Valuation of a Ductile Vessel Rupture by R-Curve Analysis with CT-Specimens and Wide Plate Tests

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Abstract

A large volume, thin-walled feedwater vessel was weakened in the longitudinal direction by a slit sealed from the inside. With the help of compact-tension-specimens and wide plates attempts were made to analyse the failure by means of elastic-plastic fracture mechanics, in which account was taken of the bulging of the vessel by use of the so called "Folias factor". With J_R-curves obtained from wide plate tensile tests the crack driving force curves provide stresses at crack initiation and instability which are approximately 20 to 30 % below the corresponding values of the internal pressure test. With regard to stable crack growth very good agreement was achieved.

1. Introduction

A slit sealed from the inside was machined longitudinally into the base material of a decommissioned large volume feedwater vessel. It was loaded by internal pressure until instability of the slit, and the events at failure were monitored by means of timing wires, clip gauges, TV, and high speed camera techniques /1/. The test data for the vessel was as follows:

Material:	StE 43 according to Table 1
Dimensions:	O.D. x T = 3000 x 21 mm
	Length = 14 000 mm
Slit:	Length = 600 mm
Pressure medium:	Water
Testing temperature:	Room Temperature

Subsequent to the measurements performed the stable crack growth started at an internal pressure of approximately 1.8 MPa (nominal stress σ_n = 128 MPa), Table 2. The crack extended at each crack tip by Δa = 70 mm at a maximum internal pressure of 3.6 MPa (nominal stress

σ_n = 255 MPa). Under the same maximum load, it enlarged to Δa-values of about 145 mm until it started to extend unstably under falling load and branched off in the circumferential direction. The fracture area was strongly bulged, Fig. 1, this was considered in the approach for the failure analysis.

2. Fracture Mechanics Tests

Altogether three wide plates and several CT-specimens were removed in the circumferential direction from purely elastically loaded vessel areas subsequent to the internal pressure tests. Testing cross sections of 500 x 21 mm were chosen for the wide plates, and through-wall slits with total lengths of 60, 105, and 250 mm were machined in the central areas of the plates.

The J_R-curves from CT-specimen tests were determined according to the single specimen method /2/, and for correspondence with the flaw ends used in the vessel and the wide plates only 0.2 mm wide sawing slits were considered. The J-integral evaluation of the wide plate tensile tests was made according to the approximation method of Rice et al. /3/ and Landes et al. /4/, in which the "plane stress condition" was chosen for the computation of the contribution of the elastic strain to the J-integral.

The J_R-curves determined with CT-specimens and wide plates are compared in Fig. 2. The material characteristics obtained from the wide plate tensile tests using various slit lengths were approximately equal. At nearly similar initiation values the wide plates prove to have the higher crack resistance curves as is to be expected because of the different stress conditions (mainly plane strain condition in the CT-specimens and essentially plane stress condition in the wide plates).

3. Elastic-Plastic Fracture Analysis of the Vessel Fracture

Using the J-integral-approximation method after Shih and Kumar /5/, crack driving force curves are calculated assuming the load or stress on the sample remains constant and plotted against crack extension. The load at crack initiation can be evaluated from the J_R-curve by the J_{Ic}-value. The load at instability increases over the value at initiation and can be calculated from the J_R-curves via the known tangent construction. Thus, vessels can only be considered as plates in their development, so that the following disadvantages occur:

- Account cannot be taken of the considerable stable crack growth on the vessel
- The bulging of the vessel is disregarded.

In the failure analysis performed for the vessel fracture it was therefore attempted to consider the stable crack growth shown by J_R-curves from wide plate tensile tests and to introduce a bulging factor into the J-integral-approximation method.

When calculating the actual failure load of a thin-walled vessel with a through-wall flaw and subject to internal pressurisation the Folias bulging factor M can be used /6/. This factor expresses the additional stress caused by bulging in the vicinity of the crack and by which the crack driving force is increased. In interpreting the vessel test the bulging effect was taken into account by multiplying the nominal stress ($\sigma_n = p \cdot (O.D.-T)/2T$) with the Folias factor for the numerical determination of the crack driving force curves according to the J-integral approximation method, Table 3. The computations were performed with a fictious plate width of 5000 mm, in case of larger plate widths no size effect can be found to be worth mentioning.

The crack driving force curves determined for the feedwater vessel are represented in Fig. 3 according to the J-integral approximation methods without, and with, consideration of the bulging. The values assessed in this manner for the crack initiation and instability include the size for the stable crack growth and are compared with each other in Fig. 4. If other introduced equations are used for the bulging factor, the component curves shift only insignificantly. The failure load calculated changes then at about max. ± 3 %.

The loads determined from flat plate and CT-specimens using the standard equations were too high when compared with the test vessel results. The introduction of the bulging factor enabled a conservative assessment, whereby the agreement between test and computation is better with the material characteristics from the wide plate test. The stable crack growth measured on the test vessel can almost exactly be confirmed by means of the crack extensions measured on the wide plate tensile tests.

4. Conclusions

The wide plate tensile test is not merely an appropriate testing method for the comparative valuation of strength, deformation and fracture behaviour of various materials and welding conditions. It can also be used to determine constitutive laws for the analytic valuation of complex component geometries and the resulting stress and strain conditions. For a selected example of which all test-technical conditions were known a fracture mechanics failure analysis was made by means of crack resistance curves from tests with CT-specimens as well as from wide plate tests. For the crack initiation and the instability of a large volume, thin-walled vessel conservative values were computed by means of the J-integral approximation method transferring the bulging effect of the vessel to the equations for the plane plate. It could be shown that the fracture analysis relied on wide plate tests is in advantage against conventional small scale specimens, especially in case of stable crack growth.

5. Literature

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/6/ Folias, E.S.: The Prediction of Catastrophic Failures in Pressurised Vessels. in G.C. Sih et al. (Hrsg.), Prospects of Fracture Mechanics, Noordhoff International Publishing, Leyden, 1974.

TABLE 1: MATERIAL PROPERTY VALUES OF THE FEEDWATER TANK AT ROOM TEMPERATURE

MATERIAL	REMOVAL OF SAMPLE	$R_{p0,2}$ (MPa)	R_m (MPa)	A_5 (%)	Z (%)	A_v (J)	K_Q (MPa $\sqrt{mm}$)	K_{max} (MPa $\sqrt{mm}$)
St E 43 (BH 43 W)	LD 1)	536	694	24	55	52, 58	2 270	3 500
	CD 2)	512	688	24	63	96	2 200	3 380
	LD 1)	523	692	26	64			
	CD 2)	514	681	23	59			
	CD 3)	497	670	24	65			

1) LD... LONGITUDINAL DIRECTION
2) CD... CIRCUMFERENTIAL DIRECTION
3) FOR σ-ε-APPROXIMATION ACCORDING TO RAMBERG-OSGOOD

TABLE 2: RESULTS OF THE INTERNAL PRESSURE TEST WITH THE FEEDWATER TANK

INTERNAL PRESSURE		NOMINAL STRESS 4)				COD		CRACK
INITIATION P_i (MPa)	MAXIMUM P_{max} (MPa)	ABSOLUTE σ_i (MPa)	ABSOLUTE σ_{max} (MPa)	RELATED $\frac{\sigma_{max}}{R_{p0,2}}$	RELATED $\frac{\sigma_{max}}{\sigma_{flow}}$	COD_i (mm)	AT P_{max} COD_{max} (mm)	Δa 3) (mm)
1,8	3,6	128	255	0,51	0,44	2,2	25 1) 45 2)	70 1) 145 2)

1) AFTER REACHING THE MAXIMUM PRESSURE (P_{MAX})
2) AT INSTABILITY
3) $2a + 2\Delta a$ ... LENGTH OF THE FLAW + STABLE CRACK GROWTH ON BOTH SIDES
4) $\sigma_n = p \cdot (O.D. - T) / 2T$

TABLE 3: EQUATIONS FOR THE DETERMINATION OF CRACK DRIVING FORCE CURVES OF CENTRE CRACKED WIDE PLATES (CCP), BASING ON THE J-INTEGRAL BY CONSIDERING A BULGING FACTOR /5/

EQUATIONS:

$$J = J_{el} + J_{pl}$$ ELASTIC AND PLASTIC PART OF J

$$J_{el} = \frac{\pi \cdot a \cdot \bar{F}^2}{E' \cdot 4W^2 \cdot T^2} \cdot f^2\left(\frac{a}{W}\right)$$

E' = E FOR PLANE STRESS

$E' = E/(1-\mu^2)$ FOR PLANE STRAIN

$a = a_{eff}$ (EFFECTIVE CRACK LENGTH)

$$J_{pl} = \alpha \cdot \sigma_o \cdot \varepsilon_o \cdot a\left(\frac{c}{W}\right) \cdot h_1\left(\frac{a}{W}, n\right) \cdot \left(\frac{F}{F_o}\right)^{n+1}$$

MODIFIED BY A BULGING FACTOR FOR THIN WALLED VESSELS WITH AXIAL FLAW

$$\bar{F} = \sigma_n \cdot A_n \cdot M_F = F \cdot M_F$$

$$M_F = \sqrt{1 + 0{,}317\,\lambda^2} \quad \text{WITH} \quad \lambda^2 = \frac{a^2}{R \cdot T} \cdot \sqrt{12\,(1-\mu^2)}$$

DESIGNATIONS:

F	...LOAD PER UNIT THICKNESS	h_1	...FUNCTION OF THE GEOMETRY AND MATERIAL
F_o	...LIMIT LOAD PER UNIT THICKNESS	$f(a/W)$	...FUNCTION OF THE GEOMETRY
W, c	...DIMENSIONS OF THE WIDE PLATE	σ_n	...NOMINAL STRESS
a	...HALF LENGTH OF THE FLAW	A_n	...NOMINAL CROSS SECTION
α, n	...CONSTANTS TO DESCRIBE THE MATERIAL FLOW PROPERTIES AFTER RAMBERG-OSGOOD	M_F	...BULGING FACTOR AFTER FOLIAS
		R	...RADIUS (CENTRE WALL)
σ_o, ε_o	...GENERALLY THE VALUES AT YIELD STRESS ($\varepsilon_o = \sigma_o/E$)	T	...THICKNESS OF THE WALL

DIMENSIONS O.D. x T = 3000x21mm
LENGTH 14000 mm
MATERIAL ST E 43
SLIT LENGTH 600mm

INTERNAL PRESSURE 3,6MPa (σ_n = 255MPa)
PRESSURE MEDIUM WATER, A_B/A_R = 0,07

FIGURE 1: FRACTURE OF THE FEEDWATER TANK

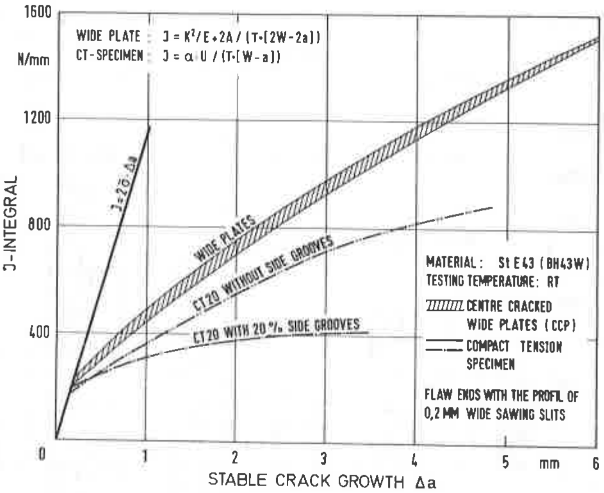

FIGURE 2: J_R-CURVES (MATERIAL CHARACTERISTICS) FROM WIDE PLATE TESTS AND COMPACT TENSION SPECIMEN TESTINGS

INTERNAL PRESSURE TEST

σ_i = 127 MPa
σ_{max} = 254 MPa

$\Delta a_{p\,max}$ = 70 mm
$\Delta a_{instable}$ = 145 mm

CENTRE CRACKED WIDE PLATE

i ... initiation
c ... collapse
SG... Side Groove

PLANE STRESS

a = 300.00 mm
W = 2500.00 mm
T = 21.00 mm
L = 10000.00 mm

R_m = 670.00 N/mm²
E = 193100.00 N/mm²
μ = 0.3000
alpha = 5.3331
n = 5.5323
EPS0 = 3.10 ‰
SIG0 = 497.50 N/mm²

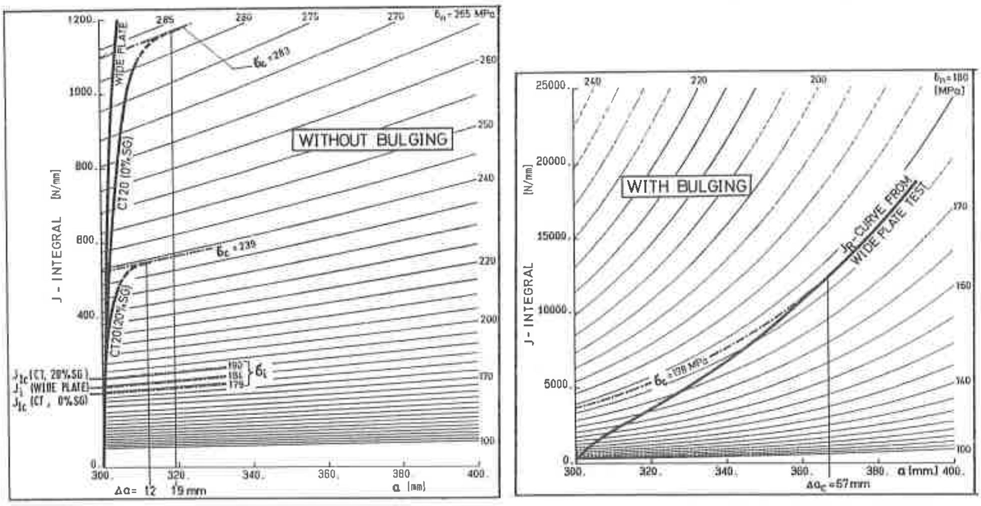

FIGURE 3: DETERMINATION OF THE FAILURE STRESSES FOR THE FEEDWATER TANK WITH J_R-CURVES FROM WIDE PLATE TESTS AND COMPACT TENSION SPECIMEN TESTINGS, ACCORDING TO THE J-INTEGRAL APPROXIMATION METHOD
LEFT: WITHOUT CONSIDERATION OF BULGING, RIGHT: WITH CONSIDERATION OF BULGING

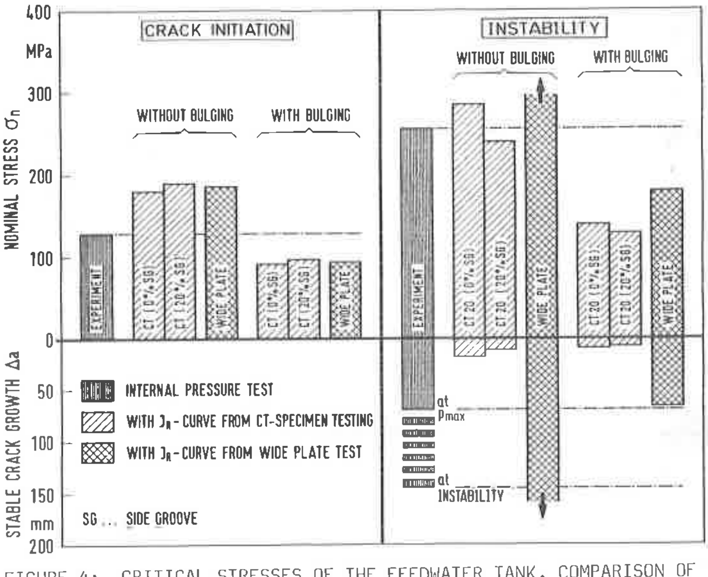

FIGURE 4: CRITICAL STRESSES OF THE FEEDWATER TANK, COMPARISON OF THE RESULTS FROM THE J-INTEGRAL APPROXIMATION METHOD WITH THOSE OF THE INTERNAL PRESSURE TEST