FINITE ELEMENT MODELING OF LOCALLY THINNED SHORT RADIUS PIPE BENDS

Usama Abdelsalam, Ph.D., P.Eng.[1] & Dk Vijay, Ph.D., P.Eng.[2]
[1] Technical Expert [2] Section Manager
Component Integrity, Operations Engineering, AMEC NSS Ltd.
Toronto, Ontario, CANADA
usama.abdelsalam@amec.com

ABSTRACT
This paper addresses the finite element modelling, analysis, and qualification of Carbon Steel pipe bends with Local Tinned Areas (LTA) under internal pressure and dead weight loading. Detailed 3D solid finite element models are constructed to represent short radius pipe bends typically used in feeder piping of the Primary Heat Transport (PHT) system in CANDU nuclear reactors. Two in-plane end-to-end bends are considered with the local thinned area located close to the middle of the second bend. Measured thickness data is used to construct idealized axial and circumferential thickness profiles ensuring a lower bound on the wall thickness over the entire bends region. Linear elastic finite element analysis is performed using the general purpose finite element program ANSYS. The pipe bends are assessed following the ASME Code SEC III NB-3221 approach and Section XI Code Case N-597-2. The results presented illustrate the effectiveness of the detailed finite element analysis in qualifying wall thickness significantly below the pressure-based thickness in locally thinned pipe bends.

Introduction
In a typical CANDU reactor, 380 or 480 Fuel Channels (FC) are arranged horizontally in a lattice inside the Calandria Vessel. The nuclear fuel bundles are placed inside the Fuel Channels. The heavy water flowing inside the Fuel Channels transports the heat energy generated from the nuclear reaction to the steam generators. The flow of the heavy water coolant through the Fuel Channels is provided by Primary Heat Transport (PHT) pumps and carried through pipes running from the inlet headers and removed through pipes connecting to the outlet header. Each Fuel Channel is connected to two pipes called inlet and outlet feeders. Feeders are made of Low Carbon Steel SA-106 Gr. B pipes with tight radius bends/elbows welded to the Grayloc hub that is assembled to the end-fittings at the ends of the Fuel Channels with a bolted connection. The pipe sizes used for feeders in a typical CANDU reactor are in the 2-3.5” outer diameter range with thickness in the 0.218-0.3” range. Figure 1 shows a typical CANDU reactor face with inlet (blue) and outlet (red) feeders connecting the Fuel Channels to inlet and outlet headers.

Feeders as part of the Primary Heat Transport system (PHT) are classified as Class 1 piping components. Therefore, feeders were designed according to ASME B&PV Code Section III Division 1 Subsection NB-3600 (Piping Design). It is observed that the outlet feeders encounter considerable wall thinning due to the flow accelerated corrosion (FAC) phenomenon. The wall thinning is more pronounced at the tight radius elbow/bend regions close to the Grayloc hub. The reduced wall thickness leads to higher stresses that need to be assessed to demonstrate feeders' fitness for continued service under specified loads. This paper focuses on the pressure and dead weight loads only.

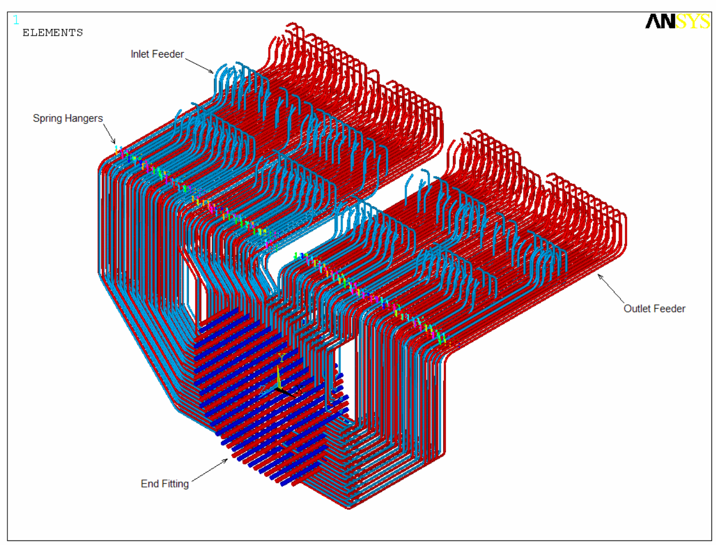

Figure 1: CANDU Reactor Face

The pressure requirement in the ASME SEC III protects against the catastrophic collapse of the designed components due to a single application of the primary load. The basic criterion for internal pressure loading under the ASME Code SEC III NB-3600 “Piping Design” rules is given in NB-3640 “Pressure Design“. This criterion is applicable for straight pipe segments as described in NB-3641.1. For curved segments of pipe, NB-3642 provides guidance relating to pipe bends in NB-3642.1 where the minimum wall thickness, t_{min}, required for a design pressure is determined using a simple formula. For curved segments of pipe, NB-3642.1 “Pipe Bends” adopts the same equation for determining the wall thickness for the straight segments of pipe with three limitations. Of special relevance to this paper, the second limitation, expressed in the form of Table NB-3642.1(b)-1, guides the designer when ordering a pipe to use a higher than t_{min} thickness for the pipe prior to bending. For instance, for a 3inch pipe diameter, the recommended minimum thickness prior to bending is $1.25t_{min}$. When a straight pipe is bent, the extrados thins out and the intrados thickens. As such, the thickness on the intrados will be even higher than $1.25t_{min}$ after the bending operation. In other words, the code acknowledges that a pipe bend with uniform thickness having the pressure based thickness of NB-3640.1 equation is not acceptable.

Under NB-3630 “Piping Design And Analysis Criteria” it is stated that “*(c) When a design does not satisfy the requirements of NB-3640 “Pressure Design” and NB-3650 “Analysis of Piping Products”, the more detailed alternative analysis given in NB-3200 or the experimental stress analysis of Appendix II may be used to obtain stress values for comparison with the criteria of NB-3200 “Design By Analysis*”. Considering the design pressure loading, the design by analysis rules of NB-3221 requires that general primary membrane stress intensity, P_m, meet the S_m limit (NB-3221.1), the local membrane stress intensity, P_L, meet the $1.5S_m$ limit (NB-3221.2) and the primary membrane (P_m or P_L) plus primary bending stress intensity, P_b meet the $1.5S_m$ limit (NB-3621.3). Moreover, the ASME Code provides relief from the linear elastic analysis rules of NB-3621 by applying plastic analysis techniques as per NB-3228 as stated under article NB-3621 “Design Loadings”. In summary, there are three options to meet the pressure requirements for a piping component during the design stage; Equation 1 of NB-3640, linear elastic approach in NB-3221, and plastic analysis in NB-3228.

The wall thinning may be general or local depending on the piping geometry and the fluid flow characteristics. For fitness for service assessments, the wall loss needs to be considered. The ASME Code SEC III, being a construction code, does not provide explicit guidance as to how to deal with locally thinned areas (LTA). EPRI [5] provides guidance and acceptance criteria for the evaluation of Carbon Steel piping erosion/corrosion wall thinning. A three-step evaluation process is proposed based on the ASME code design requirements and defines the degree of wall thinning (depth and extent) which can be safely left in service. This guidance is consistent with the ASME Code SEC XI Code Case N-597-2 that provides a criterion to assess the LTA for Class 2 and Class 3 pipes. Osage et al. [6] provided an overview of the latest technology at the time for the assessment of non-crack like flaws including erosion/corrosion, pitting, blisters, shell out-of-roundness, weld misalignment, bulges and dents. With regard to LTAs, they provided a review and evaluation of available methodologies for LTA assessment including effective area methods (ASME B31G), extensions to the effective area method, and thickness averaging approaches. Zhang et al. [7] calculated the plastic collapse load of a single elbow using a finite element analysis model. Only pressure loading is considered and as such, both the geometry and loading are symmetric with respect to the in-plane plane of the elbow. To preserve the model symmetry, only symmetric thinning patches could be modelled. The thinned regions were modeled by removing elements resulting in sharp transitions from the LTA and the surrounding material. The effects of the LTA location, bend radius, and LTA size are investigated. S. Iyer and R. Kumar [8] presented an assessment of LTA in class 1 piping components using the finite element method and following the ASME Code SEC III NB-3221 criteria. Two tight radius bends connected by a straight piece of pipe were considered. S. Iyer [9] re-iterated the methodology and procedure in his previous paper with more focus on the calculation of stress indices considering the local nature of the thinned areas to be used in the piping analysis. On the regulatory side, J. Jin [12] summarized the regulatory view point regarding the fitness for service assessments employing the ASME Code elastic and plastic methodologies emphasizing the opinion of maintaining the same margin of safety.

In this paper, double tight radius bends are considered under pressure and dead weight loading only. It should be noted that the methodology and procedures developed for this study is independent of the geometry or the configuration of the piping system. The analysis presented in this paper focuses on the development of axial and circumferential thickness profiles that idealize the measured thickness over the entire tight radius bends region. The idealized profiles are combined with a variable thinning rate function to develop the predicted thickness profiles corresponding to a target operation period. These idealized profiles are implemented in detailed finite element models to perform the pressure assessment of typical CANDU feeder pipe bends according to the ASME Code SEC III NB-3221 criteria. Out-of-roundness is considered and is represented by an elliptical cross-section at the middle of the bend that gradually tapers down to a circular cross-section at the ends of each bend. The results of the analysis are presented for all locations covering the entire tight radius bends region.

Finite Element Model

In the finite element modelling presented in this paper, the full feeder length is considered. Solid brick elements are used at the tight radius bends region to provide flexibility in introducing wall thinning profiles on the inner surface only. The rest of the piping away from the area of interest is modelled using pipe elements.

Feeder Piping Geometry

Figure 2 illustrates a typical CANDU feeder model with a close up view showing the lower portion with the tight radius bends and the Grayloc hub. The tight radius bends and the Grayloc hub are called the feeder extension. The focus of this paper is the tight radius bends where the most significant wall thinning is observed. As such, the feeder extension portion and the attached straight segment of pipe are modelled using ANSYS SOLID95 elements. Three through-thickness layers of ANSYS SOLID95 brick elements were used along with seventy two elements along the circumferential direction. The rest of the feeder up to the header nozzle weld is modelled using pipe elements. The general purpose finite element program, ANSYS is used to setup the numerical models, perform the stress analyses, and post-process the results. The nominal piping cross-section dimensions used to build the geometric models are:

- Outer Diameter, D_o = 2.361 in (60 mm)
- Nominal Thickness, t_n = 0.218 in (5.54 mm)
- Bend Angle, θ = 50^o
- Bend Radius, R = 3 in (76.2 mm)

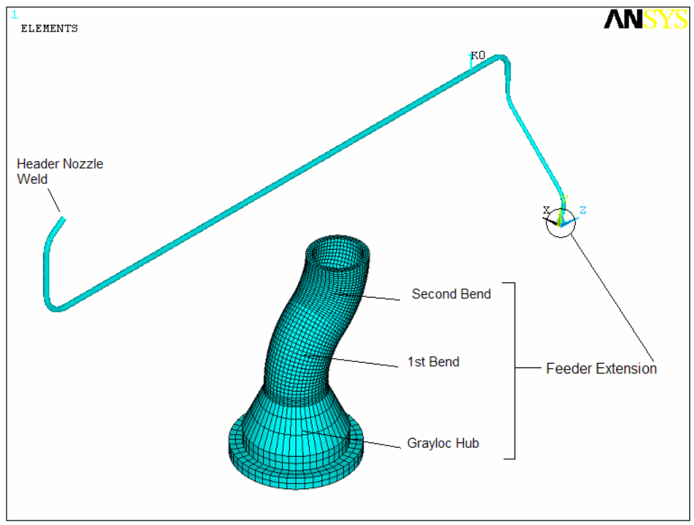

Figure 2: Typical CANDU Feeder Model

Material Model

A linear-elastic isotropic material model, using the properties of ASME material SA-106 Grade B [1], is used for the analysis (at 605 °F).

- Elastic Modulus, E = 26.7×10^6 psi
- Poisson's Ratio, ν = 0.3
- Allowable stress Intensity, S_m = 17.26 Ksi

Pressure Based Thickness

The pressure based allowable thickness for a straight pipe, t_{min}, is calculated in accordance with the ASME Section III, NB-3641.1(1) as follows:

$$t_{\min} = \frac{PD_o}{2(S_m + Py)} + A$$

P is the internal Design Pressure (1455psig), D_o is the outside diameter of the pipe, A is the corrosion allowance, y is equal to 0.4, and S_m is the max allowable stress intensity for the material at the design temperature. Therefore, the pressure-based thickness for a straight pipe segment calculated using the above formula is,

t_{min} = 0.096 in → 2.45 mm

In the central area of a pipe bend, Osage et al [6] presented a criterion for the allowable thickness that is developed using the required thickness of a toroidal vessel compared to a straight pipe. This criterion is illustrated graphically in Figure 3 for 2" and 2.5" pipe bends where,

t_{aloc} is the allowable local wall thickness

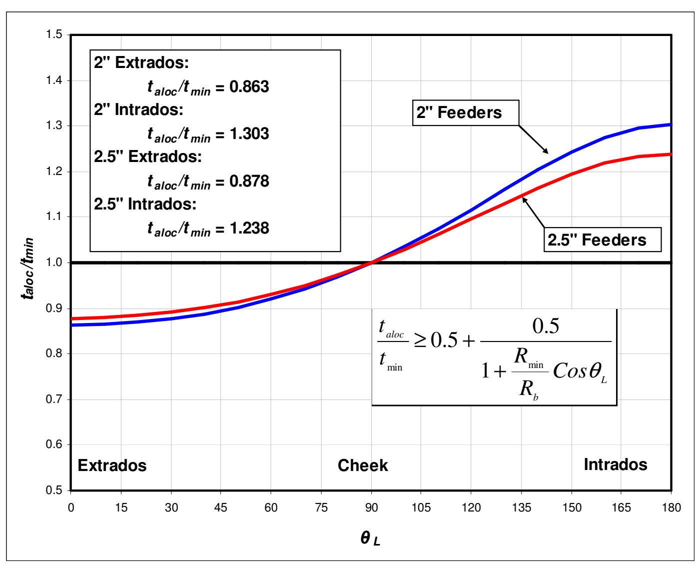

Figure 3: Allowable Thickness in Pipe Bends.

R_{min} is the mean radius of the piping item based on t_{min}.
R_b is the bend radius of curvature
θ_L is the circumferential angle.

This criterion is adopted by SEC XI Code Case N-597-2 [3 & 4].

For the 2" feeder considered in this paper with a thin spot centered at the intrados, the allowable local minimum thickness is $1.303t_{min}$ = 0.125in = 3.19mm. It is worth noting that for 2.5" feeders, the allowable local minimum thickness at the center of the intrados is $1.238t_{min}$. This is close to the ASME Code recommended wall thickness of $1.25t_{min}$ as per Table NB-3642.1(b)-1.

Axial & Circumferential Thickness Profiles

To closely simulate the pipe bend wall thickness distribution, the actual measured thickness data is used as illustrated in Figure 4 to develop a bounding thickness profile. The thickness measurements are performed using a bracelet tool that has 14 probes equally spaced along the circumference covering a 140^o angle. For the intrados scan, the tool is centered with the intrados of the first bend and moved axially to cover both bends. As such, the second half of the intrados scan represents the extrados scan for the second bend. Similarly, the second half of the extrados scan represents the intrados scan over the second bend. Figure 4 shows the minimum measured thickness plots for the intrados, extrados, left cheek, and right cheek scans of the tight radius bends region along the axial direction of the feeder. The idealization of the measured data is plotted in red and it is bounding along the entire tight radius bend region in the axial direction. It is evident in this figure that the maximum thinning is downstream from the transition between the first and second bends. In the circumferential direction, Figure 5 illustrates the comparison between the idealized profile and the measured thickness data at the cross-section having the minimum local thickness of 2.7mm.

To develop the projected idealized profiles corresponding to a target operation period, a uniform thinning rate is traditionally assumed. However, using a uniform thinning rate could be either conservative or non-conservative considering that not all locations started with the same thickness (extrados started thinner than intrados). For instance, if the thinnest spot is at the intrados, assuming a uniform thinning rate produces a too conservative estimate of the projected thickness on the extrados. To reduce the conservatism, a location dependent thinning rate function is adopted instead.

The location dependent thinning rate is developed realizing that the intrados started thicker than nominal and the extrados started thinner. In this investigation, a 5% thicker than nominal intrados and 5% thinner than nominal extrados are used to approximate the original thickness. As such the thinning rates at the bend middle section extrados and intrados are as follows:

Extrados Thinning Rate = $(0.95t_{nom}-t_{measured})$/EFPY
Intrados Thinning Rate = $(1.05t_{nom}-t_{measured})$/EFPY

Close to the cheeks, both the intrados and extrados have original thickness equal to the nominal thickness. This increase and decrease in the initial wall thickness is consistent with data obtained from thickness measurements of inlet feeders (where in-significant thinning occurs) and spare bends. Figure 6 illustrates the assumed axial distribution of the original thickness and the idealized thinned profile along the second tight radius bend. Figure 7 shows the axial distribution of the calculated thinning profile along the second tight radius bend.

Table 1 summarizes the FEA model statistics (minimum and maximum) of the predicted thickness, original thickness, and thinning rate for the second bend. The maximum thinning rate in the model is 0.173mm/EFPY at the intrados of the second bend. EFPY stands for Effective Full Power Years of continuous operation. The maximum thinning rate at the extrados is 0.11mm/EFPY. Figure 8 shows the locally thinned spot on the inside surface of the intrados of the second tight radius bend.

As recorded in Table 1, the minimum local thickness introduced in the finite element model is 2.37mm which is significantly lower than the allowable thickness of 3.19 mm for the inner portion (intrados) of a pipe bend.

Out of Roundness

Bending of pipes introduces out of roundness to the short radius bends. The out-of-roundness is represented by an elliptical cross section with the major axis connecting the left and right cheeks of the bend. 8% out of roundness is used in constructing the FEA models for this paper. The maximum out of roundness is placed at the center of each bend. The beginning and end of each bend is modeled as a perfect circle.

Boundary Conditions & Loading

The finite element model is fixed in all six degrees of freedom at the two terminal ends; at the Grayloc hub flange and at the header nozzle weld. The location of the rigid hanger support is constrained in the vertical direction. A linear spring is attached at the spring hanger location with the appropriate spring constant.

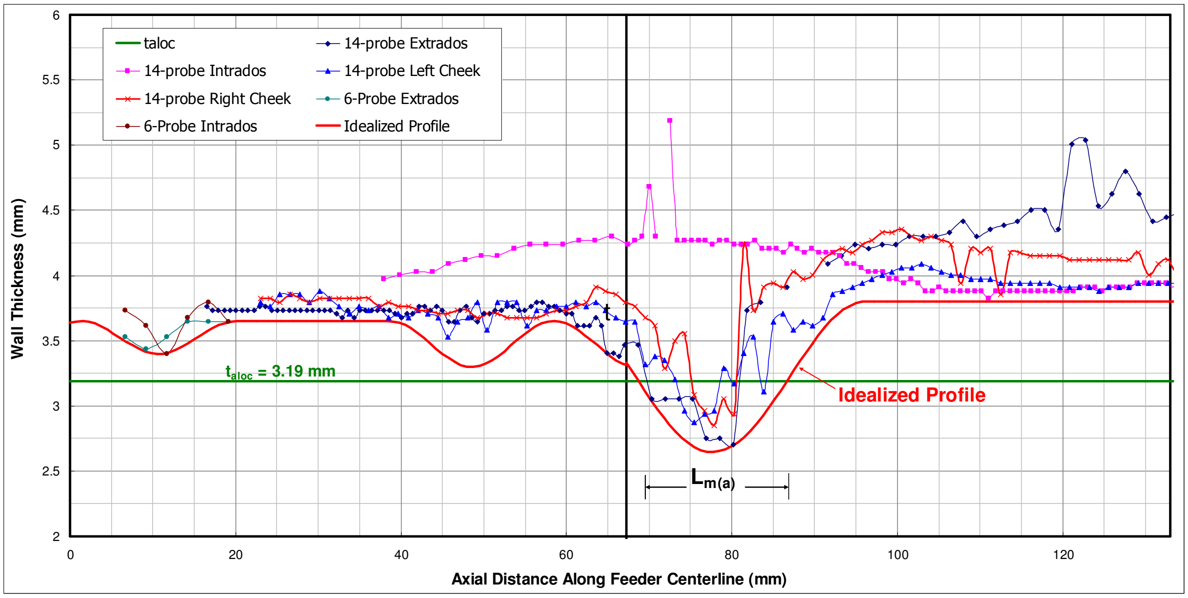

Figure 4: Measured & Idealized Axial Thickness Profiles

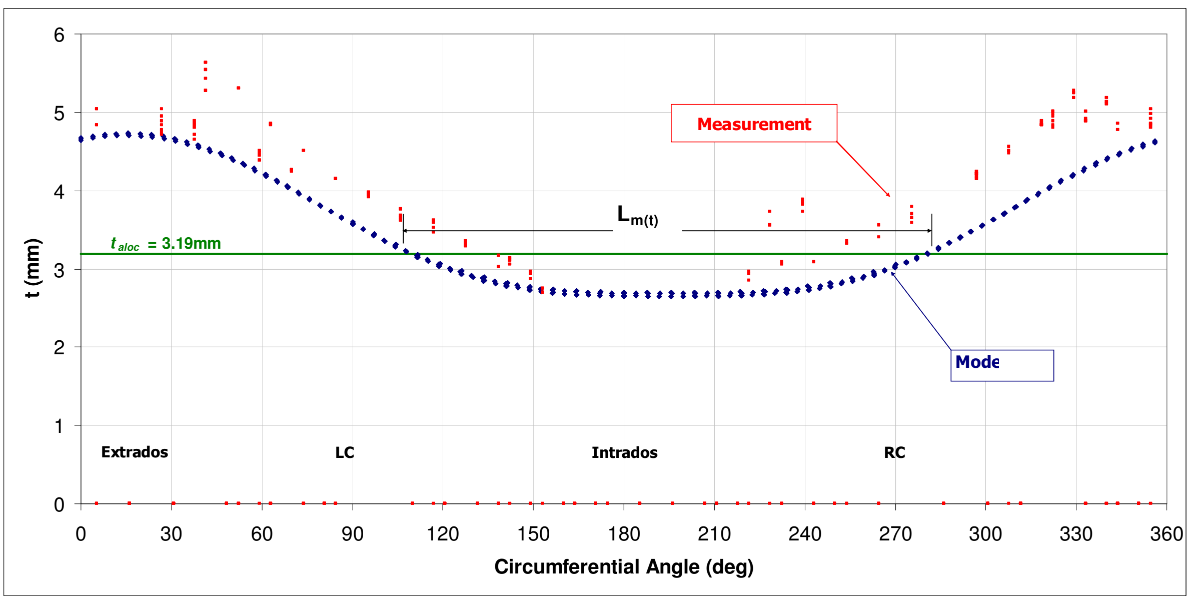

Figure 5: Measured & Idealized Circumferential Thickness Profiles

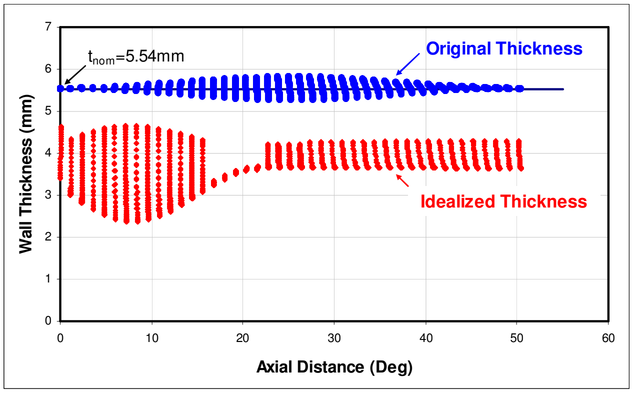

Figure 6: Original & Idealized Thickness Profiles

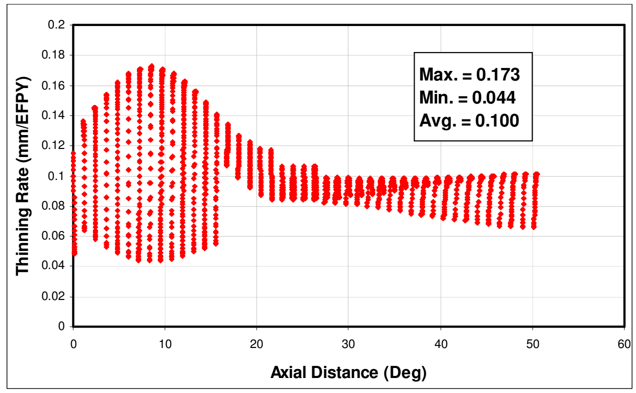

Figure 7: Axial Distribution of Thinning Rate

Table 1: Thickness Profile Statistics along Tight Radius Bends

	t_p (mm)	t_o (mm)	α (mm/EFPY)	t_{nom} (mm)	Straight t_{min} (mm)	Intrados t_{aloc} (mm)	Extrados t_{aloc} (mm)
Min	2.37	5.26	0.044	5.54	2.44	3.19	2.05
Max	4.66	5.81	0.173				

t_p predicted minimum thickness
t_o original thickness used to calculate the thinning rate
α calculated thinning rate
t_{nom} Nominal thickness

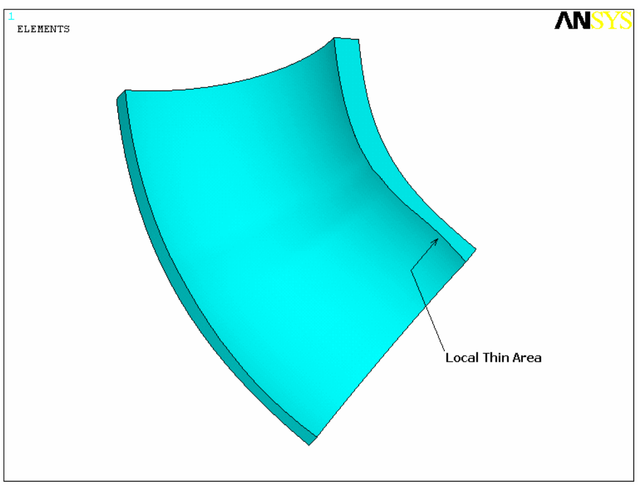

Figure 8: Local Thinning at the Intrados

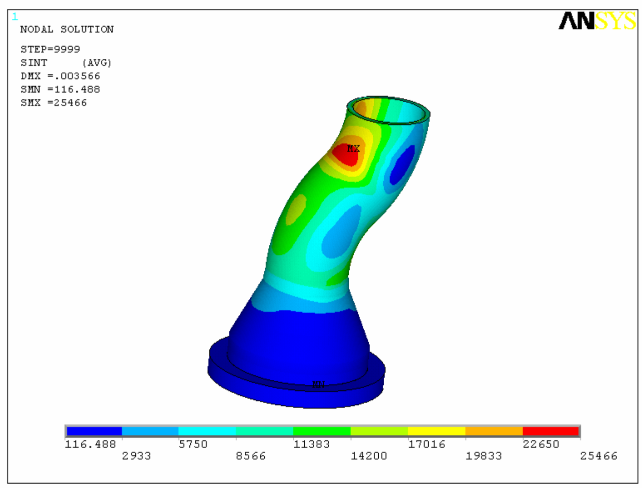

Figure 9: Pressure Loading Stress Intensity Plot

Finite Element Results

The solution for the primary stress intensity (using the full feeder models) is organized as follows:

- Apply the internal design pressure and dead weight of the pipe metal and water as a static load.
- Perform a linear elastic finite element static analysis applying the load in one step. Figure 9 illustrates the stress intensity contour plot for the feeder extension under the applied pressure loading. As shown on the figure, the maximum stress intensity is at the intrados of the second tight radius bend at the local thin spot.
- Linearize the resulting stress solution across the wall thickness to obtain the corresponding membrane, and membrane plus bending stress intensities. The linearization is carried out at every location over the entire tight radius bends region using ANSYS path operations.

- Plot the linearized stress intensity results and check against ASME SEC III NB-3221 criteria. The maximum general membrane stress intensity, P_m, is checked against S_m and the maximum local membrane plus bending, P_L+P_b, stress intensity is checked against $1.5S_m$ over the whole tight radius bend region. In the locally thinned areas, the local membrane stress intensity, P_L, is checked against $1.5S_m$.

The above procedure is followed and the results are presented in Figures 10, 11, 12, and 13 where,

- The horizontal axes represent the axial direction starting from the Grayloc hub weld (top graph) or the circumferential direction starting from the centre of the extrados (two bottom graphs).
- The left vertical axis represents wall thickness or stress intensity.
- Each point on a graph represents the result of stress linearization along a path going from one node on the inner surface to a corresponding node on the outer surface of the two tight radius bends.

Figure 10 shows the distribution of the wall thickness over the entire tight radius bends region at each single through thickness path (Classification LINe) from one node on the inner surface to a corresponding node on the outer surface. The top graph shows the axial distribution illustrating the major thin spot downstream from the transition between the two bends in the axial direction. The second and third graphs on Figure 10 show the thickness distribution on the first and second bends distributed circumferentially, respectively. It is worth noting that the thin spot on the second bend is centered at the intrados and extends over a considerable portion of the circumference.

The compliance with the ASME Code SEC III NB-3221 elastic criteria for pressure loading is illustrated graphically. The primary membrane stress intensity in the general thinned areas (P_m) is compared to S_m represented by a horizontal line. Stress intensity points below the S_m line meet the general membrane stress intensity criterion of ASME SEC III NB-3221.1. The local primary membrane stress intensity (P_L) in the locally thinned areas is compared to $1.5S_m$ represented by a second horizontal line. Stress intensity points below the $1.5S_m$ line meet the local primary membrane stress criterion of ASME SEC III NB-3221.2 as long as the extent of the region with stress intensity higher than $1.1S_m$ is limited by $\sqrt{R_{min} t_{min}}$ in both the axial and circumferential directions (R_{min} is the mean radius and t_{min} is the minimum wall thickness). The primary membrane (P_m or P_L) plus primary bending (P_b) stress intensity everywhere is compared to $1.5S_m$. Stress intensity points below the $1.5S_m$ line meet the ASME SEC III NB-3221.3. Table 2 summarizes the results of the stress linearization as obtained from the analyses including the internal pressure and dead weight.

Figure 11 (a), (b), and (c) show the distribution of the primary membrane stress intensity in both the axial and circumferential directions. The stresses away from the local thin spot are classified as general primary membrane and it is shown that the S_m limit of NB-3221.1 is met. As can be observed from graph (a), the maximum stress intensity is at the second bend. The maximum local primary membrane stress intensity is located at the local thin spot on the intrados of the second tight radius bend. At this location the stress is classified as local primary and it is checked against the 1.5Sm limit of NB-3221.2. Figure 12 and Figure13 show the primary membrane plus primary bending Code check along the inner and outer surfaces of the tight radius bends, respectively.

Table 2: Linearized Stresses along Tight Radius Bends

	P_m (Ksi)	P_L (Ksi)	$(P_m+P_b)_i$ (Ksi)	$(P_m+P_b)_o$ (Ksi)	$(Total)_i$ (Ksi)	$(Total)_o$ (Ksi)
	S_m (17.26)	1.5 S_m (25.89)	$1.5S_m$ (25.89)	$1.5S_m$ (25.89)	N/A	N/A
1st Bend	15.22		23.92	18.40	24.34	18.33
2nd Bend		19.10	24.09	25.62	24.67	25.47

P_m	General Primary Membrane Stress Intensity
P_L	Local Primary Membrane Stress Intensity
P_b	Primary Bending Stress Intensity
S_m	Allowable Stress Intensity
$t_{p,min}$	Predicted Minimum Wall Thickness at 18.75EFPY
$()_i$	Value along inner surface
$()_o$	Value along outer surface

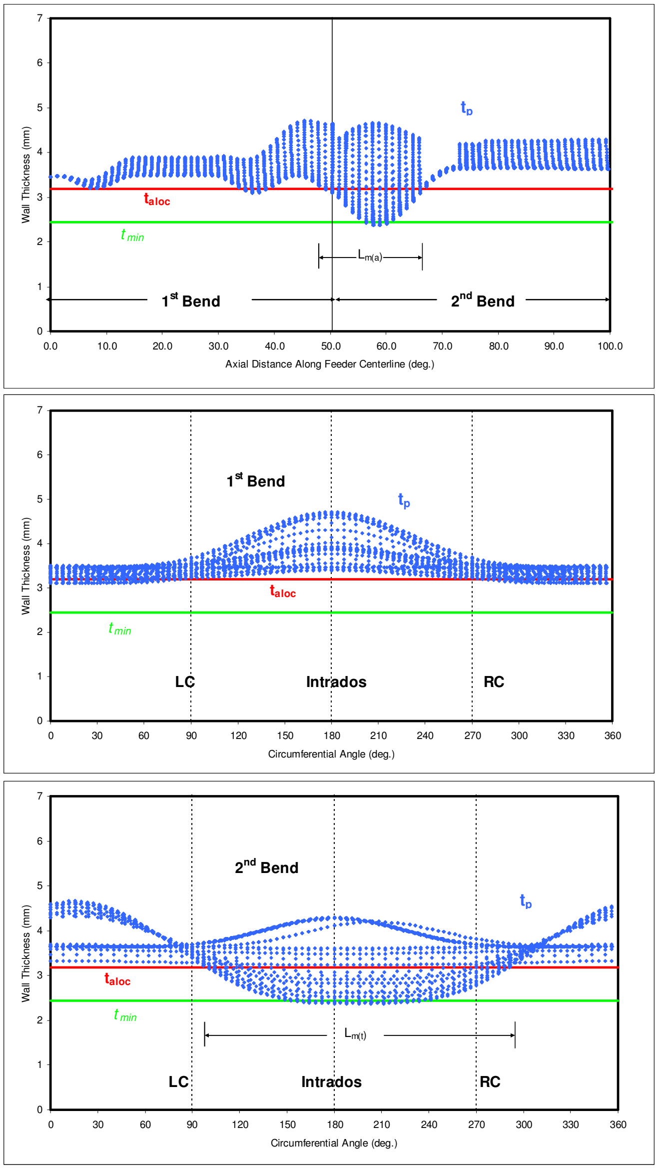

Figure 10: Idealized Thickness Profiles

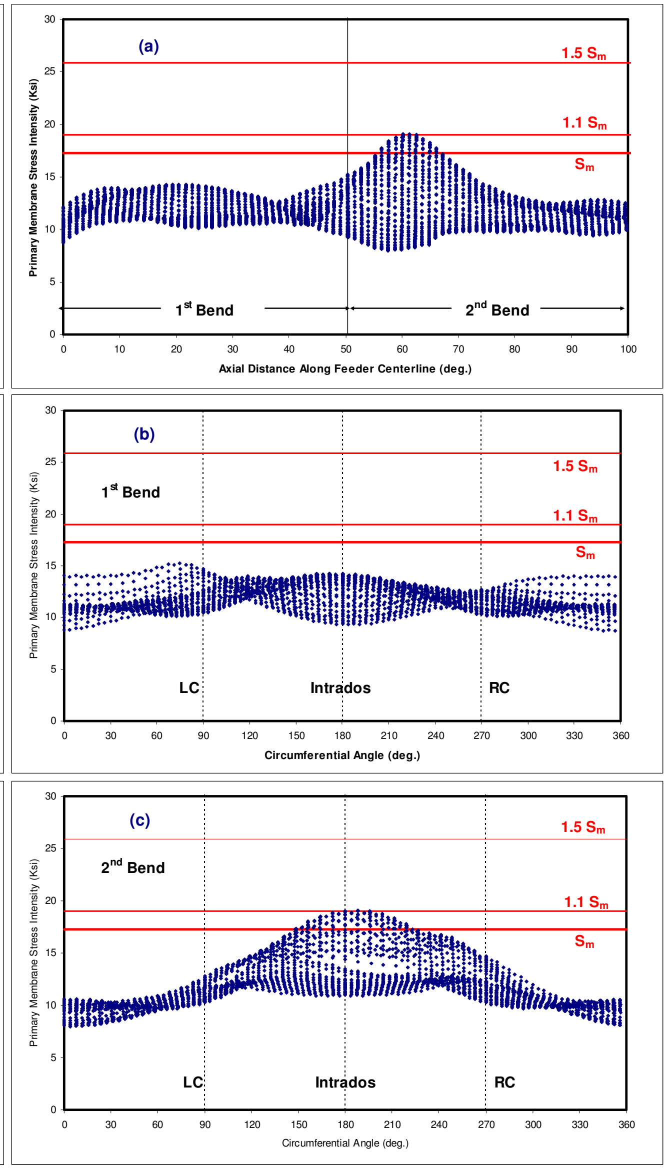

Figure 11: NB-3221.1 (P_m) & NB-3221.2 (P_L) Check

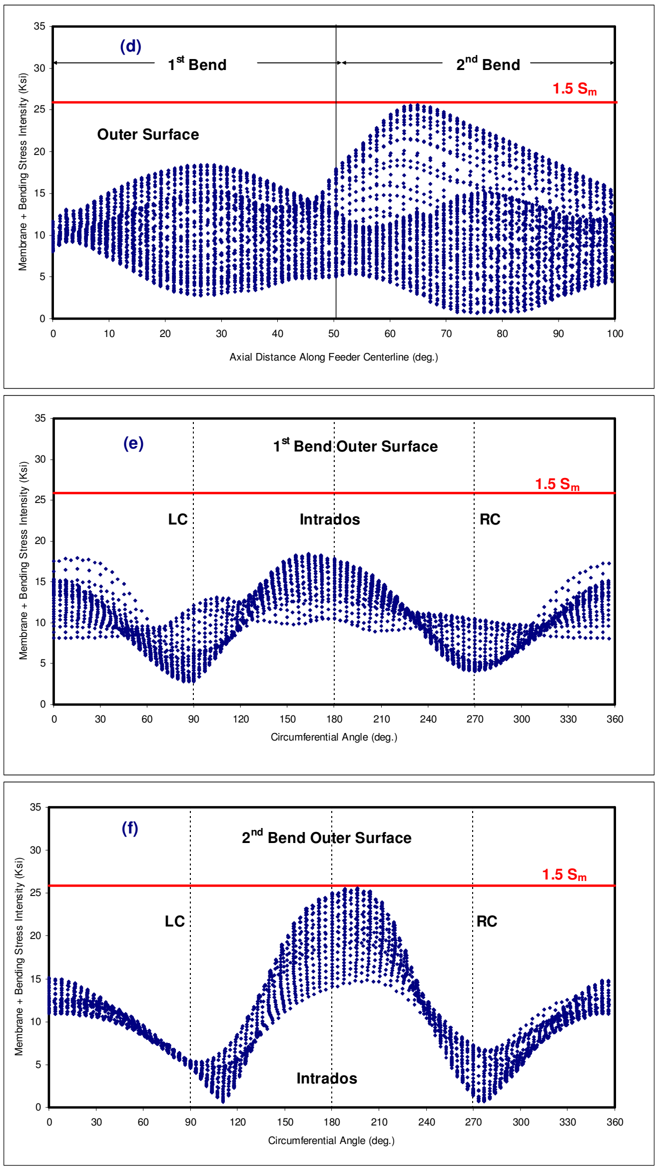

Figure 12: NB-3221.3 (P_m+P_b) Check (Outer Surface)

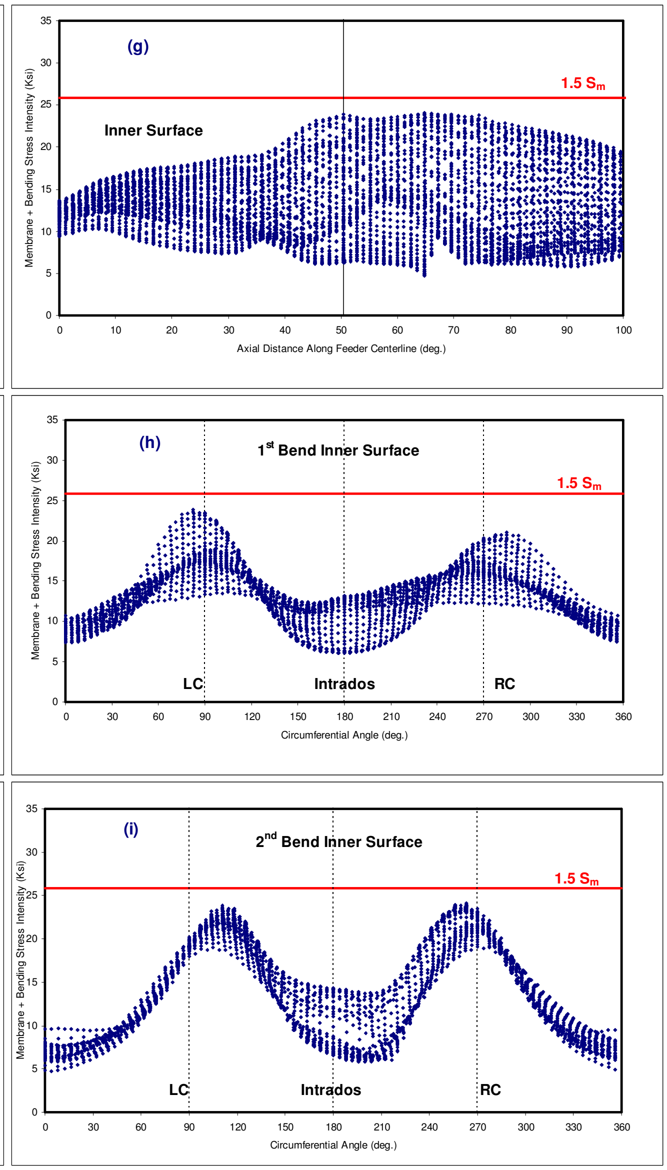

Figure 13: NB-3221.3 (P_m+P_b) Check (Inner Surface)

ASME Section XI Code Case N-597-2 Evaluation

The detailed finite element analysis evaluation of the local thinned area is compared to the evaluation procedure following the approach of the ASME Code Case N-597-2. Table 1 summarizes the feeder bend characteristic dimensions used in the Code Case evaluation.

Table 3: Characteristic Dimensions of the Locally Thinned Area at the Intrados of the 2nd Bend

R_b	R_o	t_{nom}	t_{min}	R_{min}	t'_{min}	R'_{min}	$\sqrt{(R'_{min}t'_{min})}$	$t_{p,min}$
76.2	29.98	5.54	2.45	28.76	3.19	28.39	9.51	2.37

R_b is the Radius of curvature of the pipe bends
Ro is the outer radius of the pipe cross-section
t_{nom} is the nominal pipe thickness
R_{min} is the mean radius of the pipe bend based on t_{min}.
R'_{min} is the mean radius of the pipe bend based on t'_{min}.

The axial and circumferential extents of the local thinned area are calculated based on the idealized profiles as shown on Figure 10 and compared to the limited area criteria as follows,

$L_{m(a)}$ (14.9 mm) > $\sqrt{(R'_{min}t'_{min})}$ (9.51 mm) → Unlimited Axial Extent
$L_{m(t)}$ (96.1 mm) > $\sqrt{(R'_{min}t'_{min})}$ (9.51 mm) → Unlimited Circumferential Extent

Therefore, the wall thickness for the inner portion of the pipe bend is evaluated using the Code Case article -3622.4 (Local Thinning – Unlimited Transverse Extent).

The criterion for evaluating unlimited circumferential extent is $t_{p,min} \geq t_{aLoc}$ (Table -3622-1 of the Code Case)

$L_{m(a)} / \sqrt{(R'_{min}t'_{min})} = 1.58$ → $t_{aLoc} / t'_{min} = 0.87$ → $t_{aLoc} = 2.77$ mm

Since $t_{p,min}$ (2.37 mm) < t_{aLoc} (2.77 mm), it is concluded that the criterion for the unlimited circumferential extent is not met.

Figure 14 shows a graphical representation of the Limited Circumferential (LC) and Unlimited Circumferential (UC) Code Case criteria for local thinned areas. It is noted that the Code Case qualified thickness of 2.77mm is 17% higher than the 2.37mm thickness qualified by the detailed FEA using ASME NB-3221 elastic analysis rules. This difference amounts to roughly 2.35 EFPY of additional operation time gained when using the detailed FEA to qualify the feeder. This gain is attributed to the fact that the UC criteria assumes that the full circumference is thinned out uniformly. In the case addressed in this paper, the circumferential extent of the wall thickness below the t'_{min} does not satisfy the LC criteria but rather only a little larger than half the full circumference.

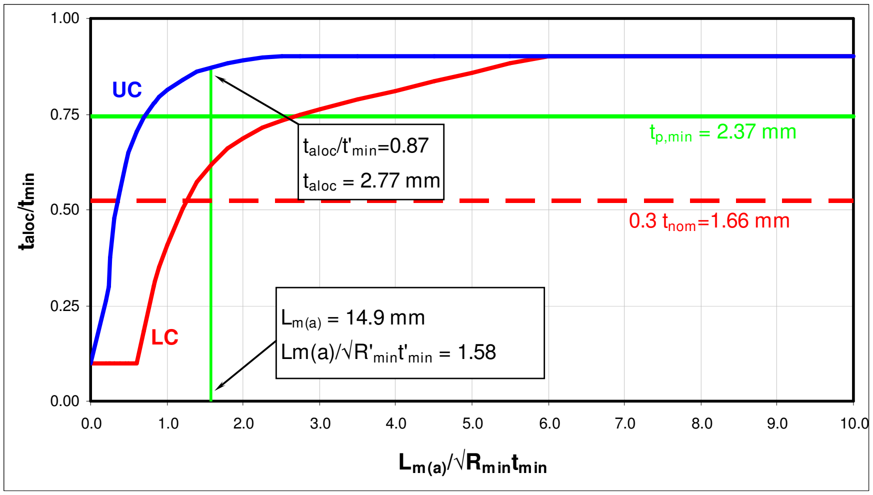

Figure 14: ASME SEC XI Code Case N-597-2 Allowable Wall Thickness for Limited Circumferential (LC) and Unlimited Circumferential (UC) local Areas Applied to 2" Pipe Bend

Conclusions

The linear elastic rules of the ASME Code SEC III NB-3221 are used to assess the structural integrity of thinned short radius pipe combined bends under internal pressure loading. Three dimensional finite element models are constructed to simulate general and local inner wall thinning. The thinning profiles are smoothly varied in both the axial and circumferential directions and are constructed as a lower bound to the measured wall thickness distribution over the entire tight radius bends region. The stress intensity obtained from the finite element solution corresponding to the pressure loading plus dead weight is linearized through the wall thickness producing membrane, bending and peak stress components. The results of the linearization are plotted in both the axial and circumferential directions and compared to the ASME Code SEC III NB-3221.1, 2, and 3 criteria.

It is demonstrated that a local wall thickness of 2.37mm that is less than the allowable wall thickness of the corresponding straight pipe is qualified according to NB-3221 rules. Using the ASME Code SEC XI Case N-597-2 a significantly higher allowable local thickness of 2.77mm is qualified. The comparison demonstrates the effectiveness of the detailed modelling using the finite element method in extending the useful life of the feeder pipe considered.

Results regarding the effects of out-of-roundness under internal pressure and bending moment will be communicated in a future publication. Results from other loading types will also be communicated in future publications.

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