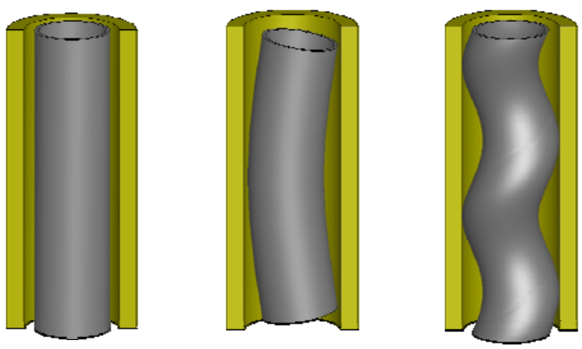
Figure 4 shows that the plastic strain starts to develop at 196°C and increases to approximately 0.092% at 275°C. In this case, there is no incremental plastic strain in the cooling stage or in any subsequent thermal cycles over this temperature range. It should be noted that in the case of "ultra-high temperature" production (i.e. up to 350°C), some casing materials (such as K55 and L80) may reach yield in tension at the end of a cycle (Xie, 2006). This will lead to incremental plastic deformation in further cycles, making low-cycle fatigue a critical failure mode of the casing, especially for CSS wells.

4. Analysis of Casing Buckling in Cement Voids

4.1 Description of Loads

The axial loads resulting from thermal expansion of the casing can cause casing buckling where lateral support for the casing is not provided (e.g. due to a void in the cement sheath). The buckling mode can vary from a single in-plane “bow” to a continuous series of “corkscrews” (helical buckle) depending on the magnitude of axial strain (Xie, 2006). Figure 5 illustrates the development of in-plane and helical buckling modes with increasing axial strain. The casing string can buckle at high temperature due to large compressive forces caused by thermal expansion. As the casing cools from the peak temperature, the casing buckling curvature will decrease as the casing goes into tension. However, some residual curvature resulting from the plastic buckling deformation will remain in the casing even at the end of a thermal cycle.

The assessment of casing resistance to buckling is important for two reasons. First, the casing may fail in connections due to excessive plastic strain associated with severe buckling. Second, well serviceability/accessibility may be impaired due to large casing curvature induced by buckling.



(a) Initial configuration (b) In-plane buckling mode (c) Helical buckling mode

Figure 5. Illustrative representation of casing buckling development in a cement void interval.

4.2 Analysis Models

Figure 6 shows a schematic representation of the finite element model developed for the casing buckling analyses. The casing was modeled using three-dimensional beam elements capable of simulating large deformations. It was assumed that a discrete annular gap exists between the casing outside diameter and the adjacent cement or formation to represent a void region (e.g. as might occur for a thermal well with a poorly-cemented interval). The outer radial boundary (e.g. formation interface) over the unsupported interval was conservatively assumed to be very stiff, thus providing rigid radial support for the casing if it deformed sufficiently to contact the borehole wall. The interaction between the casing and the rigid borehole was modeled using pipe-in-pipe contact elements. Initial geometric imperfections in a helical mode should be assumed prior to the buckling analysis. Note that temperature variation and the resulting thermally-induced loads were the only loading conditions applied to this casing model in the buckling analysis.

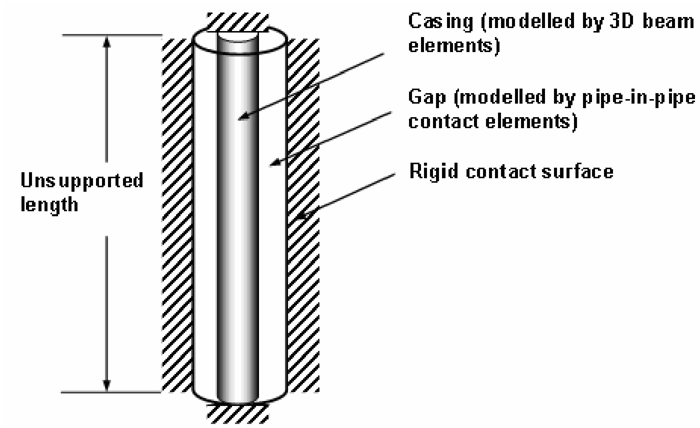


Figure 6. Schematic of finite element model for casing buckling analysis.

4.3 Analysis Example

The following analysis example is presented here to illustrate the application of this model for the consideration of potential casing buckling. This example considered the buckling of a 244.5 mm, 59.5 kg/m L80 casing under the thermal cycle loading noted above. Figure 7 shows the impact of temperature on the average axial stress and the resulting curvature and plastic strain experienced by the unsupported casing segment, with a cement void gap of 5 mm. Casing buckling initiates immediately after the casing yields during heating, shown in Figure 7 by a sharp increase in local curvature. With continued heating and thermal expansion, the initial in-plane buckling mode transforms to a helical shape because the radial confinement provided by the rigid formation boundary suppresses further lateral displacement of the casing. As the temperature is increased to the maximum value (275°C), helical buckling and the resulting local casing curvature continue to increase along with steam relaxation during the hold phase. When the casing cools, the curvature decreases as the compressive loads decrease, and with continued cooling, the casing passes from compression into tension.

Figure 8 presents the results of casing strain and curvature as a function of the radial cement voidage (i.e. where 0% voidage represents no voidage and fully supported casing, while 100% voidage represents full voidage or no cement in casing-formation annulus). As shown in Figure 8, the casing has 0.35% thermal strain and zero curvature if it is fully supported by cement. This total thermal strain of 0.35% consists of 0.26% elastic strain and 0.09% plastic strain, as shown in Figure 4. If there is a region where there is no cement (i.e. 100% voidage), casing buckling can result in 1.45% total casing strain and 138º/30 m local casing curvature. With this degree of curvature, it may not be possible to install equipment or access the wellbore below this region of the well. Also, the high plastic strain could result in casing failure (e.g. at a connection). This example demonstrates that casing buckling can cause serious concerns for casing structural integrity and well serviceability, and it illustrates the importance of ensuring that there is good cement placement in thermal wells.

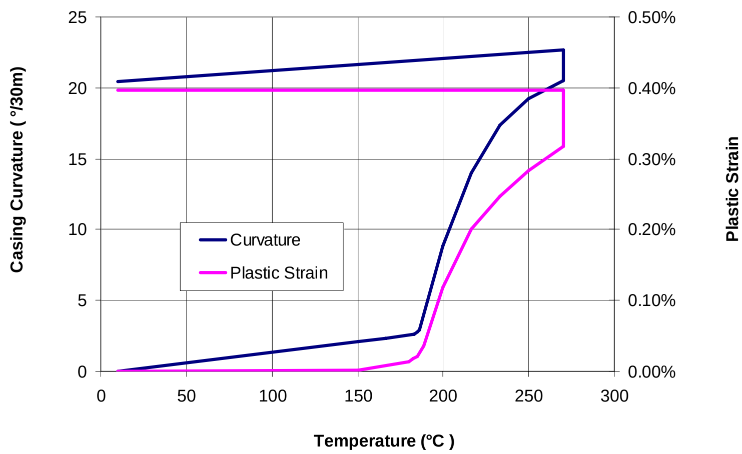


Figure 7. Casing curvature and plastic strain vs. temperature for casing under buckling.

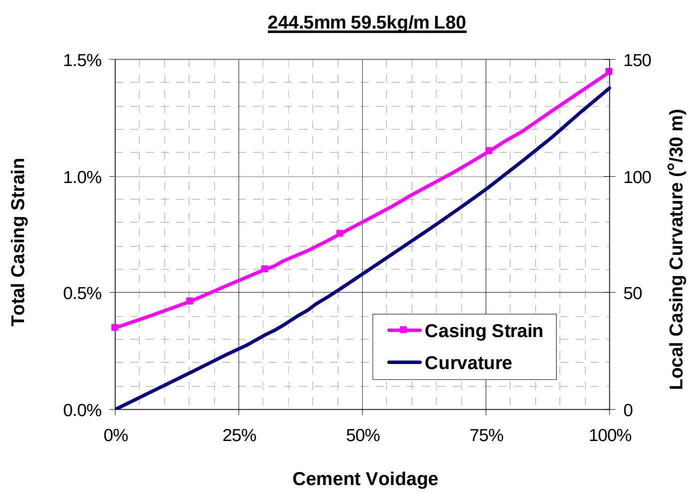


Figure 8. Casing strain and curvature vs. cement void at the end of the hold phase.

5. Analysis of Casing under Formation Shear Movement

5.1 Description of Loads

As evident from field experience in Canada and elsewhere, thermal wells are at risk of being exposed to formation movements such as those associated with non-uniform thermal expansion and contraction of various formation layers and reservoir pressure effects during operation. The relative lateral shifting of formation layers often occurs at a thin layer at a particular depth interval. This shift can cause severe shear loading of the casing strings that penetrate these intervals. In many cases, because the zone is thin, the resulting shear displacement occurs over a very short interval, which causes high curvatures and corresponding large strains in the casing.

5.2 Analysis Models

Figure 9 shows a schematic representation of the finite element model used for the analysis of casing deformation under formation shear movement. The casing was modeled using axisymmetric solid elements that accommodate large, non-linear, asymmetric displacements. For this example and to simplify the analysis, the initial casing curvature was not considered in the formation shear loading analysis. This is reasonable since the formation shear movement results in very large local casing curvature; therefore, ignoring the initial wellbore curvature has little impact on the analysis results. The formations were modeled using formation spring elements, with one end of each formation spring element attached to the casing system and the other end attached to a global node at which the shear displacement was imposed.

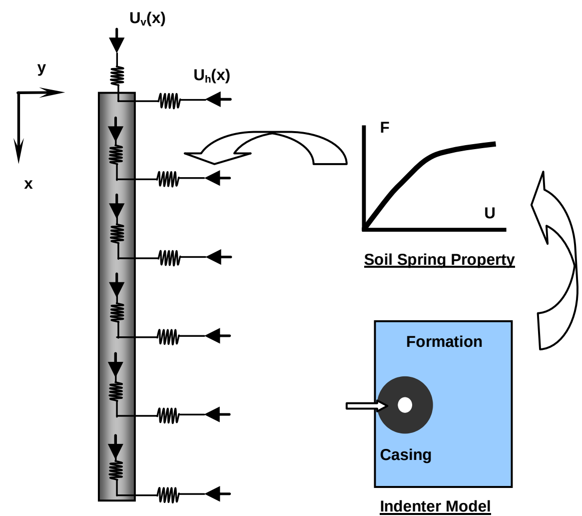


Figure 9. Schematic representation of finite element model for analyzing casing under formation shear movement.

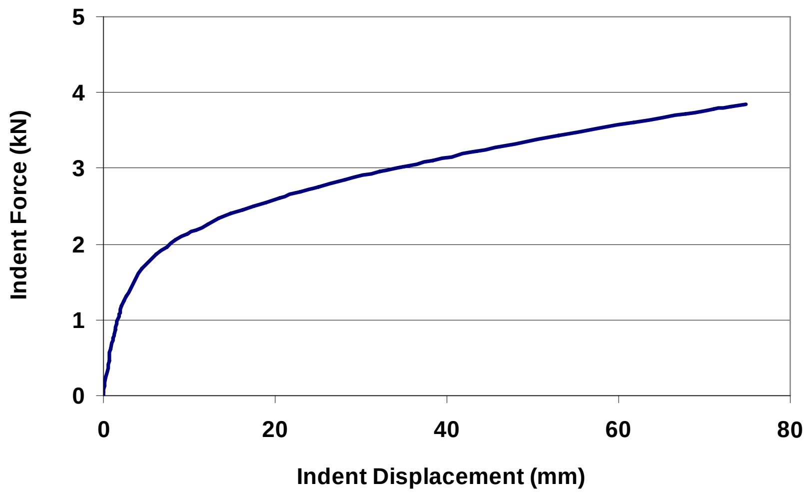


Figure 10. Indenter curve for 244.5 mm casing into the McMurray formation.

The stiffness and strength of the formation springs were determined using indenter curves generated by a finite element analysis of a rigid casing indenting into the formation, as shown in Figure 9. The indenting model consisted of a two-dimensional, plane-strain slice of formation material in the horizontal plane with a borehole in the center and a rigid indenter to represent the cement and casing. The indenter was moved laterally to impinge on the borehole wall and penetrate the formation. The Abaqus slide-line contact elements were used to model the interaction between the formation and indenter.

Figure 10 presents a typical indenter curve for a 244.5 mm OD casing acting at a 380 m depth in the McMurray formation (i.e. the typical production zone for SAGD wells in the Athabasca oil sands of Western Canada). The indenter curve appears to be initially linear to approximately 2 mm of formation displacement. However, as the formation yields, the force-displacement relationship becomes non-linear and the load-carrying capacity of the formation reduces as displacement is increased.

5.3 Analysis Example

This design example considers a 244.5 mm, 59.5 kg/m L80 casing under 30 mm formation shear displacement, which is consistent with the displacement observed in several field cases. It is also assumed that the formation shear movement occurs after heating the casing to 275ºC, also a reasonable scenario. The shear plane is assumed to be located at the mid-height of the casing model and the shear displacements are applied to the soil-end nodes of the soil spring elements in opposite directions over the two adjacent zones (i.e. relative to the shear plane).

Figure 11 presents the calculated lateral displacement and curvature along the casing within the shear interval resulting from the imposed formation shear movement. Note the lateral casing deformation is concentrated within the shear interval, with the deformation extending only about

0.5 m axially in either direction from the shear plane. The peak casing curvature of 250º/30 m occurs just below and above the shear plane. A plastic strain contour plot from a three-dimensional solid element model is also shown in Figure 11. As shown, the two peak curvature locations correspond to areas with the maximum plastic strain. The maximum plastic strain in this case was 1.8%, resulting from the combined effects of thermal cycle loading and high local curvature from formation shear movement.

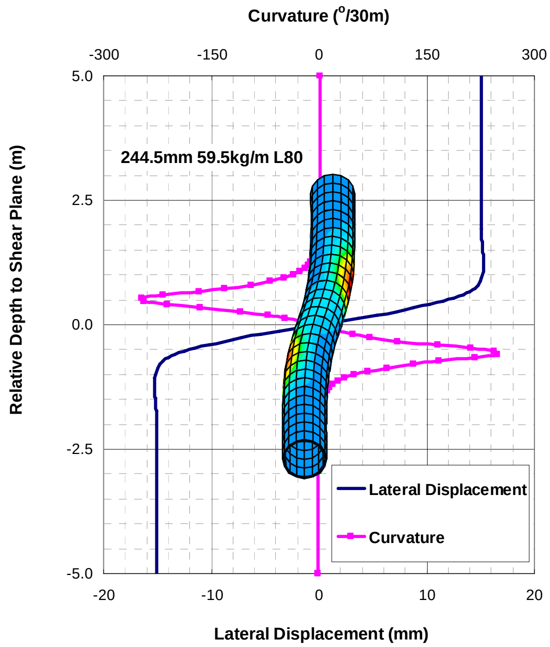


Figure 11. Casing lateral displacement and curvature caused by formation shear movement.

6. Conclusions

This paper presented numerical considerations in modeling casing deformation for thermally-operated wells. Three operation load scenarios were considered and modeled, including thermal cycle loading, casing buckling and formation shear movement. Results from analyses such as those described in this paper are often used by thermal operators to develop a sound basis for a plastic strain-based design of thermal well casings.

It was noted that the limitation of constitutive modeling of cyclic plasticity and creep strains with many of the commercial finite element programs is the key concern for thermal well designers in assessing the casing response through multiple thermal cycles. As a result of this limitation, the current suggested approach is to assess thermal casing behavior based on analyses of casing material response under monotonic or single cycle load conditions. Further work is needed in developing a more reliable constitutive model for cyclic plasticity scenarios. This work will include developing cyclic plasticity theory and formulations, implementing the corresponding constitutive model into programs, and developing a cumulative damage criterion for assessing casing material damage through multiple thermal cycles.

7. Acknowledgement

The work was supported by C-FER Technologies, Canada. Technical review by Mr. T. Zahacy of C-FER Technologies is greatly appreciated.

8. References

1. CNRL Report, Wolf Lake and Primrose Expansion. Volume 1. Project Description. October 2000.
2. Ellyin, F., Xia, Z. and Wu, J., A New Elasto-Plastic Constitutive Model Inserted Into the User-Supplied Material Model of ADINA, Computers and Structures, Vol. 56, No. 2/3, pp.283-294, 1995.
3. Fu, Y., Yang, P., Han. G., and Hao, Z., Research of Casing Damage Mechanism and Prevention Measures for Thermal Production Wells of Heavy Oil, First World Heavy Oil Conference, Beijing, China, November 2006. Paper Number WHOC-2006-655.
4. Humphreys, K. J., Solanki, S.C. and Link, R.A, Qualification of Grade-55 Casing for Thermal Recovery Service; C-FER Final Report for Joint Industry Members, C-FER Project 88-14, 1991.
5. IOL Report, Application for Approval of Cold Lake Expansion Project. Section 4, Volume 1. February 1977.
6. Kaiser, T., Yung, V., and Bacon, R., Cyclic Mechanical and Fatigue Properties for OCTG Materials, SPE/PS-CIM/CHOA 97775, 2005 SPE Thermal Operations and Heavy Oil Symposium, Calgary, Alberta, Canada, 1-3 November, 2005.
7. Mroz, Z., On the Description of Anisotropic Work Hardening, Journal of Mech. Phys. Solids, 15 (1967), pp.163-175.
8. Xia, Z., and Ellyin, F., A Constitutive Model with Capacity to Simulate Complex Multiaxial Ratcheting Behaviour of Materials, International Journal of Plasticity, Vol. 13, No. 1/2. pp.127-142, 1997.
9. Xie, J., Understanding the Mechanisms of Well Casing Deformations; C-FER Final Report to Joint Industry Members, C-FER Project 99023, 2000.
10. XIE, J. Casing Design for Heavy Oil Wells. First World Heavy Oil Conference, Beijing, China, November 2006. Paper Number WHOC-2006-415.