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Primary Stress Index B_2* for the Evaluation of postulated or detected Circumferential Flaws at the Connection Straight-Pipe / Bend

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1 ABSTRACT

For detected or postulated circumferential flaws at the weld connecting a straight-pipe and a bend the first step of the common evaluation procedures is the determination of the stress distribution. Therefore the common piping calculation programs can be used. In these programs for calculating the primary and secondary stresses and for checking if the primary and secondary stress limits are satisfied the following well-known equations (1) and (2) are implemented.

$$B_1 \frac{PD_0}{2t} + B_2 \frac{D_0}{2I} M_i \leq 1.5 S_m \tag{1}$$

$$C_1 \frac{P\,D_0}{2t} + C_2 \frac{D_0}{2I} M_i + C_3 E_{ab} \left| \alpha_a T_a - \alpha_b T_b \right| \leq 3 S_m \tag{2}$$

The primary membrane and bending stresses have to be considered in the evaluation procedures for circumferential flaws. One example for an evaluation procedure is given in [1]. The important issue is the determination of the primary bending stress for the connection straight-pipe/bend. Therefore an appropriate but conservative factor B_2 has to be used.

In this paper it is investigated if the factor B_2^*=0.7xh(-2/3) which is well established for the evaluation of wall thickness reductions at the connection straight-pipe/bend can be used for the evaluation of detected or postulated circumferential flaws (at this connection). To check if B_2^* is appropriate and conservative for the evaluation of circumferential flaws at the connection straight-pipe/bend a parametric finite element study is carried out. In the parametric study it is investigated if for the factor B_2^* the following equation is satisfied:

$$B_2^* \geq \frac{J_{StraightPipe/Bend}}{J_{StraightPipe}} \tag{3}$$

The results of the parametric finite element study show that B_2^* can be used for common evaluation procedures like the method give in [1] and that for very expanded flaws and small bend parameters the flaw size has to be taken into account.

2 INTRODUCTION

At different locations of piping systems, for example at the connection straight-pipe/bend, often postulated or detected circumferential flaws have to be evaluated. It has to be decided if the circumferential flaws are acceptable or if the component has to be exchanged or repaired. In this paper a method of evaluating postulated or detected circumferential flaws at the connection straight-pipe/bend is described.

For circumferential flaws at the weld connecting a straight-pipe and a bend the first step of the common evaluation procedures is the determination of the stress distribution. Therefore the common piping calculation programs or analytical methods based on the transverse beam theory can be used. In these programs for calculating the primary and secondary stresses and for checking if the primary and secondary stress limits are satisfied the following well-known equations (1) and (2) are implemented.

$$B_1 \tfrac{PD_0}{2t} + B_2 \tfrac{D_0}{2I} M_i \leq 1.5 S_m \tag{1}$$

$$C_1 \tfrac{P\,D_0}{2t} + C_2 \tfrac{D_0}{2I} M_i + C_3 E_{ab} \left| \alpha_a T_a - \alpha_b T_b \right| \leq 3 S_m \tag{2}$$

The primary membrane and bending stresses have to be considered in the evaluation procedures for circumferential flaws. One common evaluation procedure is given in [1]. The important issue is the determination of the primary bending stress for the connection straight-pipe/bend. Therefore an appropriate but conservative factor B_2 has to be used.

If the factor B_2=1 is used, the calculated bending stress is neither correct nor conservative for the connection straight-pipe/bend. But if the factor B_2=1.3xh(-2/3) given in the codes and safety standards [2], [3] and [4] for 90°-bends is used, the calculated bending stress seems to be overly conservative for the connection straight-pipe/bend. So in this paper it is investigated if the factor B_2^*=0.7xh(-2/3) which is well established for the evaluation of wall thickness reductions at the connection straight-pipe/bend can be used for the evaluation of detected or postulated circumferential flaws at this connection. The development of B_2^* and the evaluation method for wall thickness reductions at the connection straight-pipe/bend using B_2^* is described in [5]. To check if B_2^* is appropriate but conservative for the evaluation of circumferential flaws at the connection straight-pipe/bend a parametric finite element study is carried out. In the parametric study it is investigated if for the factor B_2^* the following equation is satisfied:

$$B_2^* \geq \frac{J_{StraightPipe/Bend}}{J_{StraightPipe}} \tag{3}$$

3 FINITE ELEMENT ANALYSIS

3.1 Procedure

We built two parametric finite element models for circumferential surface cracks in straight-pipes and for the same flaws and the connection straight-pipe/bend. For the surface crack at the connection straight-pipe/bend first the circumferential position with the maximum crack opening stress has to be determined. For both surface cracks – in the straight-pipe and at the connection straight-pipe/bend – the J-Integral was determined and with these two values and the following equation a new B_2 can be calculated:

$$B_2^J = \frac{J_{StraightPipe/Bend(FEM)}}{J_{StraightPipe(FEM)}} \tag{4}$$

We compared this new B_2 with B_2^*=0.7xh(-2/3) and with the results which we obtained by implementing B_2^*=0.7xh(-2/3) in the J-calculation method given in procedure [1].

3.2 Straight-pipe/bend geometries considered

For our parametric finite element analysis we considered for the straight-pipe and the bend the parameters given in Table 1. With these geometries typical values for the bend parameter (h) are presented.

Table 1: Investigated Bends

Bend No.	Do [mm]	R [mm]	t [mm]	h [-]	B_2 [-]
1	114.3	152.5	2	0.10	6.17
2	273	381	6.3	0.13	4.94
3	406.4	610	8.8	0.14	4.92
4	168.3	228.5	4.5	0.15	4.54
5	114.3	152.5	3.6	0.18	4.09
6	88.9	114.5	3.2	0.20	3.81
7	60.3	76	2.9	0.27	3.13
8	114.3	152.5	6.3	0.33	2.73
9	60.3	76	4	0.38	2.46
10	76.1	95	5.6	0.43	2.29
11	114.3	152.5	8.8	0.48	2.11
12	60.3	76	5.6	0.57	1.89

3.3 Investigated Flaw Size

According to the German VdTÜV-Standard [6] the following flaw sizes are considered:

- Crack shape: semi elliptical
- Crack depth: $a = 0.3 \times t$
- Crack length: $2c = 6 \times a$

3.4 Finite Element Models

For the numerical linear elastic analysis we used the finite element program ANSYS. The finite element models for the straight-pipe and the connection straight-pipe/bend are shown in Figure 1. The length of the straight-pipe at both ends of the bend is $5 \times D_o$. In the straight-pipe model the flaw is halfway along the complete length $10 \times D_o$.

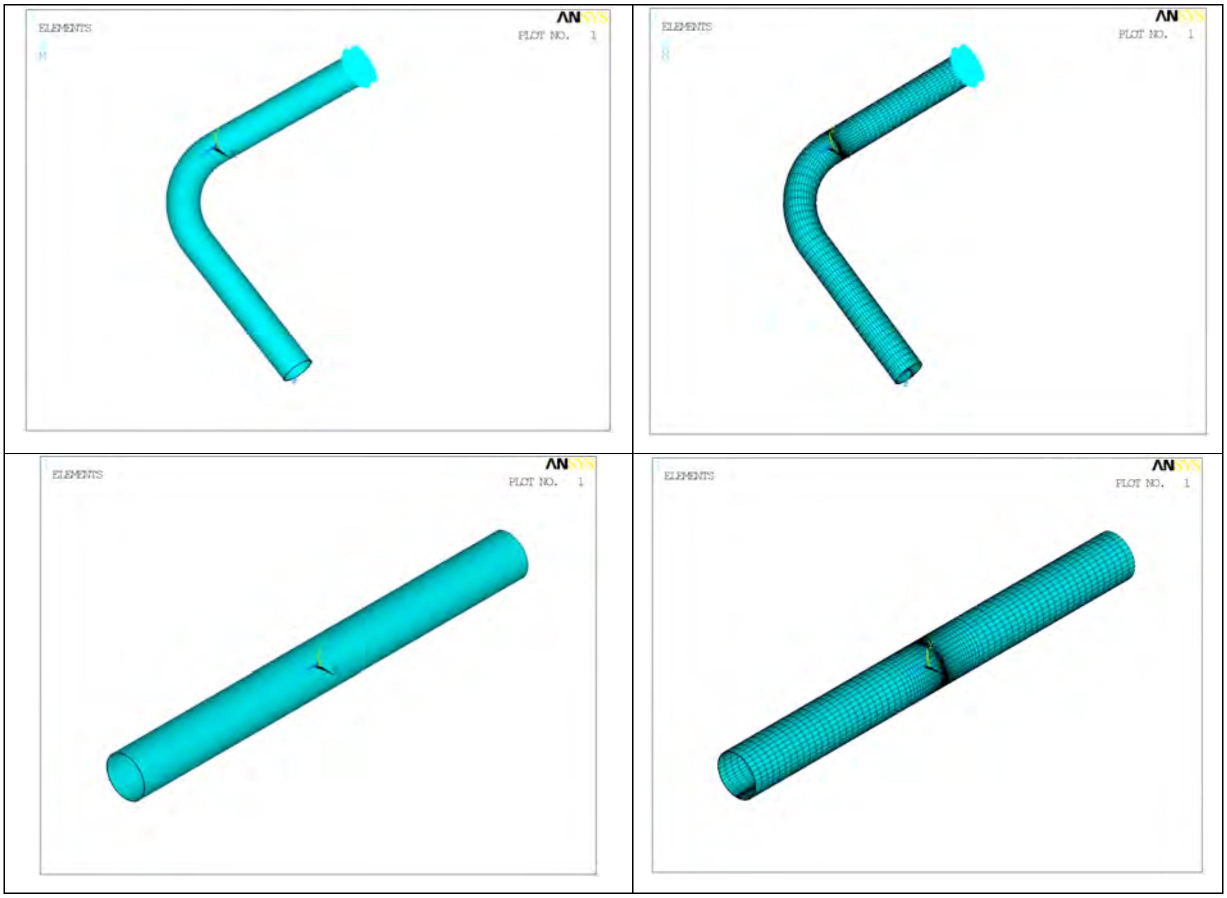

Figure 1: Finite element models, straight-pipe and connection straight-pipe/bend

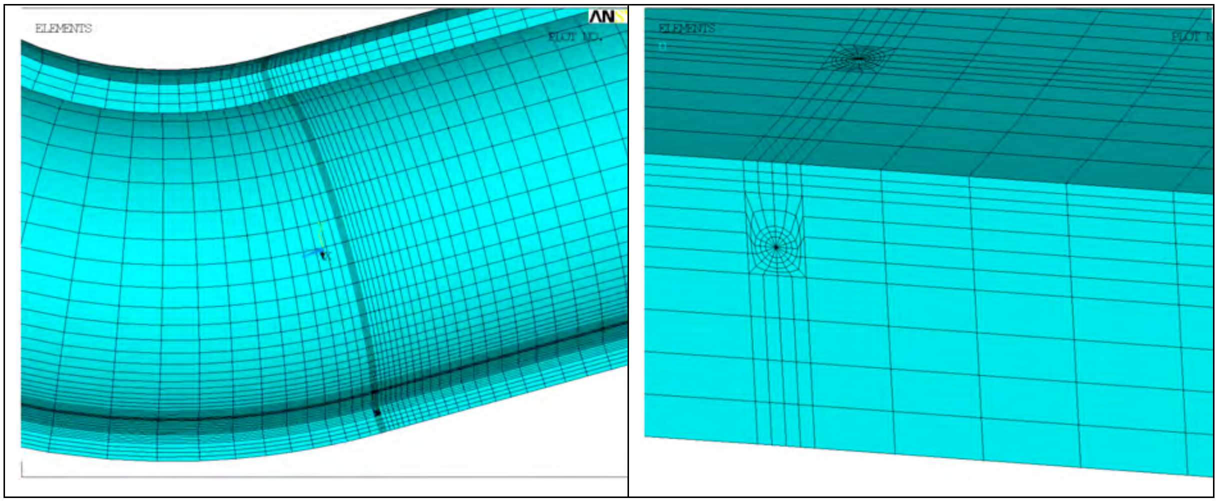

Figure 2: Details of the crack mesh

For the calculations we used 20-node solid elements. The crack tips are meshed by special crack tip elements. These elements are based on 20-node solid elements. Details of the crack mesh are shown in Figure 2. The mesh quality used guarantees realistic results. Although the focus of this paper is not on the calculation of the J-Integral we meshed the part of the crack in an appropriate way to get reliable results. We used the same crack mesh for the straight-pipe and for the connection straight-pipe/bend.

3.5 Finite Element Results

The parameter variations given in Table 1 are considered in the finite element analysis. For all the calculated finite element models the J-Integral was determined. Therefore we use several paths round the crack tip. For all the paths we obtained the same J-values, so an important (mesh-)quality check is satisfied. The J-values obtained with the finite element models and with the analytical method given in [1] are listed in Table 2. For the connection straight-pipe/bend it has to be emphasized that it is very important to confirm that the crack is at the circumferential position with the maximum crack opening stress.

Table 2: J-Integral, bending moment: 1 kNm

Bend No.	Do [mm]	R [mm]	t [mm]	h [-]	B_2* [-]	J [N/mm] Straight-pipe		J [N/mm] Connection Straight-pipe /bend	
						FEM	[1]	FEM	[1]1)
1	114.3	152.5	2	0.10	3.32	2.24E-02	2.73E-02	1.15E-01	3.01E-01
2	273	381	6.3	0.13	2.66	2.22E-04	2.80E-04	7.23E-04	1.98E-03
3	406.4	610	8.8	0.14	2.65	3.22E-05	4.03E-05	1.05E-04	2.83E-04
4	168.3	228.5	4.5	0.15	2.44	2.17E-03	2.80E-03	5.83E-03	1.67E-02
5	114.3	152.5	3.6	0.18	2.20	1.28E-02	1.71E-02	2.67E-02	8.29E-02
6	88.9	114.5	3.2	0.20	2.05	3.98E-02	5.47E-02	8.60E-02	2.30E-01
7	60.3	76	2.9	0.27	1.69	2.12E-01	3.15E-01	3.00E-01	8.96E-01
8	114.3	152.5	6.3	0.33	1.47	7.63E-03	1.19E-02	7.85E-03	2.56E-02
9	60.3	76	4	0.38	1.33	1.58E-01	2.64E-01	1.41E-01	4.65E-01
10	76.1	95	5.6	0.43	1.23	4.49E-02	7.88E-02	4.22E-02	1.20E-01
11	114.3	152.5	8.8	0.48	1.14	5.63E-03	1.01E-02	5.55E-03	1.31E-02
12	60.3	76	5.6	0.57	1.02	1.17E-01	2.33E-01	1.19E-01	2.42E-01

1) Primary stress based on B_2*

For the surface crack in the straight-pipe the comparison of the finite element J-values with the procedure given in [1] shows that the procedure [1] seems to be conservative. For the thin-walled cross-sectional areas the finite element results and the analytical results are nearly the same for the crack in the straight-pipe. For the more thick-walled cross-sectional areas the analytical results obtained with procedure [1] are conservative compared with the finite element results.

For the connection straight-pipe/bend the J-values obtained with procedure [1] show a strong conservatism compared with the finite element results if the primary stress in procedure [1] is based on the factor B_2^*=0.7xh(-2/3).

4 EVALUATION AND CONCLUSION

In Figure 3 for procedure [1] the ratio of the J-Integral for the straight-pipe and for the connection straight-pipe/bend is shown. In this case the primary stress is based on the factor B_2^*=0.7xh(-2/3). Also for the finite element results the ratio of the J-Integral for the straight-pipe and for the connection straight-pipe/bend is shown in Figure 3.

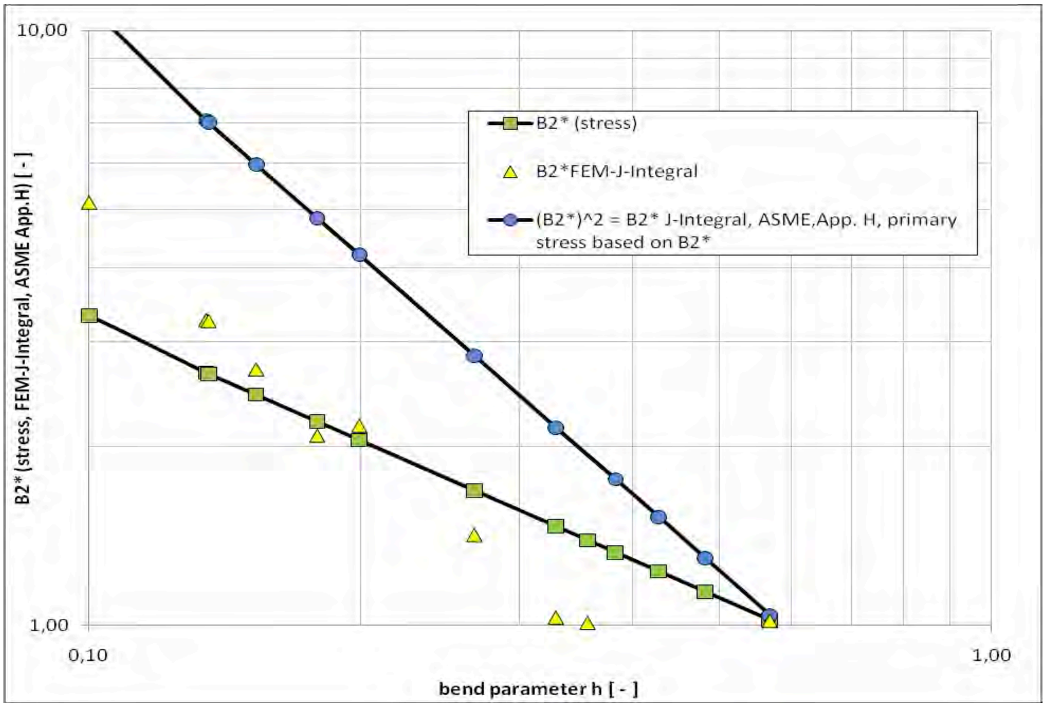

Figure 3: B_2* and the J-Integral ratio obtained with procedure [1] and finite element calculation

Figure 3 und Figure 4 show that for the connection straight-pipe/bend it is conservative to determine the primary stress by using the factor B_2^*=0.7xh(-2/3) and then to determine the J-integral with procedure [1]. The comparison of the results in Table 2 also shows that for all bends (except for h=0.1) equation 5 is satisfied, if the analytical results for the straight-pipe and the finite element results for the connection straight-pipe/bend are used.

$$B_2^* \geq \frac{J_{StraightPipe/Bend;FEM}}{J_{StraightPipe;[1]}} \qquad (5)$$

For the straight-pipe the conservatism of the J-values obtained with procedure [1] compared with the finite element results is also shown in Figure 4.

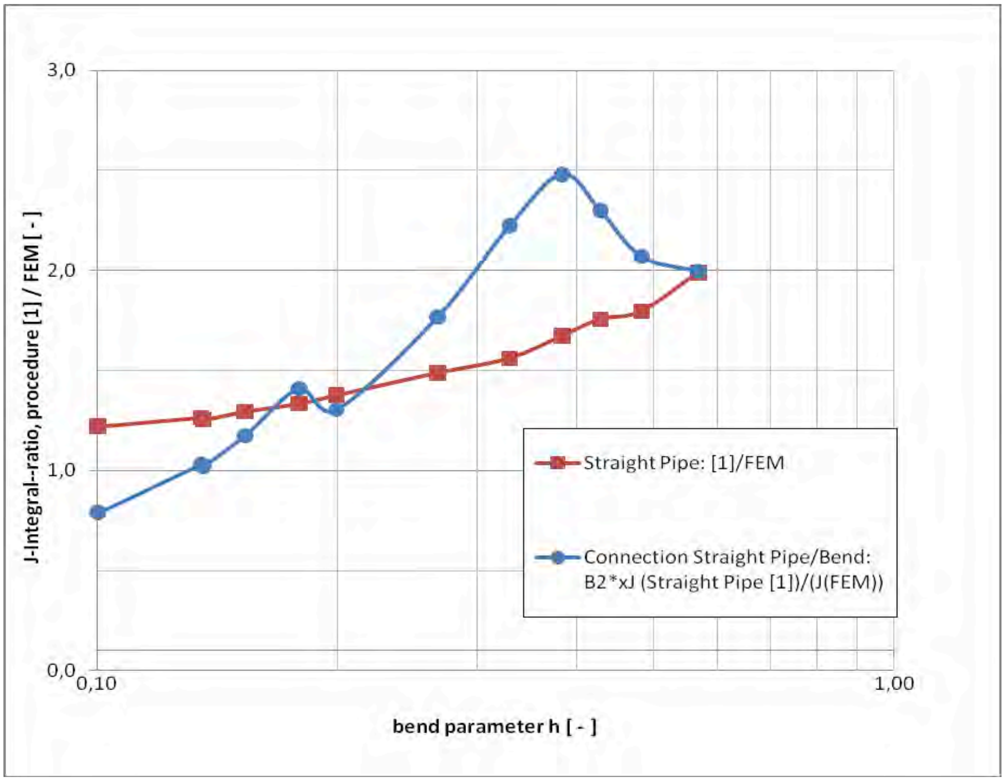

Figure 4: J-Integral obtained with procedure [1] and finite element calculation

In our experience for the estimation of postulated or detected flaws or surface cracks at the connection straight-pipe/bend the primary stress should first be determined by using the B_2^*=0.7xh(-2/3). It is not necessary to use the factor B_2=1.3xh(-2/3) which is for the crown of a bend. Then the J-Integral should be calculated for example according to the procedure given in [1]. If this value exceeds the allowable material value it could be estimated by equation 5 and Figure 4 if it is overly conservative and if it is worth performing a more detailed analysis.

The results shown in this paper can be used to estimate possible safety margins, but they should not be used instead of an estimation according to the official standards.

NOMENCLATURE

B_1 = primary stress index for pressure (membrane stress)
B_2 = primary stress index for bending (in general for the crown of the bend)
B_2^* = primary stress index for bending (stress based, for the connection straight-pipe bend)
C_1 = secondary stress index for pressure
C_2 = secondary stress index for bending
C_3 = secondary stress index (range of temperature at a structural or material discontinuity)
D_o = outside diameter (of pipe)
E_{ab} = average modulus of elasticity of the two sides of a gross structural or material discontinuity
I = moment of inertia
J = J-Integral
h = characteristic bend parameter tR/r_m^2
M_i = resultant moment

P = design pressure
R = nominal bend radius
r_m = nominal mean pipe radius
S_m = allowable design stress intensity value
$T_{a,b}$ = range of average temperature on side a (b) of a structural or material discontinuity
t = nominal wall thickness
$\alpha_{a,b}$ = coefficient of thermal expansion on side a(b) of a gross structural or material discontinuity

References

[1] ASME Code Section XI, Division 1, Appendix H
[2] ASME Code Section III, Division 1, Subsection NB (Class 1 Components) and Subsection NC (Class 2 Components)
[3] KTA 3201.2, Komponenten des Primärkreises von Leichtwasserreaktoren, Teil2: Auslegung, Konstruktion und Berechnung
[4] KTA 3211.2, Druck- und aktitvitätsführende Komponenten von Systemen außerhalb des Primärkreises, Teil2: Auslegung, Konstruktion und Berechnung
[5] Wieland Holzer, Robert Kauer, Christian Hüttner, Assessment of local decreases in wall thickness reductions at the connections straight-pipe/bend using stress concentration factors, SMiRT 16, Washington, 2001
[6] VdTÜV-Bericht Nr. 62, Rev. A, 02.02.2009, Bruchmechanische Nachweise zur Absicherung eingeschränkter Leckannahmen bei Rohrleitungen (Bruchausschluss)