A STUDY OF MECHANICAL INTEGRITY FOR UNEQUAL WALL THICKNESS TRANSITION JOINTS IN PIPELINE

by

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ABSTRACT

Unequal wall thickness transition joints are used in energy pipelines to connect straight pipe segments to thicker walled pipe sections such as cold bends and fittings. Due to the operational loads, changes in the pipe horizontal and vertical alignment, and variations in the soil type, axial loads and bending moments are generated along the pipeline. Through the wall thickness transition, stress concentrations develop due to the differences in pipe geometry, stiffness, material grade and mechanical strength.

Current engineering practice and standards provide guidance on back-bevel design for wall thickness transitions. An alternative configuration, the counterbore-taper design recommended by TranCanada PipeLines, is intended to reduce stress concentration effect across the transition, facilitate welding processes, and improve NDT quality, productivity and reliability.

Through a parametric study, using finite element methods, the relative mechanical response of the back-bevel and counterbore-taper wall thickness transition is evaluated. The numerical modelling procedures are verified with analytical equations and numerical simulations available in the public domain literature. The influence of element type, mesh topology, wall thickness mismatch (t_2/t_1), material grade on the limit load, pressure containment response, associated with the onset of plastic collapse, are evaluated. In terms of strength performance associated with stress concentration effects, the significance of element type, mesh topology, pipe diameter (D), pipe diameter to wall thickness ratio (D/t), wall thickness mismatch (t_2/t_1), material grade on the limit load, counterbore length, taper angle and radial girth weld offset (i.e., Hi-Lo) are examined.

The improved performance of the counterbore-taper weld transition; relative to the back-bevel design as recommended by current practice, was demonstrated in this study through equivalent limit load capacity for pressure containment and reduction in the stress concentration factor for combined loading. The minimum counterbore length was found to be consistent with industry recommended practices, and was related to the pipe diameter and wall thickness mismatch. Guidance on the selection of joining methods to advance current engineering practice is provided.

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1 INTRODUCTION

1.1 Overview

Oil and gas are major energy resources that influence our daily lives and economy. Pipelines are the primary means for transporting these resources from the producing regions to the end user. As the growth in U.S and Canadian oil and natural gas production, new build pipelines and expansion of existing systems are required to supply the markets and energy demand. On a global scale, there are more than one million kilometers of natural gas transmission pipelines with many factors to consider in the engineering design and operation including the route length and alignment, terrain unit, soil type and strength, and loads due to operating conditions and external forces (Kenny, 2011; Pike and Kenny, 2012; Pike et al., 2012) .

Unequal wall thickness transition joints are utilized along pipeline routes to connect pipe segments to thicker wall thickness items (e.g. coldbends, fittings). As there is a change in vertical or horizontal alignment associated with these sections, excessive axial load and bending moment can be generated at these connections with the resulting presence of stress concentration. It has been observed that the high stress concentration at the weld increases the risk of hydrogen assisted cracking which can initiate pipeline failures such as fracture or rupture. The back-beveled joint, as the conventional joining method, is recommended in codes ASME B31.8 and CSA Z662. TransCanada PipeLines has determined that when there is no special transitioning technique, the stress concentration at the girth welds is higher and the crack in the weld is more difficult to detect. The counterbore-tapered joint, with the thicker wall pipe bored for a certain distance to match the nominal wall thickness of the thinner pipe, can effectively reduce the stress concentration at the girth welds and contain the same carrying capacity, which has been widely utilized in pipeline industry in North America for over 30 years.

This study focuses on comparatively evaluating the back-beveled and couterbore-tapered joints through numerical modelling procedures. Validated against the numerical data and analytical solutions from literature available in public domain, a parametric study on pipe carrying capacity and stress concentration effect was developed with the consideration of several pipe design parameters including pipe diameter, wall thickness mismatch ratio, taper angle, pipe material grade and couterbore length. Recommendations on the selection of pipe joints were incorporated with current engineering practice and provided graphically.

1.2 Scope and Objectives

Most studies on unequal wall thickness transitions have focused on the mechanical response of back-beveled joints with respect to burst pressure capacity and stress concentration effects using analytical solutions, physical models and finite element simulation (e.g., George and Rodabaugh, 1959; Mohareb et al., 1993; Lotsberg, 1998; Zhu and Leis, 2005; Law et al., 2010; Baek et al., 2012). These studies have examined the influence of diameter and wall thickness mismatch, weld taper angle, and steel grade on the mechanical response of back-bevel transition joints. A recent study by Martens et al.,

(2014) presents a comparative assessment of the mechanical response of back-beveled and counterbore-tapered joint for pressure containment and effects of stress concentration.

In this study, finite element modelling procedures are developed to assess the mechanical response of back-beveled and counterbore-tapered wall thickness transitions with respect to the onset of plastic collapse for pressure containment and stress concentration effects for combined loads. The numerical simulation procedures are verified using analytical solutions and comparisons with the result from other numerical modelling studies. Once confidence in the models was developed, a range of variables were examined including pipe diameter, D/t ratio, axial force and moment. The numerical study assessed the mechanical stress response, including stress path, initial yield and onset of plastic collapse, for back-bevel and counterbore-taper joint designs with the incorporation of initial imperfection, weld misalignment, material variation. Then, the study was extended to assess the stress concentration at the weld region considering the effect of pipe diameter, D/t ratio, counterbore length of counterbore-tapered joints.

Specifically, the objective of this work is:

1. To develop 3-D Finite Element (FE) modelling procedures for back-beveled and counterbore-tapered joints for unequal wall thickness transition segments;
2. To expand the knowledge on back-beveled and counterbore-tapered joints, through parametric studies, for better understanding of limit load capacity for pressure containment and stress concentration effects due to combined loads; To advance

industry practices and guidelines on back-beveled and counterbore-tapered joints for integration within pipeline industry.

1.3 Thesis Layout

The thesis is divided into five chapters with the first two chapters demonstrating the general overview of this research and literature review, respectively. The literature review summarizes existing database in terms of informative background in pipeline fabrication/construction, numerical simulations and analytical equations for unequal wall thickness transition joints. Current engineering practices and design codes on the specifications for joining unequal pieces of pipes are also reviewed.

Chapter 3 and 4 are publications that discuss in detailed on the development of numerical models, validation against the available analytical equations from public literature domain and design codes and advancements of this study.

Chapter 3 mainly discusses the carrying capacity of unequal wall thickness transition joints when they are subjected to combined loading conditions including internal pressure, axial load and bending moment. Numerical models using 3-D continuum shell elements with the incorporation of imperfections and misalignments of both types of joints were developed and validated by previous research work and analytical equations proposed by Mohareb (1993). A parametric matrix was developed to expand the current database that could be utilized for selection guidelines of back-beveled and counterbore-tapered joint. This study was published in the 2014 International Pipeline Conference proceedings.

Chapter 4 extends the study performed in the earlier chapter and focuses on the variables of wall thickness mismatch ratio and material grade mismatch ratio. Then, numerical modes using 3-D continuum brick elements that accounts for through thickness stress variation were developed for assessing the stress concentration factor at weld region which was validated by the analytical solutions from Lotsberg (1998) and DNV-RP-C203. Design parameters including the counterbore length, pipe diameter and D/t ratio were specifically analyzed. This study has been prepared for submission to a leading journal.

Chapter 5 consolidates the work has been done on this subject and draws conclusive remarks as a part of the research program. Results and conclusions obtained from earlier chapters are compiled into different scenarios. Recommendations are formulated for further study. The refinement of weld material grade, the incorporation of anisotropy and physical experimentation will build confidence in numerical modelling procedures to predict the mechanical response of back-beveled and counterbore-tapered joints that advances current engineering practices.

2 LITERATURE REVIEW

2.1 General

Unequal wall thickness transition joints as presented in Figure 2-1 are utilized for connecting two pieces of pipes or pipe and fitting with different wall thicknesses and material grades. Normally, the thicker pipe is machined to have a taper transition for minimizing stress concentration at the joint and easier welding procedures when joining the unequal wall thickness pipe segments together.

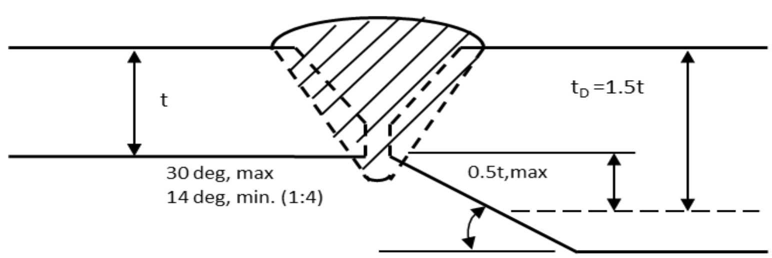


Figure 2-1: Unequal wall thickness transition joint (Back-beveled joint)

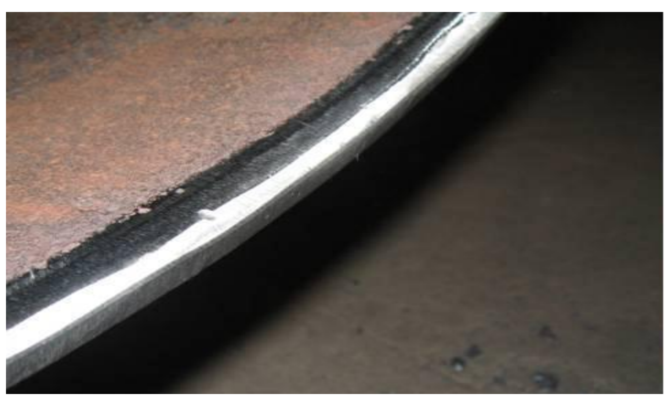
The conventional transitioning procedures are presented in Figure 2-2 including fit-up, grinding and cutting. Figure 2-2 (a) presents a Dearman style clamp is used for aligning the thinner item to the thicker item before transitioning. Figure 2-2 (b) demonstrates a soapstone is applied for sketching the inner diameter of the thinner pipe onto the vertical section of the thicker piece. Then, the transition is made by grinding or grinding combined with oxy-fuel cutting. Figure 2-2 (c) shows the taper in the thicker pipe after transitioning process. During the taper angle formation process, round taper surfaces should be avoided and flat taper angles are preferred with the consideration of stress concentration effect between weld and taper transition.

After the transitioning process is complete, the wall thickness at the weld bevel is measured using calipers. Then, fit-up for welding is completed by Dearman style clamps. The high-low misalignment in the circumferential can be adjusted by the Dearman style clamp during this procedure. When the optimal alignment is obtained, the root pass welding can be achieved; and if the alignment is not acceptable for a root pass welding, backwelding method can be used.

There are also other options for transitioning which involves cutting, beveling and tapering. Steel Split Frame® (Figure 2-3) can be easily attached to a curved surface and allows cutting, beveling and tapering in a single setup. This equipment is available for pipe diameter size ranging from 4 to 80 inch OD for straight pipe or pipe bends.

(a)

(b)



(c)

Figure 2-2: Transitioning procedures (DNV JIP-Field segmented fittings)

Figure 2-3: Aggressive Equipment Corporation's Steel Split's Frame® equipment

The detailed design requirements and guidance for unequal wall thickness transition are provided in technical standards including ASME B31.8 and CSA Z662. According to the design codes, acceptable conditions include internal offset, external offset and combination offset. The internal offset describes the condition when the outside diameters match but the wall thicknesses are unequal; for the external offset, the inside diameters match while the wall thicknesses are unequal; and for the combination offset, both the inside and outside diameter have offsets when the wall thickness is unequal.

From the past experience, this type of joint has several weaknesses: First, the girth welds at unequal wall thickness transition are more likely to introduce high stress concentrations and weld cracks. Second, the presence of excessive axial stresses and bending moment in the pipe body at discontinuities of unequal wall thickness transition increase the possibility of crack initiation and growth. Third, this type of transition welds, especially the internal offset condition, causes the difficulties for inspection techniques (NDT process). Also, the irregular surface at the weld root decreases the inspection quality and time.

Targeting these drawbacks of the transition welds, TransCanada and other pipeline operators have accepted a counterbore-tapered design for unequal wall thickness transition joint as presented in Figure 2-4. Compared to the traditional joining method (i.e., back-beveled joint design), the couterbore-tapered design includes a certain length (i.e., ‘L’ in Figure 2-4) that the thicker pipe or fitting is bored to match the wall thickness of the thinner pipe. By moving the wall thickness transition taper away from the weld, the stress concentration in heat affected zone (HAZ) is effectively reduced. Thus, the likelihood of cracking is decreased and the fatigue life of the weld is enhanced. Another major benefit for this design is improving the welding and Nondestructive testing (NDT) quality, as well as diminishing the welding and NDT process time. The matching of wall thickness of pipe to pipe or pipe to fitting requires an easier welding procedure. For NDT process, the cracks or other defects in the weld are much more accessible to detect than the welding with unequal wall thickness.

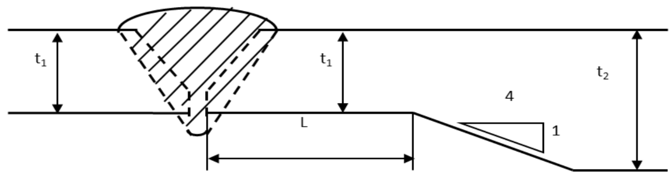


Figure 2-4: Counterbore-tapered joint design for unequal wall thickness transition joint

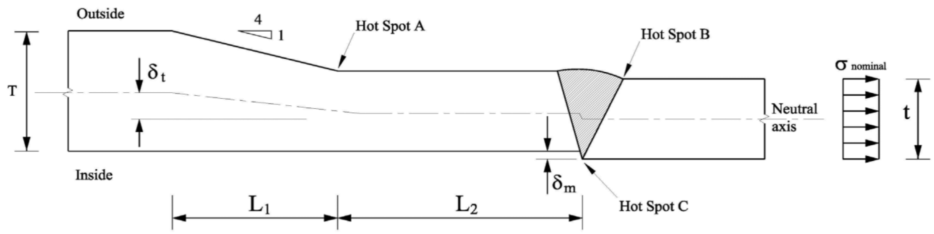


Figure 2-5: Geometry with thickness transition away from the butt weld (DNV-RP-C203)

This design philosophy was first developed in the 1970s and 1980s by hand calculations. DNV-RP-C203 (2011) introduced this design as "more machining of the ends of the tubular with the purpose of separating the geometric effects from the thickness transition from the fabrication tolerances at the weld". One of the most important design factors for counterbore-tapered joint is the length from the wall thickness transition to the weld region called couterbore length (i.e., 'L' in the Figure 2-4, 'L_2' in the Figure 2-5). Appropriate counterbore length will minimize the interaction of stress concentration effect from different sources. The design requirement from TransCanada for the length of counterbore is "greater than or equal to L_0 but not less than 50 mm and an extra 25 mm may be required to provide for cutting and repairing after hydrotest".

Where,

$$L_0 = 0.85\sqrt{D \cdot T_2}\,, \qquad \text{Eq. (2.1)}$$

Where T_2 is the wall thickness of the thicker pipe.

More importantly, this counterbore design could be applied to unequal wall thickness if the wall thickness change ($T_2 - T_1$) is larger than $0.3T_1$. Otherwise, the thicker wall pipe or fitting may be back beveled as the traditional joining method (back-beveled joint).

For the same design factor of counterbore length, DNV-RP-C203 proposes that the stress concentration is small when the length is greater than or equal to $1.4l_e$.
Where,

$$l_e = \frac{\sqrt{rt}}{\sqrt[4]{3(1-v^2)}}, \qquad \text{Eq. (2.2)}$$

Where r is the radius to mid surface of the pipe, t is the thickness of the thinner pipe, and v is the Poisson's ratio.

DNV also demonstrates the conditions when the counterbore length is shorter than l_e. The detailed equations for stress concentration factor (SCF) calculations are presented in the following section 2.2.3 in this chapter. Based on hand calculations, the counterbore length proposed by TransCanada Pipelines is longer than it proposed by DNV-PR-C203. The further investigation on the optimal counterbore length is highly demanded and included in Chapter 4 of this study.

2.2 Design standards

2.2.1 Canadian Standard Association - Oil and Gas Pipeline Systems

CSA Z662 (2010) covers the design, construction, operation and maintenance of oil and gas industry pipeline systems that include liquid hydrocarbons (crude oil, multiphase fluids, condensate, liquid petroleum products, natural gas liquids, and liquefied petroleum gas), oilfield water, oilfield steam, carbon dioxide used in oilfield enhanced recovery schemes and gas.

Section 7.3.1 demonstrates the detailed welding and transitioning requirements for joints configurations. In general, it requires joint configurations for butt welds to be accomplished by the single-V, double-V or other suitable groove types. Also, it provides the examples of end preparations and combinations of end preparations of pipes and butt welding fittings for pipe wall thinner than or over 19.1 mm in thickness.

For joining unequal thickness items, it demands that the transition should be made with a taper or a tapered weld or a prefabricated transition piece with less than half pipe diameter in length. It should be noted that the sharp edge of the groove or notch that connects the weld with the slanted surface of the transition should be avoided in order to reduce stress concentration from the geometry. The requirement of the slope of taper is not greater than 30 degrees and not less than 14 degrees.

In this design standard, three categories of butt welding between unequal thickness items are accepted in terms of wall thickness of each component, including internal diameters unequal, external diameters unequal and internal and external diameters unequal. The detailed requirements for each category are presented in the following paragraphs.

For internal diameters unequal joints, when the nominal internal offset is equal to or less than 2.4 mm, it recommends that no special treatment is necessary and full penetration can be utilized. When the nominal internal offset is more than 2.4 mm and there is no access to the inside of the piping for welding, the transition with a taper on the inside of end of the thicker item should be made. When the nominal internal offset is more than 2.4 mm but does not exceed one-half thickness of the thinner pipe and there is access to the inside of the piping for welding, the transition shall be made with a taper at the end of thicker item or a taper weld. When the nominal internal offset is more than one half of the thickness of the thinner pipe, and there is access to the inside of the piping for welding, the transition shall be made with a taper on the inside of the end of thicker item, or with a taper weld to one half wall thickness to the thinner pipe with combination of a taper from that point.

For external diameters unequal joints, when the nominal external offset is less than one half the thickness of the thinner item, the transition should be made with a taper weld. When the nominal external offset is more than one half of the thickness of thinner item, the transition should be made with a taper weld to one half of the thinner pipe with combination of a taper from that point.

For internal and external diameters unequal joints, the particular attention should be paid to proper alignment. Also, this design standard has the limitations with respect to material grade for unequal wall thickness components. It requires that the unequal wall thickness transition joints could be made between pipes and fittings with equal or unequal specified minimum yield strength. Usually, for the unequal wall thickness items have equal specified minimum yield strength, all the requirements should be met except the minimum taper angle of 14 degree. For the unequal wall thickness items with unequal specified minimum yield strength, the tensile strength of the weld metal should have at least equal strength to the item with higher specified minimum yield strength. Furthermore, the unit strength (product of the specified minimum yield strength and the design wall thickness) of the thicker item should be equal to or greater than the thinner item with the higher specified minimum yield strength.

2.2.2 American National Standard - Gas Transmission and Distribution Piping System

ASME B.31.8 (2003) covers gas transmission and distribution piping systems, including gas pipelines, gas compressor stations, gas metering and regulation stations, gas mains, and service lines up to the outlet of the customer's meter set assembly. Appendix I includes the detailed rules for end preparations for butt welding sections having unequal wall thickness and specified minimum yield strength. Similar to CSA code, ASME B31.8 has the same end preparations notes and also divided the butt welding for unequal wall thickness into three conditions, which are unequal internal diameters, unequal external diameters and unequal internal and external diameters joints. It should be noted that there is slightly differences for unequal internal diameters condition. When the pipe operates at hoop stresses of less than 20% of specified minimum yield strength, if the offset is less than or equal to 1/8 inch (3.175 mm), no special treatment is required. When the hoop stress level is higher than 20% of specified minimum yield strength, the same regulations in CSA code for internal diameters unequal could be applied.

2.2.3 Det Norske Veritas - Fatigue Design of Offshore Structures (2011)

DNV RP C-203 (2011) presents recommendations with respect to fatigue analyses based on fatigue tests and fracture mechanics. Section 3.3.7 illustrates the stress concentration factors for tubular butt weld connections. It indicates that the stress concentration at butt weld connections are due to eccentricities from different sources including difference in diameters, difference in thickness, out of roundness and center eccentricity. It may be conservative to calculate the combined effect of stress concentration from different sources by direct summations. Normally, the out of roundness provides the largest contribution to the resulting eccentricity. It should be noted that the thickness transition placed on the outside is recommended for tubular butt weld connections subjected to axial loading because of less severe S-N curve for the outside weld toe than the inside weld root. The slope of the transition taper is usually fabricated to 1:4.

For the combined effect of stress concentration due to thickness transition on the outside from different sources, the SCF could be calculated as the following formula:

$$SCF = 1 + \frac{6(\delta_t + \delta_m - \delta_0)}{t} \frac{1}{1+(\frac{T}{t})^{\beta}} e^{-\alpha} \qquad \text{Eq. (2.3a)}$$

Where δ_t is the eccentricity due to the difference in wall thickness, δ_m is the eccentricity due to misalignment, and δ_0 equals to 0.1t, which is the misalignment inhrent in S-N data. The α and β can be defined as

$$\alpha = \frac{1.82L}{\sqrt{Dt}} \frac{1}{1+(\frac{T}{t})^{\beta}}; \qquad \text{Eq. (2.3b)}$$

$$\beta = 1.5 - \frac{1.0}{Log\left(\frac{D}{t}\right)} + \frac{3.0}{[Log(\frac{D}{t})]^2}; \qquad \text{Eq. (2.3c)}$$

For the combined effect of stress concentration from different sources that applies to the thickness transition placed on the inside, the calculation of SCF could be used as following formula:

$$SCF = 1 + \frac{6(\delta_t - \delta_m)}{t} \frac{1}{1+(\frac{T}{t})^{\beta}} e^{-\alpha} \qquad \text{Eq. (2.4)}$$

Then, DNV presents the weakness of full penetration welding procedures for the butt welds between items of unequal wall thickness. First, it requires good workmanship during construction in order to accomplish the full penetration welds. Second, it is difficult to perform non-destructive examination (NDT) to detect defects in the root area as the limitations in the NDT techniques. At last, the fatigue life is associated with the initial crack growth while the defects are small. So more machining of the ends of the tubular is proposed as shown in Fig. 5. The resulting SCFs for hot spots in Fig. 5 could be calculated as the following formulas:

For hot spot A:

$$SCF = 1 + \frac{6\delta_t}{t}\frac{1}{1+(\frac{T}{t})^{\beta}}e^{-\alpha} + \frac{3\delta_m}{t}e^{-\sqrt{t/D}}e^{-\gamma}cos\gamma \qquad \text{Eq. (2.5a)}$$

The variables, β and γ can be defined as:

$$\alpha = \frac{1.82L}{\sqrt{Dt}}\frac{1}{1+(\frac{T}{t})^{\beta}}; \qquad \text{Eq. (2.5b)}$$

$$\beta = 1.5 - \frac{1.0}{Log\left(\frac{D}{t}\right)} + \frac{3.0}{[Log(\frac{D}{t})]^2}; \qquad \text{Eq. (2.5c)}$$

$$\gamma = \frac{L_2}{l_e}. \qquad \text{Eq. (2.5d)}$$

For hot spot B:

$$SCF = 1 + \frac{6\delta_t}{t}\frac{1}{1+(\frac{T}{t})^{\beta}}e^{-\alpha}e^{-\gamma}cos\gamma + \frac{3\delta_m}{t}e^{-\sqrt{t/D}} \qquad \text{Eq. (2.6)}$$

For hot spot C:

$$SCF = 1 - \frac{6\delta_t}{t}\frac{1}{1+(\frac{T}{t})^{\beta}}e^{-\alpha}e^{-\gamma}cos\gamma \qquad \text{Eq. (2.7)}$$

2.3 Previous studies

This section summarizes the important aspects of the previous studies with respect to unequal wall thickness transition joints done by several institutions. From literature, George and Rodabaugh (1950s) first introduced the concept of taper and bridging effect between two unequal thickness sections under internal pressure. The bridging effect refers to "the stronger or the thicker material on either side of the taper supporting the material in the taper". This experimental work defined the conditions that the plastic collapse in the thinner wall pipe when the wall thickness ratios is no greater than 1.5 and the taper angle is less than 30 degree. These results provided a basis for the study of butt weld transitions between unequal wall thickness sections and were adopted in ASME B31.8.

Leis (2005) from Battelle found little other work was available on this subject to guide code transition joint design while line pipe manufacturing has made great progress. Then, they carried out a further investigation on the load capabilities and limitations of transition joints. This work covered a review of failure history of transition joints and an analytical assessment of the effect with respect to several design parameters including wall thickness mismatch ratio, angle of transition taper, material grade mismatch ratio and yield to tensile ratio.

In the assessment of failure frequency, Leis indicted that from the database of reported incidents by OPS in the interval from 1985 through 2002, there was lack of information for gas transmission pipeline incidents that identified transition joints as the cause. In brief, the transition joints could be regarded as a less significant construction threat than other construction features. For the failure history of transition joints, Leis concluded that the following conditions were involved from Battelle records:

- Transition joints between line pipe and a heavier wall sections (hub from flange, stub from fitting);
- Transition joints with small or nonexistent grade differences;
- Transition joints with external transition taper on the heavier wall fitting, rather than internal diameter taper bore;
- Transition joints under combined loading conditions (pressure and axial tension) or differential loading conditions (differential settlement);
- Transition joints under cyclic loading (mechanical or thermal load);
- Initial imperfections or defects in transition joint (lack of penetration flaws);
- Limited serviceability due to fracture-controlled crack growth.

In the most recent study done by Leis and Zhu (2005), the plastic collapse controlled failure of unequal wall thickness transition joints was conducted by numerical and analytical methods. A 2-D axisymmetric finite element model was used for analyzing unequal internal and external diameters transition joint using commercial FEA software package ABAQUS Standard. The eight node quadratic axisymmetric solid element with reduced integration CAX8R was used and the FEA model is presented in Figure 2-6.

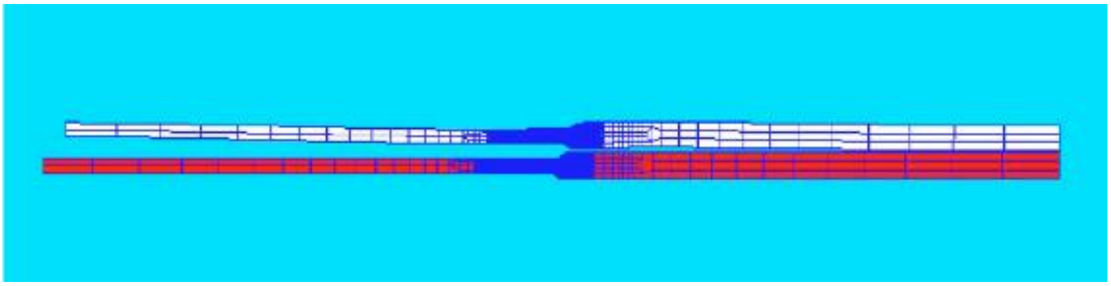


Figure 2-6: Axisymmetric model of transition joint with the original (white) and deformed (red) state under end open condition (Leis & Zhu, 2005)

A wider range of parameters include wall thickness mismatch ratios and material properties that is beyond the limits provided by ASME code were considered to investigate the plastic collapse behavior and location. From the detailed FEA numerical calculations, the primary factors that affect plastic collapse failure locations were selected as wall thickness mismatch ratio and tensile strength mismatch ratio. Then, based on the two first order parameters and the formulations for plastic collapse failure of pipeline that was derived from plastic instability and finite strain theory, an analytical solution to determine the failure location of transition joints was developed for both end-opened and end-capped conditions under internal pressure only.

This analytical solution could be used to ensure the plastic collapse failure to occur in the thinner pipeline when the following conditions are satisfied:

$$\frac{(Y/T)_2}{(Y/T)_1} > \frac{\sigma_{y1}}{\sigma_{y2}}\frac{t_1}{t_2} \quad \text{Eq. (2.8)}$$

Where σ_{y1} is the yield stress of the thinner wall pipe; σ_{y2} is the yield stress of the thinner wall fitting; *Y/T* is the ratio of ultimate tensile stress to specified minimum yield stress and *t* is the wall thickness.

Correspondingly, a plastic collapse assessment diagram (PCAD) was then determined and validated by the numerical results as presented in Figure 2-7.

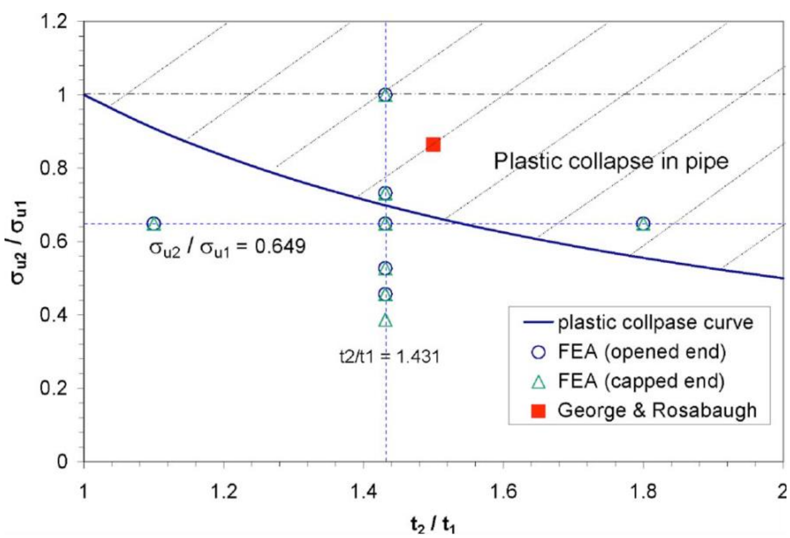


Figure 2-7: Plastic collapse assessment diagram and validation (Lei & Zhu, 2005)

It should be mentioned that in this work Leis came up with several important demonstrations and assumptions that is summarized as:

- The location of transition joint (diameter mismatch) and the taper angle has small effect on the plastic collapse controlled failure;
- Anisotropy has a little effect on the numerical simulations of plastic collapse failure;
- The weld-induced residual stress effect is not noticeable for plastic collapse failure and was ignored in this study;

- The low strength components could be joined to modern high strength grades pipe (API X80 and Grade B) which can be beyond the current code limitations.

In conclusion of Leis research, plastic collapse failure of unequal wall thickness transition joints was investigated by numerical simulations and analytical solutions. The experimental work on unequal thickness transition joint with different wall thickness mismatch and material properties mismatch is recommended to further validate the plastic collapse criterion and PCAD diagram. Other than the plastic collapse controlled failure, the fracture controlled failure of unequal wall thickness joints is recommended to frame a sound knowledge integrating the present work for unequal wall thickness transition joints.

Australian pipeline design standard AS 2885.2 has the requirements for the welded joints that the pressure design wall thickness ratio of the thicker pipe component to the thinner pipe component should not be greater than 1: 1.5. However, the standard also requires the pipe pressure design thickness to calculate with a maximum design factor of 0.8. Law (2010) from ANSTO came up with a conclusion that there is a limitation of 1.5:1for material grade ratio between the thicker component and the thinner component. Based on his assumption, if the wall thickness ratio of the welded joints can be increased, the pipe material grades combination can also be relaxed. Then, Law and his associates carried out a project to assess the grades and thickness limits for welded joints with a wider range of material grade combinations that include grade ratios meeting and exceeding the limit of 1.5 using finite element analyses. Similar to Leis (2005) study, an axisymmetric FEA model was used for all welded transition joints with D/t ratios of 35, 55 and 100 and 4:1

taper. The loading conditions considered in this study were internal pressure only, axial loading only and combined axial loading with internal pressure. For the internal pressure loading condition, the performances of welded transition joints that have grade ratios less than 1.5 were approximately the same with those with grade ratios exceeding 1.5 due to the bridging effect. However, for axial loading condition, the axial failure stress was low when the grade ratio was high and all failures located at the taper. For the combined loading condition, it was indicated that the compressive loads have significant effect on the internal pressure capacity. Besides, Law demonstrated that the transition taper on the inside or outside of the pipe has little effect on the strength of transition joints, which is different from DNV-RP-C203 for offshore steel structure design. To summarize Law's research, it is recommended that testing of pipes with welded transition joints between different material grades should be performed to validate the FEA results. Also, the current grade ratios limits should not be relaxed without further estimation with the consideration of the exposure of pipes to axial load and bending in service.

Baek (2012) conducted a research on the unequal wall thickness transition joints with different taper angles using finite element analyses. The unequal internal diameter transition joints were modelled by commercial software package Abaqus/Standard (v6.10). The detailed FEA model was not included in the published work. The selected taper angles ranged from 4 degree to 45 degree and some of them exceeded the limitation for back-beveled joints in CSA and ASME code. The effect of taper angles on the load carrying capacity was performed under internal pressure only, tensile load only and bending moment only. In the parametrical study, the wall thickness ratio was considered and selected as 1.22, 1.54 and 1.89. It can be concluded that the change of taper angle has little effect on the tensile load capacity and bending moment capacity when the wall thickness ratio is less than 1.5 and has considerable effect when the wall thickness ratio is larger than 1.5. However, for internal pressure capacity, the taper angle does not have effect on the failure pressure due to hoop stress.

Chen and Liu (2014) from CRES (Center for Reliable Energy Systems) conducted a comparative study of counterbore-tapered and back-beveled welded joints using finite element analyses performed by Abaqus/Standard (v6.10). A 3-D finite element model using 8 node linear brick element C3D8RH with symmetric boundary condition was used for modelling back-beveled and counterbore-tapered joints, as presented in Figure 2-8.

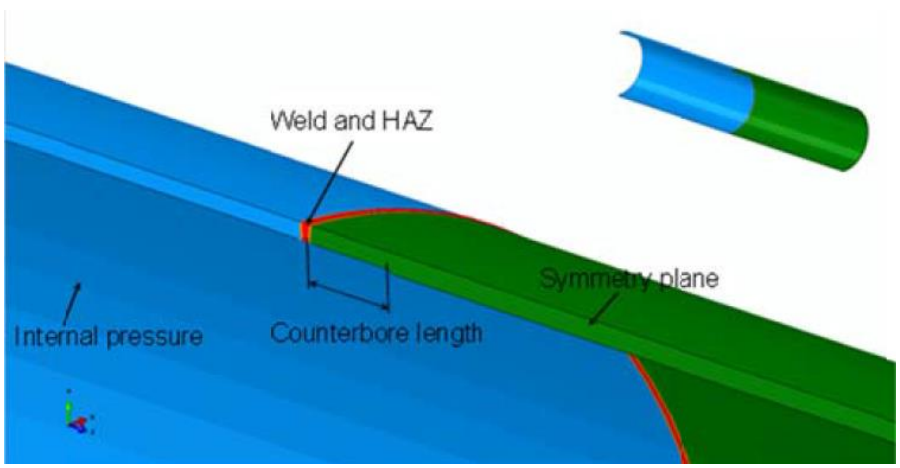


Figure 2-8: 3-D finite element model for counterbore-tapered joint (Chen and Liu, 2014)

Before this study, little work has been done on the assessment of counterbore-tapered joints apart from DNV-RP-C203. This research included the comparison of two types of joints with respect to plastic collapse controlled failure and fracture controlled failure. For the plastic collapse controlled failure, they analyzed the internal pressure capacity for back-beveled and counterbore-tapred joints Due to the bridging effect, pipes with both joints failed at the same pressure level. For the fracture controlled failure, comparisons conducted in terms of stress concentration factor and stress intensity factor under operational internal pressure and longitudinal tensile load. In the analysis of stress concentration factor, a 2 mm hi-low misalignment was introduced in the models. The pipe was pressurized with a pressure factor of 0.72 and the longitudinal load due to end cap effect. The stress concentration factor was evaluated as the ratio of averaged longitudinal stresses at the weld root divided by the uniform longitudinal stresses in the remote pipe wall. In the stress intensity factor calculation, the J-integrals were evaluated from the crack under the same loading condition as the analysis for stress concentration factor. The stress intensity factor was evaluated by the maximum K value at the deepest point of the crack front, which were converted from J-integrals as followed:

$$K = \sqrt{\frac{JE}{1-v^2}} \qquad \text{Eq. (2.9)}$$

Then, a parametrical study was accomplished using two pipe dimensions (30 and 45 in) with respect to counterbore length L (as shown in the Fig. 4 in the section 2.1) ranging from 20 mm to 500 mm.

From Chen & Liu's work, the internal pressure containment capacity for back-beveled and the counterbore-tapered joints are the same when the thicker pipe has the same nominal strength as the thinner pipe. Then, it can be concluded that the counterbore-tapered always produces lower stress concentration factor (SCF) and stress intensity factor (SIF) than back-beveled joints. Lastly, the counterbore length recommended by TransCanada PipeLines can be considered as the most appropriate in the consideration of effectively lowering the SCF and SIF values and economically boring the thicker pipes.

In conclusion of previous studies, the unequal wall thickness transitions with back-beveled and counterbore-tapered joints were examined by finite element analysis and analytical solutions. First, to have more confidence in the performance of transition joints, physical experimental work is demanded to validate current existing continuum finite element models including 2-D axisymmetric and 3-D brick elements. Second, the mechanical response of transition joints under combined loading conditions including internal pressure, axial load and bending moment were not included in the previous finite element work due to the limitations of existing finite element models. Third, the design parameters for back-beveled and counterbore-tapered joints should be further investigated based on previous assessments with the purpose of improving the reliability of transition joints between unequal wall thickness or material grade items and advancing the applications of counterbore-tapered joint in oil and gas transmission pipelines.

3 MECHNICAL INTEGRITY EVALUATION OF UNEQUAL WALL THICKNESS TRANSITION JOINTS IN TRANSMISSION PIPELINES

This paper has been published in the proceedings of International Pipeline Conference (IPC 2014-33141, Calgary, Canada). This paper was a collaborative effort including myself, Dr. Shawn Kenny and Mr. Michael Martens from TransCanada PipeLines. As the primary author, I was responsible for developing and calibrating the numerical modelling procedures, conducting the data analysis and synthesizing the results within this paper. Dr. Shawn Kenny and Dr. Amgad Hussein were responsible for providing supervision and guidance during this study, and editorial comments in the preparation of this paper. Mr. Michael Martens was responsible for providing the context and motivation for this paper.

Authors: Xiaotong Huo, Shawn Kenny, Amgad Hussein and Michael Martens

3.1 Abstract

Transition welds joining pipe segments of unequal wall thickness are typically designed using back-bevel butt welds in accordance with industry recommended practices. An alternative approach, for joining transition pieces, would be the use of a counterbore-taper design, which has been successfully utilized by TransCanada PipeLines.

In comparison with the back-bevel joint design, the counterbore-taper design provides a simple geometry that facilitates the welding process for joints of unequal wall thickness,

improves the NDT quality and reliability, and increases the process efficiency for welding and NDT tasks. The counterbore-taper design reduces the effect of stress concentrations at the weldment and enhances fatigue life.

A parameter study, using continuum based finite element methods, was conducted to comparatively examine the mechanical performance of a pipe joint, using back-bevel and counterbore-taper designs, with unequal wall thickness and different material grade. The parameters examined include pipe diameter, D/t ratio, axial force and moment. The numerical study assessed the mechanical stress response, including stress path, initial yield and onset of plastic collapse, for back-bevel and counterbore-taper joint designs. Based on these preliminary investigations, the performance of each transition joint design was evaluated and guidance on the selection of the joints design method was provided.

3.2 Introduction

Pipelines have been extensively used in the oil and gas industry as an efficient and economic hydrocarbon transportation infrastructure. The mainline pipe wall thickness may need to be increased through transition segments to meet stress based design criteria. Transition welds joining pipe segments of unequal wall thickness are typically designed using back-bevel butt welds in accordance with technical standards including ASME.B31.8 and CSA Z662.

The counterbore-taper design is commonly used for joining pipe segments with equal material strength in industry. In comparison with back-bevel butt welds, the geometry of the counterbore-taper joint can reduce the stress concentration effect at the circumferential girth weldment and provide more efficient welding process. In this study, the utilization of the counterbore-taper design is considered for joining two unequal material grades pipes. However, the mechanical response of counterbore-taper joint with unequal wall thickness and material grades subject to combined loads has not been systematically examined.

George and Rodabaugh (1959) first introduced the concept of taper and "bridge effect" between two unequal wall thickness sections of an X52 pipe and a Grade B pipe with a taper ratio of 4:1, 8:1 and 16:1. The experimental results showed the plastic collapse under internal pressure occurred in the thinner wall thickness, higher material grade pipe section at a location approximately 230 mm from the taper transition. A taper ratio of 4:1 was recommended with a specified maximum taper ratio of 16:1, which was adopted in ASME.B 31.8.

Zhu and Leis (2005) developed a plastic collapse criterion and plastic collapse assessment diagram (PCAD) to estimate the failure location for unequal wall thickness transitions for both closed and open end conditions, with internal pressure, over a range of high-strength grade pipe materials. The wall thickness and tensile-strength mismatch were established as the governing parameters. A simple criterion was established to define plastic collapse failure in the thinner wall pipe segment when $\frac{\sigma_{UTS2}}{\sigma_{UTS1}} > \frac{t_1}{t_2}$.

The Australian Standard AS 2885.2 specifies requirements on the design thickness ratio of the thicker walled to thinner walled component shall not be greater than 1.5. Since the pressure design thickness is limited and depends on the pipe strength, the material grade ratio between the thin and thick walled pipe is also limited by the same factor. Law and Tuft (2010) compared the failure pressure and axial stress between pipe joints with grade ratios that satisfied and exceeded this 1.5 limit. Different loading conditions were considered including pressure, axial load and combined loading for restrained pipe segments with a transition taper of 4:1. Baek and Kim (2012) also examined the effect of taper angle on the plastic collapse for loading conditions with tension, internal pressure and bending. The tensile strength and moment capacity were not influenced by the taper angle for wall thickness ratios less than 1.5 but increased with ratios greater than 1.5. The taper angle had no effect on the burst pressure for all pipe joint combinations.

In this study, a systematic comparison is conducted and the knowledge base is extended through an examination of the mechanical response of transition joints with unequal wall thickness and material grade for combined loading condition with internal pressure, axial tensile force and bending moment. A parameter study was conducted, using continuum finite element modelling procedures, to examine the effects of pipe diameter (D), diameter to wall thickness (D/t) ratio and loading condition on the pipe segment strength capacity and stress distribution for the back-bevel and counterbore-taper joint design methods.

The mechanical performance of each joint design is evaluated and engineering guidance on the joint design provided with reference to current industry practice. The results from this study will provide a technical basis to assess the burst strength and fatigue life resistance of the joint design that will be addressed in a future publication.

3.3 Pipe Joining Methods

A transition joint or segment is required when two pieces of unequal wall thickness and strength pipe are to be joined through circumferential girth welding process. Three acceptable conditions for joint designs are provided in codes ASME B31.8 and CSA Z662 including internal diameters unequal, external diameters unequal, and both internal and external diameters unequal.

In this study, an internal diameter unequal condition was examined with different material grades, API X60 (Grade 415) and API X70 (Grade 485), and taper angle of 4:1 (14°), in accordance with CSA Z662 as shown in Figure 2-1.

The counterbore-taper joint, as shown in Figure 2-4, has been examined as a joining method for pipe segments with equal pipe strength. The design has been adopted, by some companies, for transition joints with unequal material grades since it provides a simple geometry that facilitates the welding process for joints of unequal wall thickness, improves the NDT quality and reliability, and increases the process efficiency for welding and NDT tasks. However, the counterbore thicker pipe transition may lead to a decreased carrying capacity because of the wall thickness shrinkage in the lower material strength pipe component.

In this numerical simulation study, the mechanical performance of the back-bevel joint design is comparatively evaluated with the counterbore-taper design with respect to the parameters of material grade, wall thickness, applied loads, and boundary conditions.

3.4 Finite Element Modelling

The mechanical performance of the transition joint was examined using continuum finite element modelling procedures. The commercial software package Abaqus Standard (version 6.12) was used for the numerical simulation. The parameters examined in the sensitivity analysis are summarized in Table 3-1.

The unequal wall thickness transition joints were modeled in three dimensions using reduced integration 4-node shell element (S4R) with a uniform mesh size of 72 nodes in pipe circumferential direction. The mesh density requirements were established through a mesh sensitivity analysis. The wall thickness variations were defined on a nodal basis for the homogeneous shell sections and the reference surface was set to top surface in order to model internal diameter unequal condition. The taper angle was 4:1 for both the back-bevel and counterbore joints. Pipe body imperfections were defined as initial perturbations through nonlinear elastic-plastic bifurcation analysis. The effects of a girth weld radial offset, with amplitude of 0 mm and 2 mm, on the mechanical response of the transition joint design was also examined.

Table 3-1: Parameters matrix for the stress analysis

Parameters	Back-bevel	Counterbore-taper
Nominal Diameter	406 mm (16”), 914 mm (36”)	
D/t	40 ,60 ,80	
Material Grade	Grade 485 MPa-415 MPa (API 5L X60-X70)	
Taper Angle	4:1	
Pipe Length	8D	
t2/t1	1.5	
Girth Weld Radial Offset	0 mm, 2 mm	

The material grades for the thinner and thicker wall thickness pipe segment were 485 MPa (API 5L X70) and 415 MPa (API 5L X60) respectively. The weldment material strength was defined as 10% overmatch on the stronger pipe segment (i.e. material grade of 485 MPa). The pipe body and weldment stress-strain relationship was defined by the Ramberg-Osgood expression and implemented within the numerical modelling procedures as piece-wise smooth continuous representation. The material behaviour was considered to be isotropic with von Mises yield criterion. The effect of local weld induced residual stress state was not considered in this model but can influence the local buckling response.

Two reference nodes at each pipe end on the longitudinal centerline defined the boundary conditions. All nodes at the pipe end were connected to the reference point with all degrees of freedom except for the radial direction, which was released to allow for the mechanical response of the pipe section to internal pressure and load effects. The bending moment and axial force was applied as an external load to the reference nodes. The boundary condition for this model is pinned and roller at each reference point.

In this study, the axial stress, equivalent (von Mises) stress, stress path and stress condition (i.e. compression or tension face) were examined. The mechanical performance of the transition joints were evaluated on the basis of two limit states that included the initial yield condition and the onset of plastic collapse. For the onset of plastic collapse several criteria are available to determine the plastic instability load that includes zero slope, twice elastic slope and tangent intersection methods. The zero slope method defines the limits based on mechanical response tending to perfect plasticity. The twice elastic slope method defines the plastic instability limit as the intersection point between the load-deflection curve and a straight line with twice the slope of elastic response, which was adopted by ASME (2007). The tangent intersection method defines the plastic instability limit as the intersection of tangent lines with the initial elastic and plastic response on the load-deflection curve.

The arc-length algorithm with large deformation formulation was adopted to trace the nonlinear loading path and calculate the plastic instability load in this study. The bending moment capacity for plastic collapse was used to define the load factor for the Riks method. Converged solutions for plastic collapse were obtained when the system was subjected to zero or a relative low axial tension. In future work, the mechanical response of the back-bevel and counterbore-taper joint design will be examined for other loading conditions and limit states (e.g. plastic collapse).

3.5 Results and Discussions

3.5.1 Overview

The results are presented in non-dimensional form for internal pressure (*p*), bending moment (*m*) and axial force (*n*). The applied internal pressure (*P*), bending moment (*M*) and axial force (*N*) was normalized with the yield pressure (P_y), yield moment (M_p) and yield axial force (N_p) of the thinner wall thickness (i.e. higher material grade) pipe segment.

$$p = \frac{P}{P_y}, P_y = \frac{\sigma_y t}{r} \qquad \text{Eq. (3.1)}$$

$$m = \frac{M}{M_p},\ M_p = 4r^2 t\sigma_y \qquad \text{Eq. (3.2)}$$

$$n = \frac{N}{N_p}, N_p = 2\pi r t\sigma_y \qquad \text{Eq. (3.3)}$$

In the stress analysis conducted, all pipe joints are pressurized with internal pressure p=0.8 without the end-cap effect with respect to the development of axial loads. For a defined magnitude of applied internal pressure (*p*) and axial force (*n*), the bending moment capacity (*m*) was evaluated.

The plastic moment capacity of a pipe section, however, is a function of the internal pressure and axial load magnitude being applied. Mohareb (1995) derived an analytical expression to predict the plastic moment capacity of a pipe subject to internal pressure, axial force and bending moment:

$$m_n = \pm\, cos(\pi p_n), \qquad \text{Eq. (3.4a)}$$

where m_n and p_n can be defined as:

$$m_n = \frac{M^P_{\sigma_\theta, P_e}}{M^P_{\sigma_\theta, max}} \qquad \text{Eq. (3.4b)}$$

$$M^P_{\sigma_\theta, max} = 2r_{av}^2 t\sigma_y \sqrt{4 - 3(\frac{\sigma_\theta}{\sigma_y})^2} \qquad \text{Eq. (3.4c)}$$

$$p_n = \frac{\frac{P_e}{P_y} - \frac{1}{2}(\frac{\sigma_\theta}{\sigma_y})}{\sqrt{4 - 3(\frac{\sigma_\theta}{\sigma_y})^2}} \qquad \text{Eq. (3.4d)}$$

The effectiveness of using the analytical expression to estimate the plastic moment capacity of the pipe segments was examined. Accurate estimates are required in order to improve the convergence and accuracy of the Rik's algorithm when establishing the limit state conditions in this study. Comparison of the initial yield conditions using the analytical expression developed by Mohareb (1995) and the finite element simulations of a 406 mm diameter pipe, with back-bevel and counterbore-taper joint design, is shown in Figure 3-1. Based on the normalized moment-axial force interaction diagram, there exists excellent correspondence between the analytical solution and numerical simulation for a pipe with perfect (i.e. ideal) geometry. The estimated moment capacity of the back-bevel was higher than the corresponding counterbore-taper joint design. However, the pipe geometry examined can be considered perfect or ideal where the effects of bifurcation perturbations, physical imperfections (e.g. pipe ovality) and girth weld radial offset were not included in this specific analysis. Similar results were observed for the 914 mm pipe diameter case. On this basis, the analytical expression (Eq. 3. 3-4) developed by Mohareb (1995), was considered to be appropriate to define the estimated plastic moment capacity for use in the Rik's algorithm. The observed response (Figure 3-1) is consistent with other similar studies.

3.5.2 Initial Yield Response for Ideal Pipe Geometry

Through a parameter study, the bending moment and axial force interaction curves, at initial yield, for an ideal (i.e. perfect) pipe geometry were established. The normalized moment-axial force interaction curves are shown in Figure 3-2 for the 406 mm and 914 mm pipe diameter with D/t ratio of 60. A normalized design factor pressure term of 0.8 was used. A similar characteristic response was also observed for the 406 mm pipe diameter with D/t ratio of 40 and 80. Based on ideal pipe geometry, the back-bevel joint was observed to have marginally greater normalized moment (m) and axial force (n) capacity at initial yield conditions for normalized axial forces (n) greater than 0.25.

However other engineering parameters, including the axial stress magnitude, sense (i.e. tensile or compressive) and longitudinal distribution relative to the girth weld location, were observed to have different characteristics with potential significance and impact on practical engineering design. For the combined loading condition (i.e. pressure, axial force and bending), initial yield of the back-beveled pipe joint was observed to occur within the higher material grade (485 MPa) near the circumferential girth weld location. For axial pure loading conditions (i.e. m = 0), initial yield occurred in the taper angle transition region.

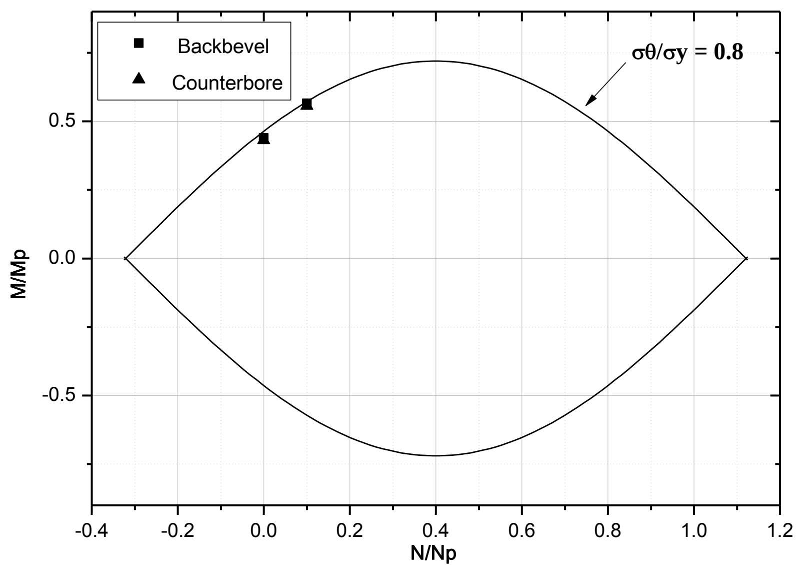
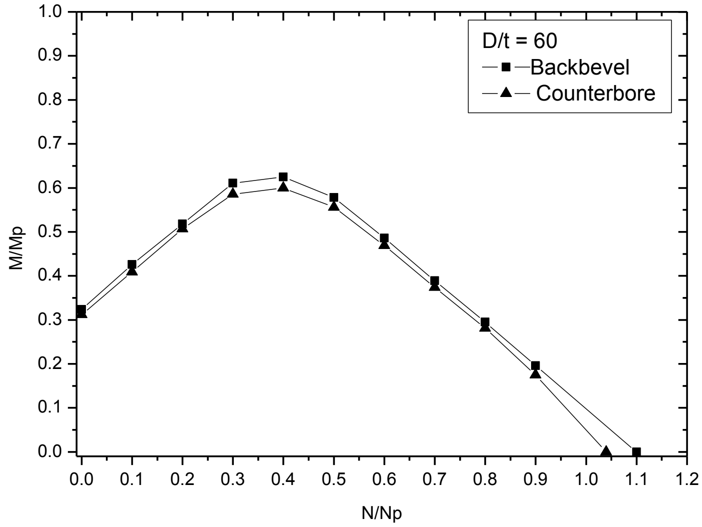


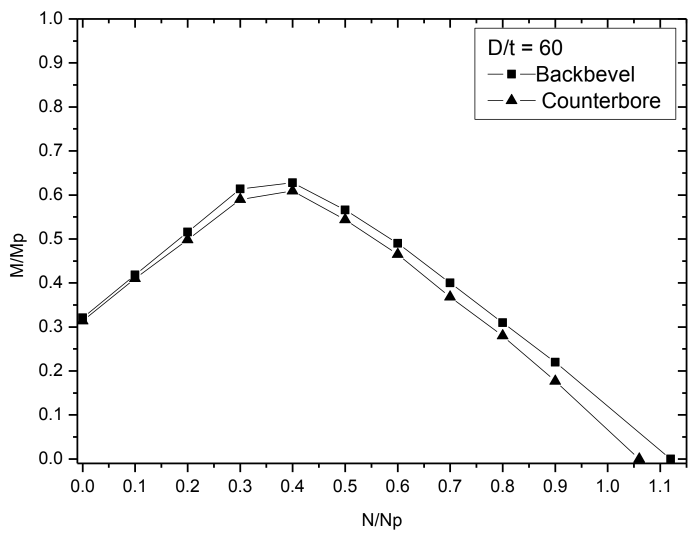
Figure 3-1: Limit load curve for plastic instability

The numerical modelling procedures were calibrated with a grade 450 (X60), 273.1 mm (10”) OD pipeline with a 12.7 (0.5”) wall thickness that corresponds to a pipe diameter to wall thickness (D/t) ratio of 22. The pipe length was 12 m with a length to diameter ratio of 44. An elastic modulus of 207 GPa was used with the Ramberg-Osgood expression defining the stress-strain relationship with piecewise continuous representation.



D/t = 60
Backbevel
Counterbore
M/Mp
N/Np
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
0.0 0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8 0.9 1.0 1.1 1.2

(a)

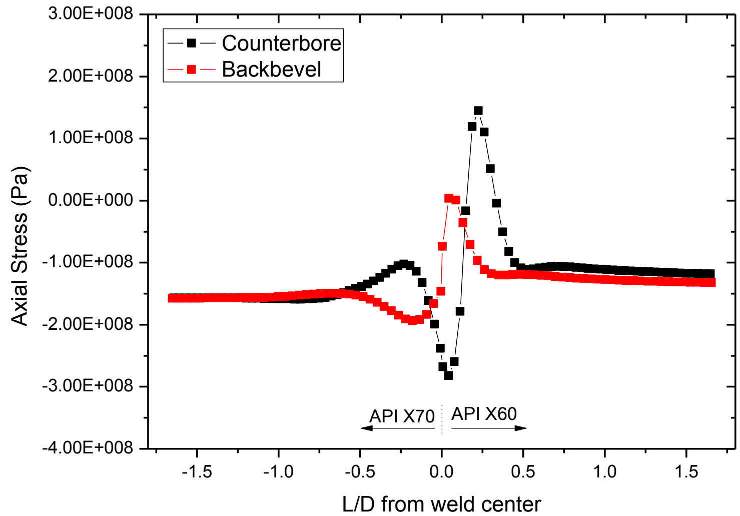


D/t = 60
Backbevel
Counterbore
M/Mp
N/Np
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
0.0 0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8 0.9 1.0 1.1

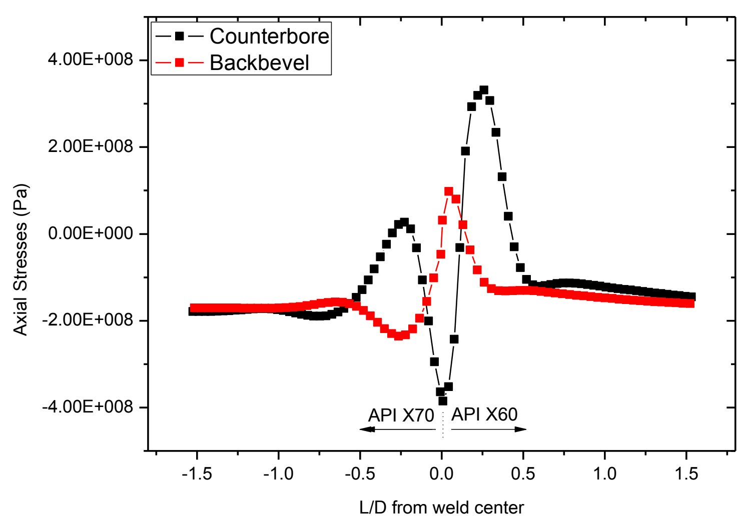
(b)

Figure 3-2: Normalized moment-axial force interaction curves for initial yield with (a) 406 mm pipe diameter with D/t = 60 and (b) 914 mm pipe diameter with D/t = 60

Initial yield of the counterbore-taper joint design, however, for combined loading was observed to occur within the wall thickness reduction zone of the lower grade material (415 MPa) near the girth weld for the thicker pipe wall with compression face yielding and near the taper transition for tension face yielding. For pure axial loading conditions (i.e. $m = 0$), initial yielding occurred in the transition length, Lo of Figure 2-4, of the thicker wall, lower grade material pipe segment. These observations are illustrated in Figure 3-3 for a 406 mm pipe diameter with D/t ratio of 60 at the initial yield and onset of plastic collapse. For the back-bevel joint design, the peak tensile stress at the onset of plastic collapse is almost centered on the circumferential girth weld location, whereas, the counterbore-taper stress state at this location is compressive. Thus from the viewpoint of, the counterbore and taper design shifts the peak tensile stress away from the circumferential girth weld, which has a positive impact on reducing the potential for pipe rupture due to tensile stress state near girth weld flaws, improving pipe fatigue life, and mitigating issues that negatively affect welding procedures.


Counterbore
Backbevel
Axial Stress (Pa)
3.00E+008
2.00E+008
1.00E+008
0.00E+000
-1.00E+008
-2.00E+008
-3.00E+008
-4.00E+008
API X70
API X60
-1.5
-1.0
-0.5
0.0
0.5
1.0
1.5
L/D from weld center

(a)

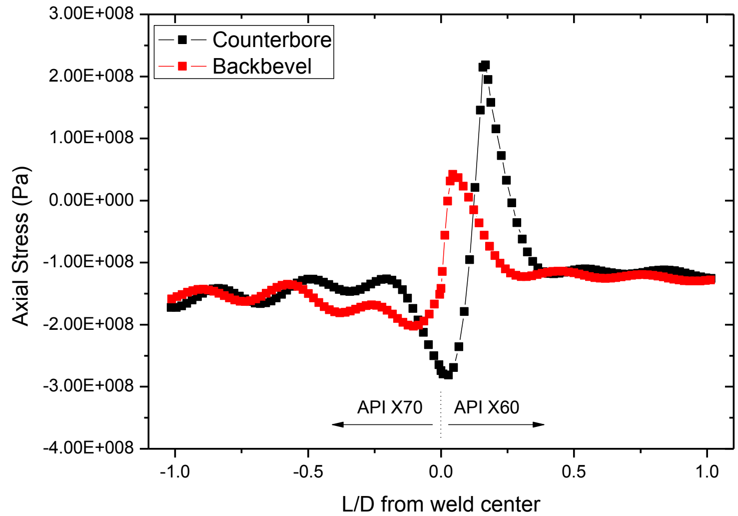

Counterbore
Backbevel
Axial Stresses (Pa)
4.00E+008
2.00E+008
0.00E+000
-2.00E+008
-4.00E+008
API X70
API X60
-1.5
-1.0
-0.5
0.0
0.5
1.0
1.5
L/D from weld center

(b)

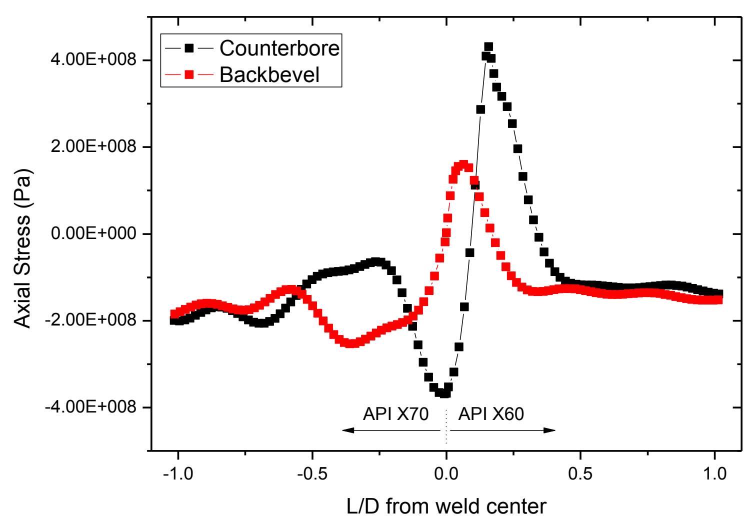
Figure 3-3: Longitudinal distribution of axial stress for 406 mm pipe with D/t of 60 at (a) initial yield and (b) onset plastic collapse

For both joint designs, the initial yield zone location was observed on the compression or tension face depending on the loading conditions (i.e. values of p, m and n). For pure bending or normalized axial force (n) less than 0.4, then initial yield occurred on the compression face extreme fiber. For combined loading with the normalized axial force equal to 0.4, then initial yield occurred simultaneously on both the tension and compression face. For combined loading conditions with the normalized axial force (n) greater than 0.5, then initial yield occurred on the tension face.

The longitudinal distribution of axial stress for the 406 mm pipe diameter with D/t of 60 with bifurcation imperfections is shown in Figure 3-4. The mechanical response exhibits similar trends as the perfect circular pipe (Figure 3-3) but with marginally higher tensile stress amplitude. A similar response was observed for the larger 914 mm pipe diameter, as shown in Figure 3-5. The key observation is the back-bevel transition joint design focuses tensile stress state on the circumferential girth weld location.

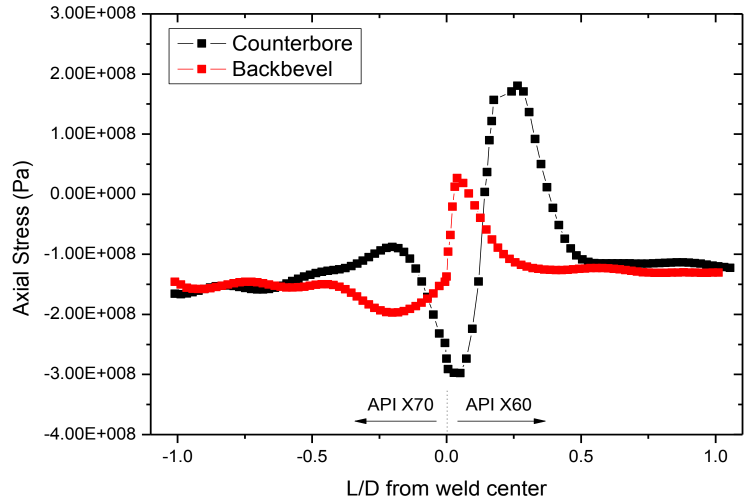

3.00E+008
2.00E+008
1.00E+008
0.00E+000
-1.00E+008
-2.00E+008
-3.00E+008
-4.00E+008
Axial Stress (Pa)
Counterbore
Backbevel
API X70
API X60
-1.0
-0.5
0.0
0.5
1.0
L/D from weld center

(a)

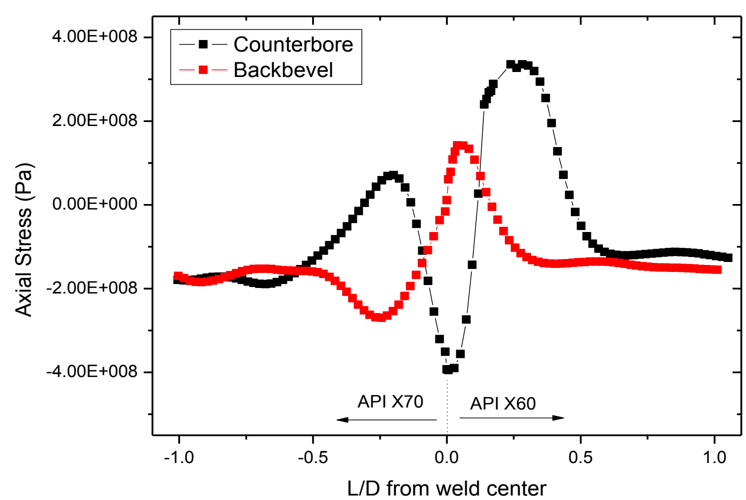

4.00E+008
2.00E+008
0.00E+000
-2.00E+008
-4.00E+008
Axial Stress (Pa)
Counterbore
Backbevel
API X70
API X60
-1.0
-0.5
0.0
0.5
1.0
L/D from weld center

(b)

Figure 3-4: Longitudinal distribution of axial stress for 406 mm pipe with D/t of 60 with bifurcation perturbations at (a) initial yield and (b) onset plastic collapse

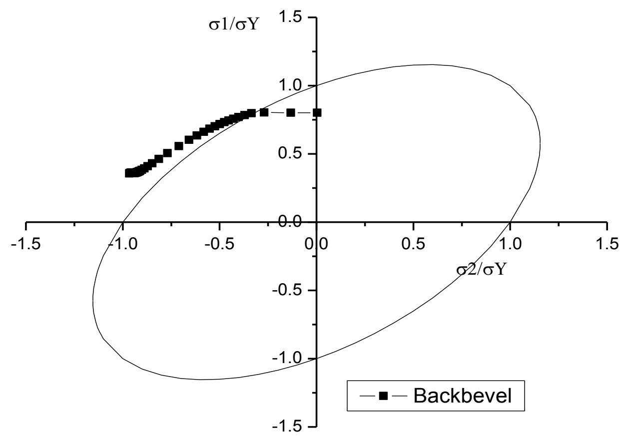


(a)

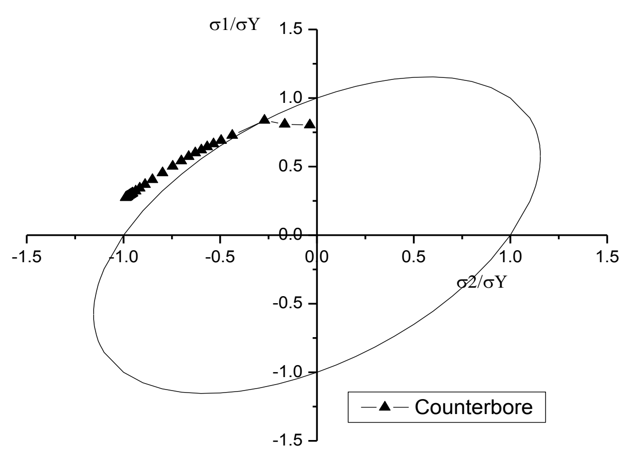


(b)

Figure 3-5: Longitudinal distribution of axial stress for 914 mm pipe with D/t of 60 with bifurcation perturbations at (a) initial yield and (b) onset plastic collapse

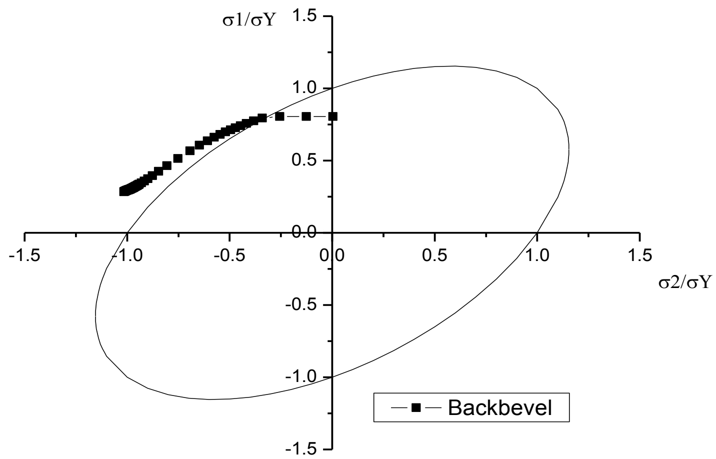


(a)

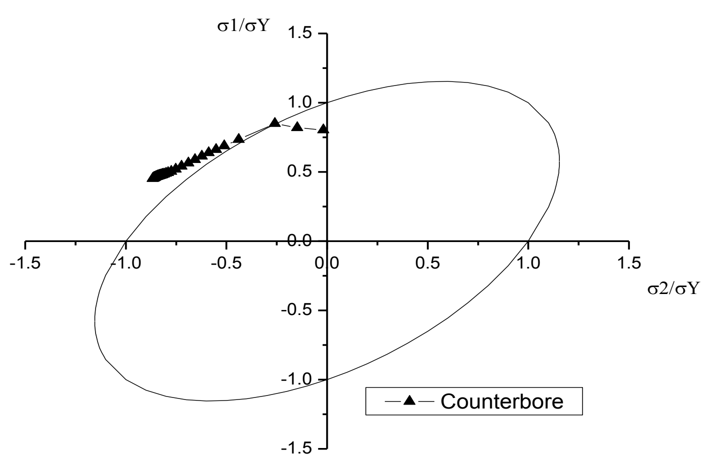


(b)

Figure 3-6: Stress path at the buckle crest for 406 mm pipe with D/t of 60 and bifurcation perturbations for (a) back-bevel and (b) counterbore-taper joint design



(a)



(b)

Figure 3-7: Stress path at the buckle crest for 914 mm pipe with D/t of 60 and bifurcation perturbations for (a) back-bevel and (b) counterbore-taper joint design

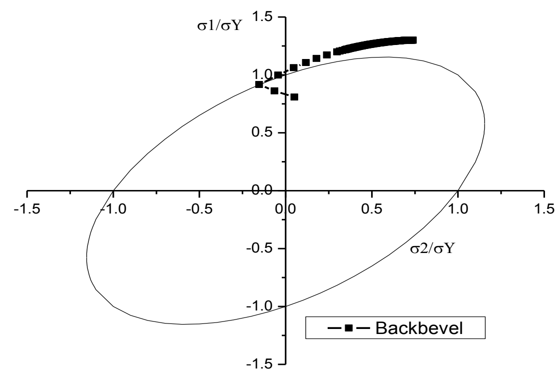
The stress path at the buckle crest on the pipe compression face extreme fiber for the back-bevel and counterbore-taper joint design is illustrated in Figure 3-6. Although there are differences in the longitudinal distribution of axial stress (Figure 3-4), the stress path at the buckle crest on the compression face is similar for the two joint designs. In comparison with the larger 914 mm pipe diameter, as shown in Figure 3-7, increasing the pipe diameter reduces the stress amplitude at the onset of plastic collapse for the same D/t ratio. The stress path response to other parameters; such as girth weld radial offset, however will show a more significant effect. This is discussed in further detail within the next section.

3.5.4 Influence of Girth Weld Radial Offset

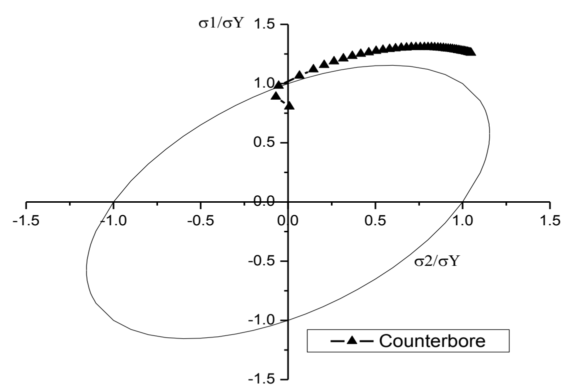
In addition to the effects of internal pressure, the girth weld radial offset results in shifting the relative position of the neutral axis for each pipe segment on either side of the circumferential girth weld. This will introduce an offset or eccentricity of the section forces that may influence the mechanical behaviour of the joint design. The girth weld radial offset was modelled by shifting (i.e. offsetting) the centerline axis of the thinner wall pipe segment (i.e. higher grade 485 MPa material) with 2 mm amplitude in the vertical position. The bifurcation perturbations were also superimposed on the pipe geometry. All other parameters as defined in Table 3-1 were not modified.

The stress path at the buckle crest on the pipe compression face extreme fiber for the back-bevel and counterbore-taper joint design, with bifurcation perturbations and girth weld radial offset imperfection, is shown in Figure 3-8. In comparison with the numerical simulations for a pipe joint design incorporating only bifurcation perturbations, the radial offset had a significant influence on the stress path. There was also a significant influence on the longitudinal distribution of axial stress across the girth weld due to the radial offset, as shown in Figure 3-9. In comparison with Figure 3-4 (a), the radial offset imperfection focused the peak tensile stress on the girth weld centerline and amplified the tensile stress magnitude for both transition joint designs. The tensile stress response for the back-bevel transition was observed to exceed the yield strength of the lower grade pipe joint (Grade 415 MPa). A similar response was observed for the larger 914 mm pipe diameter with the back-bevel and counterbore-taper transition joint designs.

Studies on the local buckling response of girth weld linepipe have shown other factors; including the mesh density, mesh distribution or bias, material strength mismatch across the girth weld and relative offset with respect to the applied loading condition, can have a significant influence on the pipe mechanical response [0,0,0-0]. For example, Fatemi et al. (2012) demonstrated the development of stress concentrations and local buckling mechanisms for girth weld pipe joints was influenced by differences in the material grade of each pipe joint on either side of the girth weld and how the radial offset was defined across the girth weld in relation to the applied loads and boundary conditions. Furthermore, numerical studies conducted by Al-Showaiter (2008), on pipe joints with uniform material grade and pipe wall thickness, has shown the coupled influence of D/t, internal pressure, girth weld parameters; including offset amplitude, offset orientation and residual stress, on the peak moment and local buckling response of girth weld pipelines. Future investigations should examine the effect of these parameters on the stress path and mechanical stress response for both the back-bevel and counterbore-taper transition joint designs.

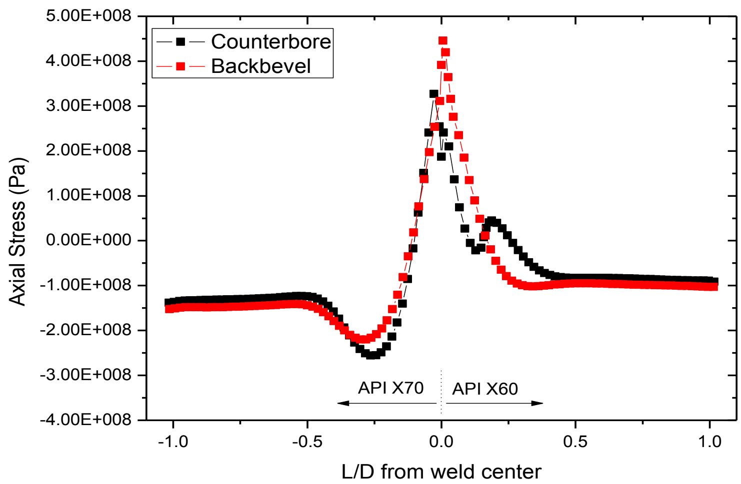


(a)

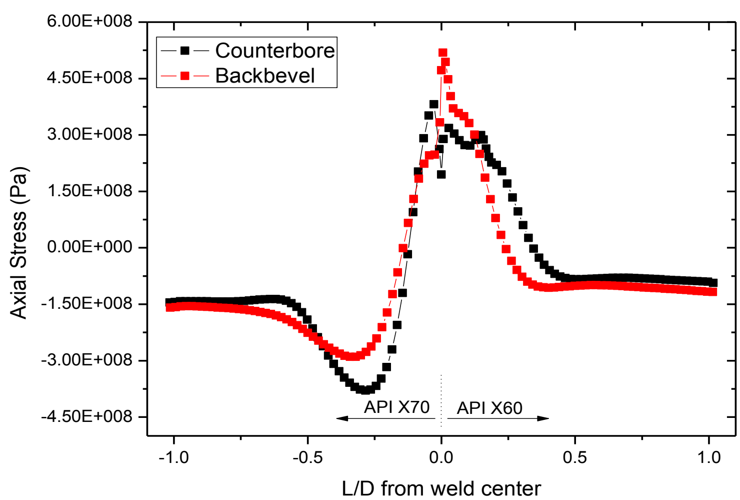


(b)

Figure 3-8: Stress path at the buckle crest for 406 mm pipe with D/t of 60 and girth weld radial offset imperfection for (a) back-bevel and (b) counterbore-taper joint design



(a)



(b)

Figure 3-9: Longitudinal distribution of axial stress for 406 mm pipe with D/t of 60 at (a) initial yield and (b) onset plastic collapse

3.6 Conclusion

In this study, the mechanical response of a transition welds joining pipe segments of unequal wall thickness and material grade were evaluated using continuum finite element methods. The transition joint designs examined were the back-bevel and counterbore-taper. The pipe segments with these transition joints were subject to combined loading with internal pressure, axial force and bending moment over a range of pipe diameters (406 mm & 914 mm) and D/t ratios (40, 60 & 80). The mechanical stress response for each joint design was investigated and comparatively evaluated with respect to; including stress path, and the longitudinal distribution of axial stress at initial yield and onset of plastic collapse.

For an ideal pipe section; that is without bifurcation perturbations, physical pipe body imperfections or girth weld imperfections, the back-bevel joint was observed to have marginally greater strength capacity, in comparison with the counterbore-taper transition design, for initial yield when the normalized axial force was greater than 0.25. It is recommended that both types of joints should not locate on the high bending moment zone. However, the distribution and magnitude of tensile stresses near the circumferential girth weld for the back-bevel design were less favorable than the corresponding mechanical response for the counterbore-taper joint design. The localization of axial tensile stress state on the circumferential girth weld has negative implications on the pipe mechanical response with respect to pipe rupture, flaw size acceptance criteria, fatigue life and welding procedures.

Incorporating bifurcation perturbations and radial offsets at the girth weld had a significant influence on the stress path during the loading event up to the onset of plastic collapse, and the longitudinal distribution and magnitude of axial stress for both transition joint designs. For some of the load cases examined, in comparison with the counterbore-taper transition joint, the back-bevel transition joint had a relatively greater negative impact on the mechanical stress response with respect to the localization of tensile stress at the circumferential girth weld location. The limited numerical study illustrated, for some design conditions, the back-bevel design may exceed longitudinal tensile yield strength whereas for the corresponding counterbore-taper design remained within elastic limits.

This preliminary study requires further investigations before definitive conclusions on the mechanical performance envelopes for the back-bevel and counterbore-taper transition joints can be established. Some of the parameters that should be examined include the effect of girth weld residual stress amplitude and distribution, girth weld radial offset amplitude, orientation and sense, variation in material grade across transition joints, relative shape or characteristics of the stress-train relationship for each pipe joint, and compressive axial loads. There are several factors that may influence the numerical procedures that should be further examined as part of these studies including mesh density and mesh distribution or bias. Furthermore, experimental studies are required to provide physical data for the calibration and verification of the simulation tool. On this basis a rigorous numerical parameter study can be conducted to establish engineering design guidelines on the mechanical performance of transition joints.

3.7 Acknowledgments

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3.8 References

ASME B31.8 (2010). Gas Transmission and Distribution Piping Systems. The American Society of Mechanical Engineers.

CSA Z662 (2010). Oil and Gas Pipeline Systems, Canadian Standards Association.

George, H. H. and Rodabaugh, E. C. (1959). “Test of Pups Support Bridging Effect.”, Pipe Line Industry, OCT., pp. 218-233.

Zhu, X. K. and Leis, B. N. (2005), "Plastic Collapse Assessment Method for Unequal Wall Transition Joints in Transmission Pipelines", J. PVT, 127(4): 449-456.

Law, M., Tuft, P. and Venton, P. (2010). “Thickness Limit for Welded Joints between Pipes of Different Yield Strengths.” J. Pipeline Eng., 9(2):99-105.

Baek, J.H., Kim, Y.P. and Kim, W.S. (2012). “Effect of taper angle on plastic collapse of pipe joint with different wall thickness and strength.” Proc., IPC-90129:9p.

DNV-RP-C203 (2010). Fatigue Design of Offshore Steel Structures, Det Norske Veritas, 178p.

ABAQUS (2012). Abaqus Standard User's Manual (Version 6.12).

Al-Showaiter, A., Taheri, F. and Kenny, S. (2011). “Effect of misalignment and weld induced residual stresses on the local buckling response of pipelines.” J. PVT 133(4), 7p..

Liu, P. F., Zheng, J. Y. and Ma, L. (2008). “Calculations of plastic collapse load of pressure vessel using FEA.” J. Zhejiang University Science, 9(7):900-906.

Robertson, A., Li, H. and Mackenzie, D. (2005). “Plastic collapse of pipe bends under combined internal pressure and in-plane bending.” J. PVP, 82:407-416.

Lotsberg, I. (2007). “Stress concentration factors at welds in pipelines and tanks subjected to internal pressure and axial force.” Marine Structure, 21:138-159.

Mohareb, M.. (1995). Deformational Behaviour of Line Pipe. Ph.D. Thesis, University of Alberta, 220p.

Hauch, S. and Bai, Y. (1999). “Bending moment capacity of pipes.” Proc., OMAE, 122(4): 243-252.

Kyriakides, S. and Corona, E. (2007). Mechanics of Offshore Pipelines: Vol. I Buckling and Collapse. Elsevier, 401p.

Fatemi, A. and Kenny, S. (2012). “Characterization of initial geometric imperfections for pipelines and influence on compressive strain capacity.” Proc., ISOPE-12-TPC-0304, 7p.

Corona, E., Lee, L.H., and Kyriakides, S. (2006) “Yield anisotropic effects of buckling of circular tubes under bending.” J. Solids and Structures, 43:7099-7118.

Fatemi, A., Kenny, S., Sen, M., Zhou, J., Taheri, F. and Paulin, M. (2008). “Investigations on the local buckling response of high strength linepipe.” Proc., IPC2008-64407, 9p.

Fatemi, A., Kenny, S., Sen, M., Zhou, J., Taheri, F. and Paulin, M. (2009). “Influence of material and geometric imperfections on the local buckling response of plain and girth weld high strength linepipe.” Proc., 5th International Pipeline Technology Conference, PIPE-56, 22p.

Al-Showaiter, A., Taheri, F. and Kenny, S. (2008). “Parametric study on the effect of weld misalignment on the local buckling response of pipelines.” Proc., IPC2008-64004, 9p.

4 EVALUATION OF BACK-BEVELED AND COUNTERBORE-TAPERED JOINTS IN ENERGY PIPELINES

This peer reviewed paper has been finalized and is ready to submit to an international peer review journal and International Pipeline Conference (IPC 2016-64390, Calgary, Alberta). This paper was a collaborative effort including myself, Dr. Shawn Kenny, Dr. Amgad Hussein and Mr. Michael Martens from TransCanada PipeLines. As the primary author, I was responsible for developing and calibrating the numerical modelling procedures, conducting the data analysis and synthesizing the results within this paper. Dr. Shawn Kenny and Dr. Amgad Hussein were responsible for providing supervision and guidance during this study and editorial comments in the preparation of this paper. Mr. Michael Martens was responsible for providing the context and motivation for this paper.

Authors: Xiaotong Huo, Shawn Kenny, Amgad Hussein and Michael Martens

4.1 Abstract

Wall thickness transition joints are used to connect energy pipeline segments; such as straight pipe to a fittings, with different wall thickness. The transition joint may be subject to axial forces and bending moments that may result in a stress concentration across the transition weld and may exceed stress based design criteria. Current engineering practices, such as CSA Z662, ASME B31.4, and ASME B31.8, recommend the use of back-bevel transition welded connections. An alternative transition weld configuration is the counterbore-taper design that is intended to reduce the stress concentration across the transition.

In this study, the relative mechanical performance of these two transition design options (i.e., back-bevel and counterbore-taper) is examined with respect to the limiting burst pressure and effect of stress concentrations due to applied loads. The assessment is conducted through numerical parameter study using 3D continuum finite element methods. The numerical modelling procedures are developed using Abaqus/Standard. The performance of continuum brick elements (C3D8I, C3D8RH, C3D20R) and shell element (S4R) are evaluated. The continuum brick element (C3D8RI) was the most effective in terms of computational requirements and predictive qualities.

The burst pressure limits of the transition weld designs were evaluated through a parameter study examining the significance of pipe diameter to wall thickness ratio (D/t), wall thickness mismatch ratio (t_2/t_1), material Grade 415 and Grade 485 and end-cap boundary condition effects. The limit load analysis indicated the burst pressure was effectively the same for both transition weld designs. The effect of pipe diameter, D/t, t_2/t_1, and counterbore length on the stress concentration factor, for each transition weld design, was also assessed. The results demonstrate the improved performance of the counterbore-taper weld transition; relative to the back-bevel design as recommended by current practice, through the relative decrease in the stress concentration factor. The minimum counterbore length was found to be consistent with company recommended practices and related to the pipe diameter and wall thickness mismatch.

4.2 Introduction

Energy transmission pipelines deliver oil and gas products, over long distances, from facilities to an end user. The pipeline may be connected at specific locations; such as road crossings, bends due to changes in the pipe route alignment or above ground transitions, with thicker walled segments; such as fittings, field cold bends and induction bends.

The wall thickness transition or mismatch can be designed using back-bevel butt weld (Figure 4-1a) in accordance with current practice (e.g., ASME.B31.8, ASME.B 31.4 and CSA Z662). The plastic collapse, for internal pressure, of back-bevel weld transitions has been examined over the past 50 years through experimental, analytical and numerical simulation (e.g., George and Rodabaugh, 1959; Zhu and Leis, 2005; Law et al., 2010; Baek et al., 2012) and forms the basis for current engineering practice. Practical design limits on taper geometry through the transition weld (e.g., minimum of 4:1), and minimum ratios of pipe strength and wall thickness mismatch (e.g., maximum to minimum wall thickness ratios should be less than or equal to 1.5) between pipe segments has been established.

An alternative strategy is to employ a counterbore-taper weld transition (Figure 4-1b), which also facilitates the welding process and improves NDT quality, productivity and reliability. Recent numerical investigations by Huo and Kenny (2014), using the shell S4R element, comparatively assessed the stress response for each joint design option (i.e., back-bevel and counterbore-taper transition) with respect to the stress path, and the longitudinal distribution of axial stress at initial yield and onset of plastic collapse. The study examined the significance of axial load, bending moment, D/t and girth weld radial offset parameters. The back-bevel design was found to have greater magnitude of tensile stress across the girth weld and localization of tensile stress through the wall thickness transition zone, which exceeded the yield strength. The counterbore-taper design was found to moderate the stress concentration effects. Furthermore, a recent numerical study by Martens et al. (2014) demonstrated the counterbore-taper design reduces the stress concentration and intensity across the butt welded joint relative to the conventional back-bevel wall thickness transition. The counterbore-taper transition length was also determined to be a significant parameter. These studies established the improved mechanical performance of the counterbore-taper transition, relative to the conventional back-bevel design, with respect to mitigating the development of cracks during construction and operation, improving mechanical performance for stress based assessment, welding and flaw qualification procedures, and fatigue life.

The objective of this study is to extend these recent investigations (i.e., Huo and Kenny, 2014; Martens et al., 2014) through a more comprehensive numerical parameter study. The influence of element type, mesh topology, wall thickness mismatch (t_2/t_1), material grade on the limit load, pressure containment response for the back-bevel and counterbore-taper wall thickness transitions are evaluated. In terms the stress concentration factor, associated with loads applied to a pipe segment with an unequal wall thickness transition, the significance of element type, mesh topology, pipe diameter (D), pipe diameter to wall thickness ratio (D/t), wall thickness mismatch (t_2/t_1), material grade on the limit load, counterbore length, taper angle and radial girth weld offset (i.e., Hi-Lo) are evaluated. For each phase, the numerical modelling procedures are verified with physical data and numerical simulations available in the public domain literature.

4.3 Finite Element Modelling Procedures

The continuum finite element modelling procedures were developed using Abaqus/Standard (v6.12). The pipe segment and wall thickness transition, for both design option (Figure 4-1), were modelled using conventional shell element (S4R) and continuum solid element (C3D8I, C3D8RH, and C3D20R). The S4R element is a 4-node general-purpose shell element with finite membrane strain and reduced integration with hourglass control. The C3D8I element is a fully integrated, 8-node linear brick element with an incompatible mode (i.e., bubble function) to improve bending performance through an additional internal degree of freedom to address the effects shear locking and mitigate volumetric locking. The C3D8RH element is a hybrid formulation with constant reduced integration with hourglass control that are primarily used with incompressible or near incompressible material behaviour (Abaqus Benchmarks Manual) where the solution is dependent on the loading history (i.e. hydrostatic forces) and path (i.e. displacement history).

For the S4R element model, the pipe wall thickness was defined on a nodal basis for the homogenous shell sections with the reference surface defined by outer (top) surface (Figure 4-2a). The taper angle 4:1 (i.e., 14 degrees) for back-bevel and counterbore-taper joint was modelled by defining analytical expression fields within Abaqus/Standard. The boundary conditions were specified at reference points located at each pipe end on the longitudinal centerline axis. Kinematic coupling was used to connect the reference points to the pipe end nodes with all degrees of freedom except for the radial direction defined by the local coordinate. This action released radial constraints on the pipe end mechanical response with respect to the effects of internal pressure and end cap forces. The pipe segment length was 8D to mitigate end boundary effects. Through a convergence study a uniform distribution of 72 nodes along the circumferential direction was used. The mesh density was refined, in the longitudinal direction, within a 1D pipe segment across the weld and wall thickness transition region. The girth weld radial offset was a 2 mm hi-low misalignment imposed at the 12 clock position for the thinner walled pipe was modelled and examined.

For the continuum solid model, a plane of symmetry was used to reduce the computational effort (Figure 4-2b). The essential and natural boundary conditions were defined at two reference points located at each pipe end on the longitudinal centerline axis. A rigid section at each pipe end was created to connect the reference points to the R3D3 elements at each pipe end. A mesh density study was established to assess the influence of the mesh density on the numerical predictions with respect to pipe mechanical response. Through a convergence study a uniform distribution of 72 nodes along the circumferential direction and 5 through thickness was used. The mesh density was refined, in the longitudinal direction, within a 1D pipe segment across the weld and wall thickness transition region.

The pipe material grade examined was Grade 415 (API X60) and Grade 485 (API X70). The stress-strain relationships defined by Ramberg-Osgood expression (Walker and Williams, 1995) and implemented within the numerical modelling procedures as a piece-wise smooth continuous representation. Isotropic properties and the von Mises yield criterion were considered to be representative of the material behaviour. The weldment material strength was defined as 10% overmatch on the X70 pipe.

The pressure load was applied onto the inner surface of the pipe for both continuum shell and brick element model and the nonlinear equations were solved using the modified Riks method. The end cap force was applied onto the reference points on both sides of the shell model and onto the pipe end surface directly to transfer more effectively.

4.3 Limit Load Analysis – Pressure Containment

4.3.1 Overview

The pressure capacity or limit load (i.e. onset of plastic instability) of the unequal wall thickness design options (i.e., back-bevel and counterbore-taper) was evaluated using 3D finite element modelling procedures. Kirkemo (2001) indicated that as the internal pressure increases, the pipe cross-section expands uniformly until through thickness yielding has been reached where the pipe expansion becomes unstable. This instability leads to localization of the stress state and kinematics, which could be influenced by natural variations (e.g., wall thickness, material properties) and defects (e.g., corrosion), and ultimately will lead to pipe rupture with loss of pressure containment capacity.

4.3.2 FE modelling procedure verification

The finite element modelling procedures were verified through comparison with analytical studies and finite element simulations available in the public domain literature. Zhu and Leis (2003) developed collapse models to predict the failure pressure for defect-free and corroded pipelines and validated with experimental data. Two classical strength failure criteria (i.e., Tresca and von Mises) were examined and analytical equations for the limit load of long uniform thin-wall pipes with end-opened and end-capped conditions were developed. The limit pressure for plastic instability for a uniform thin-wall pipe with an end-open condition is

$$P_{Limit} = (\frac{2}{3})^{\mathrm{n}} \frac{2t_o}{D_0} \sigma_{UTS} \quad \text{Eq. (4.1)}$$

where D_0 and t_0 are the initial average pipe diameter and pipe wall thickness. The strain hardening exponent, n, was related to the yield strength to tensile strength ratio (Y/T)

$$n = 0.239(\frac{1}{\mathrm{Y}/\mathrm{T}} - 1)^{0.5} \quad \text{Eq. (4.2)}$$

The limit pressure for plastic instability of a uniform thin-wall pipe with an end-cap condition is

$$P_{Limit} = \frac{4t_0}{3^{\frac{n}{2}} D_0} \sigma_{UTS} \quad \text{Eq. (4.3)}$$

Law and Tuft (2010) calculated the burst pressure for pipelines with back-bevel joint using finite element methods. For a pipe segment with D/t of 55, wall thickness mismatch of 1.5, and back-bevel taper of 4:1, the burst pressure was predicted to be 1.162×SMYS (specified minimum yield strength). The main pipe had a material Grade 485 (X70), and thicker walled pipe has material Grade 415 (API X60).

Based on the theoretical model developed by Zhu and Leis (2003), the estimated limit pressure for the open-end pipe segment (Eq. 4.1) was 1.09×SMYS and 1.16×SMYS for the Grade 485 (API X70) and Grade 415 (API X60) materials, respectively. The estimated limit pressure for the closed-end pipe segment (Eq. 4.3) was 1.25×SMYS and 1.32×SMYS for the Grade 485 (API X70) and Grade 415 (API X60) materials, respectively.

In this study, a 3D shell (S4R) element model was developed to estimate the limit load for the pipe parameters examined by Law and Tuft (2010), which was predicted to be 1.19×SMYS and 1.06×SMYS for the end-cap and end-open conditions, respectively. Failure occurred in the thinner walled, Grade 485 (API X70) pipe, which is consistent with the analytical predictions of Zhu and Leis (2003). Differences in the limit pressure for end-cap and end-open conditions are directly related to the boundary conditions and imposed loads that influence the mechanical response (Figure 4-3a) and stress path (Figure 4-3b). The longitudinal stress generated by the end cap effect leads to higher plastic instability pressure, where on reaching the yield condition, then pipe expansion becomes more localized with the longitudinal stress state, in the region of pipe failure, is tensile for the end-open condition.

4.3.3 Effect of element type

The influence of element formulation, including conventional shell element (S4R) and continuum solid elements (C3D8I, C3D8RH, C3D20R), on estimating the limit loads for plastic instability failure was investigated. The thin shell theory, which also known as Kirchhoff theory, assumes that normal to the shell reference surface remain normal after deformation and the transverse stress is negligible. The three-dimensional continuum theory accounts for the transverse stress and change of thickness. In choosing a thin shell or a three-dimensional element for numerical modelling, the decision will depend on the specific context and analysis. Thin-wall theory is generally applicable when the D/t is greater than 20. In this study, the D/t was 48 and 57 for the thicker-walled and thinner-walled pipe segments, respectively.

Finite element models were developed for the back-bevel and counterbore-taper wall thickness transition with a pipe diameter of 914 mm, 15.9 mm and 19.1 mm wall thickness ($t_2/t_1 = 1.2$) and material Grade 485 (API X70). Results from the FE results were examined with respect to the limit load for plastic instability and the hoop stress at the weld root. For an open-end condition, the S4R model predicted a limit load of 1.06×SMYS whereas the continuum solid element models predicted a limit load of 1.05×SMYS. A comparison of the limit load and average hoop stress at the weld root is summarized in Table 4-1.

In terms of the limit load or stress state at the weld root, there was no significant influence of the element type on the predictions. The C3D8I model predicted higher hoop stress for the counterbore-taper model at the weld root. The S4R element model was the most computationally efficient and was used for the parameter study examining the influence of wall thickness and material grade as presented in the following subsections. is for all elements. For continuum solid elements, the C3D8RH element model was the most efficient. The 3D conventional shell element model was chosen for the followed parametrical study for limit load assessment with the concern of accuracy and computational costs.

A general sensitivity analysis was also conducted to examine the continuum solid element performance with respect to beam (pipe) bending response. From this analysis, it was concluded that the C3D20R and C3D8I exhibited improved computational performance over the C3D8RH element model in terms of solution quality and computational effort. The C3D8RH also exhibited shear locking when the number of through thickness elements was limited.

4.3.4 Effect of wall thickness mismatch (t_2/t_1) and material grade

The "bridging effect" of taper transitions was first investigated more than 60 years ago that examined transition between a Grade 360 (API X52) pipe and Grade 240 (API Grade B) fitting subject to internal pressure (George and Rodabaugh, 1959). The "bridging effect" refers to the reinforcement from the stronger wall section to the thinner wall pipe component, which is related to the location of the plastic instability. Normally, the failure location of the unequal wall thickness transition joint occurs within the thinner pipe segment at a distance away from the weld and taper region, which is dependent on the wall thickness mismatch ratio (t_2/t_1).

For unequal wall thickness transitions, using a back-bevel design where the SMYS of each component is not the same, CSA Z662 requires the wall thickness mismatch ratio (t_2/t_1) to be less than 2.5, the tensile strength of the weld metal to be equal to or greater than the higher SMYS pipe strength, and "the unit strength (i.e., product of the SMYS and design wall thickness) of the item having the lower specified minimum yield strength shall be equal to or greater than the unit strength of the item having the higher specified minimum yield strength".

For the back-bevel design, Zhu and Leis (2005) developed a plastic collapse assessment diagram (PCAD) for pipe failure under internal pressure, which would occur in the thinner pipe with higher strength when using a back-bevel wall thickness transition. A simplified equation for both end-cap and end-open conditions was developed to determine the wall thickness and material grade requirements,

$$\frac{\sigma_{UTS2}}{\sigma_{UTS1}} > \frac{t_1}{t_2} \qquad \text{Eq. (4.4)}$$

The wall thickness mismatch ratio requirement $\left(t_2/t_1 < 1.5\right)$ presents difficulties in the welding process when using the back-bevel joint. The counterbore-taper joint transition provides a simpler geometry for line-up and welding where the pipe segments being joined have equal wall thickness (Figure 4-1a). This configuration also allows for higher wall thickness mismatch ratios. Based on TransCanada PipeLine (TCPL) company best practices, the counterbore-taper joint design is recommended for the following condition,

$$\frac{t_2}{t_1} - 1 > 0.3 \quad \text{Eq. (4.5)}$$

As the counterbore-taper joint design includes a segment with the same wall thickness as the thinner pipe, the plastic collapse assessment diagram (Zhu and Leis, 2005) cannot be used to assess this transition design. The wall thickness mismatch ratio plays an important role on the instability mechanism and failure location. For pipe segments with the same material grade, as the pipe wall thickness increases, the plastic instability will occur within the thinner pipe segment. Variations in the material grade and wall thickness transition will have a combined effect on the failure location and burst pressure.

A parameter study was conducted to assess the adequacy of the joint design selection requirement (Eq. 4.5), the effects of D/t, wall thickness mismatch ratio and material grade for back-bevel and counterbore-taper wall thickness transitions (Table 4-2). A NPS 914 mm (NPS 36") diameter pipe subject to internal pressure with end-open boundary condition was examined. The thinner pipe segment (Figure 4-1b) had a wall thickness (t_1) of 12.7 mm and 15.9 mm with a D/t_1 of 72 and 58 and unit strength of 6160 kN m and 7712 kN m, respectively. For the thicker walled segment (#1), the D/t_2 ranged from 36 to 64 and the unit strength ranged from 1.03 to 1.6 times the unit strength of the thinner walled segment (#1).

As shown in Figure 4-4, the limit load estimates for the back-bevel and counterbore-taper joint are effectively identical when the wall thickness mismatch is greater than 1.3, which supports the design recommendation as stated by Equation (4.5). For the pipeline with counterbore-taper joint design, the failure location shifted from the transition length connecting the pipe segments into the thinner pipe as the wall thickness mismatch ratio (t_2/t_1) increased. The back-bevel joint design exhibits less sensitivity with the wall thickness mismatch ratio (t_2/t_1) as the D/t_1 increases. The limit load for pressure containment is governed by the thinner wall segment when the wall thickness mismatch ratio (t_2/t_1) is greater than 1.3, for both the back-bevel and counterbore-taper design. The higher material grade of thicker pipes or fitting provides reinforcement on the thinner pipe segment, which is consistent with the "bridging effect".

Based on the FE simulations conducted in this study, the wall thickness selection requirement for counterbore-taper joints Equation (4.5) was conservative for pipelines with uniform Grade 485 (API X70) material through the unequal wall transition. Further study across a broader range of geometric (e.g., pipe diameter, internal or external transitions, variation in diameter) and material (e.g., pipe grade, weld overmatch) should be conducted to further assess this conservatism.

4.4 Stress concentration effects

4.4.1 Overview

Stress concentrations at girth weld connections arise from a shift in the longitudinal axis of the pipe mid-wall that may occur due to variation in wall thickness, pipe diameter or pipe section ovality (i.e., out-of-roundness) across the girth weld, and misalignment during the welding process (e.g., radial or Hi-Lo offsets). Due to these geometric imperfections or eccentricities, the applied loads induce bending stress across the unequal wall thickness transition joint that results in a stress concentration. Fatigue cracks may be initiated from the notch region within this transition zone between the pipe base material and weldment. Longitudinal stress due to operational, environmental or external loads may initiate and extend circumferential cracks within the weldment and heat affect zone (HAZ) regions. The longitudinal stresses in the joints are resulting from end cap effect of internal pressure, pipe bending or thermal load. In this section, the mechanical performance of back-bevel and counterbore-taper joints is analyzed with respect to the stress concentration developed through the transition zone.

4.4.2 FE modelling procedure verification

The FE modelling procedures and assessment of the stress concentration factors at hot spots within the girth weld, for back-bevel and counterbore-taper joints, were compared with the analytical solutions recommended by DNVGL RP-C203. The recommended practice was based on work conducted by Lotsberg (1998) where analytical expressions for the stress concentration factors for pipe subject to internal pressure and axial force based on shell theory. The effects of fabrication tolerances on butt welds in pipelines with wall thickness transitions are evaluated with comparison to finite element analysis for verification.

As defined in DNV RP-C203, if the wall thickness transition is located on the inside of the pipe and the weld is performed on the outside only with a radial inward offset (Hi-Lo) misalignment, as shown in Figure 4-5a, then the stress concentration factor can be estimated

$$SCF = 1 - [\frac{6(\delta_t - \delta_m)}{t}]\,[\frac{1}{1+(\frac{T}{t})^{\beta}}]e^{-\alpha}\ for\ \frac{T}{t} \leq 2 \qquad \text{Eq. (4.6a)}$$

where δ_t is the eccentricity δ_t is the eccentricity due to wall thickness change ($\delta_t = 0.5[T - t]$), δ_m is the maximum misalignment amplitude, t is the wall thickness of the thinner pipe, and T is the wall thickness of the thicker pipe. The transition length parameter, α, and pipe geometry parameter, β, are defined as

$$\alpha = 1.82\frac{L}{\sqrt{Dt}}\frac{1}{1+(\frac{T}{t})^{\beta}} \qquad \text{Eq. (4.6b)}$$

$$\beta = 1.5 - \frac{1}{log(\frac{D}{t})} + \frac{3}{[log(\frac{D}{t})]^2} \qquad \text{Eq. (4.6c)}$$

Figure 4-6 demonstrates the stress concentration factor calculated by Equation (4.6) with the variation of D/T ratio for same pipe diameter and different T/t ratios. For the same diameter pipe, the increase of D/T ratio will lead to higher stress concentration and the increase of T/t will lead to a decline of stress concentration factor, which can be related to the pipe stiffness.

As defined in DNV RP-C203, if the wall thickness transition is located on the outside of the pipe and the weld is performed on the outside only with a radial outward offset (Hi-Lo) misalignment, as shown in Figure 4-5b, then the stress concentration factor can be estimated

$$SCF = 1 - [\frac{6(\delta_t + \delta_m - \delta_0)}{t}] [\frac{1}{1 + (\frac{T}{t})^{\beta}}] e^{-\alpha} \quad \text{Eq. (4.7)}$$

where δ_0 is the misalignment parameter, $\delta_0 = 0.1t$, inherent in the S-N data as per DNVGL RP-C203.

The FE model modelling procedures were developed that incorporated the 3D shell (S4R) and continuum solid elements (C3D8I, C3D8RH, C3D20R) for a Grade 485 (API X70) unequal wall thickness transition. A NPS 914 (NPS 36") pipe diameter with a wall thickness transition of 15.9 mm and 19.1 mm ($t_2/t_1 = 1.20$) with a radial inward (Hi-Lo) misalignment of 2 mm was analyzed. The internal pressure and end cap force were applied onto the pipe model.

The stress concentration factors (SCF) for this analysis are summarized in Table 4-3 for a back-bevel joint design. The SCF was established by averaging the local axial stress at the hot spot of the weld root and divided by the mean remote axial stress. The shell S4R element provides poor representation of the local stress field and overestimates the SCF, relative to other the performance of other elements and the analytical solution defined by

Equation (4.6). For this specific problem, the continuum solid element C3D8RH provides the best correspondence with the analytical solution.

A recent study conducted by Martens et al. (2014) was also used to further assess the FE modelling procedures using continuum solid elements. A NPS 1067 (NPS 42") pipe diameter with a wall thickness transition of 15.9 mm and 19.1 mm ($t_2/t_1 = 1.20$) and material Grade 485 (API X70) was analyzed. An internal pressure and associated end cap force was applied as the loading conditions to develop a hoop stress of 0.72 times the yield strength. The FE analysis conducted in this study and the analysis conducted by Martens et al. (2014) used the C3D8RH element. The back-bevel and counterbore-taper wall thickness transition designs were analyzed. As summarized in Table 4-4, the predicted SCF from this study is in agreement with the analytical solution, Equation (4.6), however, the SCF predicted by Martens et al., (2014) is greater by a factor of 2.8 and 2.1 for the back-bevel and counterbore-taper designs, respectively.

4.4.3 Effect of element type

Due to this discrepancy, a sensitivity study was conducted to assess the importance of element type on the SCF predictions for simple loading conditions including bending, axial load, and combined load condition for internal pressure, axial force and bending.

For the pipe flexure problem, a cantilever boundary condition was used with vertical point load condition. The mesh convergence study examined C3D8I, C3D8RH and C3D20R elements with different mesh topologies including 2×20 (through thickness×circumference), 4×40 and 5×40. The tip deflections (Table 4-5) and root axial stress (Table 4-6) for the FE simulation were analyzed and normalized with respect to the analytical solution. The C3D8I element model was the most effective in terms of solution quantity and computational effort. The C3D8RH element was the most sensitive to mesh refinement. The cantilever (i.e., end fixed) pipe FE models were also subject to an axial load. The relative performance of each element provided the same accuracy with respect to axial elongation with minor sensitive to mesh refinement. However, the C3D8I and C3D20R element provided greater numerical stability in predicting constant axial stress than the C3D8RH element model.

Element performance was also examined for the back-bevel and counterbore-taper transition joints subject to combined loading conditions. The loading conditions included internal pressure and axial force, and internal pressure plus flexure. The C3D20R and C3D8RH element FE models exhibited some numerical issues, particularly for large deformation response. As shown in Figure 4-8, the C3D20R element FE model exhibited shear locking within the wall thickness transition for the combined internal pressure and axial load condition. For the internal pressure, axial force and bending load condition, the C3D8RH element FE model, exhibited mesh distortion with large magnitude of artificial strain energy (> 0.1%), associated with hourglass controls, at large deformations.

The sensitivity study supported using the C3D8I element for conducting further parameter studies on the mechanical performance of the back-bevel and counterbore-taper wall thickness transition joints.

4.4.4 Effect of counterbore length

As the transition length (L) for the counterbore-taper joint (Figure 4-1b) increases, the geometric effects due to the wall thickness transition on load interaction, stress state and SCF at the girth weld joint will be mitigated. The effects of fabrication tolerances, girth weld offsets and other perturbation will not be affected. The DNVGL RP-C203 states the geometric effects will be small when

$$L \geq 1.4 l_e = 1.4\left[\frac{\sqrt{rt}}{\sqrt[4]{3(1-\upsilon^2)}}\right] \qquad \text{Eq. (4.8)}$$

where *r* is the pipe radius to the mid-wall, *t* is the pipe nominal wall thickness and ν is the Poisson's ratio. For a Poisson's ratio of 0.3, then Equation (4.8) yields

$$L \geq 1.4 l_e = 0.77\sqrt{Dt} \qquad \text{Eq. (4.9)}$$

TCPL recommended practices state the transition length for the counterbore-taper joint should be

$$L = 0.85\sqrt{Dt_2} \qquad \text{Eq. (4.10)}$$

but not less than 50 mm, whereby an extra 25 mm may be required to provide for cutting and repairing after hydrotest operations. The TCPL recommended practice is more conservative than the DNV RP-C203 guidelines where the thicker wall section may be greater than the thinner wall by at least a factor of 1.5 depending on the design standard used.

A parameter study was conducted to examine the effect of counterbore length (nominal lengths of 25 mm, 50 mm, 70 mm, 90 mm 120 mm & 200 mm) and taper angle (14° or 1:4 & 30°) on the SCF and compare the mechanical response with the conventional back-bevel joint design. The pipe configuration examined by Martens et al. (2014) was selected for this parameter study. A NPS 1067 (NPS 42") pipe diameter with a wall thickness transition of 15.9 mm and 19.1 mm ($t_2/t_1 = 1.20$) and material Grade 485 (API X70) was analyzed.

The longitudinal SCF predicted by Martens et al. (2014) is illustrated in Figure 4-9a and the SCF from this study is presented in Figure 4-9b. Each study, within itself, exhibits similar response where the back-bevel joint has a higher SCF than the counterbore-taper joint for any transition length, and as the transition length increases then the SCF decreases.

For the present study, as shown in Figure 4-9b, the SCF for the back-bevel joint design corresponds with the analytical equations (DNVGL RP-C203; Lotsberg, 1998) for the

SCF at the weld root. The minimum counterbore transition lengths recommended by DNVGL RP-C203 (Equation 4.9) and TCPL (Equation 4.10) are also shown. For the back-bevel joint, the SCF increases with increasing taper angle and was insensitive for the counterbore-taper design, which is consistent with the findings of these studies (DNVGL RP-C203; Lotsberg, 1998; Martens, et al., 2014).

4.4.5 Effect of pipe geometric properties

The influence of nominal pipe diameter, D/t, wall thickness mismatch (t_2/t_1) and counterbore transition length was conducted. The parameters evaluated in this study are summarized in Table 4-6 with a variation in the nominal pipe diameter (D) of NPS 609 mm, 914 mm, and 1067 mm with a nominal wall thickness (t_1) of 9.8 mm, 15. 9 mm, and 15.9 mm, respectively. Influence of the wall thickness mismatch (t_2/t_1 = 1.2 & 1.5) and counterbore transition length (25 mm, 50 mm, 70 mm, 90 mm, 120 mm & 200 mm) was also examined.

As shown in Figure 4-10, the back-bevel wall thickness transition joint exhibited higher SCF, by a relative multiplier of 1.1 to 1.5, than the counterbore-taper design across the range of parameters examined. For the back-bevel joint, the SCF was influenced more by changes in the wall thickness mismatch (t_2/t_1) rather than pipe diameter. Increasing the wall thickness mismatch (t_2/t_1), by a factor of 1.25, increased the SCF, by a multiplier of approximately 1.1, for the back-bevel joint. There was no consistent trend on the SCF for the back-bevel joint with changes in pipe diameter, where the relative variation in the SCF was by a multiplier of 1.05 for a 1.75 multiplier change in diameter. Figure 4-11(a),

(b) and (c) illustrate the axial stress distribution across weld and taper transition for NPS 609 mm pipe with 25mm, 90mm and 200mm counterbore length at the same loading condition (i.e. internal pressure and end cap force). The counterbore-tapered with 25 mm length contains the highest axial stresses at the weld due to the combined effect of weld misalignment and wall thickness change. The 90mm and 200mm counterbore length present similar axial stress value but the 90mm is slightly lower than the 200mm, which can be due to the reduced pipe stiffness as the counterbore length increases.

The mechanical response of the counterbore-taper transition joint was more complex and this was attributed to the interaction between geometric effects (e.g., changes in eccentricity due to wall thickness variation, transition length, taper angle and length) with the stress response (e.g., axial and bending field, pipe stiffness). For each pipe diameter, increasing the wall thickness mismatch (t_2/t_1) did not have any significant influence at the two extreme transition lengths (i.e., 20 mm & 200 mm) examined in the parameter study. For changes in the wall thickness mismatch (t_2/t_1), there is greater discrepancy in the SCF for intermediate transition lengths as the pipe diameter decreases. The onset of this discrepancy corresponds with the minimum transition lengths used in current practice (Equation 4.9 and 4.10). As the wall thickness mismatch (t_2/t_1) increases and the nominal pipe diameter decreases then there appears to be greater interference effects between the geometric parameters and stress field.

4.6 Conclusions

A numerical modelling study, using finite element methods, was conducted to assess the mechanical performance of unequal wall transitions using back-bevel and counterbore-taper joint designs. The relative mechanical performance of these two design options was examined with respect to the limiting burst pressure and effect of stress concentrations due to applied loads.

The study investigated the importance of element selection, including the conventional shell (S4R) and solid continuum (C3D8I, C3D8RH, C3D20R) elements. The continuum brick element (C3D8RI) was the most effective in terms of computational requirements and predictive qualities.

The burst pressure limits of the transition weld designs were evaluated through a parameter study examining the significance of pipe diameter to wall thickness ratio (D/t), wall thickness mismatch ratio (t_2/t_1), material Grade 415 and Grade 485 and end-cap boundary condition effects. The limit load analysis indicated the burst pressure was effectively the same for both transition weld designs.

In terms of the longitudinal stress concentration factor (SCF), the counterbore-taper wall thickness transition can significantly reduce the stress concentration effect within the weld region in comparison with the back-bevel joint. The finite element analysis confirmed current industry practice for the selection of the minimum transition length, and was found to be dependent on the pipe diameter and wall thickness mismatch.

4.7 Acknowledgements

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4.8 References

ABAQUS (2012). Abaqus Standard User's Manual (Version 6.12).

ABAQUS (2010). Abaqus Benchmarks Manual (Version 6.10).

ASME B31.4. Pipeline Transportation Systems for Liquids and Slurries. The American Society of Mechanical Engineers. 2012.

ASME B31.8. Gas Transmission and Distribution Piping Systems. The American Society of Mechanical Engineers. 2014.

Baek, J.H., Kim, Y.P. and Kim, W.S. (2012). “Effect of taper angle on plastic collapse of pipe joint with different wall thickness and strength.” Proc., IPC-90129:9p.

CSA Z662. Oil and Gas Pipeline Systems, Canadian Standards Association. 2015.

DNVGL RP-C203. Fatigue Design of Offshore Steel Structures, Det Norske Veritas, 201p., 2014.

George, H. H. and Rodabaugh, E. C. (1959). “Test of Pups Support Bridging Effect.” Pipe Line Industry, OCT., pp. 218-233.

Huo, X., Kenny, S. and Martens, M. (2014). “Mechanical Integrity Evaluation of Unequal Wall Thickness Transition Joints in Transmission Pipeline.” Proc., IPC-33141:9p.

Law, M., Tuft, P. and Venton, P. (2010). “Thickness Limit for Welded Joints between Pipes of Different Yield Strengths.” J. Pipeline Eng., 9(2):99-105.

Lotsberg, I. (1998). “Stress concentration factors at circumferential welds in tubulars.” J. Mar Struct., 11(6): 207-230.

Martens, M., Chen, Y., and Liu, M. (2014). “Comparative Integrity Evaluation of Counterbore-taper and Back-bevel Weld Joints.” Proc., IPC-33374:9p.

Walker, A.C. and Williams, K.A.J. (1995). “Strain based design of pipelines.” Proc., OMAE, Vol.5, 6p.

Zhu, X. K. and Leis, B. N. (2005). “Plastic Collapse Assessment Method for Unequal Wall Transition Joints in Transmission Pipelines.” J. PVT, 127(4): 449-456.

Kirkemo, F. (2001). " Burst and Gross Plastic Deformation Limit State Equations for Pipes: Part 1 - Theory." Proc. 11th International Offshore and Polar Engineering Conference, ISOPE-I-01-136.

Table 4-1 Element sensitivity on limit load and hoop stress at weld root for back-bevel (B-B) and counterbore-taper (C-T) wall thickness transitions

Element Type	**Limit Load**		**Average Hoop Stress at Weld Root**	
	B-B	**C-T**	**B-B**	**C-T**
S4R	1.06×SMYS	1.06×SMYS	591 MPa	564 MPa
C3D8I*	0.99	0.99	1.00	1.05
C3D8RH*	0.99	0.99	1.00	1.00
C3D20R*	0.99	0.99	1.00	1.00

* - normalized with respect to the S4R magnitude

Table 4-2 Effects of joint design parameters on limit load for pressure containment

t_1 (mm)	**t_2 (mm)**	**t_2/t_1**	**D/t_2**	**Grade 2**	**Unit Strength 2 / Unit Strength 1**
12.7	15.9	1.25	58	415, 485	1.07, 1.25
12.7	17.5	1.38	52	415, 485	1.18, 1.38
12.7	19.1	1.5	48	415	1.29
12.7	20.6	1.62	44	415	1.39
12.7	22.2	1.75	41	415	1.50
12.7	23.8	1.87	38	415	1.60
15.9	19.1	1.2	48	415, 485	1.03, 1.20
15.9	20.6	1.3	44	415, 485	1.11,1.30
15.9	22.2	1.4	41	415	1.19
15.9	23.8	1.5	38	415	1.28
15.9	25.4	1.6	36	415	1.37

Table 4-3 Stress concentration factors

Solution	FEA S4R	FEA C3D8I	FEA C3D8RH	FEA C3D20R	Equation (4.6)
SCF	2.60	1.13	1.04	1.31	1.05

Table 4-4 Stress concentration factors back-bevel (B-B) and counterbore-taper (C-T) wall thickness transitions

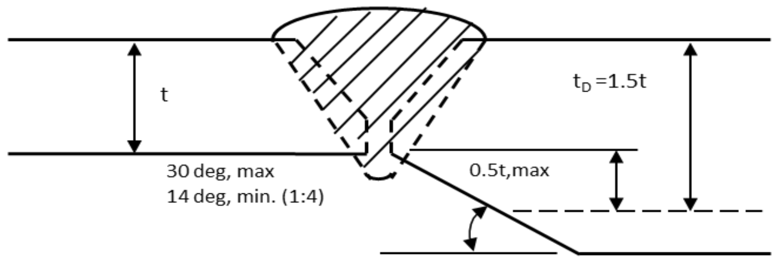
Reference	**SCF at Weld Root**		**Average Axial Stress At Weld Root (MPa)**	
	B-B	**C-T**	**B-B**	**C-T**
Martens et al. (2014)	3.10	1.95	N/A	N/A
This study	1.12	0.91	2.34	1.92

Table 4-5 Sensitivity study on continuum solid elements for cantilever pipe simulation

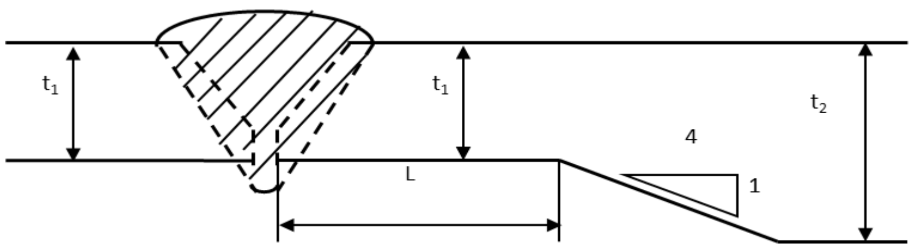
Normalized Root Stress			
Element	**Mesh Topology (through thickness×circumference)**		
	2×20	**4×40**	**5×40**
C3D8I	1.04	1.05	1.05
C3D8RH	1.39	1.12	1.09
C3D20R	1.05	1.05	1.05

Table 4-6 Sensitivity study on continuum solid elements for cantilever pipe simulation

Normalized Tip Deflection			
Element	**Mesh Topology (through thickness×circumference)**		
	2×20	**4×40**	**5×40**
C3D8I	0.82	0.98	1.01
C3D8RH	0.68	0.85	0.89
C3D20R	0.85	0.97	1.00

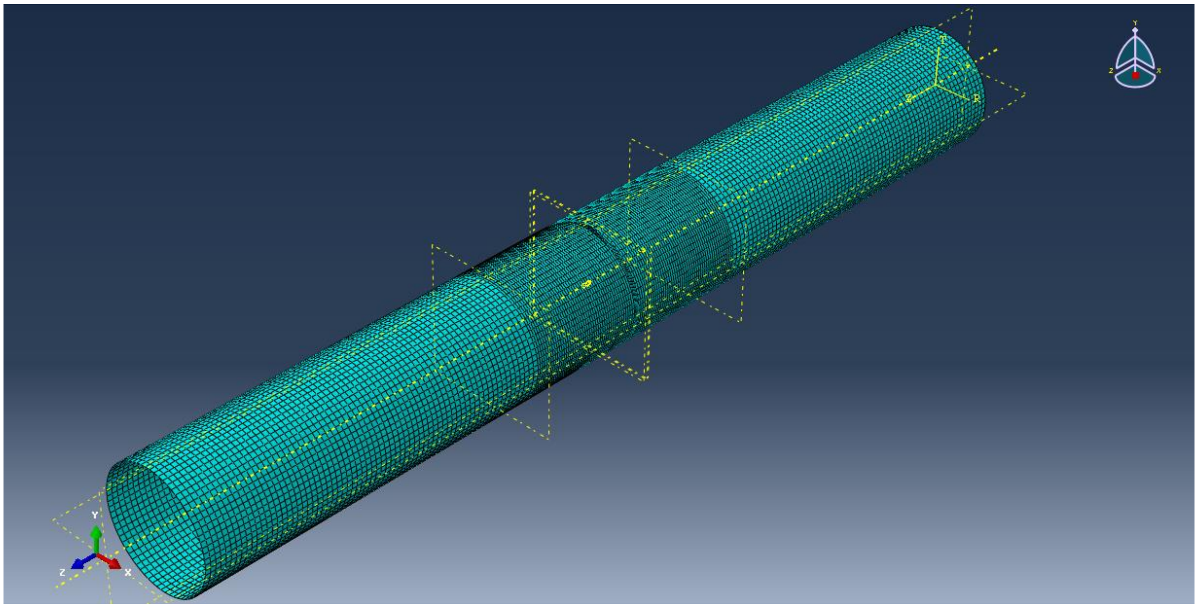


(a)



(b)

Figure 4-1 Configurations of unequal wall thickness transitions (a) Back-bevel joint (b) Counterbore-taper joint



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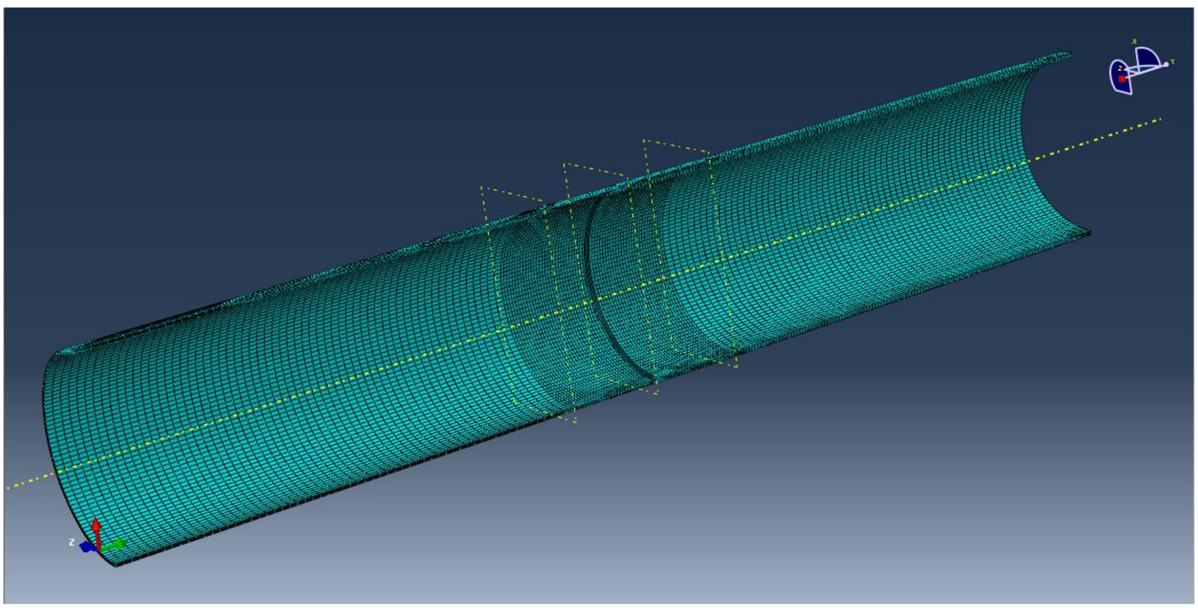
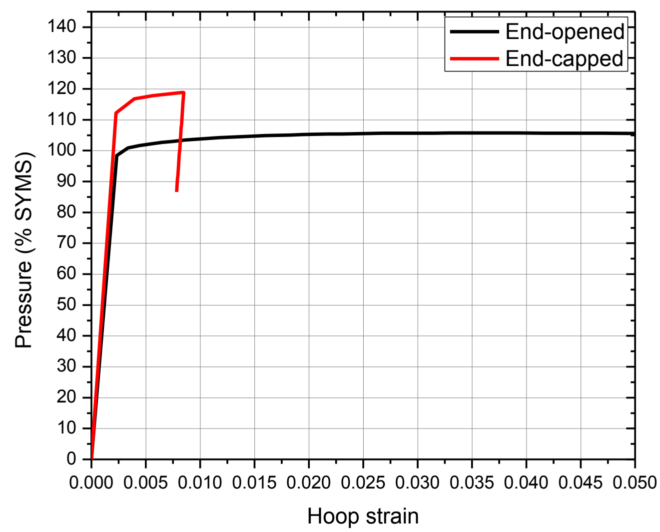
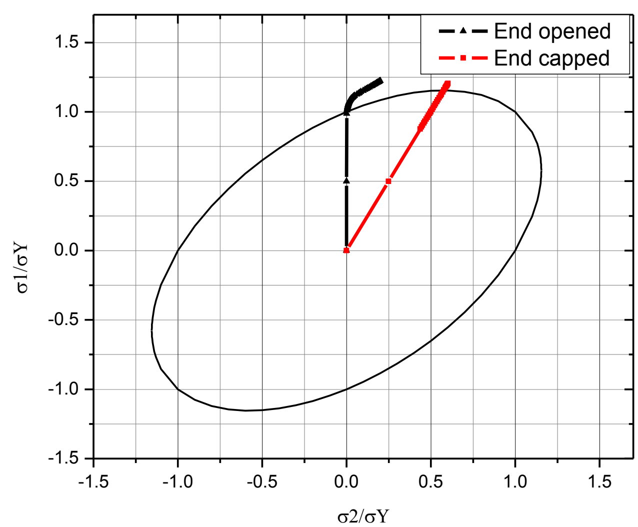


(b)

Figure 4-2 Representative finite element models for the limit load burst pressure analysis using (a) shell and (b) continuum solid elements

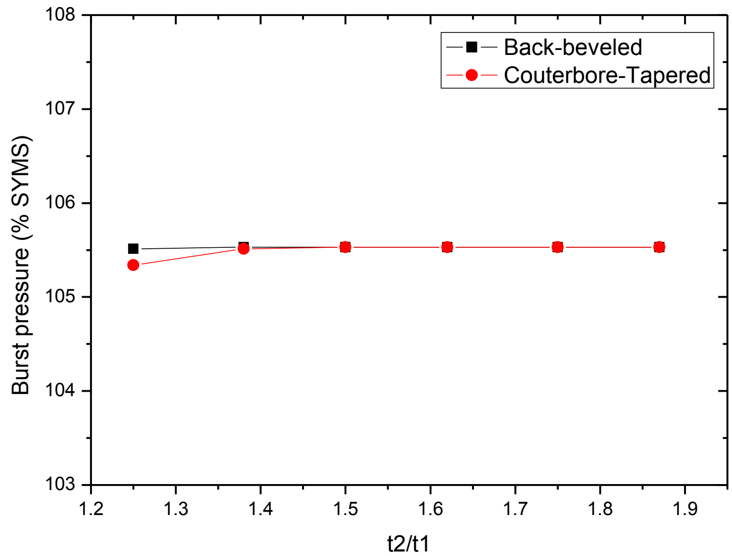


(a)

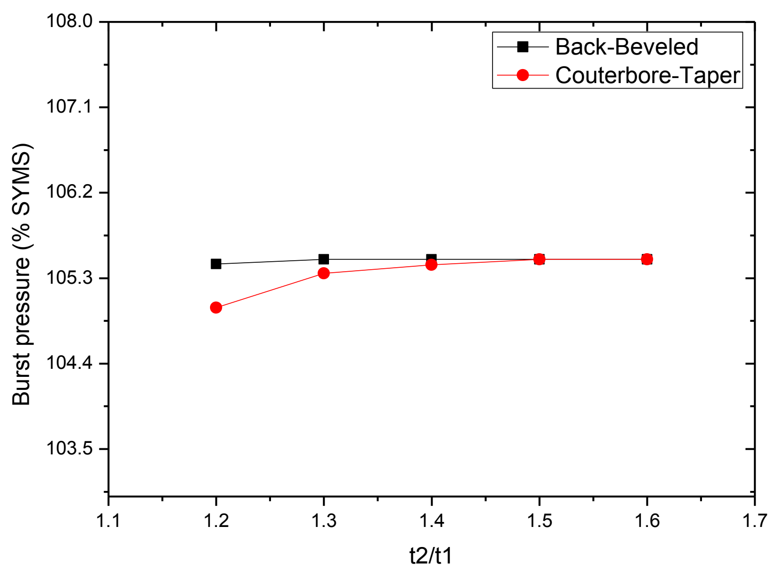


(b)

Figure 4-3 Finite element prediction of limit load for (a) mechanical response for hoop strain-pressure relationship and (b) von Mises stress path during loading



(a)



(b)

Figure 4-4 Finite element prediction of limit load for D/t_1 of (a) 72 and (b) 58

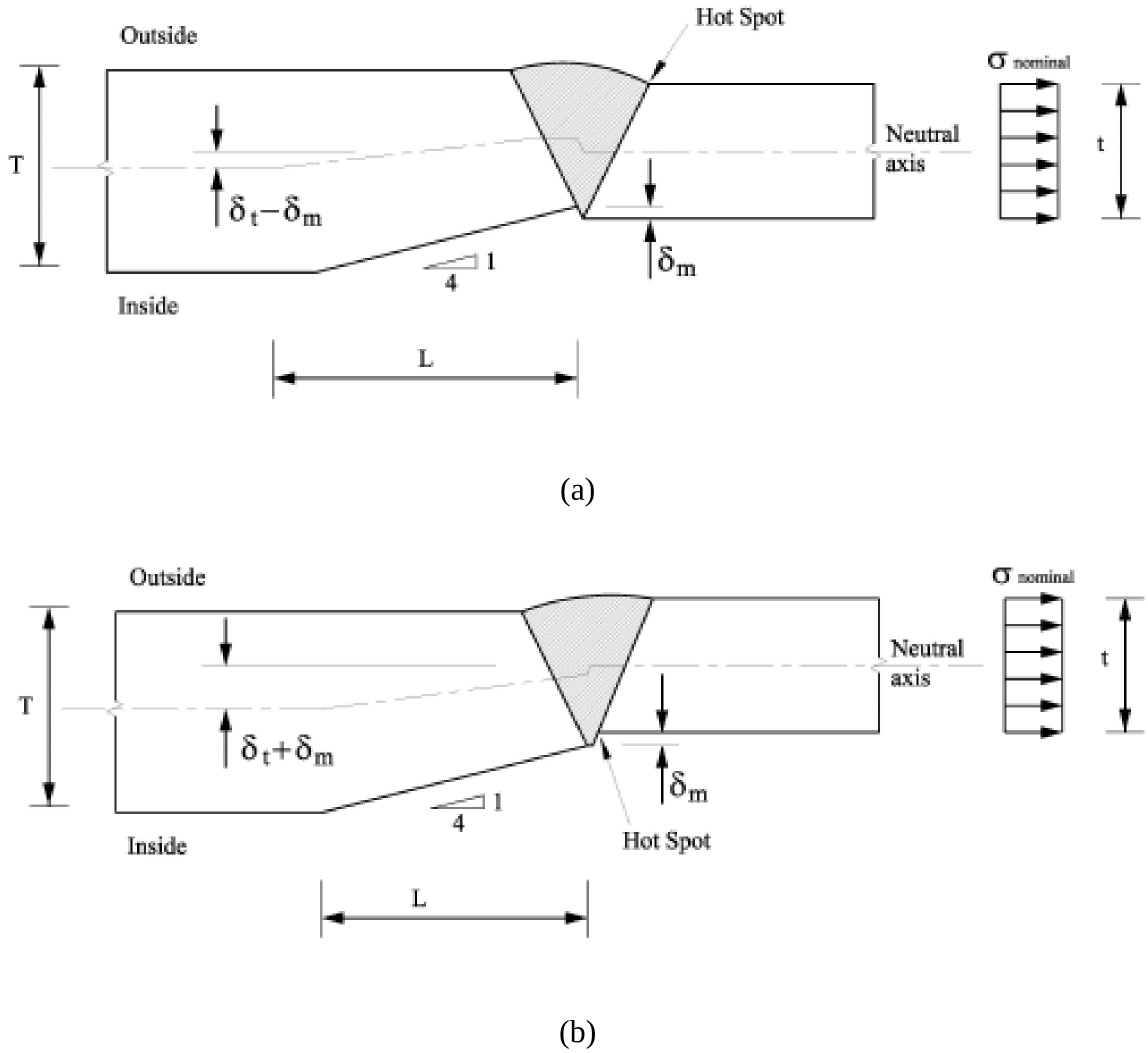
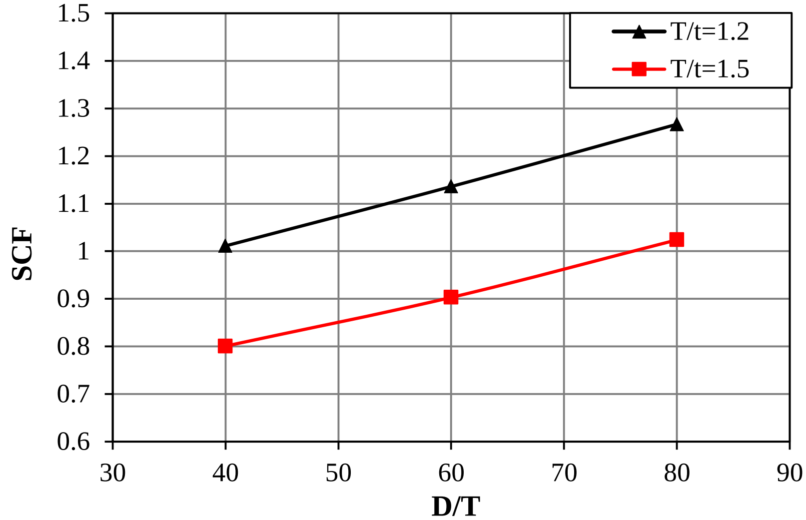
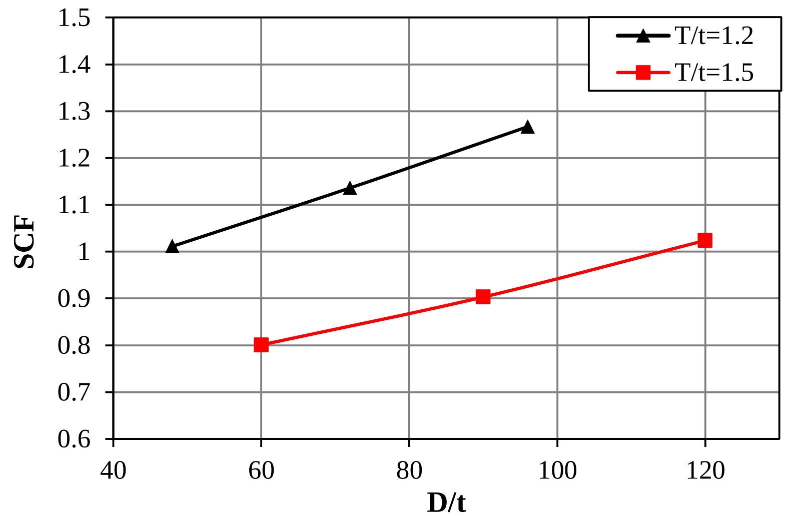


Figure 4-5 Pipe geometry and fabrication tolerances for unequal wall thickness transitions

(a) radial inward and (b) radial outward (Hi-Lo) offset misalignment (DNV RP-C203)

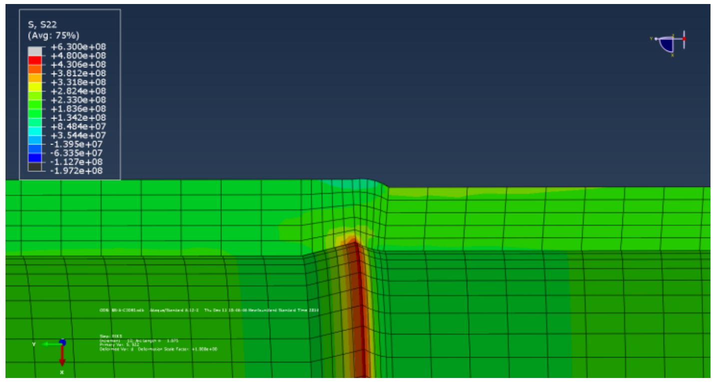


(a)

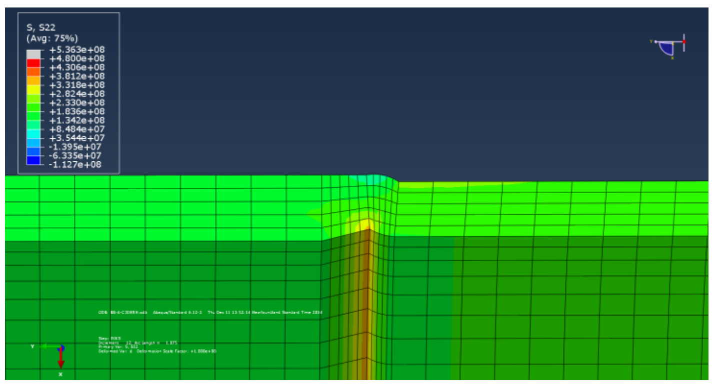


(b)

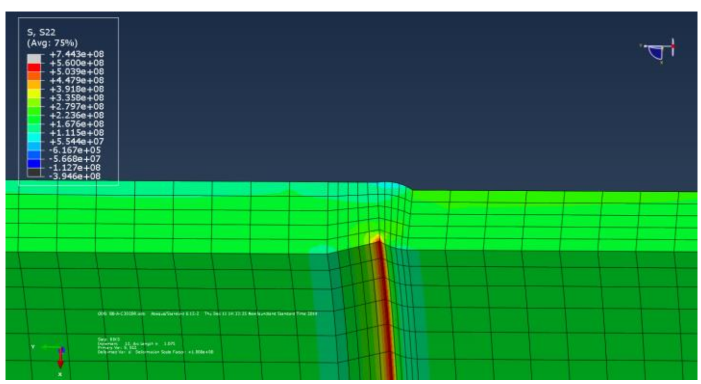
Figure 4-6 Stress concentration factor calculated by equation (4.6) with the variation of (a) D/T (b) D/t



(a)

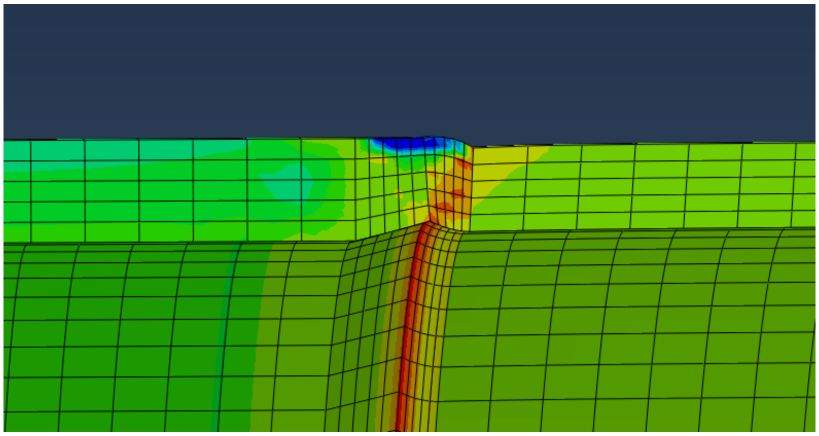


(b)

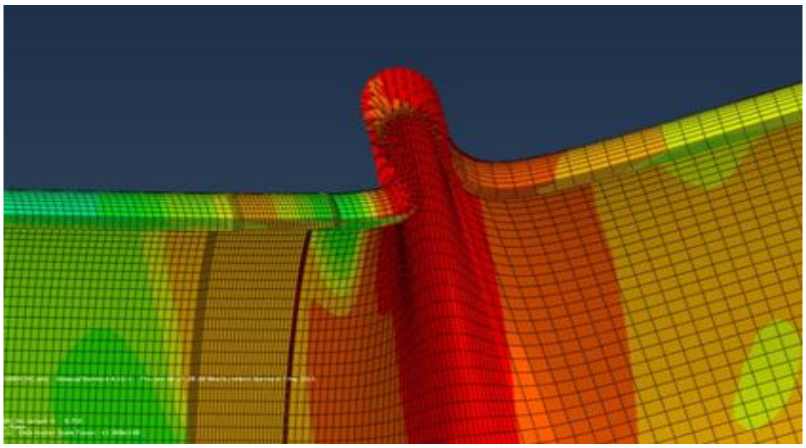


(c)

Figure 4-7 Stress concentrations at the hot spot of the weld root for back-bevel unequal wall thickness transition using (a) C3D8I, (b) C3D8RH and (c) C3D20R elements

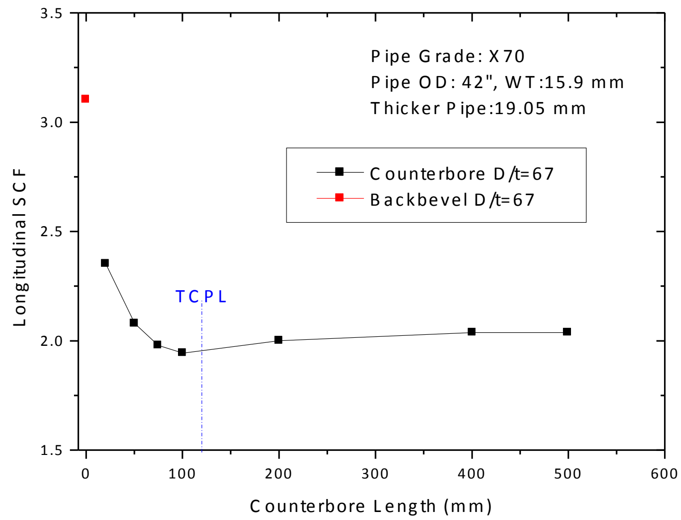


(a)

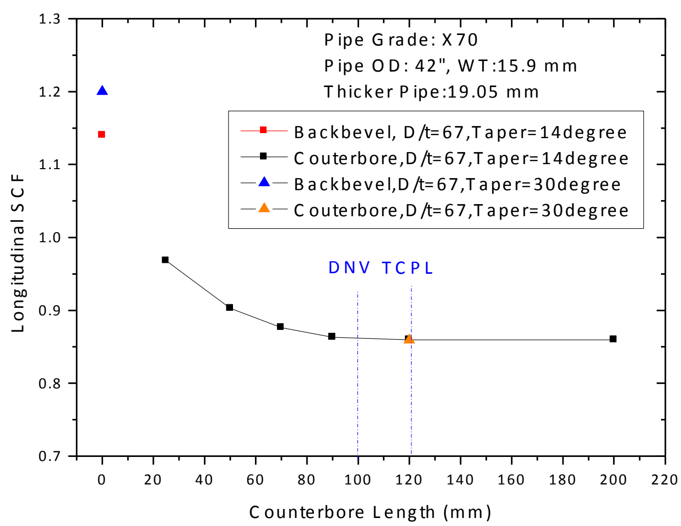


(b)

Figure 4-8 Representative numerical issues from sensitivity study (a) shear locking response of C3D20R and (b) C3D8RH element FE model for combined internal pressure and axial load condition

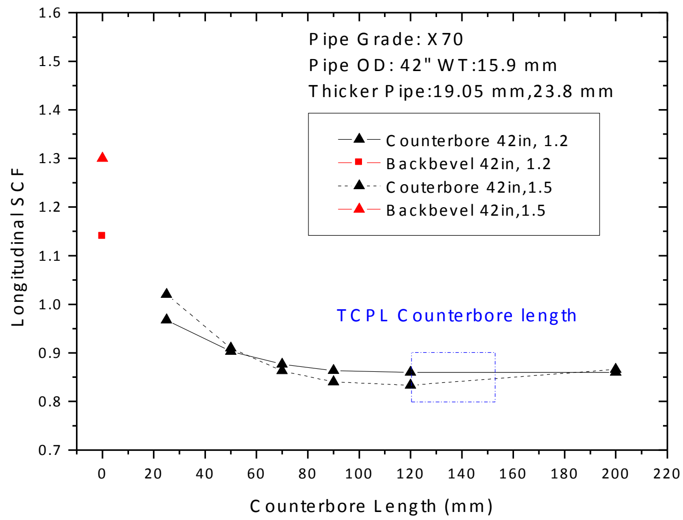


(a)

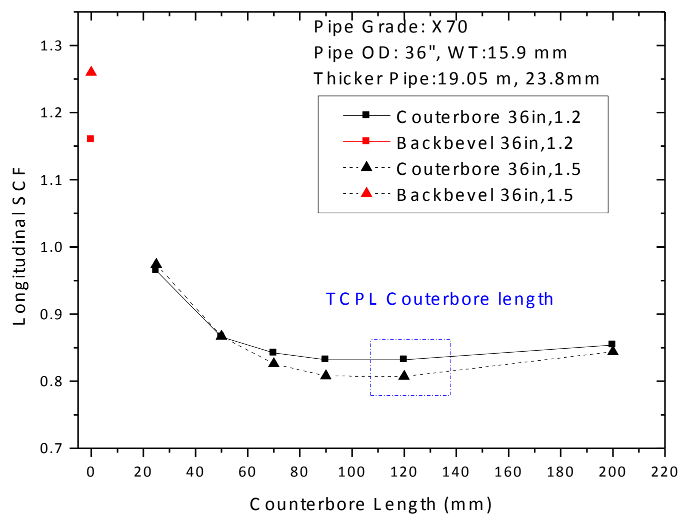


(b)

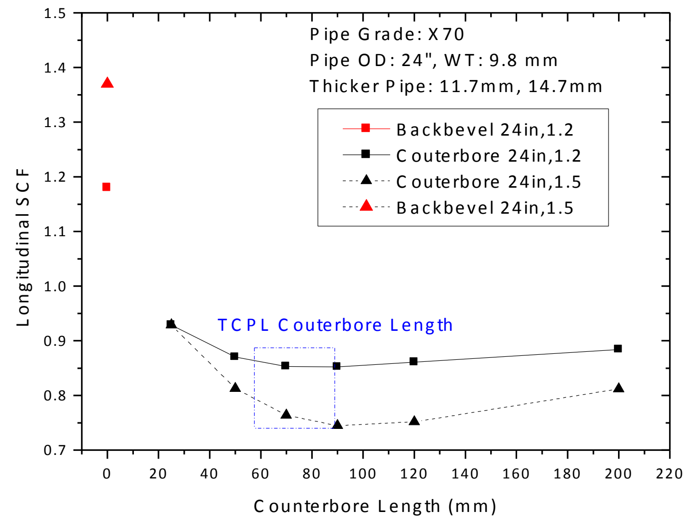
Figure 4-9 SCF factors for (a) NPS 42 from Martens et al. (2014) (b) NPS 42 with the effect of taper angle


Pipe Grade: X70
Pipe OD: 42" WT:15.9 mm
Thicker Pipe:19.05 mm,23.8 mm
Counterbore 42in, 1.2
Backbevel 42in, 1.2
Couterbore 42in,1.5
Backbevel 42in,1.5
TCPL Counterbore length
Longitudinal SCF
Counterbore Length (mm)

(a)

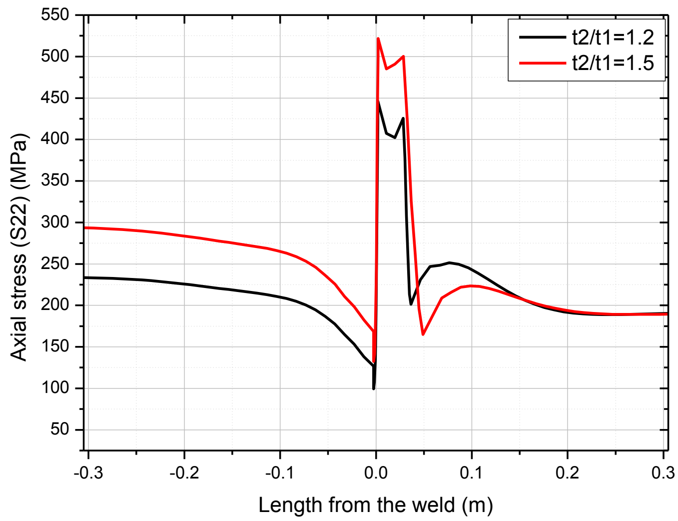

Pipe Grade: X70
Pipe OD: 36", WT:15.9 mm
Thicker Pipe:19.05 m, 23.8mm
Couterbore 36in,1.2
Backbevel 36in,1.2
Couterbore 36in,1.5
Backbevel 36in,1.5
TCPL Couterbore length
Longitudinal SCF
Counterbore Length (mm)

(b)

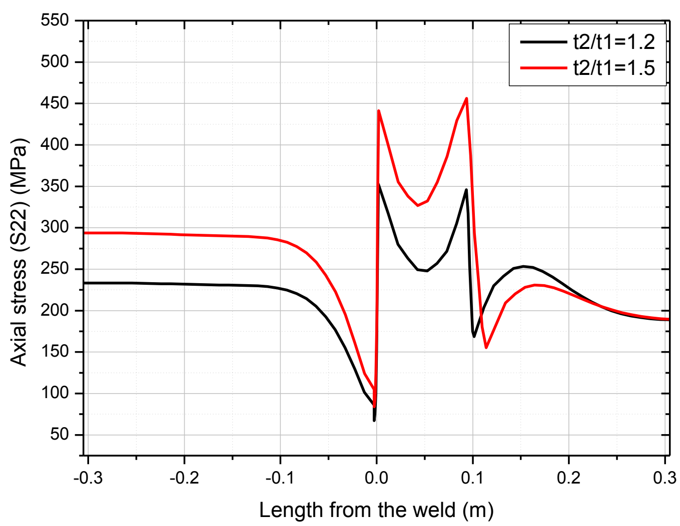


(c)

Figure 4-10 SCF factors for the nominal (a) 1067 mm, (b) 914 and (c) 609 mm diameter pipelines with back-bevel and counterbore-taper wall thickness transition joints


550
500
450
400
350
300
250
200
150
100
50
-0.3
-0.2
-0.1
0.0
0.1
0.2
0.3
Axial stress (S22) (MPa)
Length from the weld (m)
t2/t1=1.2
t2/t1=1.5

(a)


550
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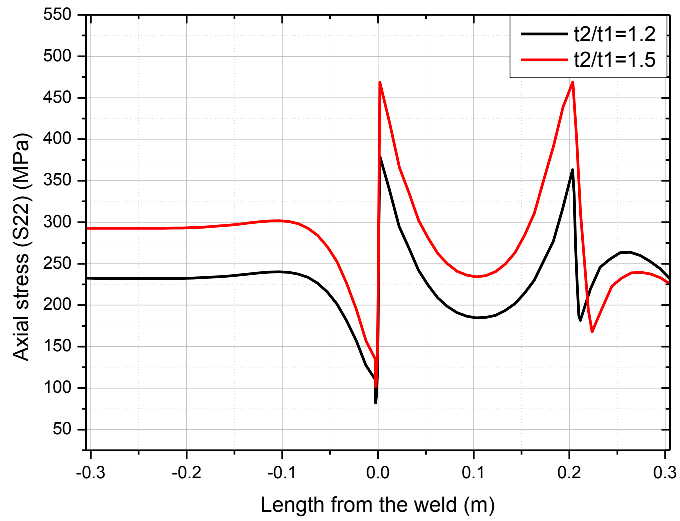
-0.2
-0.1
0.0
0.1
0.2
0.3
Axial stress (S22) (MPa)
Length from the weld (m)
t2/t1=1.2
t2/t1=1.5

(b)



(c)

Figure 4-11 Axial stress distribution across weld and taper transition for NPS 609 mm pipe with counterbore-tapered joint (a) 25 mm counterbore length (b) 90 mm counterbore length (c) 200 mm counterbore length

5 CONCLUSIONS AND RECOMMENDATIONS

Unequal wall thickness transition joints are used to connect the mainline pipe with thicker walled transition segments such as cold bends and elbow fittings. The transition joint may be subject to axial forces and bending moments that may result in a stress concentration across the transition weld and may exceed stress based design criteria. Current engineering practices, such as CSA Z662, ASME B31.4, and ASME B31.8, recommend the use of back-bevel transition welded connections. An alternative transition weld configuration is the counterbore-taper design that is intended to reduce the stress concentration across the transition.

A numerical modelling study, using finite element methods, was conducted to assess the mechanical performance of unequal wall transitions using back-bevel and counterbore-taper joint designs. The relative mechanical performance of these two design options was examined with respect to the limiting burst pressure and effect of stress concentrations due to applied loads.

The study investigated the importance of element selection, including the conventional shell (S4R) and solid continuum (C3D8I, C3D8RH, C3D20R) elements. The continuum brick element (C3D8RI) was the most effective in terms of computational requirements and predictive qualities.

The burst pressure limits of the transition weld designs were evaluated through a parameter study examining the significance of pipe diameter to wall thickness ratio (D/t), wall thickness mismatch ratio (t_2/t_1), material Grade 415 and Grade 485 and end-cap boundary condition effects. The limit load analysis indicated the burst pressure was effectively the same for both transition weld designs.

In terms of the longitudinal stress concentration factor (SCF), the counterbore-taper wall thickness transition can significantly reduce the stress concentration effect within the weld region in comparison with the back-bevel joint. The finite element analysis confirmed current industry practice for the selection of the minimum transition length, and was found to be dependent on the pipe diameter and wall thickness mismatch.

Further numerical modelling investigations should extend the study over a broader range of design parameters including pipe geometry (i.e., diameter, wall thickness mismatch), operational (i.e., internal pressure, differential temperature) and loading (i.e., tensile and compressive axial load, bending moment) conditions, welding procedures (i.e., Hi-Lo offset, diameter and section ovality mismatch) and fabrication processes (i.e., residual stress in cold bend or fitting). From his extended sensitivity analysis, graphical and mathematical relationships defining the stress concentration factor and counterbore length requirements, over a broader range of parameters, can be established. Furthermore, experimental efforts are suggested are required to provide physical data for the calibration and verification of the simulation tool. On this basis a rigorous numerical parameter study can be conducted to establish engineering design guidelines on the mechanical performance of transition joints.

6 REFERNCES

ASME B31.8 (2010). Gas Transmission and Distribution Piping Systems. The American Society of Mechanical Engineers.

ABAQUS (2012). Abaqus Standard User's Manual (Version 6.12).

Al-Showaiter, A., Taheri, F. and Kenny, S. (2011). “Effect of misalignment and weld induced residual stresses on the local buckling response of pipelines.” J. PVT 133(4), 7p..

Baek, J.H., Kim, Y.P. and Kim, W.S. (2012). “Effect of taper angle on plastic collapse of pipe joint with different wall thickness and strength.” Proc., IPC-90129:9p.

CSA Z662 (2010). Oil and Gas Pipeline Systems, Canadian Standards Association.

Corona, E., Lee, L.H., and Kyriakides, S. (2006) “Yield anisotropic effects of buckling of circular tubes under bending.” J. Solids and Structures, 43:7099-7118.

DNV-RP-C203 (2010). Fatigue Design of Offshore Steel Structures, Det Norske Veritas, 178p.

Fatemi, A. and Kenny, S. (2012). “Characterization of initial geometric imperfections for pipelines and influence on compressive strain capacity.” Proc., ISOPE-12-TPC-0304, 7p.

Fatemi, A., Kenny, S., Sen, M., Zhou, J., Taheri, F. and Paulin, M. (2008). “Investigations on the local buckling response of high strength linepipe.” Proc., IPC2008-64407, 9p.

Fatemi, A., Kenny, S., Sen, M., Zhou, J., Taheri, F. and Paulin, M. (2009). “Influence of material and geometric imperfections on the local buckling response of plain and girth weld high strength linepipe.” Proc., 5th International Pipeline Technology Conference, PIPE-56, 22p.

George, H. H. and Rodabaugh, E. C. (1959). “Test of Pups Support Bridging Effect.”, Pipe Line Industry, OCT., pp. 218-233.

Hauch, S. and Bai, Y. (1999). “Bending moment capacity of pipes.” Proc., OMAE, 122(4): 243-252.

Huo, X., Kenny, S. and Martens, M., (2014). “Mechanical Integrity Evaluation of Unequal Wall Thickness Transition Joints in Transmission Pipeline.” Proc., IPC-33141:9p.

Kenny, S. (2011). “Effect of misalignment and weld induced residual stresses on the local buckling response of pipelines.” Journal of Pressure Vessel Technology, 133(4): 7.

Kirkemo, F. (2001). " Burst and Gross Plastic Deformation Limit State Equations for Pipes: Part 1 - Theory." Proc. 11th International Offshore and Polar Engineering Conference, ISOPE-I-01-136.

Kyriakides, S. and Corona, E. (2007). Mechanics of Offshore Pipelines: Vol. I Buckling and Collapse. Elsevier, 401p.

Law, M., Tuft, P. and Venton, P. (2010). “Thickness Limit for Welded Joints between Pipes of Different Yield Strengths.” J. Pipeline Eng., 9(2):99-105.

Liu, P. F., Zheng, J. Y. and Ma, L. (2008). “Calculations of plastic collapse load of pressure vessel using FEA.” J. Zhejiang University Science, 9(7):900-906.

Lotsberg, I. (1998). “Stress concentration factors at circumferential welds in tubulars.” J. Mar Struct., 11(6): 207-230.

Lotsberg, I. (2007). “Stress concentration factors at welds in pipelines and tanks subjected to internal pressure and axial force.” Marine Structure, 21:138-159.

Martens, M., Chen, Y., and Liu, M., (2014). “Comparative Integrity Evaluation of Counterbore-Tapered and Back-beveled Weld Joints.” Proc., IPC-33202:9p.

Mohareb, M.. Deformational Behaviour of Line Pipe. Ph.D. Thesis, University of Alberta, 220p.

Pike, K. and Kenny, S. (2012). “Lateral-axial pipe/soil interaction events: numerical modelling trends and technical issues.” Proc., IPC-90055:10p.

Pike, K. and Kenny, S. (2012). “Numerical pipe/soil interaction modelling: sensitivity study and extension to ice gouging .” Proc., OTC-23731-MS:10p.

Pike, K., Kenny, S., Kavanagh, K., and Jukes, P. (2012). “Pipeline engineering solutions for harsh arctic environments: technology challenges and constraints for advanced numerical simulations.” Proc., OTC-23734-MS:10p.

Robertson, A., Li, H. and Mackenzie, D. (2005). “Plastic collapse of pipe bends under combined internal pressure and in-plane bending.” J. PVP, 82:407-416.

Zhu, X. K. and Leis, B. N., 2005, "Plastic Collapse Assessment Method for Unequal Wall Transition Joints in Transmission Pipelines", J. PVT, 127(4): 449-456.