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

U. Eisele*, K.-H. Herter* and X. Schuler*

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 it's 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.

---

* Staatliche Materialprüfungsanstalt (MPA), University of Stuttgart

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_{ieff} with the calculated component stress (crack driving force). J_{ieff} 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. Accoring to (3) q is defined as the quotient of the v. Mises equivalent stress σ_v and the first invariant of the stress tensor ($\sigma_0 = \sigma_1 + \sigma_2 + \sigma_3$) and q will become $q = (\sigma_v \cdot \sqrt{3}) / \sigma_0$. 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 accross 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_{ieff}, J_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_{ieff} (e.g. determined 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-, TPB-, 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 ($J > J_{ieff}$). If the multiaxiality quotient in the ligament is very small ($q \leq q_c \sim 0.3$) and the derivative $dq/dy \leq 0$ 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

(1) Roos, E., U. Eisele, H. Silcher: Effect of Stress on the Ductile Fracture Behaviour of Large-Scale Specimens. Constraint Effects in Fracture, ASTM STP 1171, E. M. Hackett, K.-H. Schwalbe and R. H. Dodds, Eds., American Society for Testing and Materials, Philadelphia, 1993, pp. 41-63.

(2) Roos, E.: Grundlagen und notwendige Voraussetzungen zur Anwendung der Rißwiderstandskurve in der Sicherheitsanalyse angerissener Bauteile. Habilitationsschrift an der MPA Stuttgart. Fortschrittsbericht VDI, Reihe 18: Mechanik/Bruchmechanik (Nr. 122), VDI-Verlag GmbH, Düsseldorf 1993.

(3) 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, February 1991.

(4) Forschungsvorhaben 1500 304 B: Komponentensicherheit (Phase II), Werkstoffmechanische Untersuchungen, Teil A und Teil B, Abschlußbericht, Staatliche Materialprüfungsanstalt (MPA), Universität Stuttgart, 1990.

(5) Forschungsvorhaben BMFT-FB 1500 618: RDB-Notkühlsimulation, Staatliche Materialprüfungsanstalt (MPA), Universität Stuttgart, 1990.

(6) Forschungsvorhaben 1500 279: Phänomenologische Behälterberstversuche Phase I, Abschlußbericht Phase I, Staatliche Materialprüfungsanstalt (MPA), Universität Stuttgart, 1985.

(7) Forschungsvorhaben 1500 279: Phänomenologische Behälterberstversuche (Phase II), Forschungsbericht, Staatliche Materialprüfungsanstalt (MPA), Universität Stuttgart, 1987.

(8) Forschungsvorhaben 1500 752: Rißwachstum und Bruchverhalten von rohrförmigen Komponenten mit Umfangsfehlern bei Innedruckbelastung und überlagertem wechselnden äußeren Biegemoment (BV III), Staatliche Materialprüfungsanstalt (MPA), Universität Stuttgart (1987-1992).

(9) Forschungsvorhaben 1500 801: Festigkeits- und Bruchverhalten von Abzweigen und Rohrbogen bei Innendruckbelastung und überlagertem äußerem Biegemoment, Staatliche Materialprüfungsanstalt (MPA), Universität Stuttgart, März 1993.

(10) Uhlman, D., H. Diem: Multiaxiality Quotient as Function of Crack Depth and Load for Selected Specimen and Component Geometries. Will be published on Tenth Conference on Fracture, Paper 223, 20.-23. September 1994.

(11) Schuler, X., D. Blind, U. Eisele, K.-H. Herter, W. Stoppler: Bruchmechanische Bewertung von fehlerbehafteten Komponenten unter Berücksichtigung der Mehrachsigkeit des Spannungszustandes. 18.MPA-Seminar, 8./9. Oktober 1992.

(12) Schuler, X., D. Blind, U. Eisele, K.-H. Herter: Extension of Fracture Mechanics Evaluation Methods by Consideration of Multiaxiality of Stress State for Piping Components. SMiRT 12 Conference, August 15.-20. 1993, Stuttgart, Paper G07/1.

(13) Stumpfrock, L., E. Roos, H. Huber, U. Weber: Fracture mechanics investigations on cylindrical large scale specimens under thermal shock loading. Nuclear Engineering and Design 144 (1993) 31-44, North Holland.

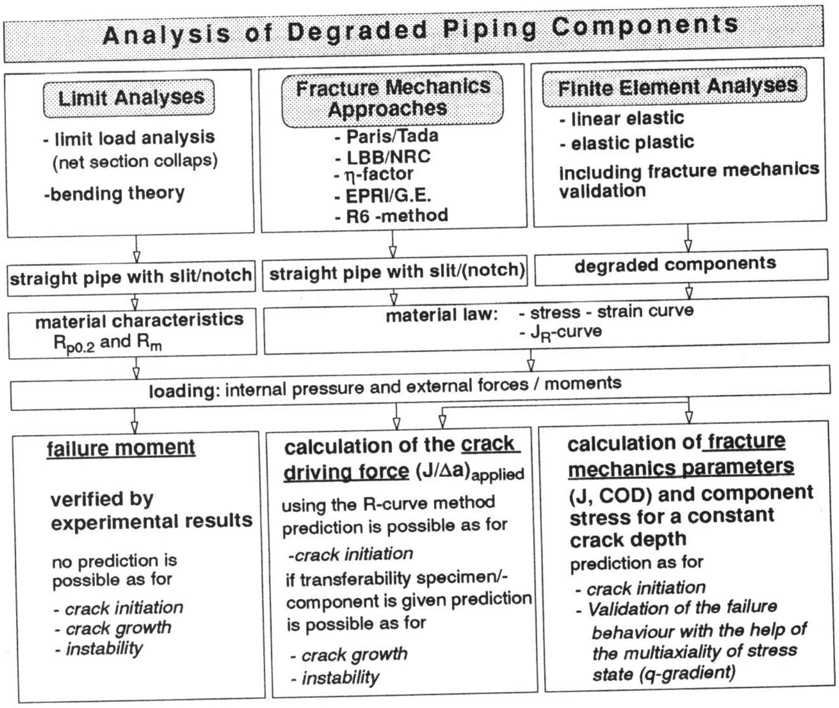

Figure 1 Evaluation of degraded piping components

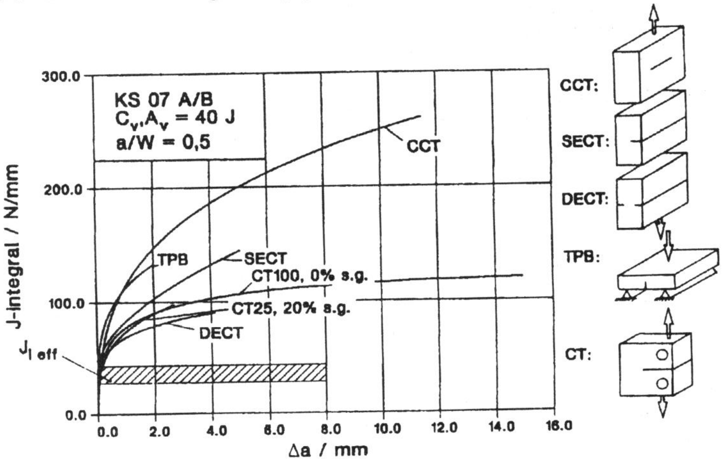

Figure 2 Crack resistance curves of specimens of various size and geometry

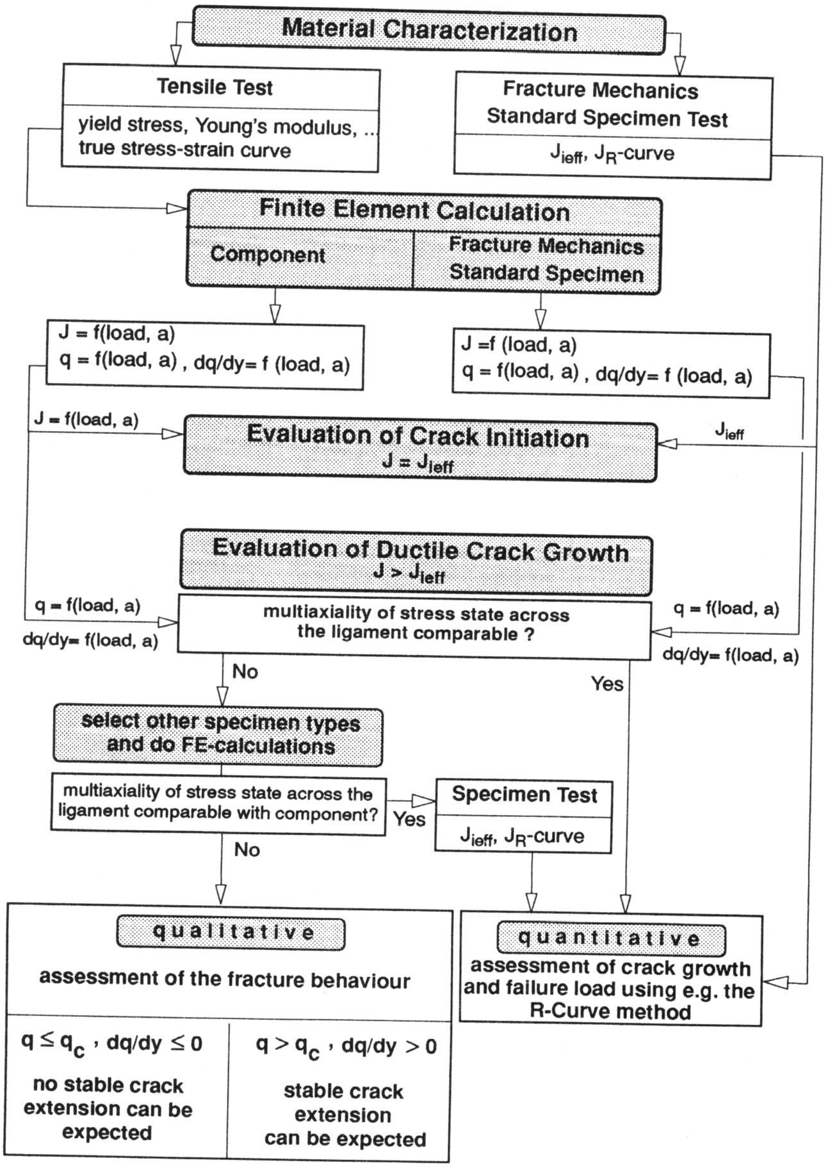

Figure 3 Flow chart for the evaluation of degraded components