Assessment of the Significance of Defects in Tubular Joints

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ABSTRACT

For the assessments of defects detected by means of NDE in circumferential welds of branch pipes of tubular joints a calculation procedure has been developed and implemented in a PC program. As resistance against fracture the initiation fracture toughness or the J-resistance curve can be used. Based on the SINTAP approach, the crack driving force is estimated in terms of J-integral, from forces and moments acting at the ends of the branch and run pipes.

INTRODUCTION

Calculation methods were developed for safety assessment of tubular joints (T-joints) of the "TH" safety injection piping system of a nuclear plant in Germany, where during the revision non destructive examination (NDE) has been performed. The assessment methods on the basis of the SINTAP procedure [1] were implemented in a PC program to enable fast safety assessments for different loading situations characterized by forces, moments and internal pressure, if defects would be found in the circumferential welds of the branch pipes.

The assessment procedure was developed in the following way: Regarding design, the T-joints of the investigated piping system could be divided into two groups referred to as TH3 and TH6 type. T-joint is loaded by 6 forces and 6 moments acting at the end of the branch pipe and at one end of the run pipe, as well as by internal pressure. Owing to the fact that deformations in the T-joints without cracks under in-service conditions are elastic, stress analyses were performed for each of 13 load components, so that stresses for arbitrary external loads can be obtained by superposition. In the numerical stress calculations the FE-code ABAQUS was used, the material behavior was assumed to be linear-elastic. Stress profiles along the circumferential weld were fitted by function of the external load, diameter and wall thickness of the branch pipe. Using these functions stresses can be estimated for similar T-joints if FE stress data are not available.

The heat affected zone (HAZ) of the weld, in which through-wall cracks are postulated, is an area perpendicular to branch pipe axis or a saddle shaped area in T-joints of type "TH6" and "TH3" type, respectively. To account for complex loading of cracks in T-joints the normal stresses (mode I) and shear stresses (mode II) in these areas are evaluated for given external loads using original FE data or their approximations. From these stresses stress intensity factors K_I and K_{II} are calculated. The normal stress criterion by Erdogan/Sih [2] for mixed mode is used to convert K_I and K_{II} in an effective K_I, which is then used in the mode I Failure Assessment Diagram (FAD) of SINTAP. These evaluations were implemented in the existing defect assessment program IWM VERB [3]. As an estimate of stress intensity factor for cracks under two-dimensional stress gradients in the HAZ area the existing solutions for cracks in cylinders and plates were combined. The calculation procedure was verified by elastic-plastic finite element analyses of T-joints with cracks.

NUMERICAL ANALYSES

T-joints without defects

Material properties of the stabilized austenitic stainless steel X 10 CrNiTi 18 9 at service conditions of T-joints are given in Table 1. In FE models built from 20-nodes elements four elements over the wall were used (Figs. 1-2).

Table 1. Mechanical properties of X 10 CrNiTi 18 9 [4]

T-Joint	Temperature, °C	Young's Modulus, GPa	Poisson's ratio, ν	Yield strength $R_{p0,2}$, MPa
TH6	50	200	0.3	228
TH3	180	192	0.3	209

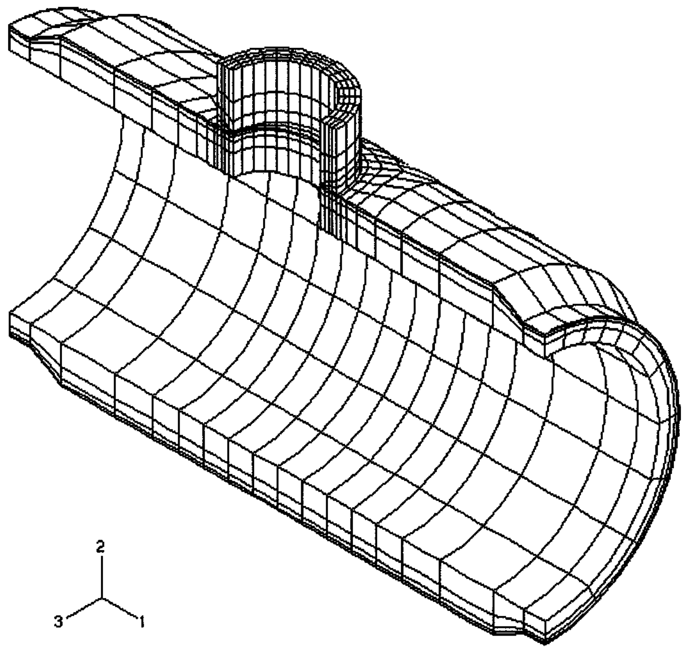


Fig. 1 Finite element model of tubular joint TH6

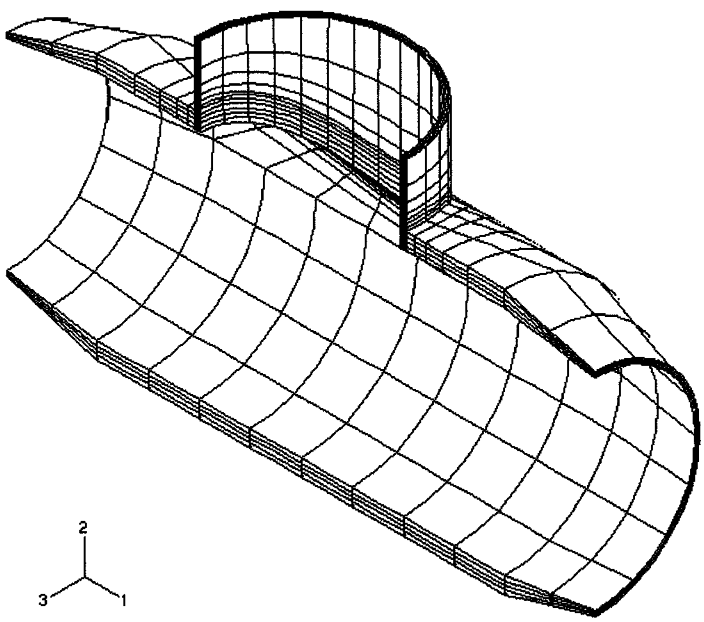


Fig. 2 Finite element model of tubular joint TH3

The calculations with the program system ABAQUS [5] have been performed for separated load components, six unit forces ($F_{x,y,z}$ = 1 kN), six unit moments ($M_{x,y,z}$ = 1 kNm), and for internal pressure (p_i = 1 MPa). Additional calculation has been done for the most severe "loading level D" (earth quake), with load parameters given in Table 2.

Table 2. Loading level D for TH6 and TH3 according to [4]

T-joint	T, °C	p_i, MPa	Run pipe Moments, kNm			Branch pipe Moments, kNm		
			M_x	M_y	M_z	M_x	M_y	M_z
TH6	50	4.15	-65.0	-55.2	-29.9	15.3	5.5	12.7
TH3	180	4.35	-9.8	-17.1	-18.6	11.6	5.3	12.3

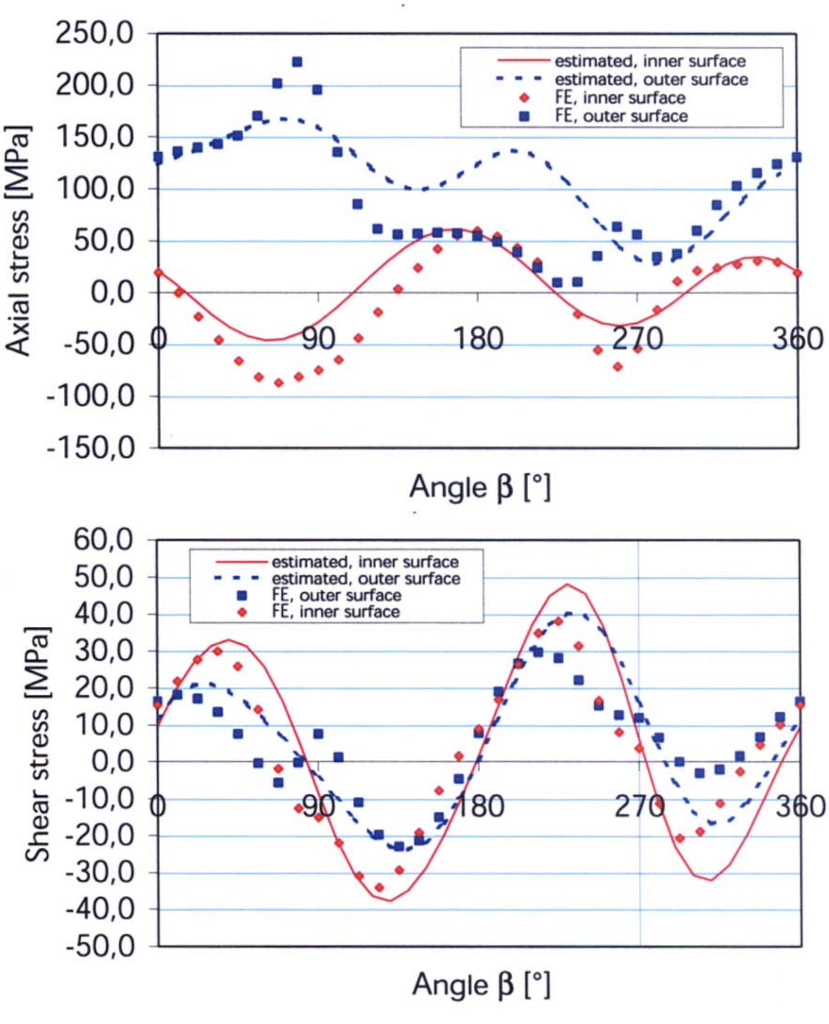


Fig. 3 Stress profiles at inner and outer surface of the branch pipe weld of the T-joint TH3

The resulting normal and shear stresses with respect to postulated crack plane on positions in the crack plane along the inner and outer circumference of the branch pipe were stored in the internal data base of the PC software. For arbitrary loading cases stresses can be evaluated within the PC software by superposition of stored FE data or estimated stress profiles. Fig. 4 shows a comparison of stress profiles for loading level D obtained by superposition of FE data and superposition of estimated data for TH3.

T-joints with through-wall cracks

For the validation of analytical estimates of $J_{I,II}$ and $K_{I,II}$ for T-joints with cracks of length $2\alpha = 60°$ and $2\alpha = 120°$ in the branch pipe weld were modeled by finite elements. The J-integral was calculated by the method of virtual crack extension in the crack plane direction and perpendicular to crack plane for mode I and mode II loading, respectively. From $J_{I,II}$ -values stress intensity factors were calculated by the relation

$$K_{I,II} = \sqrt{\frac{EJ_{I,II}}{(1-\nu^2)}} \quad . \tag{1}$$

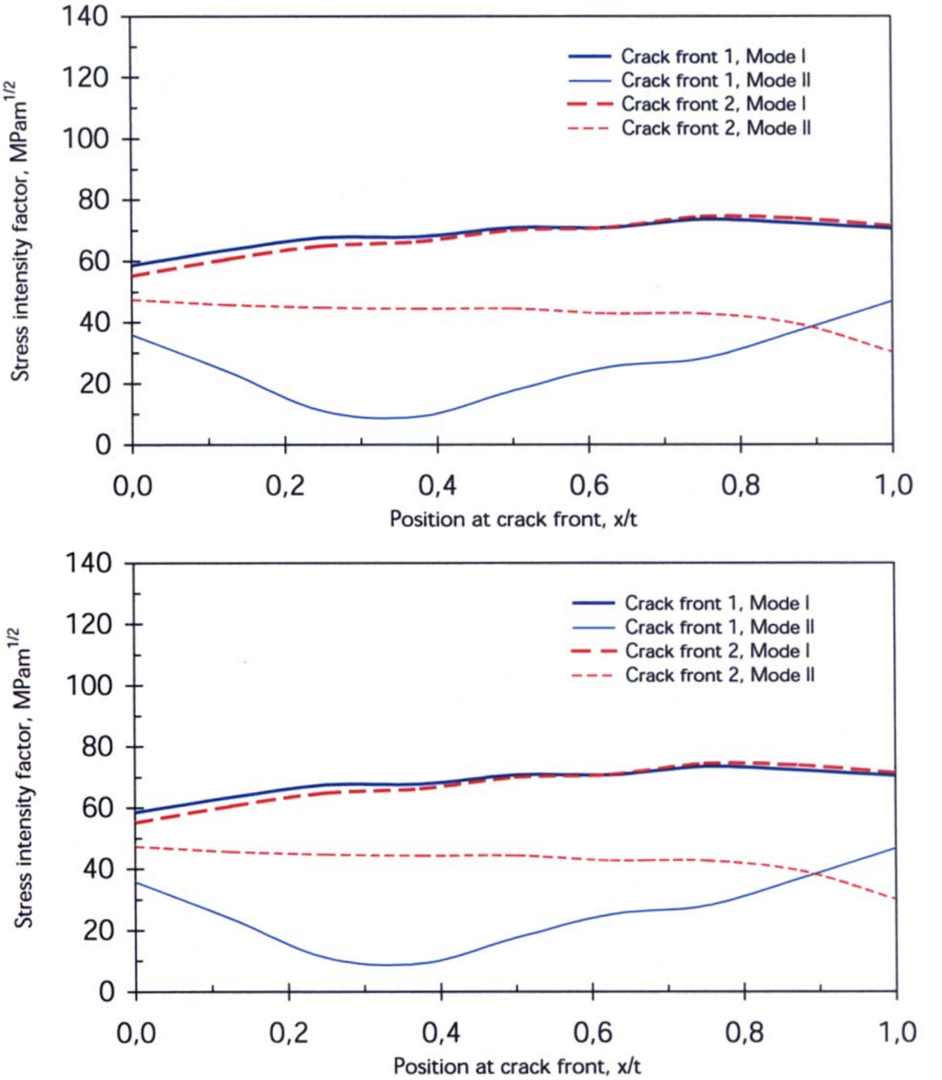
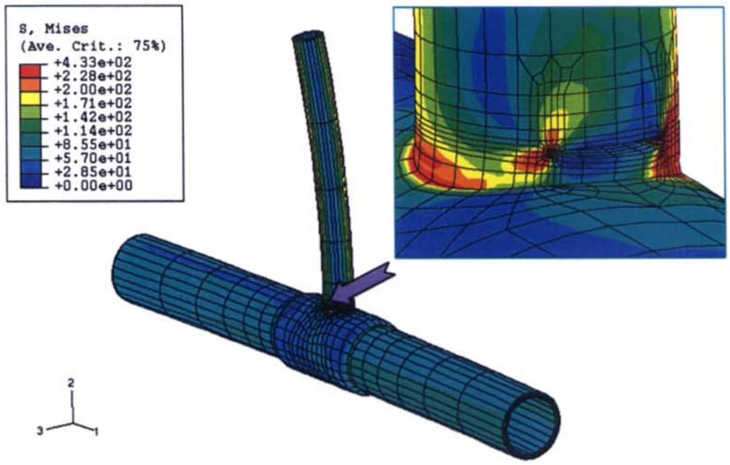
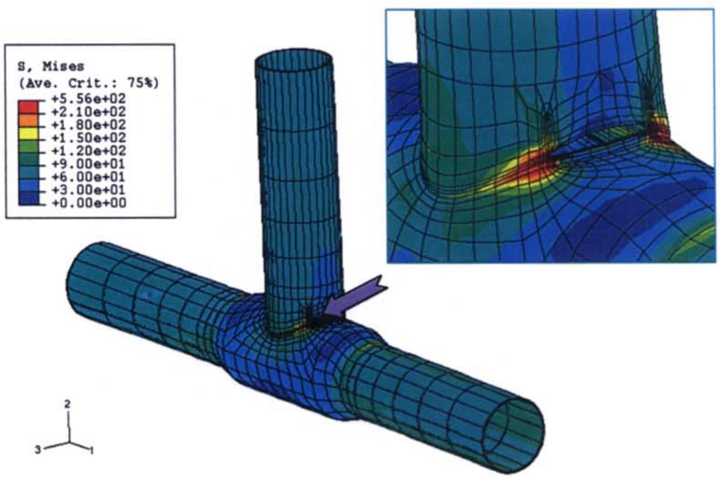


Fig. 4 Stress intensity factors K_I and K_{II} along the front of through-wall cracks in TH6. Cracks lengths $2\alpha = 60°$ (top) and $2\alpha = 120°$ (bottom).

Both linear-elastic and elastic-plastic analyses have been done. The results of the linear-elastic finite element analysis for TH6 in terms of stress intensity factor are shown in Fig. 5. Fig. 6 shows the deformation of T-joints and the equivalent stresses at the outer surface under loading level D.



TH6, $R_{p0,2}$ = 228 MPa



(b) TH3, $R_{p0,2}$ = 209 MPa

Fig. 5 Deformation of the T-joints and the equivalent stress patterns under loading level D

DEFECT ASSESSMENT CONCEPT AND PC SOFTWARE

For the fast assessments of defects detected by means of NDE in circumferential welds of branch pipes of tubular joints a calculation procedure has been developed and implemented in the PC defect assessment software IWM VERB [3]. Based on the SINTAP approach, the crack driving force is estimated in terms of J-Integral, from forces and moments acting at the ends of the branch and run pipes. Critical crack sizes, critical loads or safety margins can be calculated using initiation fracture toughness or J-resistance curves. Fig. 7 shows the input form for the calculation of safety margins. Different assessment levels can be chosen depending on material tensile data available. For the input of geometry and loading data a chart of the component can be displayed.

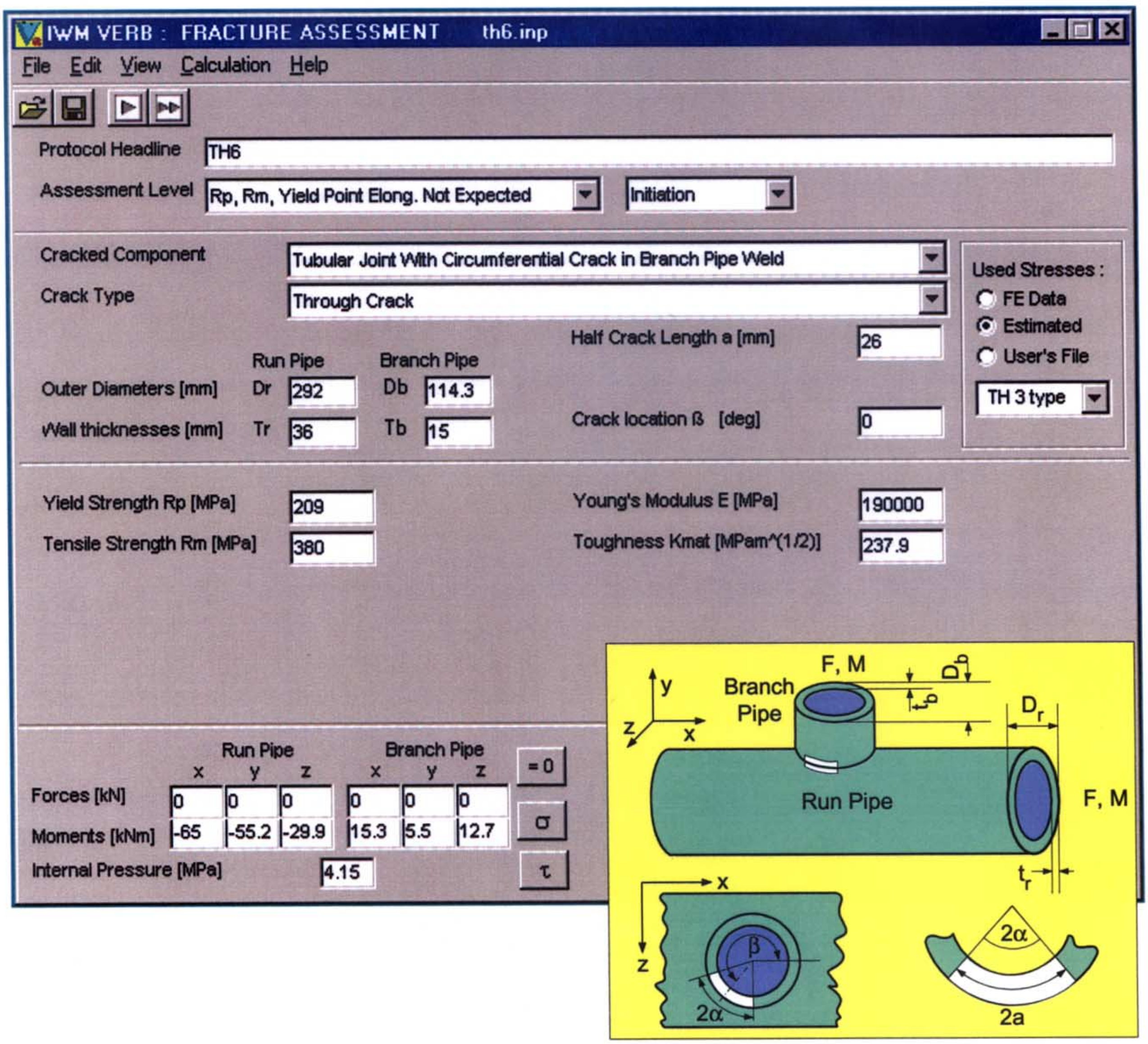


Fig. 6 Input form for the assessment of T-joints in IWM VERB

The results are presented in a failure assessment diagram. An example in Fig. 7 with the option "crack initiation" shows an assessment point in the "safe region" of the diagram well below the assessment line.

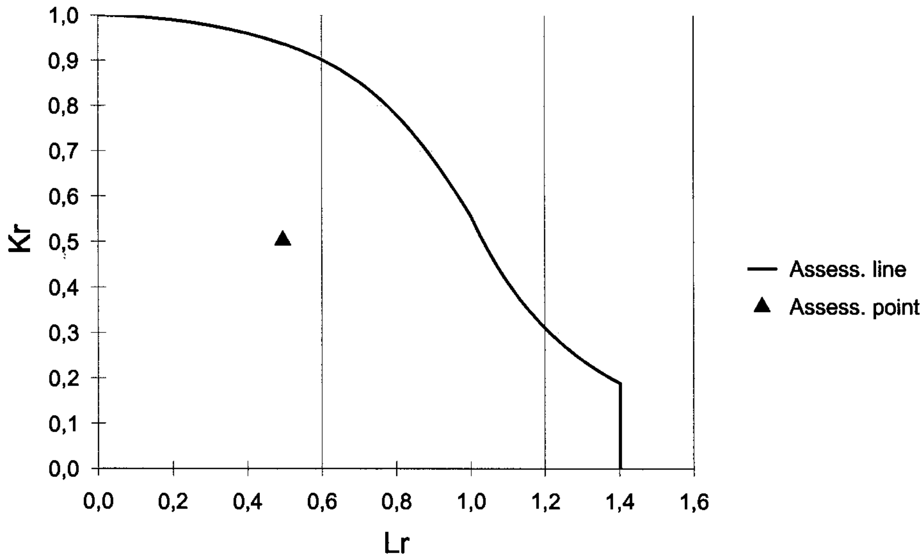


Fig. 7 Failure Assessment Diagram

To obtain the coordinates K_r and L_r of the assessment point, the values of stress intensity factor and of the plastic limit load have to be calculated. Because solutions for the stress intensity factor, K, and for the limit load, F_L, of tubular joints with cracks are available for a few special cases only, a simplified procedure has been developed to conservatively estimate stress profiles in the weld joint along the inner and outer surface of the branch pipe and to use them for calculating K and F_L of finite-length cracks at inner surface and of through-wall cracks. The calculation of parameters K and F_L for cracks in a straight pipe subjected to stresses obtained for the tubular joint is expected to be conservative for the considered problem. For semi-elliptical surface cracks at the inner surface of a pipe under two-dimensional stress gradients, available influence functions are used. In the case of through-wall cracks, a combination of solutions for a plate (to assess the influence of stress gradient in the crack length direction) and for a pipe under axial tension and a through-wall bending (to account for stress gradient over the wall) is used.

The surrounding of the branch pipe weld is considered as a straight pipe. As there are no solutions for circumferential through-cracks under two-dimensional stress gradient, two solutions are combined: a) for a circumferential crack in a pipe under axial stress and through-wall bending [6], b) for a crack in a plate under stress profile in the crack length direction [7]. Using solution b) stress intensity factors $K_{1,Plate}$ and $K_{2,Plate}$ for both crack fronts („1" and „2") under stress profile and $K_{m,\ Plate}$ under average stress over crack length are calculated. Factors $F_1 = K_{1,Plate} / K_{m,\ Plate}$ and $F_2 = K_{2,Plate} / K_{m,\ Plate}$ are used as correction factors in Eq. (2) to account for stress gradient along the crack length. Because the bending stress varies along the crack length, different bending stresses are used in calculations of $K_{1,\ Pipe}$ and $K_{2,\ Pipe}$ for crack fronts 1 and 2 by solution a). They are taken as the average value over the adjacent half of the crack. The resulting stress intensity factors for crack fronts 1 and 2 are

$$K_1 = F_1 K_{1,Pipe} \qquad (2)$$
$$K_2 = F_2 K_{2,Pipe} \,.$$

Because of the loading complexity and of inaccuracy of estimated stresses, safety factors are built in calculation procedure for stress intensity factors.

The conservatism of $J_{I,II}$ and $K_{I,II}$ values calculated by this semi-analytical procedure has been verified by results of three-dimensional FE analyses of tubular joints with cracks (Table 3).

Table 3. Comparison of K and J obtained by the analytical procedure and by FE method

	K [MPam$^{1/2}$]				J [kJ/m^2]			
	Linear-elastic analysis				Elastic-plastic analysis			
	TH3		TH6		TH3		TH6	
Crack length 2α	60°	120°	60°	120°	60°	120°	60°	120°
Analytical procedure	91,6	230,7	119,7	208,1	42,1	313,3	74,7	228
FEM	92,5	163,7	64,8	122,5	61	124,7	27,6	71

CRITICAL CRACK SIZES

For the proof of leak-before-break conditions the analytical procedure was used to calculate critical lengths of through-wall cracks in several tubular joints under most severe loading level D. Using J-resistance curves from [8] calculations were conservatively cut off at the stable crack extension of 1 mm, corresponding to J_{mat} = 468 kJ/m^2. The resulting critical crack lengths are very large (Table 4), so that for rather long defects in the circumferential weld the leak-before-break conditions are predicted.

Table 4. Critical crack lengths for loading level D

T-joint	Critical crack length [mm]
TH 2	245
TH 3	310
TH 6	108
TH 12	320

CONCLUDING REMARK

The comparison of analytical and FE results shows still some discrepancies, particularly for the T-joint TH3. Further investigations are planned to solve remaining problems.

REFERENCES

1. SINTAP: Structural Integrity Assessment Procedures for European Industry, British Steel, draft report BE95-1426, 1999 (to be published 2001)
2. F. Erdogan, G.C. Sih, On the crack extension in plates under plane loading and transverse shear, J. Basic Eng. **85D** (1963) pp. 519ff.
3. Defect assessment software IWM VERB, Fraunhofer Institut für Werkstoffmechanik, Freiburg, 2000.
4. Roth, Ermittlung von Spannungen im Verschneidungsbereich des T-Stückes, Bauteile TH3 und TH6, Arbeitsberichte Nr. KWU NDA3/00/1025a, KWU NDA3/00/1249, Siemens AG Bereich Energieerzeugung (KWU), Erlangen, 2000 (in German).
5. ABAQUS/Standard User's Manual, Version 5.8, Hibbitt, Karlsson & Sorenson Inc. (1998).
6. France, C.C. et al., New Stress-Intensity Factor and Crack Opening Area Solutions for Through-Wall Cracks in Pipes and Cylinders, Proc. ASME Pressure Vessel & Piping Conference, July, 1997
7. Tada, H. et al., The Stress Analysis of Cracks Handbook, Del Research Corporation, Hellertown, 1973
8. W. Stadtmüller et al, Beitrag zur bruchmechanischen Absicherung von Rohrleitungen aus hochzähem Werkstoff, Abschlussbericht MPA Stuttgart Nr. 8755 00 000 , Stuttgart, 1997 (in German)