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# Transferability of fracture parameters from specimens to component level

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**Abstract**

The structural integrity of components is usually performed using the specimen fracture resistance curve. However, the specimen fracture resistance curve significantly differs from the component fracture resistance. This is the most serious limitation of classical fracture mechanics. To address this issue, several tests have been carried out on fractured specimens and piping components under an Indo-German bilateral project. Two approaches, namely, two-parameter fracture mechanics and micro-mechanical models are considered to investigate the feasibility of transferability. For the two-parameter fracture mechanics approach, the $J$-integral has been used as the crack driving force and $q$ is used as a measure of stress triaxiality. The triaxiality quotient $q$ is proportional to the ratio of the hydrostatic stress and the von Mises effective stress and is an additional parameter to make a decision about the initiation value of the $J$-integral for the failure behaviour of a component. It is shown that if the triaxial conditions match for any two arbitrary geometries, it is feasible to transfer the fracture parameters. The difficulty in transferability is largely overcome by damage mechanics, which models the drop in load carrying capacity of a material with increase in plastic strain. Such modeling is done considering nucleation, growth and coalescence of voids in a material following large-scale plasticity. The Gurson–Tvergaard–Needleman and Rousselier models are used. Some of the results obtained by these models and comparisons with experimental results are presented in this paper to demonstrate the usefulness of damage mechanics in analyzing components with flaws.


*Keywords:* *J–R* curve; Stress; Triaxiality; Multi-axiality quotient; Damage mechanics

## 1. Introduction

Ductile tearing resistance of a material is conventionally characterized by a $J$-resistance ($J$–$R$) curve, which is obtained from laboratory fracture specimens. The original idea was that a unique fracture resistance curve would suffice to characterize the material. However, testing of different types of specimens and loading conditions revealed considerable differences in the $J$–$R$ curves, especially in the slopes [1]. This raises the question of transferring fracture parameters from specimens to components. It has been found that crack tip constraint or stress triaxiality influences the $J$–$R$ curves [1–4]. The crack tip constraint is a structural feature, which inhibits plastic flow and causes higher triaxiality of stresses. The standards for fracture testing often enforce high constraint conditions in specimens to obtain a conservative index of material toughness. The application of $J$–$R$ curves from these specimens to low-constraint structural applications introduces high degrees of conservatism. This can lead to an increase in safety margin, when other safety factors are included. The total conservatism inherent in a particular design can become excessively large and the true safety factor is not known. A reverse problem occurs, when the fracture toughness data are obtained on relatively low-constraint specimens and then used in high-constraint applications. This would make the design non-conservative. Thus, these issues raise a fundamental question on how to incorporate constraint effects in fracture mechanics evaluation of cracked structures.

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Table 1
Details of cracked pipe geometries

| S. No | Specimen No | Outer diameter (mm) | Thickness (mm) | Type of flaw | Type of loading | Crack dimensions |
|---|---|---|---|---|---|---|
| 1 | SPBMTWC8-1 | 219 | 15.15 | Throughwall circumferential | Four-point bending | $\theta=32.78°$ |
| 2 | SPBMTWC8-2 | 219 | 15.10 | Throughwall circumferential | Four-point bending | $\theta=46.95°$ |
| 3 | SPBMTWC8-3 | 219 | 15.29 | Throughwall circumferential | Four-point bending | $\theta=63.2°$ |
| 4 | SPBMTWC16-1 | 406 | 32.27 | Throughwall circumferential | Four-point bending | $\theta=47.98°$ |
| 5 | SPBMTWC16-2 | 406 | 32.14 | Throughwall circumferential | Four-point bending | $\theta=63.15°$ |
| 6 | SPBMTWC16-3 | 406 | 32.39 | Throughwall circumferential | Four-point bending | $\theta=78.88°$ |
| 7 | SPBMSC8-9 | 219 | 15.47 | Part-through circumferential | Four-point bending | $\theta=8.40°$, $a/t=0.129$, $a/c=0.125$ |
| 8 | SPBMSC8-11 | 219 | 15.38 | Part-through circumferential | Four-point bending | $\theta=18.8°$, $a/t=0.75$, $a/c=0.32$ |
| 9 | SPBMSC16-5 | 406 | 32.16 | Part-through circumferential | Four-point bending | $\theta=16.9°$, $a/t=0.58$, $a/c=0.31$ |
| 10 | SPBMSC16-6 | 406 | 32.04 | Part-through circumferential | Four-point bending | $\theta=21.2°$, $a/t=0.8$, $a/c=0.34$ |
| 11 | ELTWIN8-1 | 219 | 19.1 | Throughwall circumferential at intrados | Opening moment | $\theta=47.5°$ |
| 12 | ELTWIN8-2 | 219 | 18.8 | Throughwall circumferential at intrados | Opening moment | $\theta=62.6°$ |
| 13 | ELTWEX8-4 | 219 | 19.3 | Throughwall circumferential at extrados | Closing moment | $\theta=49.12°$ |

$\theta$, half crack angle.

There has been a recent surge of interest in the following approaches to describe the effect of constraint on ductile tearing resistance and thereby resolve the issue of transferability.

(i) Two parameter fracture mechanics approaches [1,5–7] where the first parameter reflects the scale of crack tip deformation (e.g. $J$-integral) and the second parameter is used to quantify the level of constraint. If the triaxial conditions are found to be similar then it is believed that the $J$–$R$ curves are transferable within certain circumstances such as the crack length not influencing the stress triaxiality [8]. These conditions are evident for geometries where the ligament length is large for the case of bending geometries and geometries that are predominately under tension. This is a simple method for structural integrity analysis relative to the micro-mechanical models, although crack growth is not considered in detail in the approach.

(ii) The local approach [9–11] describes the crack growth by modeling the local fracture by micro-mechanical models. For ductile tearing, it aims to model the damage, which occurs in three stages: nucleation, growth and coalescence of voids. Constraint effects do not arise as separate problems since triaxiality of stresses enters the model directly. However, three major limitations of these models are the numerical costs associated with the simulations particularly for 3D structures, identification of the material parameters and mesh dependency, which are still the subject of investigations.

To address the issue of transferability, several tests have been performed on power plant components such as straight pipes and elbows. Tensile and fracture specimens have been machined from these pipes and tested to obtain the tensile and the fracture resistance curves, respectively. These tests offer a means of comparing the fracture toughness properties of the laboratory specimens with the component fracture resistance. In the present paper, the crack-tip constraint conditions are evaluated in these components in order to investigate the feasibility of transfer of fracture properties from the specimens to the components. On the micro-mechanical level, Gurson–Tvergaard–Needleman and Rousselier models are applied to investigate the ductile tearing behaviour of cracked components.

## 2. Fracture experiments

As part of a Component Integrity Test Program at Bhabha Atomic Research Centre (BARC), India, 8-in./16-in. diameter straight pipes/90° long radius pipe bends (elbows) containing throughwall/part-throughwall flaws were tested. Table 1 shows the details of the cracked pipe geometries. All these specimens were made of SA 333 Gr 6 steel and tested at room temperature. Tensile and fracture specimens, namely Three Point Bend Bar (TPBB)/Compact Tension (CT) specimens, were machined from these pipes and tested to obtain the tensile and fracture properties, respectively. Details of the experiments have been discussed

Table 2
Mechanical Properties of SA333 Gr 6 steel

| Mechanical properties | Sample from 8-in. pipe | Sample from 16-in. pipe |
|---|---|---|
| Yield stress, $\sigma_0$ | 288 MPa | 312 Mpa |
| Ultimate tensile stress, $\sigma_U$ | 420 MPa | 459 Mpa |
| Young's modulus of elasticity, $E$ | 203 GPa | 203 Gpa |
| Percentage elongation | 36.2 | 39.1 |
| Percentage reduction in area | 76.64 | 76.15 |
| Poisson's ratio, $\nu$ | 0.3 | 0.3 |