Proceedings of IPC2006
6th International Pipeline Conference
September 25-29, 2006, Calgary, Alberta, Canada

IPC2006-10480

ANALYSIS OF GIRTH WELDS IN PIPELINES SUBJECTED TO LIFTING LOADS

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ABSTRACT

Williams Gas Pipeline requested that Stress Engineering Services provide engineering services to analytically assess the failures that occurred in their 30-inch Muddy Creek Loop due to cracked girth welds. The focus of the analytical effort was to simulate the lifting during the pipeline construction process. Using finite element methods, nominal bending stresses were calculated considering a specific set of criteria including 80-foot pipe joints, skid locations, and a given root pass weld thickness. These bending stresses were used to calculate a total stress that included stress concentration factors (SCFs) due to hi-low weld mismatch and weld profile geometry. For conservatism, residual stresses were also included in computing the total stress. As an example, the results showed that if a residual stress of 50 percent yield and a total SCF of 4.5 are assumed, the lift height should be limited to approximately 9 inches for a root pass weld thickness of 0.0625 inches. In this calculation, a stress limit of two times yield was used.

Once the final stress was computed considering the range of variables, a closed-form equation was developed that integrated the variables of interest for the 30-inch pipe. This equation was used to compute data points to guide Williams in establishing permissible lift heights for a range of SCFs for the welds. A stress limit of two times the yield strength was selected as the limiting value. The details of the work presented in this paper will assist pipeline operators in developing a protocol that balances the need for rapid construction and ensuring that proper girth welds are fabricated.

INTRODUCTION

Failures occurred in the Williams Gas Pipeline 30-inch Muddy Creek Loop due to cracked girth welds [1,2]. The focus of the analysis effort was to simulate pipe lifting during the pipeline construction process. Using finite element methods, nominal bending stresses were calculated considering a specific set of criteria including 80-foot pipe joints, skid locations, and a given root pass weld thickness. These bending stresses were used to calculate a total stress that included stress concentration factors (SCFs) due to hi-low weld mismatch and weld profile geometry. This paper provides calculations for stresses generated in the girth welds during the construction process. The work involved the following tasks.

- Using finite element beam models to calculate bending stresses as functions of lift height.
- Calculating stress concentration factors for a select weld profile using finite element analysis.
- Reviewing closed-form solutions available from the open literature that can be used to estimate weld SCFs.
- Using an equation to estimate the effects of hi-low weld mismatches on the SCF in the weld.
- Addressing the effects of residual stress on the total stress in the weld.
- Details on how the different combinations of SCFs are combined to calculate a total stress as a function of lift height.

Also provided is a section discussing how the methods presented in this paper can be used to develop a general tool for calculating stresses as a function of lift height. This tool will include a range of pipe geometries, weld profiles, and pipe lay conditions. The objective is to develop a resource that can be used by the pipeline industry to assess the effects of lift height on stresses generated in girth welds during the construction process.

ANALYSIS METHODS

Finite element methods were used to calculate stresses in the girth welds. Beam elements were used to calculate nominal bending stresses, while axisymmetric elements subject to asymmetric bending loads elements were used to compute the geometrically-based stress concentration factors. A closed-form solution based upon previous work was used to compute the SCFs due to hi-low weld mismatches. After calculation of the nominal stresses and stress concentrations factors, an equation was developed to describe the total stress in the given pipe.

The sections that follow provide additional details on each phase of the analysis effort. Discussions are included that address the following subjects:

- Calculating bending stresses using beam elements
- SCFs calculated using an axisymmetric model with asymmetric loading
- SCFs calculated to account for hi-low weld mismatches

Calculating Bending Stresses using Beam Elements

Finite element methods were used to calculate the nominal bending stresses in the girth welds. The pipe geometry (30-inch by 0.312-inch) was used as input and the pipe joints were assumed to be 80-feet in length. The ABAQUS general-purpose finite element code was used in the analysis using the B21H beam-type element with PIPE section properties (i.e. radius and wall thickness inputs). Elastic material properties were assumed so details relating to yield strength and elongation were not required. Only isothermal and quasi-static loading conditions were considered in the analyses.

The objective in modeling was to simulate the actual lifting process of the pipeline once the root pass weld has been created. The steps below outline the basic actual physical process used in creating the root and hot pass welds.

1. Lift the pipe joint into place by lifting at its center of gravity point.
2. Position the internal welding clamp.
3. Install the root pass weld (designate as Weld #1). For the problem at hand, the thickness of the root pas ranges from 1/16-inch to 1/8-inch.
4. Remove the weld clamp and slide the clamp toward open end of pipeline for installing next root pass (this is sometimes done before the root pass is fully completed).
5. Lift the pipe to install the skid towards the open end of the pipe. Lower the pipe back onto the skids after it has been properly positioned.
6. Install hot pass (re-designate as Weld #2) and simultaneously install new root pass generated where clamp has been positioned. Repeat from Step #1.

This sequence of events results in generating bending stresses as a function of lift height. For the current problem, a set of pipe geometry conditions were assumed that included the following variables:

- Pipeline diameter of 30 inches and wall thickness of 0.312 inches
- Weld thickness of 0.125-inches and weld span of 8-inches longitudinal to pipe. This is thought to be a conservative length to ensure calculation of the largest bending stresses.
- Pipe joint lengths of 80-feet
- Skid width of 6 inches (and height of 6 inches) positioned 8-feet from girth weld locations

Figure 1 provides a schematic illustration of the pipe geometry and how the skids were positioned relative to the girth weld locations. The total pipe assembly modeled was 437 feet. This length was selected to ensure that boundary conditions did not result in far end effects on the girth welds near the lift point. Results of the analysis demonstrated that a sufficiently long pipe assembly length was modeled. The order of weld creation is inversely related to the weld number shown in Figure 1. In other words, Weld #1 is the most recently created weld.

To calculate a range of bending stresses, the pipe assembly was incrementally lifted to a maximum height of 48 inches at the Lift Point. As will be presented in the Analytical Results section of the paper, stresses were computed as a function of height. All height measurements provided in this paper correspond to the height at the Lift Point as shown in Figure 1. Weld thickness was also an important variable considered in the analysis.

Calculating Weld Stress Concentration Factors

In the current analysis there are two primary sources of stress concentration. The first involves SCFs generated by the weld profile itself. This is a classical stress concentration that results in creating a local stress increase due to abrupt changes in geometry over a relative short length. This includes the reduced area of the incomplete weld. For the problem at hand, an axisymmetric continuum model was constructed using sample weld geometries provided by Williams Gas Pipeline. This model was subjected to bending loads to calculate the stress concentration factor. The SCF in the configuration is calculated by dividing the maximum principal stress by the nominal bending stress in the weld cross-section.

Figure 2 is a schematic diagram showing boundary conditions and loading considered the geometry as a cantilever bending configuration. Note that model shown is axisymmetric and only represents one-half of the pipe wall cross-section. In the weld region, the maximum principal stress was extracted from the finite element model for calculating the stress concentration factor. Figure 3 provides a detailed view of the weld zone from the finite element model. The radius of curvature in the notch was modeled as 0.003 inches, while the wall thicknesses were modeled as 0.305 inches (left end wall) and 0.302 inches (right hand wall).

In addition to using finite element methods to calculate stress concentration factors, it is also possible to use some of the closed-form solutions available in the open literature. Peterson's Stress Concentration Factors, by Walter Pilkey, has numerous equations for calculating SCFs for various notch geometries [3]. There is also a good discussion on notch sensitivity and the concept of an effective stress concentration factor, K_e. Notch sensitivity exists in ductile materials because as the applied load reaches a certain level, plastic deformation may be introduced. With plastic deformation the actual stress concentration factor, K_t, is reduced depending upon the material properties of the notched object.

Stress Concentration due to Hi-low Weld Mismatch

In previous research efforts SES used experimental and analytical techniques to address the effects of hi-low weld mismatches. A closed-form equation was developed that incorporates the pipe wall thicknesses and level of eccentricity to calculate a stress concentration factor [4]. This relation is provided below in Equation 1.

$$SCF = \left[1.0 + 2.6 \cdot \frac{e}{t_{thin}} \left(\frac{1}{1 + 0.7 \cdot \left(\frac{t_{thick}}{t_{thin}} \right)^{1.4}} \right) \right] \qquad (1)$$

where e = centerline eccentricity of weld (inches)
t_{thin} = thickness of thinner pipe (inches)
t_{thick} = thickness of thicker pipe (inches)

Having access to this experimentally-validated equation precluded the need for any additional analysis considering hi-low weld mismatch. Including this equation in calculating the total stress will be presented in the following section of this paper. Figure 4 plots data generated using Equation 1 for a range of eccentricities and wall thickness ratios.

ANALYSIS RESULTS

The objectives in performing the analysis efforts were to determine stresses generated in the girth weld based upon localized SCFs as well as bending stresses generated in the process of lifting the pipe. While calculation of stresses is important, the larger and more important issue involves combining the results into a single tool that can be used before construction to determine the maximum lift height for a specified allowable design criterion (i.e. stress or strain). The sections that follow provide details on the results from the finite element analyses involving the beam and axisymmetric models. Also presented is a discussion showing how a total stress is computed using the different analysis techniques and methods of this project.

Results for Analysis Using Beam Elements

The primary intent in modeling the pipeline installation process using beam elements was to determine the overall stress fields that occur as a function of lift height for a given set of pipe conditions (i.e. pipe geometry including diameter, wall thickness, and length) and weld thicknesses. ABAQUS computed stresses in the weld section of the model as a function of height. Figure 5 shows the stresses calculated using the beam model. Refer to Figure 1 presented previously for position of the welds where Weld #1 is the one closest to the end of the open pipe.

The curves shown in Figure 5 are for two types of support configurations:

- Flat ground
- Skid supports

While on average the differences in stress are minimal when comparing the flat ground and the skid-supported condition, it is important to note that there are some differences especially at the lower lift heights. The remaining calculations that compute a final stress in this work use the skid-supported conditions.

There are several important observations that can be made when reviewing the data plotted in Figure 5.

- During the early stages of the pipe lift, Weld #1 has a higher stress than Weld #2. However, there is a cross-over point where this relationship changes. The primary variable is the position of the pipe span's center of gravity relative to the weld in question.
- Because of the sag induced by gravitational loading, Weld #2 is not loaded in tension until the Lift Point of the pipe is lifted approximately 10 inches vertically.
- Using basic mechanics (and validated using the finite element model), there is an inverse linear relationship between the thickness of the weld and the stress in the pipe. In other words, if the thickness of the weld is reduced by a factor of 2, the stress in the weld increases by a factor of 2. This observation is based upon the fact that the section modulus (Z) for a thin-walled cylinder can be expressed in terms of $\pi r^2 t$ where r is the pipe radius and t is the wall (or weld) thickness. The maximum bending stress is computed by dividing the applied bending moment by the section modulus, Z.

It should be noted that the stress results presented are valid ONLY for the combination of pipe lengths and geometries presented herein, although general trends in pipe stress relative to lift height are possible for a range of pipe conditions. A more general design tool is needed to incorporate different sets of pipe geometries and lift conditions to calculate stresses.

Results for Axisymmetric Models Used to Compute SCFs

While the beam element models provided results for the nominal bending stress in the pipe, the axisymmetric models subjected to asymmetric bending loads were used to calculate exact stress concentration factors for a given weld geometry. Prior to modeling the weld geometry, the decision was made to select a weld geometry that would generate a sufficiently large SCF, but not one that would produce unrealistically large stresses. It was also recognized that notch sensitivity limits the magnitude of the SCF for mild carbon steels that have reasonable ductility, even when sharp defects are present. Using finite element analysis, a SCF was calculated for the weld geometry considered. Figure 6 provides a cross-sectional contour plot showing the maximum principal stresses from the post-processed finite element model. As noted in this figure, the peak stresses occur where the minimum radius of curvature exists in the model. Had the sharp profile occurred on the inside diameter of the pipe, the hot spot would have been located at that location. Stress contours that exceed 5,000 psi are plotted in RED. The value of 5,000 psi was selected for plotting purposes only and does not represent a nominal stress or any value specifically related to the applied load.

Using the finite element results, the stress concentration factor is calculated by dividing the maximum principal stress by the nominal bending stress in the weld region of the pipe. Using this methodology, the SCF was computed to be 3.86. It should be noted that this SCF represents an increase in the bending stress in the weld itself and not the pipe wall. In other words, to compute the maximum stress in the weld, multiply the SCF by the bending stress in the weld section (and not the pipe wall). If the thickness of the weld is less than the pipe wall, the bending stress in the weld will be larger than it would be in the base pipe.

Equation 2 provided below shows how the SCF of 3.86 was computed. In this relation, $\sigma_{\max}$ and σ_{weld} correspond to the maximum principal stress computed in the weld and the nominal bending stress in the weld section, respectively.

$$SCF = \frac{\sigma_{\max}}{\sigma_{weld}} = \frac{16{,}912\, psi}{4{,}376\, psi} = 3.86 \tag{2}$$

Of similar interest are stress concentration factors computed using closed-form solutions. A SCF of 5.42 is calculated assuming an elliptical notch. This value is reduced to 2.33 when considering the effect of notch sensitivity. In the absence of more accurate calculation tools such as finite element methods, the use of closed-form solutions can provide useful information. It should be noted that without correcting for notch sensitivity, it is possible for the closed-form solutions to result in unrealistically large stress concentration factors.

Computed SCF due to hi-low weld mismatch

Using pipe and weld thickness measurements taken from several of the Williams Gas Pipeline weld samples, a SCF due to hi-low weld mismatch was computed to be 1.45 using Equation 1 (presented previously). The input data for this calculation were as follows,
e = 0.09 inches (centerline eccentricity of weld)
t_{thin} = 0.302 inches (thickness of thinner pipe)
t_{thick} = 0.305 inches (thickness of thicker pipe)

The computed SCF of 1.45 is combined with the SCF due to the weld geometry when a hi-low weld mismatch occurs. Consequently, the total effective SCF for both the weld geometry and mismatch is 5.60, computed as the product of 3.86 (weld geometry SCF) and 1.45 (hi-low SCF).

Comparing Total Stress to an Allowable Stress

The deliverable for the combined analyses is a recommended lift height for the assumed weld geometry and strength conditions. It is necessary that the SCFs calculated consider both the weld geometry and hi-low weld mismatch, if the latter is present. To develop a total stress value, third-order polynomials were extracted from the plotted data presented in Figure 5. These polynomials were then combined to produce a single equation that could be used to compute total stress as a function of lift height. The necessary components of this equation include:

- Bending stress generated in weld (position of Weld #1) due to lifting after root pass generated
- Residual stress due to welding process (range between 15 and 100 percent of yield strength)
- Bending stress generated in weld (now position of Weld #2) due to lifting after hot pass generated with increased weld thickness
- Integration of all appropriate SCFs

Equation 3 integrates the variables listed previously.

$$\sigma_{total} = f_r \cdot \sigma_{yield} + f_w \cdot f_e \cdot \left[f_{t1} \cdot \sigma_1(h) + f_{t2} \cdot \sigma_2(h) \right] \qquad (3)$$

Where

σ_{total} = Total calculated stress (psi)

f_r = Residual stress ratio (fraction of yield strength, range from 0.15 to 1.0)

σ_{yield} = Yield strength of pipe or weld material (psi)

f_w = SCF due to weld geometry

f_e = SCF due to hi-low weld eccentricity mismatch

f_{t1} = Weld #1 thickness ratio (0.125-inches / t_{weld} | f t1 = 2.0 if t_{weld} = 0.0625 inches)

f_{t2} = Weld #2 thickness ratio (0.125-inches / t_{weld} | f t2 = 1.0 if t_{weld} = 0.125 inches)

σ_1(h) = Bending in Weld #1 from Polynomial #1 (psi)

σ_2(h) = Bending in Weld #2 from Polynomial #2 (psi)

$$\sigma_1(h) = 0.5588 \cdot h^3 - 50.064 \cdot h^2 + 1625.5 \cdot h + 1555.9 \qquad (4a)$$

$$\sigma_2(h) = -0.465 \cdot h^3 - 39.771 \cdot h^2 + 7.5343 \cdot h + 4257.5 \qquad (4b)$$

Equation 4a and 4b are polynomials that were derived by curve fitting the data plotted in Figure 5. These equations are applicable only for lift heights less than 40 inches. The resulting stresses are in units of psi and the units of the input heights, h, are inches.

There are a wide range of SCF combinations that can be considered. To clearly present what range of stresses can reasonably be expected, four combinations of SCFs were selected. It is important for the current analysis to integrate the effects of both the weld profile and the hi-low weld mismatch. While the SCF for the weld profile is normally going to the larger of the two (e.g. f_w = 3.86), integrating the effects of the SCF due to hi-low (e.g. f_e = 1.45) adds an additional level of conservatism. Figure 7 and Figure 8 show photographs of sections showing representative weld geometries responsible for generating SCFs due to hi-low and weld profiles, respectively.

For presentation purposes, several combinations of SCFs were selected and designated as stress cases. These combinations bound the problem and represent what could be expected to be the minimum and maximum levels of stress concentration for the weld profiles in question. There is no guarantee that these stress cases represent every combination of welds that might exist in a pipeline; however, based upon previous experience and the impact of the SCFs on the calculated results, they appear appropriate. Provided in Table 1 are a list of the four (4) stress cases used to generate the analysis data. Refer to Figure 7 and Figure 8 for details on typical geometries for the SCFs considered.

Using the SCFs presented in Table 1, calculations were performed to compute the total stress in the weld as a function of lift height using the variables included in Equation 3. The calculated data are presented in a series of graphs that plot total stress as a function of lift height. The intent is for Williams Gas Pipeline to use these plots to make decisions regarding permissible lift heights. The first of these graphs is Figure 9 that plots the data assuming a residual stress of 50 percent. As noted in this figure legend, the SCFs provided in Table 1 were used to generate the plotted data. The ORANGE line represents a stress limit of twice yield. This stress was selected as it represents the range of shakedown to elastic action (consistent with methodology embodied in the design by analysis rules of the ASME Boiler & Pressure Vessel Code, Section VIII, Division 2, Appendix 4) [5,6,7]. It is not recommended that conditions be permitted that cause stresses to exceed this limit. Figure 10 shows curves that consider the presence of a residual stress equal to the yield strength of the pipe (70,000 psi).

Also provided is Figure 11 that shows a set of data focused on lift heights less than 10 inches for welds with residual stresses equal to the yield strength of the pipe. These data are important as they represent the normal range of pipe lift heights that will occur in the construction process.

DISCUSSION OF RESULTS

A method has been developed to calculate the total stress in a girth weld considering a range of conditions present at the time of construction. Recognizing the potential for a wide range of variability in the pipe construction and welding process, it is important for an engineering analysis to capture a range of conditions. As an example, assumptions relating to residual stress have the potential to dominate the problem. If a residual stress ratio, f_r, of 1.0 is chosen, there is clearly a limit on how large the weld SCF can be or how much lift is permitted.

In a similar light, options exist for determining what the allowable stress should be. There is also ample evidence that placing limitations on strain, as opposed to stress, is a viable design option. The linear elastic method of stress calculation was calculated for simplicity and to minimize dependency upon stress-strain curves that invariably leads to discussions on strain hardening.

The main focus of this project has been on the solid mechanics side of calculating stresses. One could argue that the principal issue relating to failure of the welds was rooted in poor workmanship and inspection techniques. While these are valid arguments, the analysis results reported herein show that even with minimal levels of weld stress concentration there is a limit on how high the pipe can be lifted before stresses exceeding twice yield are calculated. For example, the results presented in Table 2 that show the lift height limits for combinations of SCFs as a function of residual stress levels. The data presented assume a root pass weld thickness of 0.0625 inches.

Notice from the tabulated data that the residual stress has a significant impact on limiting the permissible lift heights. The data provided in this table clearly demonstrate that even though weld quality and inspection are important, one cannot discount the mechanics of the problem and the stresses that are generated simply due to lifting. It is reasonable to assume that the second line of data (SCFs of 3.0 and 1.0) are the minimum SCF combinations that one would expect even with good welds. The limitations placed on life height for these given conditions range between 9 inches and 14.5 inches.

No consideration of the effects associated with dynamic loading was considered as part of this analysis. When pipes are lifted rapidly and/or dropped, there is the potential for generating large loads that will result in stresses larger than presented in this document. After the line-up clamp is removed, the pipe should be lowered gently and carefully onto the skids.

Historically, the pipeline industry has not been plagued by rampant girth weld failures. One of the primary reasons for the low number of failures is the ductility of steel and its ability to blunt crack-like defects. The work provided in this paper shows the potential for generating high stresses in girth welds, especially when inadequate weld workmanship exists to produce large geometric stress concentration factors.

COMMENTS AND CLOSURE

This paper has described the methods used to calculate stresses in girth welds considering a variety of factors including stress concentration factors, lift height, and residual stresses. The overall objective was to determine the level of stresses generated in girth welds during construction, especially stress levels sufficient to generate cracks. The methods used integrated finite element analyses to develop a single equation that expresses stress as a function of lift height. This general equation can also integrate SCFs due to weld geometry and hi-low weld mismatch as well as residual stress levels.

As an example, the results show that if a residual stress of 50 percent yield and a total SCF of 4.5 are assumed, the lift height should be limited to approximately 9 inches for a root pass weld thickness of 0.0625 inches. In this calculation, a stress limit of two times yield has been used.

In conducting this project an approach was taken to generate information that can be used by pipeline companies as part of their on-going construction practices. The approach is based upon elastic solid mechanics and does not consider strain-based design criteria. While one could argue that a strain-based approach has greater technical merit, it is the observation of the authors that these methods are often impractical for field purposes and require large computational efforts to derive the most basic calculations.

It is also possible to envision a project that extends the single-size results to consider a range of pipe geometries and construction conditions. This effort would be accompanied by the development of a single-source design tool that can be programmed for a PC using a menu-driven interface. This tool can be used during the construction planning phase to introduce guidance on permissible lift heights and provide additional recommendations as to when field bends might be required to account for vertical terrain height changes.

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Table 1 – Stress cases considering combinations of SCFs

Stress Case	f_e SCF due to hi-low mismatch (refer to **Figure 7**)	f_w SCF due to weld profile (refer to **Figure 8**)	**TOTAL Calculated SCF** ($f_w \cdot f_e$)
Case 1	1.0	1.0	1.0 (1)
Case 2	1.0	3.0	3.0
Case 3	1.5	3.0	4.5
Case 4	1.5	4.0	6.0 (2)

Notes:
1. The Case 1 total SCF corresponds to NO stress concentration factor. Stresses computed using this value are the minimum that can be expected for the bending stresses computed as part of this project.
2. Case 4 represents the upper bound SCF for the range of stresses considered.

Table 2 – Lift height limits for SCF and residual stress combinations

Stress Case including SCFs due to weld profile & hi-low weld mismatch (see note below)	**Permissible Lift Heights (based upon $2\sigma_{yield}$ limit)**	
	Residual Stress Level (50 percent Yield, f_r =0.5)	**Residual Stress Level (100 percent Yield, f_r =1.0)**
Stress Case #1 (f_e = 1.0 and f_w = 1.0)	*40 + inches*	*37.5 inches*
Stress Case #2 (f_e = 1.0 and f_w = 3.0)	*14.5 inches*	*9 inches*
Stress Case #3 (f_e = 1.5 and f_w = 3.0)	*9 inches*	*5.75 inches*
Stress Case #4 (f_e = 1.5 and f_w = 4.0)	*6.5 inches*	*4.35 inches*

Note: Refer to information in **Table 1** for specific information on the Stress Cases.

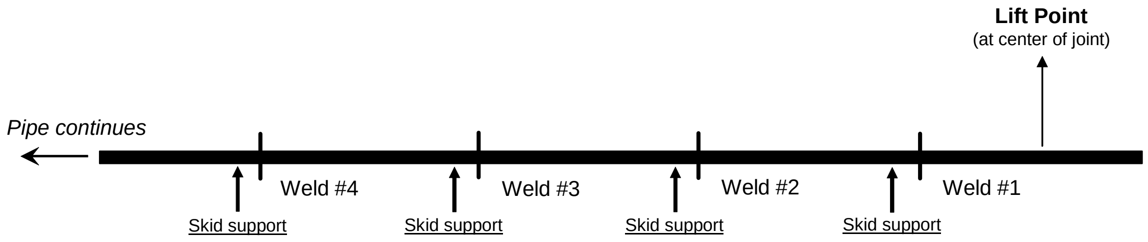

Figure 1 – Schematic showing beam element model configuration

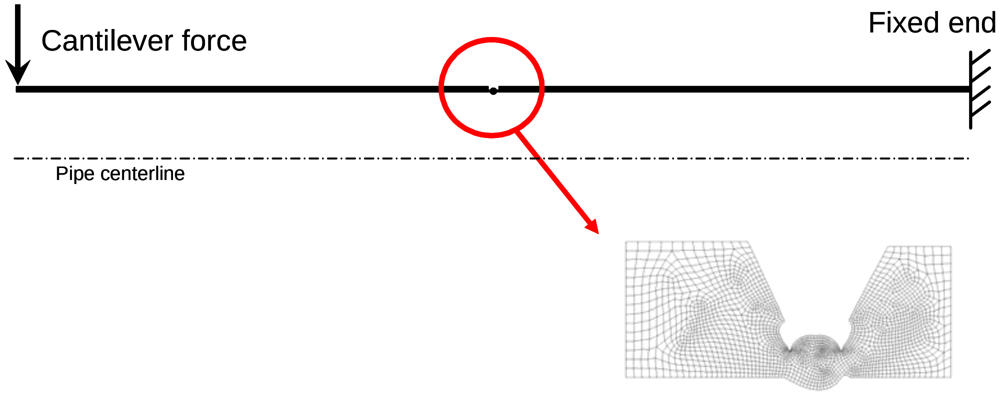

Figure 2 – Schematic showing bending load configuration

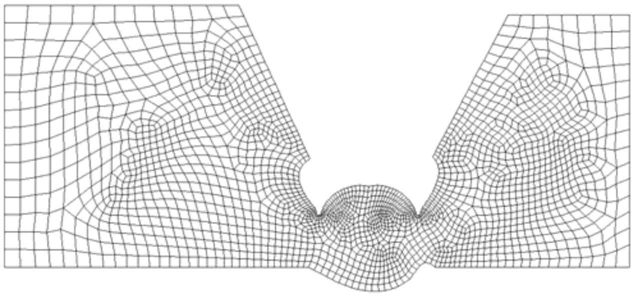

Figure 3 – Zoomed view of weld zone in finite element model

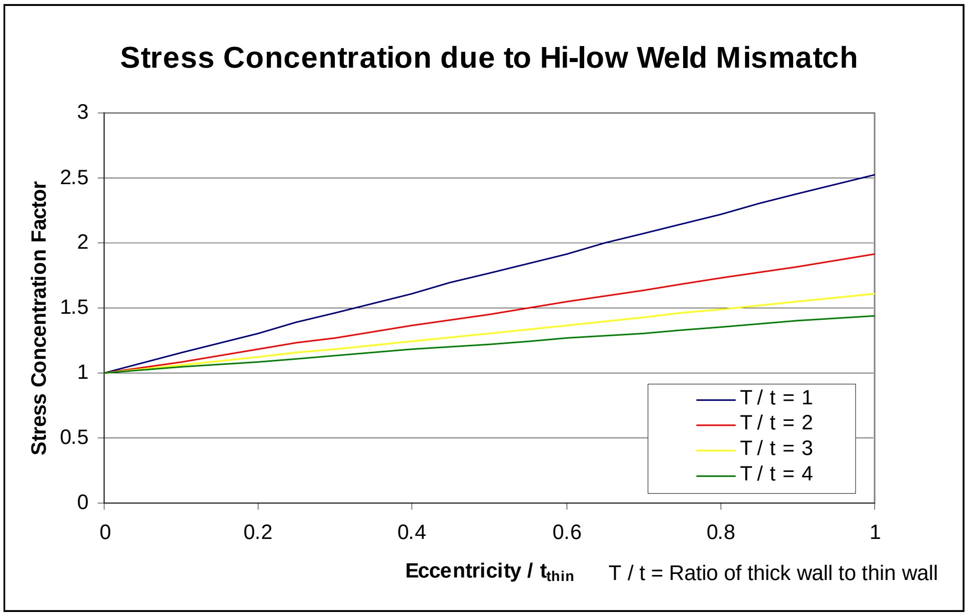

Figure 4 – Stress concentration as a function of hi-low

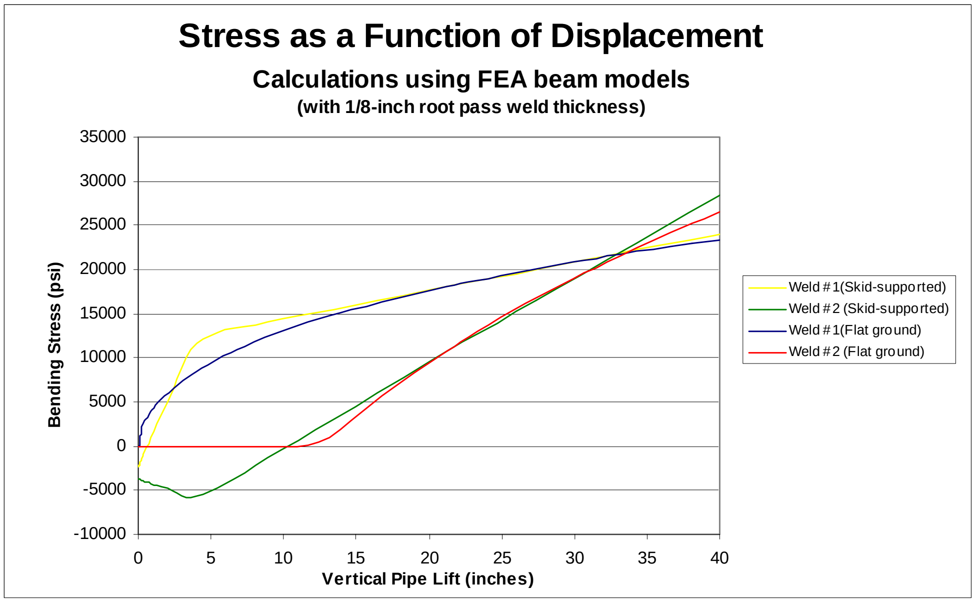

Figure 5 – Stress calculated as a function of lift height

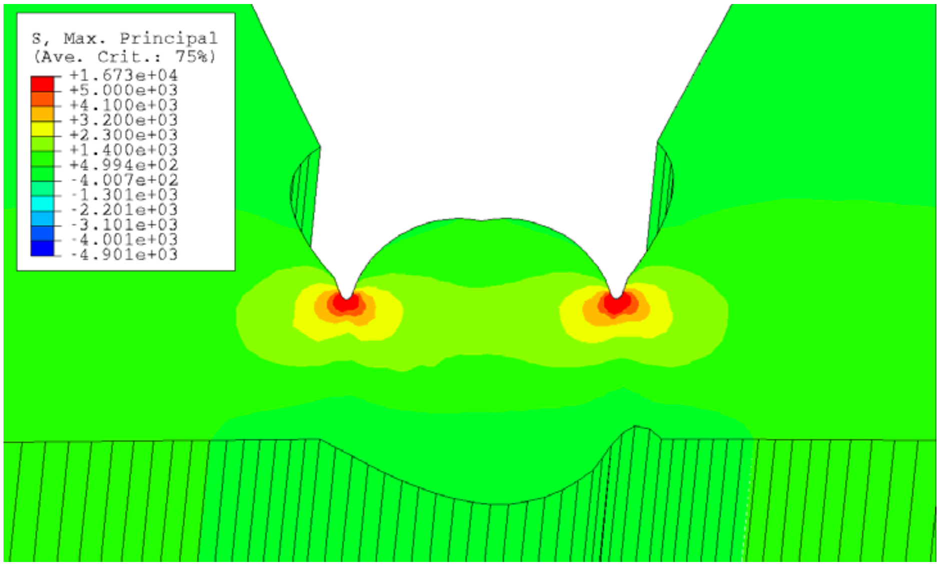

Figure 6 – Exemplar maximum principal stress contour plot of weld section
(stress contours that exceed 5,000 psi are plotted in ***RED***)

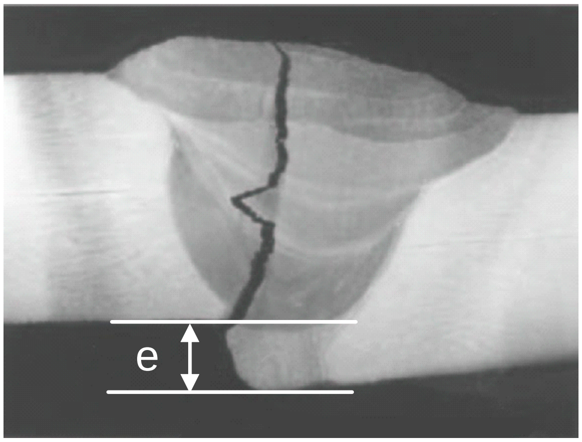

Figure 7 – Photograph demonstrating the presence of hi-low weld mismatch

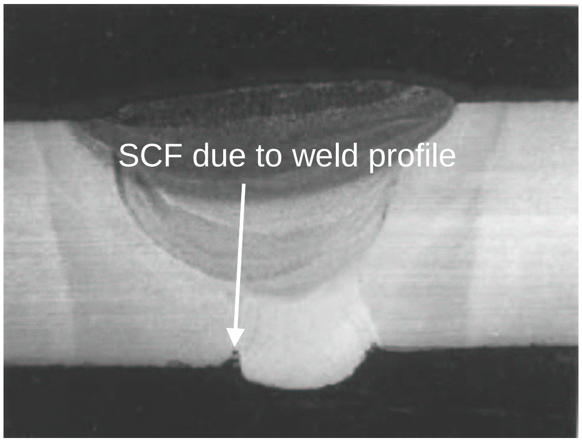

Figure 8 – Photograph demonstrating SCF-producing weld profile

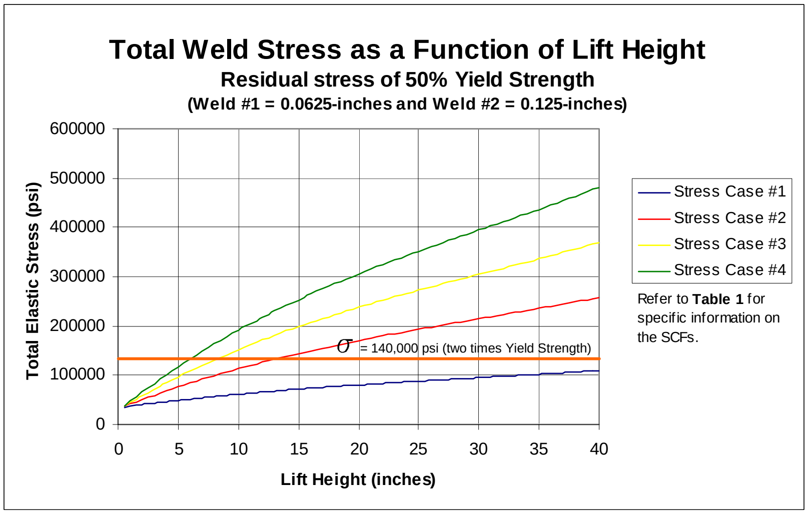

Figure 9 – Total stress computed assuming residual stress is 50 percent Yield

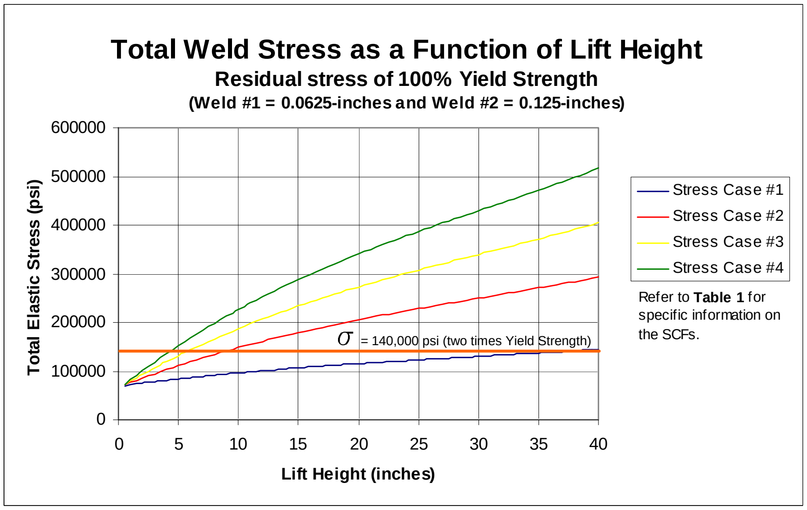

Figure 10 – Total stress computed assuming residual stress is 100 percent Yield

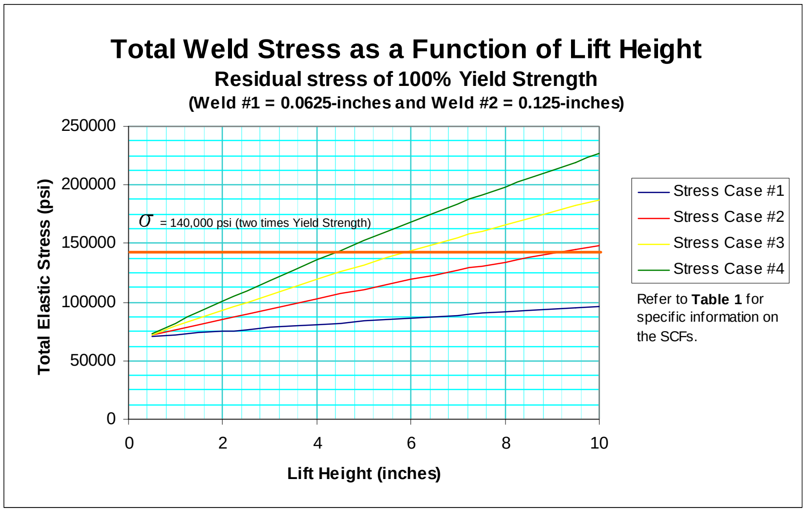

Figure 11 – Stresses computed for displacements less than 10 inches