SMiRT-12 / K. Kussmaul (Editor)

GF01/1

FRACTURE MECHANICS ANALYSES INCLUDING CONSTRAINT INVESTIGATIONS ON REACTOR PRESSURE VESSELS UNDER PRESSURIZED THERMAL SHOCK LOADING

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ABSTRACT

In the integrity assessment of reactor pressure vessels (RPV) the emergency core cooling system injection is one of the main load cases to be analyzed. For a more generic assessment parametric analyses are done concerning the load pattern, the postulated crack geometry and the material properties.

With detailed axisymmetric and 3d-finite element (FE)-models of reactor pressure vessels temperature distributions in the structures and the deformations are calculated by elastic plastic FE-analyses for axisymmetric and asymmetric strip like cooling assumptions. With it boundary conditions for finite element detail models with partly and 360° circumferential cracks are determined. Different material properties for the circumferential weld near the core mid height, the cladding and the base metal with estimated influence of neutron irradiation are considered. Crack loading based on the J-integral is calculated for different crack geometries and different parameters describing the constraint on the crack ligament with proposals for a fracture assessment concept are discussed. Furthermore simplified methods based on analytical formulas to calculate the stress distribution in the wall and the stress intensity factor are applied and compared with finite element results.

INTRODUCTION

Integrity assessment of pressure vessels are based on fracture analyses with numerical methods like finite element as well as simplified methods with analytical approximations. To qualify the different methods the results are compared especially for the case of thermal and mechanical transient loading. Calculations concerning the behaviour of RPVs and of postulated circumferential cracks in the welds near the core mid height due to loadings in connections with emergency cooling cases are presented. For that the analysis technique based on finite element programs /ADN90/ with suitable pre- and postprocessors is used. For the investigations axisymmetric and 3d-FE-models for two pressure vessels have been developed (Figs 1-2). Furthermore analytical formulas to determine the axial stress distribution in cylindrical bodies under axisymmetric or strip like cooling assumptions as

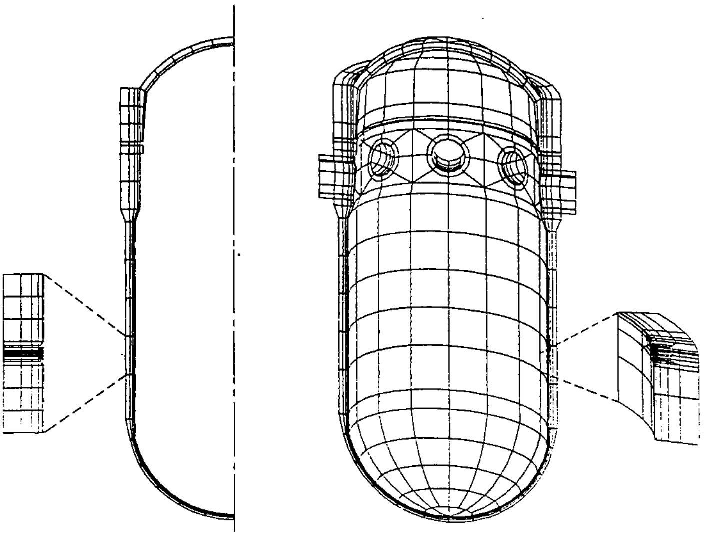

Fig. 1: RPV-1: FE-models (axisymmetric and 3d)

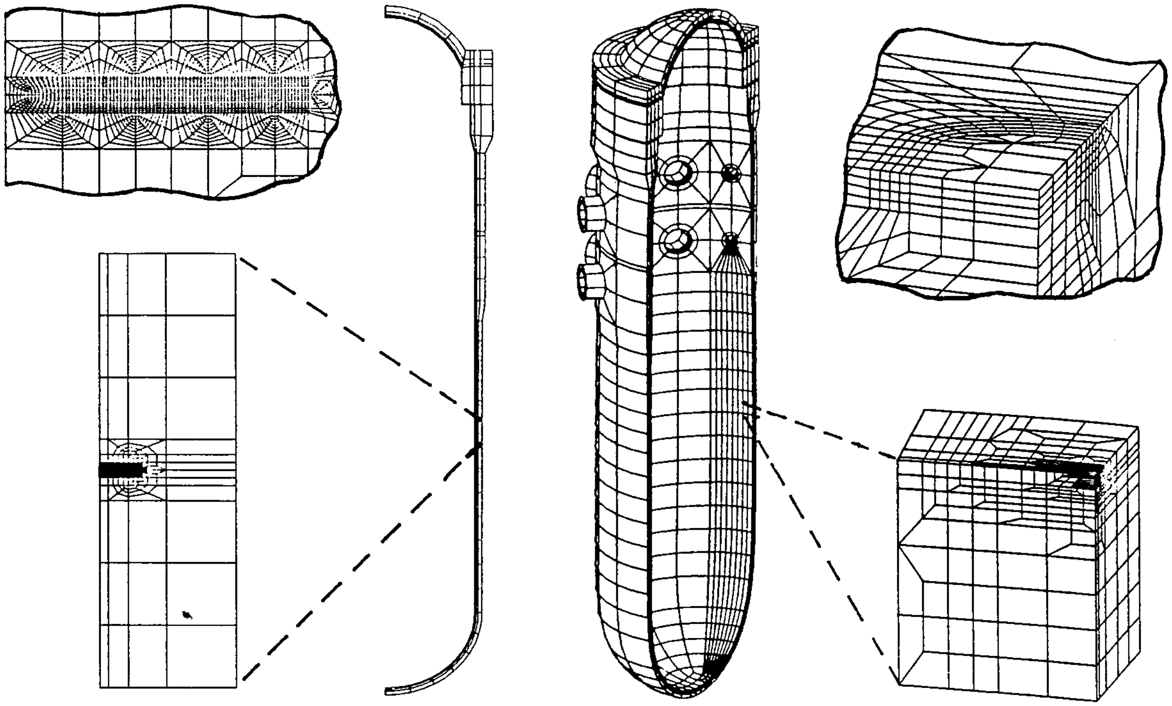

Fig. 2: RPV-2: FE-models (axisymmetric and 3d)

well as formulas of rules and regulations for stress intensity factors have been used.

In the fracture mechanical assessment the J-integral concept is applied and parameters describing the stress triaxiality (constraint) on the crack ligament in comparison to fracture specimens are taken into account. Thereby the geometry dependency of the crack resistance found in fracture specimens by /CLA89, KOR87, BRO92, HOL92/ and others can be included concerning the transfer to components. The aim is to extend the J-integral concept to a two-parameter concept which has to be verified in large scale experiments.

To evaluate the crack resistance in the component it is necessary to measure crack resistance curves with different fracture specimens by variation of the specimen's geometry and size or crack depth, respectively. For the transfer of crack resistance from specimens to components parameters characterizing the stress triaxiality near the crack front are considered. The stress triaxiality is calculated in specimens with known crack resistance curves and varying crack depth and specimen geometry or size, respectively. This stress triaxiality is compared with that of the component. The assessment of component fracture behaviour should be based on the crack resistance of those specimen which approximate the testing component best in terms of stress triaxiality. Since the stress triaxiality in the component is changing with time due to thermo-mechanical transient loading, a representative fracture resistance has to be chosen for each loading state. This methodology to determine functional relationships for the transfer of crack resistance from fracture specimens to components has to be developed and tested first in the frame of large scale tests. The presented results from exemplary applications of that fracture concept on RPVs in particular under thermo-mechanical transient loading are meant to contribute to the concept development.

COMPARISON OF ANALYSIS METHODS

The determination of membrane and bending stresses for the analytical calculation of stress intensity factors is problematic and leads to questionable results for strongly non-linear stress distributions as they arise at thermal transient loading and when taking into account the vessel's cladding. Application of e.g. the procedure in ASME rules especially short cracks yield negative membrane stresses of very large magnitude and thus very large bending stresses.

Fig. 3 shows the crack loading of a postulated circumferential crack ($a/w = 0.085$) in a RPV (wall thickness 192 mm + 7 mm cladding) as a function of time for the load case low pressure cooling injection ($T_k = 20^\circ C$) at shut off ($p = 0.5$ MPa) with axisymmetric cooling assumption. The values calculated analytically using different simplified methods are partially much larger than the FE-results and show a strong scatterband. Here the cladding being taken into account plays an essential role. To give a conclusion, one can derive that the applied simplified methods exhibit strong weaknesses especially in applications with thermo-mechanical transient loading.

INVESTIGATIONS ON STRESS TRIAXIALITY

As a parameter for describing the stress triaxiality on the ligament the difference between the crack opening stress component calculated in the FE-

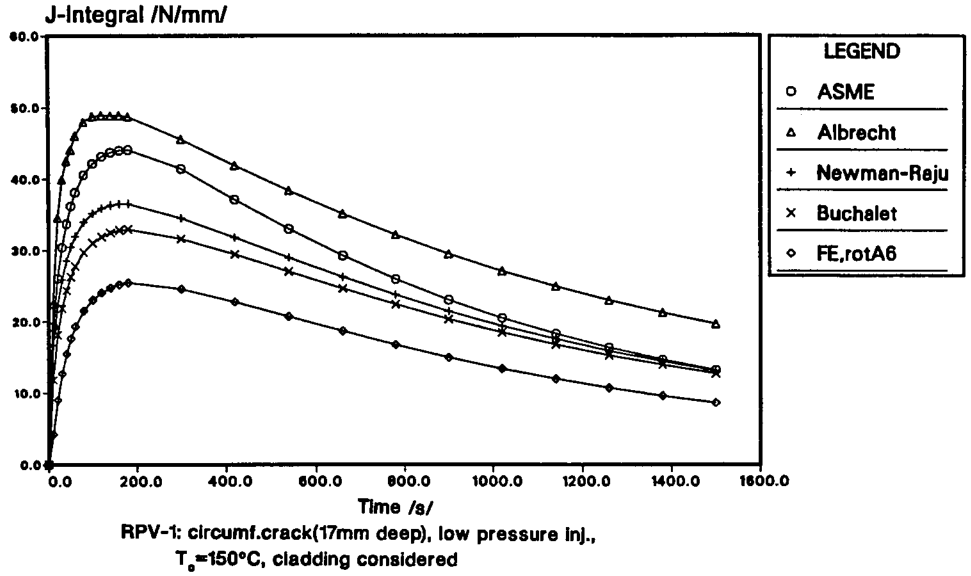

Fig. 3: RPV-1: Time history of crack loading concerning different analysis methods

model and that of a reference state of stress (e.g. HRR[1]-plane strain) has been introduced in /DOW 91/.

$$Q = \left(\sigma^{FE} - \sigma^{\text{HRR-plane strain}}\right)_{\text{crack opening comp.}} / \sigma_0$$

with σ_0 yield stress. Furthermore the stress ratio

$$q = \sum_{i=1}^{3} \sigma_{ii} / \sigma_{eff}$$

with σ_{eff} von Mises effective stress can be discussed. For the elastic stress distribution near a crack Williams /WIL57/ has derived

$$\sigma_{ij} = \frac{K_I}{\sqrt{2\pi r}} f_{ij}(\theta) + \text{non-singular terms}$$

with K_I as the stress intensity factor, r and θ polar coordinates with the origin at the crack tip (ligament: $\theta = 0$), $f_{ij}(\theta)$ a set of trigonometrical functions. From this one gets the limit cases:

$q = 2$ for plane stress state and

$q = \frac{2(1+\nu)}{1-2\nu} = 6.5$ with $\nu = 0.3$ for a plane strain state.

For a postulated circumferential crack (360°, a/t=0.11) under thermo-mechanical transient loading Q reaches values of -2.0 to -1.2 on the ligament, i.e. a lower stress triaxiality and therefore a higher crack resistance as in the reference case (see Fig. 4). The parameter q shows strong variation with partially very large triaxiality values at the beginning of the

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[1] HRR: Hutchinson, Rice, Rosengreen

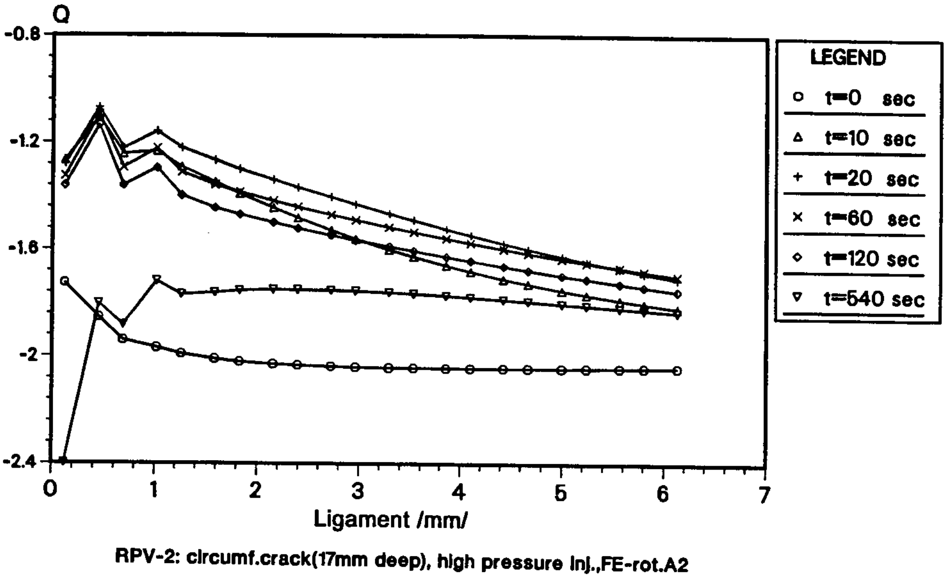


Fig. 4: RPV-2: Stress triaxiality Q on the ligament of a circumferential crack (a/w = 0.11)

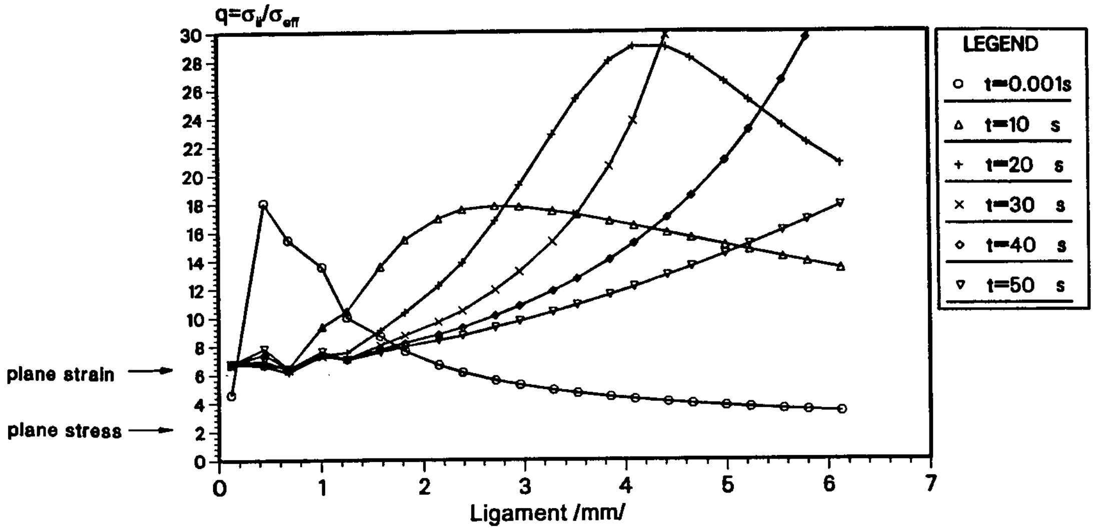
transient and eventually reaches values in the region of the elastic plane strain limit case (see Fig 5). For a deeper crack (a/w = 0.28) Q shows larger values (about -1.6 to 0.0) but q shows nearly the same limit values.

CONCLUSION

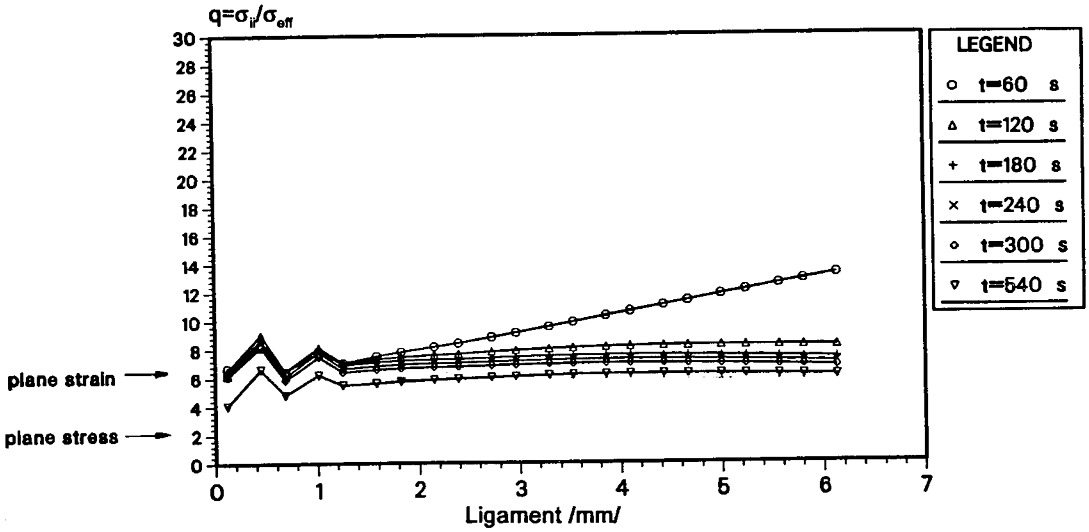
It has been shown at fracture mechanical analyses of RPVs under thermo-mechanical loading that the use of simplified methods is partially problematic. This is due to the strongly non-linear stress distributions and the discontinuities at the boundary between cladding and weld or base material. As a consequence of this, the scattering of results of different simplified fracture mechanical methods investigated and in comparison with FE results is very large and the application of the simplified methods cannot be recommended in case of transient thermo-mechanical loading.

The geometry dependency of the crack resistance and particularly its dependency on the a/w-ratio is important for safety assessments, because it allows to specify safety margins against crack initiation or growth, respectively, more precisely. With the presented evaluation of parameters describing the stress triaxiality on the ligament of postulated cracks, a partially different behaviour concerning the dependency on crack size and the load dependency relative to the plane strain reference state of stress was observed. For extension of the J-integral concept to a two-parameter concept a suitable stress triaxiality parameter has to be selected but also a procedure to determine a representative triaxiality value has to be set forth. For that the following possibilities are at hand:

- averaging over a specific region of the ligament
- extrapolation of the triaxiality distribution to the crack front



RPV-2: circumf.crack(17mm deep), high pressure inj.,FE-rot.A2



RPV-2: circumf.crack(17mm deep), high pressure inj.,FE-rot.A2

Fig. 5: RPV-2: Stress triaxiality q on the ligament of a circumferential crack (a/w = 0.11)

- introduction of a characteristical length, for example $2J/\sigma_0$ or the measurable quantity l_c (critical pore distance).

It has to be emphasized that the determination of the stresses in the immediate vicinity of the crack front is strongly dependent on the element type, the element size and the numerical solution algorithm and can only be done satisfactorily with much more effort, than it is necessary for determination of the J-integral. For solution of the problems mentioned more work with close connections between numerical and experimental simulation of the crack resistance in components with small specimens of different size and crack depth has to be done.

ACKNOWLEDGEMENT

We thank the German Ministers for Environment, Natural Protection and Reactor Safety (BMU/BfS) as well as for Research and Technology (BMFT) who sponsored our work.

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