INFLUENCE OF THE MULTIAXIALITY OF STRESS STATE ON THE DUCTILE FRACTURE BEHAVIOUR OF DEGRADED PIPING COMPONENTS

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Experimental investigations and numerical calculations by means of the finite element method concerning linear-elastic as well as elastic-plastic material behaviour were performed to develop a methodology for the fracture mechanics evaluation taking into account the multiaxiality of stress state. A description of this fracture mechanics evaluation methodology and its application on degraded piping components (T-branches and elbows with dimensions like the primary coolant lines of PWR-plants) is provided.

INTRODUCTION

Most of the common evaluation procedures, Fig. 1, are based on one-parametric fracture mechanics concepts. The range of applicability of the fracture mechanics methods is restricted, e.g. by limits of transferability of fracture mechanics material laws. If ductile crack extension is included in the components evaluation, it is important to note that the crack resistance curves depend on specimen geometry as well as specimen and defect dimensions and are influenced mainly by the multiaxiality of stress state across the ligament, Fig. 2 (1-3). Therefore an essential point of view is the interaction of fracture mechanics material laws or parameters and the multiaxiality of stress state in the component.

Within the scope of several research programs performed at MPA Stuttgart large scale specimens and components with dimensions like the primary coolant lines of PWR-plants were investigated (4-9). In addition to the experimental investigations extensive numerical calculations were performed using the finite element method concerning linear-elastic as well as elastic-plastic material behaviour.

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On the basis of these investigations a methodology for the fracture mechanics evaluation of degraded components, taking into account the multiaxiality of stress state, was developed and applied to degraded components.

EVALUATION METHODOLOGY

The investigations performed (9,11,12) have shown that:

- a quantitative assessment with regard to crack initiation is possible by comparison of the effective (physical) crack initiation value $J_{\text{eff}}$ with the calculated component stress (crack driving force). $J_{\text{eff}}$ is determined from the stretched zone as measured in a scanning electron microscope.

- on the basis of the calculated multiaxiality quotient $q$ across the ligament the limits of applicability of the fracture mechanics concepts can be estimated and a qualitative assessment with regard to the fracture behaviour of the component and the transferability of the crack resistance curve of the specimen to the fracture behaviour of the component is possible. According to (3) $q$ is defined as the quotient of the v. Mises equivalent stress $\sigma_v$ and the first invariant of the stress tensor ($\sigma_0 = \sigma_1 + \sigma_2 + \sigma_3$) and $q$ will become $q = (\sigma_v \cdot \sqrt[3]{3}) / \sigma_0$. Small values of $q$ represent a high degree of multiaxiality.

- for small multiaxiality quotients in the ligament ($q \leq 0.3$) and a derivative of $dq/dy \leq 0$ only very little or no stable crack extension before fracture can be expected (1-3). Increasing stable crack growth is to be expected if the derivative of $q$ across the ligament becomes greater than 0 ($dq/dy > 0$).

According to these results the following steps are used for the fracture mechanics evaluation of degraded components, Fig. 3:

Step 1: Make available or select material data for the component to be concerned.
   a.) Yield strength, Young's modulus, true stress-strain curve as input for finite element calculations
   b.) fracture mechanics material characterization ($J_{\text{eff}}$, $J_\text{R}$-curve)

Step 2: Perform finite element calculation for the component to be concerned using elastic plastic material behaviour.
   a.) calculation of the component stress (crack driving force), e.g. $J$-integral as a function of the load.
   b.) calculation of the multiaxiality of stress state across the ligament ($q$-gradient) as a function of the load.

Step 3: Determination of the initiation load by comparison of $J_{\text{eff}}$ (e.g. determined

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by CT20 specimen testing) with the calculated crack driving force (e.g. R-curve method) from step 2a.

Step 4: Perform a Finite Element calculation for the standard fracture mechanics specimen used in step 1b. (Calculation of the multiaxiality of stress state across the ligament (q-gradient) as a function of the load)

Step 5: Compare the calculated multiaxiality quotient q across the ligament of component (step 2b) and specimen (step 4).

Step 6: If the multiaxiality of stress state of the specimen and the component (step 5) is not comparable select other fracture mechanics specimen type (CT-, TBP-, DECT-, SECT-, CCT-, C-form-specimen,...) and do FE calculations for this type of specimen (e.g. (10)) and repeat step 5. If a specimen with a comparable multiaxiality of stress state across the ligament is available determine the fracture mechanics material characteristics of this specimen (step 1b).

Step 7: Evaluation of the fracture behaviour (J > J_{eff}). If the multiaxiality quotient in the ligament is very small (q ≈ q_c - 0.3) and the derivative dq/dy ≤ 0 only very little or no stable crack extension before fracture can be expected (in this case no Leak-Before-Break behaviour can be expected).

EXAMPLES

Examples for the application of this fracture mechanics evaluation methodology on degraded T-branches and elbows with dimensions like the primary coolant lines of PWR-plants are described in (11) and (12) and for component similar specimens in (13). Because of the limitations of this paper a more detailed description is not possible. The experimental results show good agreement with the fracture mechanics evaluation according to the methodology described.

REFERENCES


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Analysis of Degraded Piping Components

Limit Analyses
- limit load analysis
  (net section collapse)
- bending theory

Fracture Mechanics Approaches
- Paris-Tada
- LBB/NRC
- Q-factor
- EPRI/G.E.
- RS-method

Finite Element Analyses
- linear elastic
- elastic plastic
in
cluding fracture mechanics validation

straight pipe with slit/notch
material characteristics
loading: internal pressure and external forces / moments

fracture mechanics parameters
(J, COD) and component stress for a constant crack depth
prediction as for
- crack initiation
- validation of the failure
- behaviour with the help of the multiaxiality of stress state (q-gradient)

calculation of the crack driving force ($J/\Delta a$) applied
using the R-curve method
prediction is possible as for
- crack initiation
- if transferability specimen-component is given prediction is possible as for
- crack growth
- instability

failure moment
verified by experimental results
no prediction is possible as for
- crack initiation
- crack growth
- instability

Figure 1 Evaluation of degraded piping components

Figure 2 Crack resistance curves of specimens of various size and geometry
Figure 3  Flow chart for the evaluation of degraded components