Analysis of Casing String Installation in Directional and Horizontal Oil Wells

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Abstract: The combined load condition that develops in a casing string during its installation in a directional or horizontal oil well needs to be considered in the structural integrity analysis routinely undertaken as part of the well completion design process. This paper presents a non-linear finite element analysis methodology, completed using ABAQUS 6.6, which simulates the installation of casing in directional/horizontal wells. The paper describes the development of the finite element model and demonstrates its use as an effective and reliable method for assessing casing structural integrity in the design of such well completions.

Keywords: Buoyancy Force, Casing, Casing Curvature, Directional Well, Hanging Weight, Horizontal Well, Wellbore.

1. Introduction

Today, the wells drilled by the petroleum and other energy development industries cover a wide range of drilling conditions. Both highly deviated and complex horizontal well architectures are now routinely being drilled to complete reservoirs which otherwise could not be produced economically. As illustrated in Figure 1, one such application is the use of twin horizontal wells to implement the SAGD (Steam Assisted Gravity Drainage) thermal recovery process as a viable means for the in situ production of Canada's vast bitumen resources (Butler and Stephens, 1981). In this configuration, the top well is used for injecting steam into the reservoir while the lower well is used to produce the mobilized bitumen to surface. As shown in Figure 1, the SAGD wells are designed with a vertical section that penetrates through the overburden formations, an angle build section with a given well curvature which turns the wellbore from a vertical to a horizontal orientation, and a horizontal section that extends for lengths up to 1 km through the reservoir interval. The SAGD thermal wells are typically completed with one or more casing strings extending from surface down to the horizontal section that are cemented to the formation and a slotted liner extending from the casing through the open-hole horizontal section in the reservoir layer.

The combined load condition that develops in a casing string during its installation in a directional or horizontal oil well needs to be considered in the structural integrity analysis routinely undertaken as part of the well completion design process. The casing installation loads include those typically resulting from the hanging weight of the casing string and buoyancy forces that act while the string is suspended from the drilling rig on surface. In addition, as the casing string is run through the angle build section of the SAGD wellbore, it can be subjected to significant drag forces (friction forces), bending/curvature loading and possibly substantial end loads (compressive force) (Hollies et al., 2001). The stresses associated with these various installation loads will be locked into the casing string as it is cemented in place within the wellbore; therefore, they need to be estimated accurately and included when assessing the casing string integrity under the incremental loading imposed during the subsequent thermal production phase.

This paper presents a general non-linear finite element analysis methodology, completed using ABAQUS 6.6, which has been developed to simulate the installation of casing in directional/horizontal wells. A few engineering examples are analyzed in this paper to demonstrate the capabilities of the proposed numerical approach.

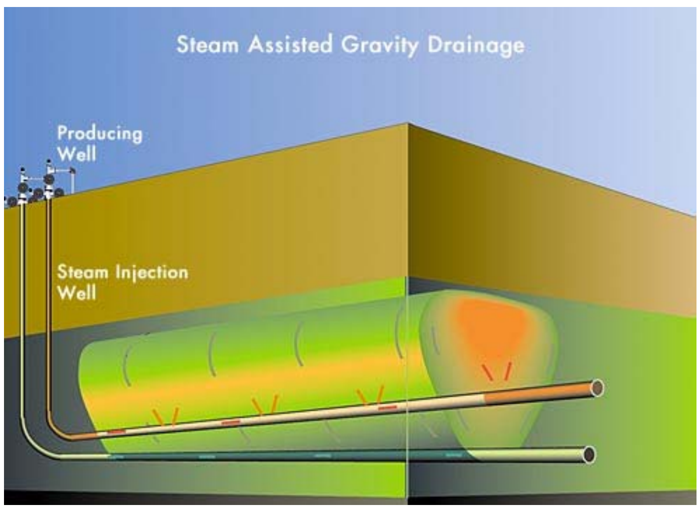

Figure 1. Casing strings in producing and steam injection wells for the SAGD (Steam Assisted Gravity Drainage) process.

2. Background

In order to determine the drag-associated axial force, it is important to understand the wellbore profile, hole geometry and borehole friction factor. The magnitude of the drag force depends on the friction factor and the magnitude of the normal forces that develop between the casing and the borehole along its length. Figure 2 shows three possible positions of the casing in a two-dimensional build section: the uppermost, middle and lowermost positions. In many horizontal well applications including SAGD developments, several wells are drilled from a common surface pad location and the build section must therefore include both hole angle curvature (to transition the well from vertical to horizontal) and azimuth curvature to establish a lateral offset from the surface location. The position of the casing within such three-dimensional build sections is more complicated as the planned azimuth changes can be expected to force the casing to be in contact with wellbore on the side planes as well.

Traditional approaches for calculating casing installation loads include either simplified model estimates or the use of finite difference methods which suffer limitations in this application. Maidla (1987) presented the following differential equation for calculating the drag-associated axial force (F_a) along the casing length (*l*):

$$\frac{dF_a}{dl} = W_u(l) \pm f_b\, C_s(l) W_N(l) \tag{1}$$

where $W_u(l)$ is the unit buoyant weight projection on the tangent direction of casing; f_b is the borehole friction factor; $C_s(l)$ is the correction factor for the effect of the surface contact area between the casing and wellbore; and $W_N(l)$ is buoyant weight projection on the principal normal direction. In the above equation, the positive sign implies an upward pipe movement, whereas the negative sign denotes a downward movement.

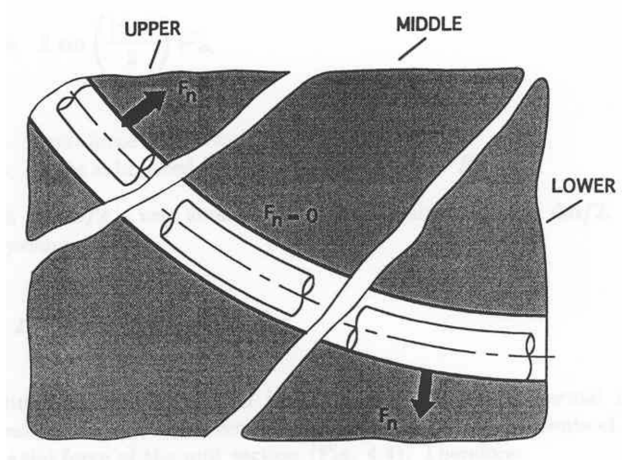

Figure 2. Possible directions of the normal forces in a build section (after Maidla, 1987).

Since the differential equation is established on the casing length which is usually defined on a curved geometry over the build section, each term in the equation involves complicated expressions with several parameters. As a result, this differential equation cannot be solved analytically. Numerical techniques such as the finite difference method can be used, but they require extensive efforts in interpreting the calculations.

It was apparent that a more practical and accurate determination of the casing installation loading could be achieved through the use of an advanced finite element method with proper contact modeling between the casing and wellbore. However, based on a literature review, little work appears to have been published describing the use of finite element analysis methods for completing such assessments.

3. Finite Element Model

A finite element methodology is introduced in this paper for analyzing casing string installation in directional and horizontal wells. The modeling and analysis was performed using ABAQUS Standard 6.6.1.

The casing string was modeled using three-dimensional beam elements (PIPE31) with pipe sectional properties to consider the load conditions associated with internal and external pressures of different magnitudes. The steel casing material is modeled using an elastic constitutive relationship with a Young's modulus of 200,000 MPa and a Poisson's ratio of 0.3. In well completions in shallow reservoir applications, the casing forces resulting from installation will typically remain well below the elastic limit, and therefore it is appropriate to use the elastic material model in the analysis. However, note that the loads imposed on the casing following installation in many thermal operations will result in yielding of the casing material.

The interaction between the casing string and wellbore was modeled using three-dimensional tube-tube interaction elements (ITT31), with the wellbore defined as a contact slide-line. The gap size was defined as the difference between the wellbore inner surface radius and the casing outer surface radius. It was also necessary to assign a friction coefficient to define the behaviour of the contact surface between the casing and wellbore. As a simplification for this assessment, the casing string was assumed to be of a constant diameter without any upsets to reflect the couplings that are typically used to join individual casing joints to form the string (i.e. the impacts of this more complex configuration deserves further investigation).

Ideally, the casing installation analysis should closely simulate the physical process employed in the field in which the string is run from surface, joint by joint, into the wellbore. Unfortunately, several trial attempts suggested that numerical difficulties associated with convergence problems create problems in modeling this progressive installation process. Therefore, the following simplified modeling procedure was followed:

1. The full casing string is first bent to conform to the wellbore configuration;
2. The casing string is then positioned along the centre of wellbore prior to initiating the contact interaction analysis; and
3. The contact interaction between casing and wellbore is then analyzed, with the string hanging weight modeled by assigning gravity loads to the casing and the buoyancy effect modeled by applying a hydrostatic pressure internally to represent a column of drilling mud as well as an external pressure on the bottom (closed) end of the casing to represent a cement column in the casing/formation annulus. Together, the hanging weight and buoyancy forces move the casing string to be in contact with wellbore, thereby generating drag forces.

In addition to the non-linear modeling of contact interaction, the analysis considered the non-linear geometry effect in order to model potential casing buckling under axial compression force.

4. Analysis of Casing Installation in SAGD Well

This section describes the use of the proposed finite element methodology to analyze the loading of a casing string installation in a SAGD horizontal well with a specified geometry. Figure 3 shows the three-dimensional view of the well trajectory profile. It indicates that the well is drilled vertically to a depth of approximately 200 m and then directionally to the horizontal orientation at a true vertical depth (TVD) of approximately 380 m and a lateral offset of 150 m. The maximum design curvature (angle build rate) for the well is 9º/30 m. The drilled wellbore has a 375 mm diameter.

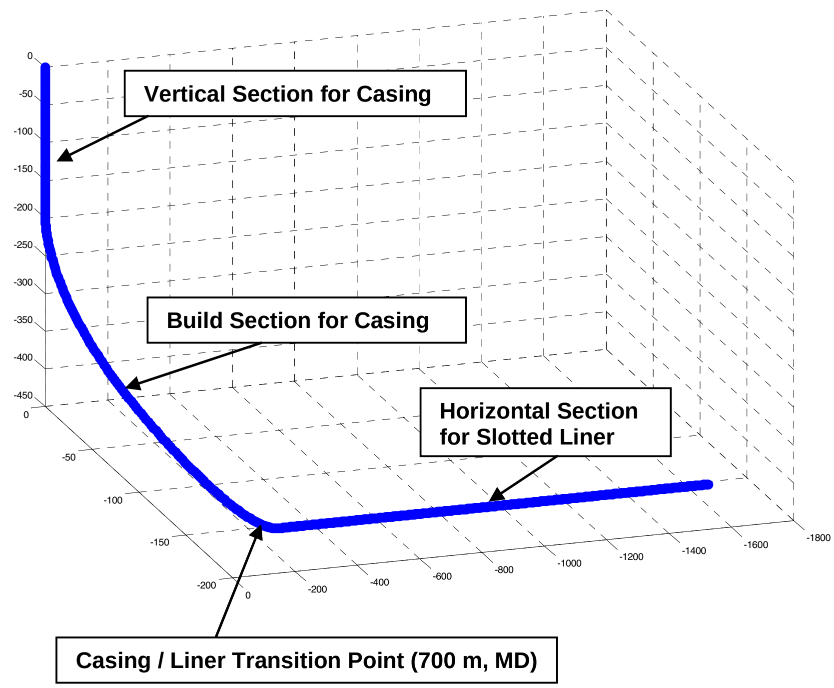

Figure 3. Three-dimensional view of a SAGD well trajectory (units in meters).

It is assumed a 298.5 mm 80.4 kg/m L-80 grade casing string is installed in this SAGD well (i.e. the casing has a minimum yield strength of 550 MPa or 80 ksi). The casing string is run through the vertical and build sections of the well to a total measured depth (MD) of 700 m, corresponding to the 380 m TVD point. In the analysis, the casing model is developed with a mesh density of 1 m per element. A sensitivity study suggested this mesh density is sufficient to generate reasonably accurate results.

The base case analysis considered a gap size of 46.5 mm (defined as the difference between wellbore radius and casing outer radius). In the analysis, the casing weight (in air) of 80.4 kg/m is used to define the hanging weight of the string. The buoyancy force is generated through the differential pressures associated with a drilling mud column with a density of 1,000 kg/m^3 inside the casing and a cement column with a density of 1,500 kg/m^3 in the casing annulus. The friction coefficient between the casing and wellbore was assumed to be 0.35.

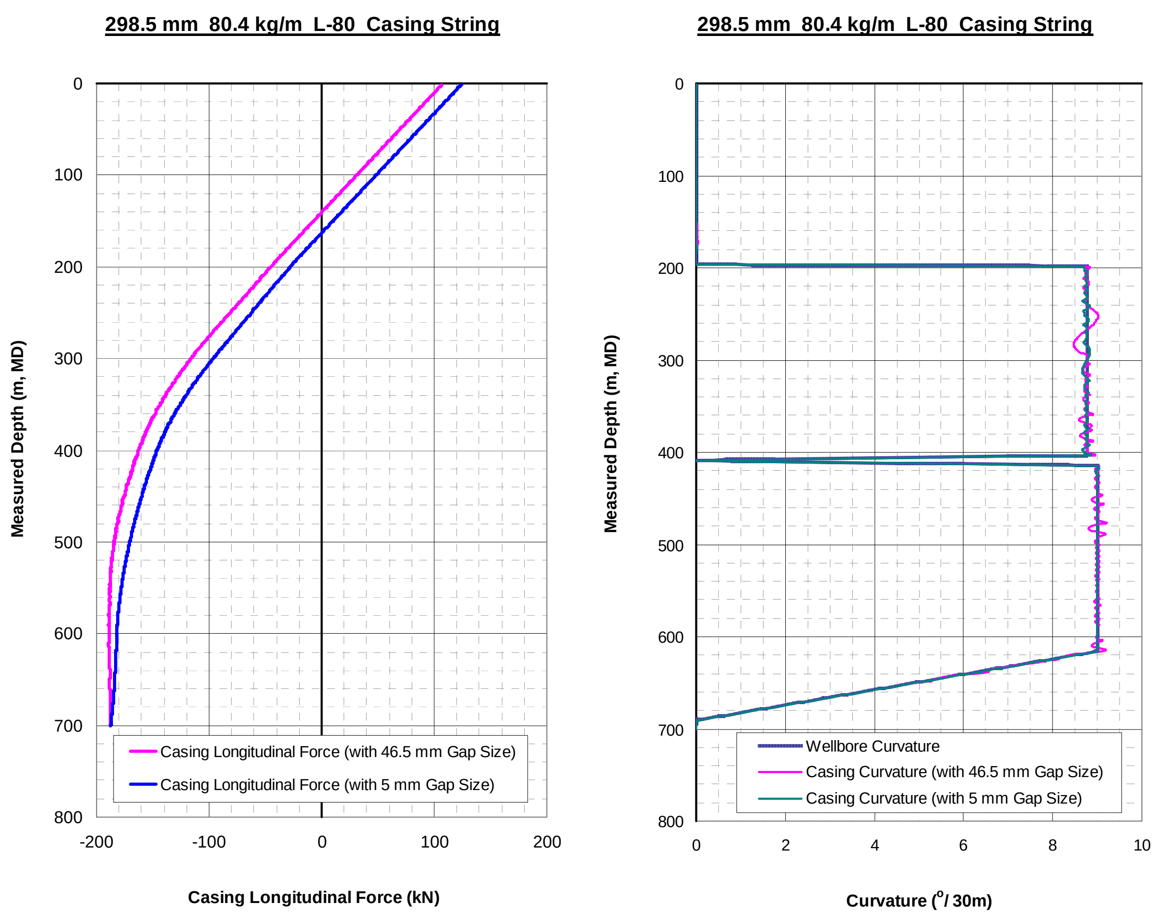

Figure 4. Distributions of casing longitudinal forces (left) and casing curvature (right) from finite element analysis.

In addition to the base case analysis, results are also presented for a parametric study performed for a case with a gap size of 5 mm. This case may represent the situation where the casing string is equipped with a large number of centralizer devices to maintain a consistent annular gap as a means to improve the quality of the cementing operations.

Figure 4 presents the casing longitudinal forces and curvatures established for the analysis cases with the 46.5 and 5 mm gap sizes. In the casing curvature plot, the curvature variations introduced by the installation loads are shown mapped with the baseline wellbore curvature to provide an overall perspective of their magnitude.

As shown in Figure 4, the casing longitudinal force starts with a maximum tension at the ground surface due to the hanging weight effects. The tensile force in the string decreases linearly until the casing reaches the build section at approximately 200 m MD. Over the build section (from 200 to 700 m, MD), the longitudinal force varies non-linearly due to the effect of the support/drag forces that act on the string. The maximum compressive force occurs at the bottom section of the casing string (700 m MD) where the buoyancy effect is the largest. The analysis results also demonstrate that a smaller gap size can influence the distribution of axial loads along the casing string in such wells. The results shown here suggest that the magnitude of the drag forces can be reduced with a smaller gap size reflecting the situation where the casing string is effectively centralized within the wellbore throughout its length.

The casing curvature plot shows that installation loads can introduce curvature variations (waves) that are superimposed on the planned build section curvature (note, the actual as-drilled wellbore curvature can be expected to vary, in some cases substantially, from the design values considered here). For the base case with the 46.5 mm annular gap, the largest curvature variations occur within the intervals between 240 and 295 m and from 475 to 495 m MD. These periodic variations reflect localized shifts in the eccentric position of the casing within the wellbore (e.g. as shown in Figure 2) that can be attributed to the contact support conditions and/or the occurrence of casing buckling under the compressive longitudinal force (compression induced waves). Note that the magnitude of the curvature variations are diminished for the case with a smaller gap size of 5 mm, reflecting the reduced ability for the casing to form tight buckles in this scenario.

Figure 5 shows the distribution of the normal contact forces and frictional drag forces that develop between casing and borehole along the wellbore length. As shown, the contact forces are concentrated within the build section of the wellbore with no contact in the vertical section due to the lack of curvature in this interval. In general, these results show that the smaller gap size led to a reduction in the magnitude of both the normal contact and friction forces.

While the analysis presented herein represents a somewhat simplified assessment of the overall problem, these initial results indicate that smaller gap sizes will tend to cause a reduction in the magnitudes of the casing/wellbore contact forces, drag forces and casing curvature variations. This finding also illustrates the importance of installing an adequate number of casing centralizers to avoid curvature localization problems in such horizontal well applications.

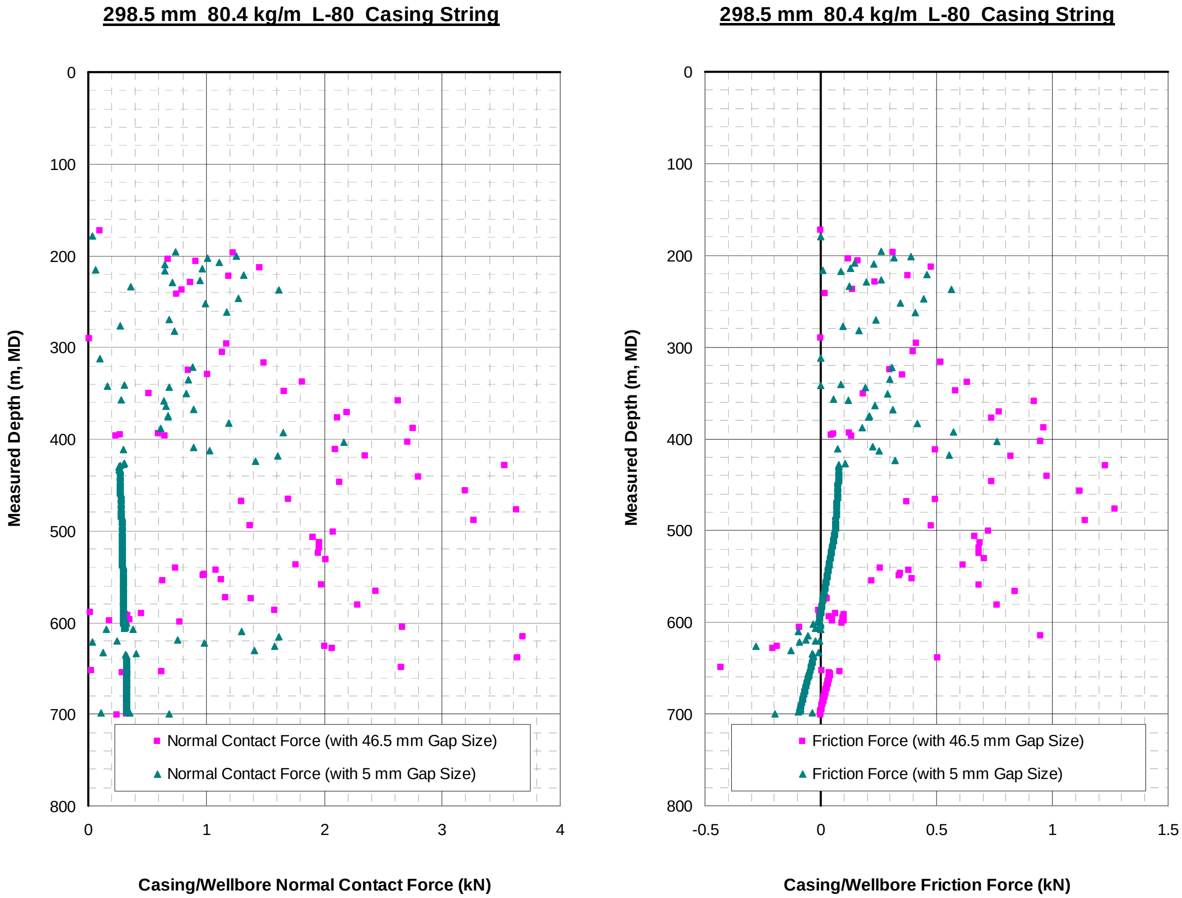

Figure 5. Distributions of normal contact force (left) and shear force (right) between casing and wellbore from finite element analysis.

5. Effect of Non-uniform Gap Size on Casing Curvature

The results in the preceding section have demonstrated that casing curvature variations can develop in the build section under installation loading conditions in situations where a large uniform annular gap exists. In practice, the presence of casing centralizers or connections will result in non-uniform gap sizes and more variable casing string/borehole contact along the wellbore. These conditions can potentially lead to further localization of the casing curvatures under the longitudinal forces that develop during the installation process.

Figure 6 illustrates the occurrence of casing curvature localization near casing connections. As both the casing outer surface and the connection outer surface tend to contact the wellbore, a localized bending wave will typically be introduced in the casing near the connection entry plane. This leads directly to a higher than average casing curvature in the critical sections. This curvature localization situation can occur within the build section of a wellbore under either axial compression or tension loading conditions. Another finite element analysis was undertaken to further investigate these effects.

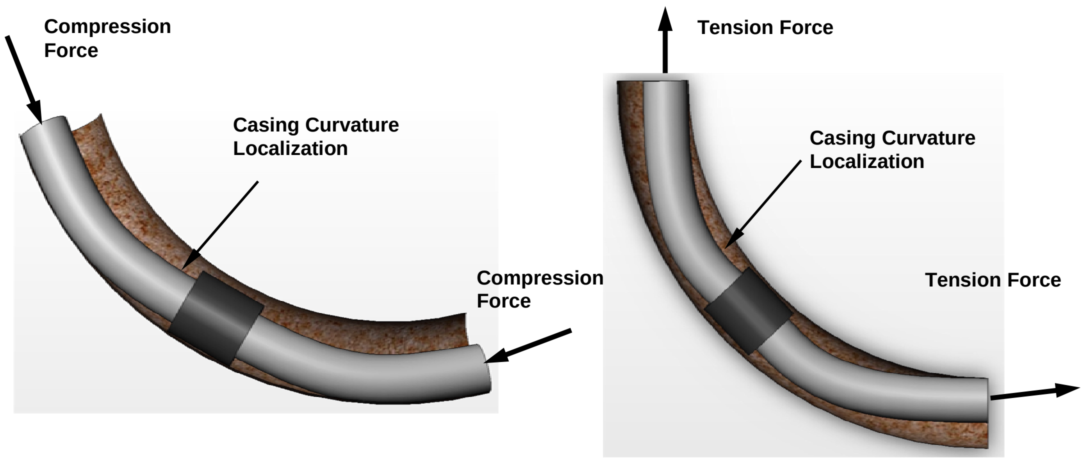

Figure 6. Illustrations of casing curvature localization near connection in build section under compression (left) and tension (right) loading cases.

The preceding base case analysis served as the starting point to evaluate the effect of non-uniform gap sizes on the resultant casing curvatures. The analysis focused on a short length of the build section with a planned wellbore curvature of 9°/30 m. A parametric assessment was completed for a number of cases with the axial force ranging from tension to compression.

The results from this investigation are presented in Figure 7, which shows that the peak casing curvature can increase significantly relative to the base condition with either axial tension or compression loading. For example, under an axial compression force of 5% of the L-80 casing material yield capacity (276.5 kN, which is equivalent to 350 m of string load), the maximum curvature increases to 10.3°/30m from the 9°/30 m initial wellbore curvature. Note that the magnification is slightly lower under tension loads of the same magnitude. This curvature localization effect should be considered in the analysis in order to achieve a more reliable design assessment as it may impact the magnitude of the inelastic strains that develop under subsequent thermal operation loads.

Figure 7. Localized curvature near casing connection based on finite element analysis.

6. Summary and Conclusions

This paper presented a finite element methodology, completed using ABAQUS 6.6, to analyze casing string installation loading conditions in directional and horizontal oil wells. As a demonstration of the proposed modeling approach, it was used to evaluate the loads that develop on a casing string run into a SAGD horizontal well with three-dimensional curvature in the build section. The effect of different casing/borehole annular gap sizes was also investigated to determine the impact of this variable on the distribution and magnitude of the forces and curvatures that develop along the casing string. The finite element model derived through this work appears to be an effective and reliable method for establishing the casing stresses and deformations that occur under installation loading conditions in directional and horizontal well applications. The results of such installation loading analyses serve as the starting point for the evaluation of casing integrity under operating load conditions, which is especially important in thermal well applications where the casing is likely to be loaded beyond yield.

7. Acknowledgement

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8. References

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