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EXTENSION OF FRACTURE MECHANICS EVALUATION METHODS BY CONSIDERATION OF MULTIAXIALITY OF STRESS STATE FOR PIPING COMPONENTS

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1 Introduction

The range of applicability of fracture mechanics methods is restricted, i.e. by limits of transferability of fracture mechanics material laws. Therefore an essential point of view is the question of transferability of fracture mechanics material laws or parameters to the component. Concerning the crack initiation the effective crack initiation value J_{i_eff} , determined on the basis of "stretched zone"-evaluation can be considered as a transferable material characteristic /1/. Beyond crack initiation the crack resistance curves depend on the geometry as well as specimen dimensions and are influenced mainly by the gradient of the multiaxiality of stress state across the ligament /1/. It is possible to make an assessment due to the transferability of the crack resistance curve of the specimen to the component by comparing the multiaxiality of stress state across the ligament of component and specimen. Furthermore, an assessment of the load bearing and failure behaviour of the component in comparison to the specimen, is approachable.

2 Components, loading parameter and material characteristics

Within the scope of a research program tests were carried out by MPA Stuttgart on degraded ferritic T-branches and semi-shell pipe bends (90 deg.) with dimensions corresponding to the main cooling pipes of pressurized water reactors (PWR) /2/. In the following fracture mechanics evaluations for one of the tested T-branches (AZ 6) and for two pipe bends (RB 5, RB 6) will be performed. Table 1 summarizes the overall dimensions and flaw geometry, the loading parameters and the material characteristics of these components.

3 Evaluation pocedure

Figure 1 schematically shows the fracture mechanics evaluation procedure for these investigations. On the one hand, the crack resistance curve (J_R -curve) and the initiation value J_{i_eff} are evaluated by CT20 (20% s.g.) specimen testing. On the other hand, the component load expressed by the J-integral is calculated by Finite Element (FE) calculations using elastic plastic material

behaviour. For these calculations the FE program ABAQUS /3/ and the virtual crack extension method according to Parks /4/ is used. In the case of the pipe bends two calculations with a constant crack depth of $a/t=0.25$ and $a/t=0.5$ are performed. J-integral values for various crack depths are determined by interpolation between these two calculations. Comparing the initiation value $J_{i\text{eff}}$ with the component load, the bending moment at which initiation occurs can be determined.

For the qualitative evaluation of the fracture behaviour beyond initiation additional calculations of the multiaxiality of stress state across the remaining cross-section are performed for CT20 specimens as well as for the components. The degree of multiaxiality is quantified according to /1/ by the multiaxiality quotient $q = \sigma_v \sqrt{3} / \sigma_0$ (σ_v =v.Mises stress, σ_0 =first invariant of the stress tensor). Small q values are denoted according to this definition for a high degree of multiaxiality.

4 Results of multiaxiality

Figure 2 shows the q -gradient across the ligament of a CT20 specimen for three load steps. The q -gradient shows over a distance of about 1/3 of the ligament values between 0.2 and 0.3 and increases considerably near the neutral axis. In comparison to this Fig. 3 shows q -gradients across the ligament of a pipe bend with a flaw depth of $a/t=0.5$ at the plane of symmetry. For internal pressure loading only the calculated q -gradient is smaller than that of the CT20 specimen. The multiaxiality quotient first of all increases clearly in the proximity of the crack tip and during increasing moment loading across the complete remaining cross-section due to bending moment load, and plasticification in the case of ductile materials. Therefore, the transferability of the full plot of the J_R -curve is not possible. In the case of bending moment loading the load bearing capacity of the pipe bend should be greater than that of the CT20 specimen.

Figures 4a and 4b show the q -gradients for the T-branch AZ 6 across the cross-sections A to D as defined in Fig. 4c. For internal pressure loading significant higher q -values in comparison to the CT20 specimen are calculated for all four cross-sections. At dominant bending moment loading only the cross-sections B and C are showing comparable q -values over a distance of about 1/8 of the ligament. Therefore, a higher load bearing capacity of the T-branch can be expected.

5 Results of fracture mechanics evaluation

T-branch AZ 6

For this component the crack initiation value is $J_{i\text{eff}}=20$ N/mm. The CT20 specimen failed by brittle fracture at a maximum J -value of 40 N/mm after a ductile crack extension of about 0.1 mm.

Figure 5 shows results of the J-integral calculation along the crack front for several load steps. If the crack initiation value of the CT20 specimen is compared with the calculated J-integral as a function of the bending moment, Fig. 6, crack initiation at the component can be expected at 1.1 MNm. A load of approx. 1.5 MNm is the result of the J_{max} -value of 40 N/mm. During the test the bending moment was increased up to 1.7 MNm. There was no failure due to leakage or break. Crack initiation was detected by

acoustic emission measurement at about 1.2 MNm. This agrees well with the predicted value of 1.1 MNm. Significant crack growth was detected at bending moments ≥ 1.6 MNm. This value is above the moment which is calculated for the failure load of the CT20 specimen.

Pipe bend RB 5 and RB 6

Figure 7 shows results of the J-integral calculation along the crack front for a pipe bend with a flaw depth of $a/t=0.5$. The maximum J-values are calculated at the plane of symmetry. Fig. 8 shows the J-integral at the plane of symmetry as a function of the crack depth in comparison with the J_R -curves for material A used for pipe bend test RB 5. Fig. 9 shows the results for the pipe bend test RB 6 respectively. On the basis of these diagrams crack initiation can be expected at bending moments between 2.3 MNm (semi-shell 2) and 3 MNm (semi-shell 1) for pipe bend RB 5 and between 0.3 MNm (semi-shell 1) and 0.6 MNm (semi-shell 2) for pipe bend RB 6. These moments are calculated on the basis of the maximum J along the crack front (local point at the plane of symmetry) and are therefore minimum values. If the calculation will be performed with an averaged J-integral along the crack front higher initiation moments will be the result.

In the test RB 5 initiation was detected by DC-potential drop measurement at a bending moment of about 4 MNm and in the test RB 6 at about 1 MNm. This correlates well with the calculated initiation moments. On the basis of Figs. 8 and 9 crack growth as a function of the bending moment is plotted in Figs. 10 and 11. The comparison with DC-potential measurements shows a higher load bearing capacity of the tested components. Such behaviour could be expected because of the multiaxiality consideration described in chapter 4.

6 Conclusions

The calculated crack initiation loads show good agreement with experimental results. The multiaxiality quotient q determined across the ligament, however, is different between CT20 specimens and the degraded components. Therefore, it is not possible to presume the direct transferability of the full plot of the crack resistance curve evaluated at CT20 specimens to the components. For that reason a greater load bearing capacity of the investigated components could be expected. This has been confirmed by the tests conducted.

7 References

- /1/ Clausmeyer, H., K. Kussmaul, E. Roos: Influence of stress state on the failure behavior of cracked components made of steel. Appl Mech Rev vol 44, no 2, (1991), pp.77-92
- /2/ Schwarz, Th., K.-H. Herter, P. Julisch and W. Stoppler: Experimental investigations on the strength and fracture behaviour of degraded piping components. SMIRT 12 vol F, (1993)
- /3/ ABAQUS: User's Manual. Version 4.8. Hibbit, Karlsson & Sorensen, Inc., (1989)
- /4/ Parks, D.M.: The Virtual Crack Extension Method for Nonlinear Material Behaviour. Computer Methods in Applied Mechanics and Engineering, Vol. 12, (1977), pp.353-364

COMPONENT		T - BRANCH		PIPE BEND			DIMENSIONS		
		AZ 6		RB 5	RB 6				
material		B		A	B		T - branch		
temperature	°C	30		20	130				
flaw	position	inside corner flaw longitudinal (run pipe axis)		both bend flanks inside, longitudinal		Inner run pipe diameter D_i : 765 mm run pipe wallthickness t_r : 45 mm Inner branch diameter d_i : 224 mm branch wallthickness t_b : 40 mm			
	geometry	spark eroded notch (quarter-elliptical) with fatigue crack		spark eroded notch with fatigue crack					
depth	a/t	0.25	s1	0.40	0.48				
	a	mm		s2	0.46			0.40	
length	l	mm		s1	21.7	26.1			
				s2	25.1	21.8			
		42		845 ($\alpha = 45^\circ$)					
load							pipe bend		
internal pressure	MPa	11.0		15.2	15.5				
pressure medium		air		air	air				
bending moment	MNm	In-plane (quasistatic)		In-plane, opening mode swelling quasistatic		inner diameter D_i : 765 mm wallthickness t : 54 mm bending radius R : 1130 mm bend angle : 90°			
		1.7		8.9 5.8					
material characteristics									
C_v	J	~ 15		200	~ 50				
$R_{p0,2}$	MPa	670		518	500				
R_m	MPa	892		651	695				
Young's modulus	MPa	209000		218000	198000				
$J_{eff}^{1.)}$	N/mm	19	s1	171	32				
			s2	171	34				

material A : 20 MnMoNi 5 5 (upper shelf impact energy > 150 J, transverse specimen)
material B : MnMoNiV-special melt (upper shelf impact energy ~ 50 J, transverse specimen)
1.) Initiation value based on stretched zone evaluation
s1 = semi-shell 1, s2 = semi-shell 2

Table 1 : Investigated components, loading parameters and material characteristics

Fig. 1 : Fracture mechanics evaluation procedure by consideration of multiaxiality of stress state

Fig. 2 : Gradient of q across the ligament of a CT 20 specimen

Fig. 3 : Gradient of q for a pipe bend with $a/t = 0.5$

Fig. 4a : Gradient of q for the T-branch AZ 6 (loading: internal pressure $p_i = 11$ MPa)

Fig. 4b : Gradient of q for the T-branch AZ 6 (loading: $p_i + M_b = 1.7$ MNm)

Fig. 4c : Flaw geometry of the T-branch AZ 6

Fig. 5 : J-integral along the crack front for T-branch AZ 6

Fig. 6 : J-Integral as function of the bending moment for T-branch AZ 6

Fig. 7 : J-Integral along the crack front for a pipe bend with $a/t = 0.5$

Fig. 8 : R-curve method applied to pipe bend RB 5

Fig. 9 : R-curve method applied to pipe bend RB 6

Fig. 10 : Comparison of calculated and measured (DC-pot.) crack growth for pipe bend RB 5

Fig. 11 : Comparison of calculated and measured (DC-pot.) crack growth for pipe bend RB 6