Assessment of Local Decreases in Wall Thickness at the Connection Straight-Pipe/Bend Using Stress Concentration Factors

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ABSTRACT

Welds are ground during manufacturing to free them from offset edges and notches and to obtain a more favorable stress curve. Apart from the above, welds are also ground to prepare them for and improve the conditions for periodic testing and inspection.

The grinding of welds may result in a local decrease in wall thickness, so that there may be local decreases from the required design-based minimum wall thickness. In order to evaluate such material-loss regions, we have established parameterized FEM computing models. In addition, we have determined appropriate stress concentration factors for typical wall-thickness decreases and various wall-thickness/diameter ratios, which enable us to determine quickly and, if necessary, directly after the on-site measurement of wall thickness, whether a detected decrease from the minimum required value is permissible.

To be able to evaluate deviations from the minimum required wall thickness in welds that form a connection to bends, we have determined the stress concentration factors for the beginning and the end of bends for common pipe bend dimensions. These stress intensification factors (SIF) were compared with these given in the literature for the crown of the bend, which are commonly used in pipeline calculations, which are based on the beam theory

In this paper, the SIFs for various grinding geometries and for the beginning and the end of common bend shapes will be presented. Stresses on the transition between bend and straight pipes caused by internal pressure and bending moments can be calculated with the help of SIFs. The SIFs which were necessary to compute general primary stress, local primary stress or primary and secondary stress, to compare the values obtained with the permissible values are given.

INTRODUCTION

Welds are ground during manufacturing to free them from offset edges and notches and to obtain a more favorable stress curve. Apart from the above, welds are also ground to prepare them for and improve the conditions for periodic testing and inspection. The grinding of welds may result in decreases from the required design-based minimum wall thickness (hereinafter referred to as "undergrinding"). As an independent expert organization, we evaluate stresses occurring in the region of welds which connect straight pipe lengths and pipe bends. This is particularly interesting, since pipe bends currently installed in nuclear power stations are frequently designed without straight pipe ends. In light of the above, such welds -- depending on bend shapes and loading -- may still be affected by stress intensificiation .

Currently there are no regulations or methodologies governing identification of the impact caused by bend shapes and undergrinding geometries. In light of the above, we had to develop a methodology, which identified, on the one hand, the stress intensification at the transition bend/straight pipe caused by the bend shape and, on the other hand, the stress intensification caused by weld geometry.

For this purpose, we verified in a Finite Element Analysis (FEA) the stress intensification factors (SIF) pertaining to undergrinding in the region of welds connecting straight pipes which had already been published in literature and presented them graphically for various undergrinding geometries and the loading types of bending moment and internal pressure. The factors considering bending moments were additionally multiplied by SIFs, as shown in equation (1), which take the transition to the subsequent pipe bend into account.

$$\alpha_{total} = \alpha_{weld\ geometry} \times \alpha_{pipe\text{-}bend\ impact} \qquad (1)$$

As far as internal pressure is concerned, for the transition between bend and straight pipe, the impact of the adjoining pipe bend is less relevant for this type of loading. This is also confirmed by the following facts: in cases involving internal pressure, for example, the primary SIF pertaining to the bend quoted in [1] is equal to that of the straight pipe and the SIF pertaining to primary and secondary stress for the pipe bend itself amounts only to a maximum of 1.3 in the bend shapes examined by us.

This presentation will first address the methodology by which we computed the SIFs of the various undergrinding geometries. It will then provide information of how we identified the SIFs pertaining to the transition between bend and straight pipe. Finally, this contribution will illustrate and evaluate the combination of the various types of SIFs.

SIFS FOR UNDERGRINDING GEOMETRIES

In [2] the results of a parametric study were published. This parametric study included SIFs for circumferential (rotation symmetrical) material-loss at welds caused by grinding (hereinafter referred to as "undergrinding") relating to the following load types: bending moments and internal pressure.

Within the scope of our tests and inspections which we conducted as an independent expert organization to verify the permissibility of weld undergrinding, we verified the SIFs published in [2] by means of our own parametric Finite Element Analyses (FEA). Our FEAs were based on the FE program, ANSYS. We used “harmonic elements“ in our FEAs, so that we could also impose non-axisymmetric loading (e.g. bending moments) on the axisymmetric model and thus determine and evaluate the results for all angles at the circumference. We varied the geometry-related data outlined in Figure 1. Due to the constraints of testing technology, a maximum permissible grinding angle of ≤15° must not be exceeded, so that an echo without errors can still be obtained in ultrasonic testing.

In our parametric FEA we took into consideration that the types of loading of internal pressure and bending moments had a different impact on circumferential and axial stress components. Below, we evaluated the relevant stress components caused by internal pressure and bending moment.

The following reference stress was selected for the load type of internal pressure:

$$\sigma_{Np} = p \text{ x } D_m/(2T) \quad (2)$$

For weld undergrinding, the circumferential stress caused by internal pressure is calculated as follows from the above reference stress and the SIF pertaining to the circumferential direction:

$$\sigma_t = \beta_{tp} \text{ x } \sigma_{Np} \quad (3)$$

For weld undergrinding, the axial stress component caused by internal pressure is calculated as follows from the above reference stress and the SIF pertaining to the axial direction. The axial stress component due to the resulting bending moment is determined by dividing the bending moment by the bending section modulus of the undergrinding's cross section. The axial stress component caused by undergrinding is thus calculated by the following equation:

$$\sigma_{axp} = \beta_{ax} \text{ x } \sigma_{Np} + M_b/W_{bu} \quad (4)$$

To determine the SIFs in the circumferential and axial direction, we conducted parametric FEAs for various pipe shapes and undergrinding geometries. The selected pipe shapes and undergrinding geometries ensured coverage of the majority of undergrinding geometries which, according to our experience, are found in practice. In Figures 2, 3 and 4 we illustrated the axial and SIFs computed for internal pressure. Additionally, we defined the circumferential SIFs occuring at a distance of 0.5x(RT)0.5 from the maximum stress value. This makes it possible to decide whether the stress caused by undergrindings may be classified as local primary membrane stress or whether it must be treated as general primary membrane stress. In line with the German code of practice on nuclear power stations [1] and the ASME Code [3], stress caused by a fault or imperfection can be classified as local primary membrane stress, if the stress values occurring at a meridional distance of $0.5x(RT)^{0.5}$ from the stress peak do not exceed a value that is 1.1 times the allowable primary stress.

The SIFs computed by us and identified in [2] demonstrate the same tendency with respect to depth and length of undergrinding. To simply compare the SIFs that we had computed for typical pipe cross sections with the results outlined in [2] proved difficult, since [2] did not include any information about the pipe cross-sections covered by the SIFs presented in the graphics.

As far as bending moments are concerned, our parametric FEAs demonstrated that it was sufficient to use the bending section modulus pertaining to the undergrinding's (and thus reduced) cross section in stress computation, in order to identify stress intensification compared with the original, intact pipe cross section.

SIFs Allowing Bend Impact Consideration

These SIFs quoted in various codes and standards apply to the crown of the bend or to the area in which peak values occur. The stresses occurring at the transition between bend and straight pipe are clearly smaller than these maximum values. However, they still exceed the stresses of the straight pipe. The information contained in this presentation refers to a 90° bend, i.e. an elbow. At first, the presentation will explain how the SIFs which are relevant for the verification of our parametric FEAs are incorporated in the current codes of practice. Then, the results of our investigations pertaining to the transition bend/straight pipe will be presented.

SIFs Pertaining To Pipe Bends Outlined In KTA 3201.2 [1] And ASME-Code (NB 3680) [3]

Primary stress is calculated as follows, for example in the KTA 3201.2 standards, with the help of equation 8.4-1 and in ASME-Code NB 3652 as per equation (9). The primary stress must be smaller than 1.5 times the design stress intensity value S_m.

$$B_1 x (P x D_o)/(2 x T) + B_2 x (D_o/(2 x I)) x M \leq 1,5 S_m \quad (5)$$

The first term of the sum is used to calculate the stress component caused by internal pressure. The second term of the sum identifies the stress component caused by bending moments. In each case, the terms of the sum refer to a cylindrical pipe cross-section. The terms are multiplied with the appropriate SIFs (SIF) pertaining to the various pipe components. As far as internal pressure is concerned, only the axial stress is computed by means of the applicable SIFs. In the codes of practice and standards, the circumferential stress caused by internal pressure is evaluated separately, for example, when dimensioning is dealt with.

If secondary stress components are to be identified, too, the SIFs B_1 and B_2 must be replaced by C_1 and C_2. Potential thermal stress caused by material discontinuities or structural discontinuities must be taken into account as a third term of the sum. The maximum allowable stress must be replaced by 3,0 S_m. The SIFs, B and C are generally defined in [1] and [3] as follows:

$$B, C = \sigma/S \quad (6)$$

In this context, σ is defined as elastic stress and S as nominal stress, with S referring to the ideal, intact cross-section which is outside the range of influence of other components. The B factors were derived from limit analyses. As far as C factors are concerned, σ represents the maximum stress intensity occurring in the structure under investigation. Since the pipe bend does not have any major impact on the internal-pressure-related stress which acts on the transition between bend and straight pipe, the statements made below are restricted to the SIFs B_2 and C_2 which are relevant for the stress caused by bending moments.

For pipe bends, the loading type of bending moment can be differentiated into in-plane and out-of-plane bending. Torsion may be also considered. In cases involving pure in-plane bending, the pipe bend remains in the plane formed by the two adjoining straight sides. For the 90° elbow under investigation here, a pure torsion moment occurring at one end of the elbow causes a pure out-of-plane bending moment of the same magnitude at the other end of the elbow.

Generally, SIFs B2 and C2 are quoted as a function of pipe flexibility characteristic, h.

$$h = t_n x R/r^2 \quad (7)$$

SIF C_2 pertaining to in-plane bending is expressed in [1] and [3] as follows:

$$C_2 = 1,95/h^{2/3} \quad (8)$$

Thus, in line with [1] and [3], all types of stress resulting from in-plane bending, out-of-plane bending and torsion, are covered. For the computation of stress,

$$s = C_2 x (D_o/(2 x I)) x M \quad (9)$$

the resulting bending moment, must therefore be applied in line with [1] and [3]. The resultant moment is calculated as shown in the equation below.

$$M = (M_x^2 + M_y^2 + M_z^2)^{1/2} \quad (10)$$

Apart from the background of the B_2 factor, [4] also provides information about the history which resulted in the equation (8) used to calculate the C_2 factor. According to [4], in 1974, Larson, Stokey and Panarelli stated in [5] that a factor of 1.95 covered both the impact of in-plane bending, out-of-plane bending and torsion. In this context, a factor of 1.8 was quoted for pure in-plane bending. In the meantime, the factor of 1.8 pertaining to pure in-plane bending has been confirmed by more recent investigations [6]. In line with [1] and Code Case N-319-2/3 [7], SIFs deviating from the above values may also be used for out-of-plane bending and torsion, provided the appropriate flexibility factors were introduced into the analytical beam model. The flexibility factors will not be addressed within the scope of this presentation, since we base our statements on the assumption that they are correctly introduced into the analytical beam model. In [7], the C2 factors outlined below are defined for in-plane bending, out-of-plane bending and torsion:

$$C_{2,\,z}=1{,}95/h^{2/3} \qquad \text{In-Plane} \qquad (11\text{-}1)$$

$$C_{2,\,x/y}=1{,}71/h^{0{,}53} \qquad \text{Out-of-Plane und Torsion} \qquad (11\text{-}2)$$

The equations (11-1) and (11-2) were also stated in [1] for the C2 factor pertaining to the load types of in-plane or out-of plane bending. However, a C2 factor of 1.0 is stated in [1] for the load type of torsion. Thus, [1], as in the procedure outlined in ANSI B31.3, [8], does not take into account any stress intensification caused by torsion. The SIFs i, which in line with ANSI B31.3 [8] must be taken into consideration, their combination with C factors and the methodology to be applied to stress calculation were already evaluated in detail in [9]. Due to the factor of 1.0 pertaining to the C factor representing the stress caused by torsion, the methodology defined in [1] and [8] is less conservative than the procedure outlined in [7]. The fact that the methodology outlined in [1] is less conservative than that outlined in [7] is also confirmed by [7] stating that the term B_2xM of equation (5) can be replaced as shown in equation (12) and by the fact that according to [1] a factor of 0.5 instead of 0.67 is permissible in front of the square root.

$$B_2xM=0{,}67x((C_{2x}M_x)^2+(C_{2y}M_y)^2+(C_{2y}M_y)^2)^{1/2} \qquad (12)$$

[1] and [7] use an identical approach to effect an appropriate replacement of the term C_2xM. In our opinion, the factor 0.67 used in equation (12) to replace the term B_2xM with directional C_2 factors and the pertinent section moduli is consistent with the conclusions listed in [4] that originally resulted in the definition of the factor B_2.

[4] lists the investigations which resulted in the development of the B_2 SIF, which compared to the factor of 1.95 for the SIF C_2 is preceded by a factor of 1.3, i.e. a 1.5 times smaller factor. In line with our level of knowledge, the codes of practice and standards do not differentiate, as far as the SIF B_2 is concerned, between in-plane bending, out-of-plane bending or torsion. In 1999, the results of studies addressing in-plane and out-of-plane bending were presented in [7]. These results make factors smaller than 1 appear justified for the SIF B_2, so that the assumption was confirmed that a factor of 1.3 was conservative for the SIF B_2.

SIFS PERTAINING TO THE TRANSITION BETWEEN BEND AND STRAIGHT PIPE

To determine the SIF pertaining to the transition between bend and straight pipe, we prepared a parameterized FE model based on the FE program ANSYS with shell elements for a 90° elbow. The straight pipes attached to the two ends of the pipe bend have a length of 5 times that of the outside diameter. Thus "end effects" were excluded for the transition between elbow and straight pipe. The FEA model is shown in Figure 6.

We conducted investigations for in-plane bending, out-of-plane bending and torsion. The pipe cross sections and bending radii selected ensured that the usual pipe cross sections and flexibility characteristics h were covered by the investigation.

To verify our FEA model, we determined our own elbow-related C_2 factors on the basis of peak and nominal stress values calculated by us and compared these C_2 factors to those quoted in the codes of practice and standards (cf. equations (8) and (11)). Overall, the C_2 factors calculated by us were slightly lower than those quoted in the codes of practice and standards [1], [3] and [7]. Consistent with the results of [6] and the statements made in [4], we calculated a factor of <1.95, approximately 1.80, for pure in-plane bending. For out-of-plane bending we computed C2 factors which were, at maximum, approximately 15% lower than those quoted in [1] and [7].

For the transition between elbow and straight pipe we determined the SIFs illustrated as diagrams in Figures 6 and 7 for in-plane bending, out-of-plane bending and torsion. The SIFs calculated by us for the transition between bend and straight pipe can be expressed by means of the following equation:

$$C_{2z}^{*}=1{,}05/h^{(2/3)} \qquad \text{(In-Plane-Bending)} \qquad (13)$$

$$C_{2y}^{*}=1{,}15/h^{(0{,}5)} \qquad \text{(Out-of-Plane-Bending)} \qquad (14)$$

$$C_{2x}^{*}=1{,}26/h^{(0{,}3)} \qquad \text{(Torsion)} \qquad (15)$$

As in the equations pertaining to in-plane and out-of-plane bending, we related the equation pertaining to torsion to W_b, since appropriate replacement of the term C2xM should be possible. In line with the procedure outlined in the codes of standards and the statements in [4], we apply values reduced by a factor of 1.5 to the appropriate B2 factors. Our FEAs showed that membrane stresses occurring across wall thickness were covered by these values.

COMBINATIONS OF UNDERGRINDING GEOMETRIES AND THE TRANSITION BETWEEN BEND AND STRAIGHT PIPE

The impact of undergrinding geometries is essential for computing the stress at the transition between bend and straight pipe caused by internal pressure. In contrast, the impact of the adjoining elbow is of minor significance for the stress caused by internal pressure at the transition bend/straight pipe. Thus, in equation (1), a value of 1 can be used for $\alpha_{\text{pipe bend impact}}$ representing the stress caused by internal pressure. The values to be used for $\alpha_{\text{weld geometry}}$ are listed in Figures 2, 3 and 4.

In contrast, the impact of the adjoining elbow is essential for stress caused by bending and torsion acting at the transition between bend and straight pipe. The impact of the undergrinding geometries is covered by taking into consideration the section modulus applicable to the undergrinding's cross section. Thus, in equation (1) a value of 1 can be employed for $\alpha_{\text{weld geometry}}$ pertaining to the stress values resulting from bending and torsion, provided the cross section reduced by undergrinding is employed as a reference cross section. The values to be applied to $\alpha_{\text{pipe-bend impact}}$ can be taken from Figures 6 and 7 or the corresponding equations.

Thus the stresses at the transition between bend/straight pipe can be determined for both load types by means of the defined SIFs. All SIFs required to calculate general primary stresses, local primary stresses or primary and secondary stresses and to permit comparison with the allowable values in each case were defined.

CONCLUSIONS AND OUTLOOK

The methodology presented here had to be developed to allow test results to be rapidly evaluated for their permissibility directly after conducting periodic non-destructive testing on welds connecting pipe bends and straight pipes. The methodology presented has proved its worth in practice. The results obtained by our parametric studies also enable evaluation of welds joining straight pipes, where undergrinding has occurred. Individual undergrinding geometries or bend shapes, which are not covered by our FEAs, are evaluated by means of individual verification. The applicability of a similar methodology to further components, e.g. T-pieces, reduces etc. still needs to be investigated in detail.

NOMENCLATURE

B_1	=	primary stress index for pressure
B_2	=	primary stress index for bending
C_1	=	secondary stress index für pressure
C_2	=	secondary stress index für bending
D_m	=	mean pipe diameter
D_o	=	outside diameter of pipe
h	=	characteristic bend parameter, tR/r_m^2
I	=	moment of inertia
L	=	length of decrease in wall thicknes
M	=	resultant moment
M_b	=	bending moment
M_t	=	torsion moment
M_x	=	moment, x-axis
M_y	=	moment, y-axis
M_z	=	moment, z-axis
p	=	design pressure
R	=	nominal bend radius of elbow
S	=	nominal stress
S_m	=	allowable desing stress intensitiy value
t	=	nominal wall thickness
U	=	wall thickness reduction
W_{bu}	=	section modulus (bending), reduced cross section
α_{total}	=	total stress index
$\alpha_{\text{weld geometry}}$	=	stress index for wall thickness reduction

$\alpha_{pipe\text{-}bend\ impact}$	=	stress index for connection straight pipe/bend
β_{ax}	=	stress index (axial) for pressure, wall thickness reduction
β_{tp}	=	stress index (circumferential) for pressure, wall thickness reduction
σ	=	stress intensity (elastic)
σ_{axp}	=	axial stress for pressure
σ_{Np}	=	nominal stress for pressure
σ_t	=	circumferential stress for pressure
r_m	=	mean pipe radius, $(D_o\text{-}t)/2$

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FIGURES

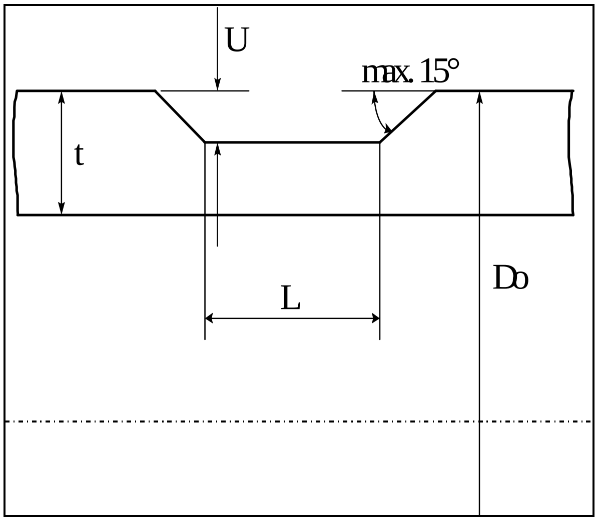

Figure 1: Circumferential undergrinding configuration

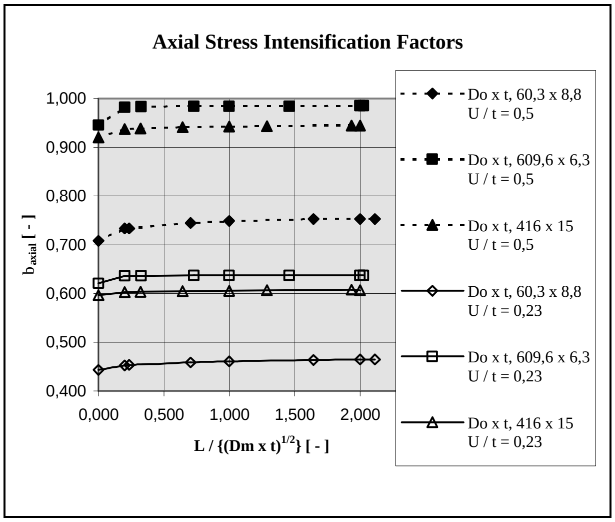

Figure 2: Axial SIFs, Internal Pressure, U/t=0,23 and U/t=0,50

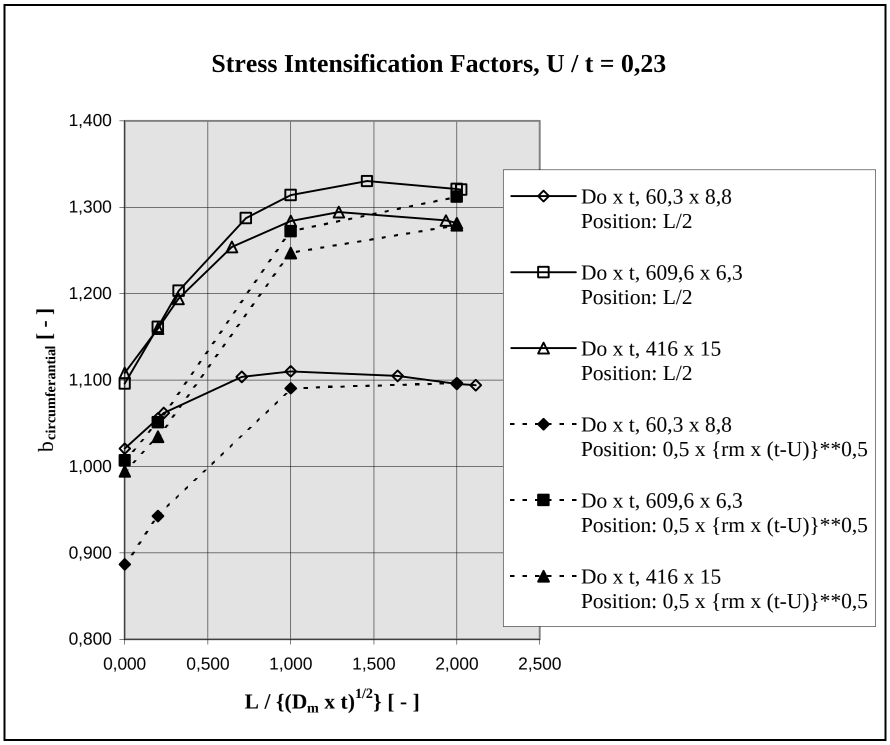

Figure 3: Cirumferential SIFs, Internal Pressure, U/t=0,23

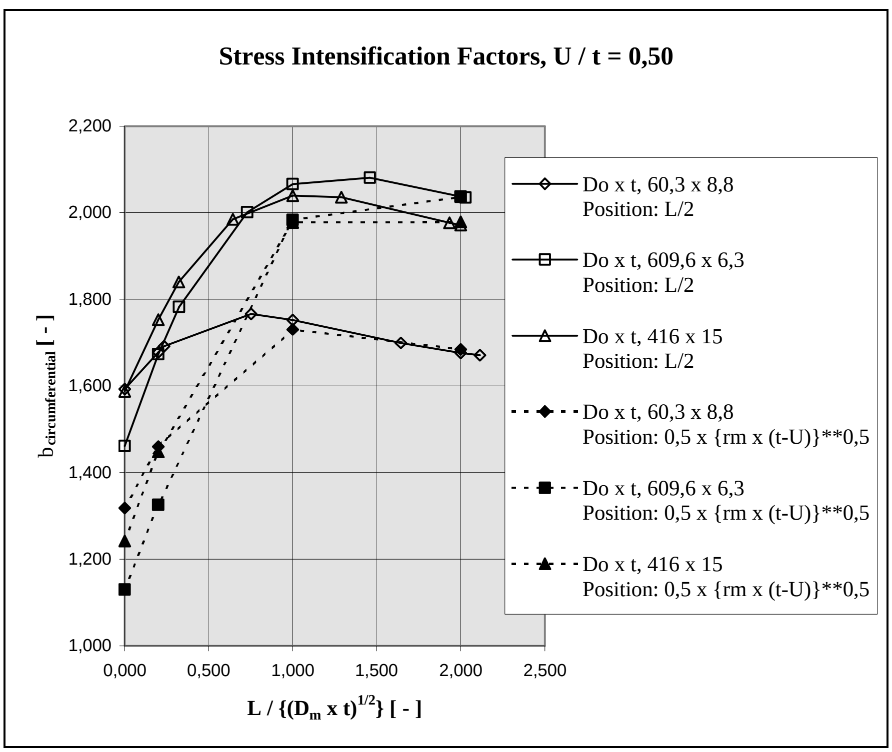

Figure 4: Circumferential SIFs, Internal Pressure, U/t=0,50

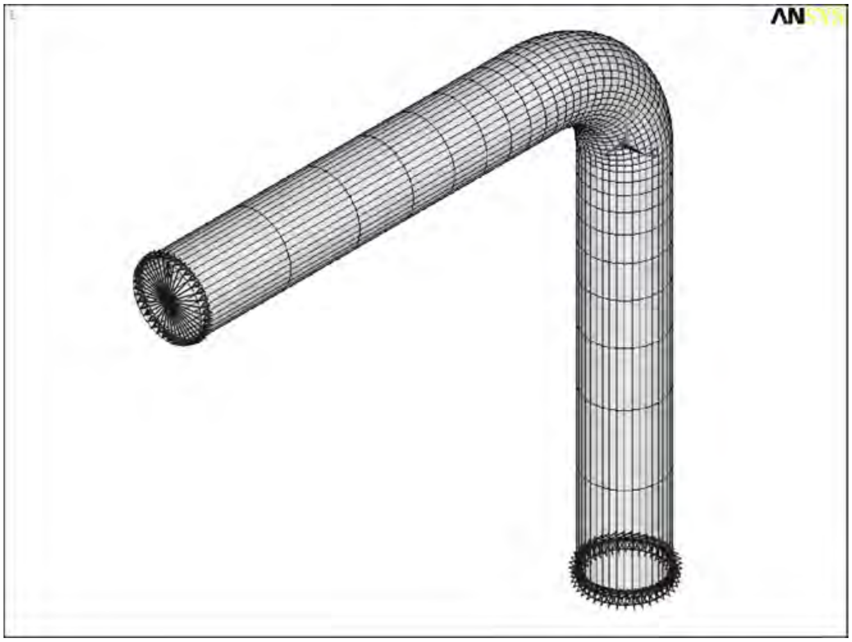

Figure 5: FEA model used for straight-pipe/bends analysis

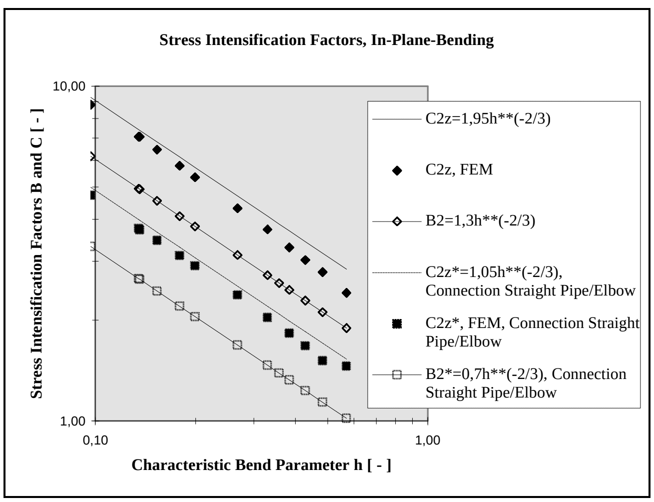

Figure 6: SIF, Connection Straight Pipe/Elbow, In-Plane-Bending

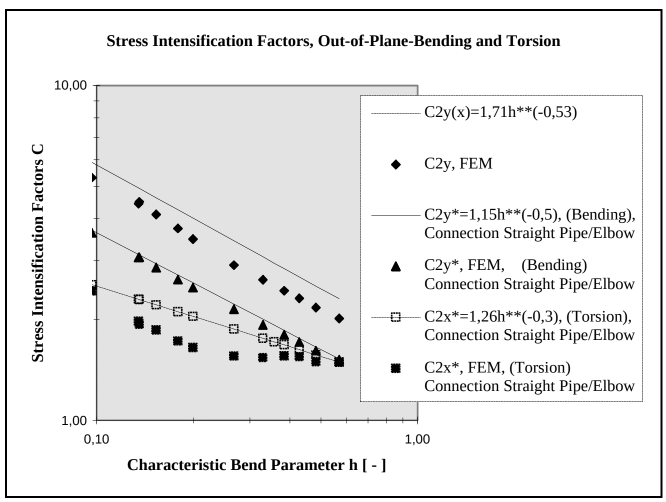

Figure 7: SIF, Connection Straight Pipe/Elbow, Out-of-Plane- Bending and Torsion