# INVESTIGATION ON THE INFLUENCE OF FLAW SHARPNESS ON STRESS STATE USING THREE-DIMENSIONAL ELASTIC-PLASTIC FINITE ELEMENT ANALYSES

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The effect of flaw sharpness in fracture behaviour has been investigated numerically by using three-dimensional elastic-plastic finite element analyses for compact tension specimens as well as for wide plates containing centre defects. By changing the defect tip geometry from a sharp crack to a notch with a well defined notch root radius the local state of stress, which is responsible for the fracture behaviour, is varied. The results are discussed, firstly, in terms of the J-integral. Mean values and the distributions along the defect fronts across the thickness are considered. Secondly, special emphasis is given to the discussion of the local stresses and a stress state characterising constraint quantity.

## INTRODUCTION

Experimental investigations (Hubo et al. (1)) performed with fracture mechanics (FM) specimens containing notches with a notch root radius of 0.1 mm showed higher critical J-integral values $J_c$ than tests with the normally used prefatigued specimens. Thereby the transition temperature $T_i$ is shifted to an about 10 K lower value. The consequence of this finding for a safety assessment after Dahl et al. (2) using finite element (FE) calculations and the J-integral concept has also been discussed in (1). Testing wide plates (WP) of CNT-type (centre notched tension) instead of those containing fatigue cracks (CCT, centre cracked tension) leads to a shift in the transition temperature $T_{gy}$, see Rosezin (3). Very conservative predictions for a series of CNT-plates have been evaluated if $J_c$-values obtained by testing fatigue-cracked specimens were applied, see Twickler (4).

In order to explain the different values of the critical J-integral $J_c$ at a given temperature and thus to explain the effect

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of the shift of transition temperatures with varying flaw sharpness quantitatively and at least to get a better understanding of the fracture event in the small scale specimens as well as in the large scale structures three-dimensional elastic-plastic FE-computations have been performed for both types of geometries.

## DESCRIPTION OF GEOMETRIES, MATERIAL AND FE-CALCULATIONS

Two types of geometries were analysed to study the influence of flaw sharpness on stress state. The first one is a so-called 1CT-J-specimen with an a/W-ratio of 0.53, whereas the second geometry is a wide plate containing a centre defect with an a/W-ratio of 0.1, see the inserts in Figure 1. For both geometries FE-computations were carried out, firstly, containing a sharp crack and, secondly, containing a notch with a notch root radius of $\rho = 0.1$ mm. A Fe 510 steel was used for this investigation.

The computations for the CT-specimens were performed at a temperature of $T = 233$ K with a yield stress value of $R_{eL} = 440$ MPa. At this temperature the cracked and the notched type failed at an experimentally determined critical J-integral value of about $J_c = 155$ N/mm and $J_c = 406$ N/mm, respectively, see (1). For the computations of the wide plates a temperature of $T = 203$ K was chosen. The corresponding yield stress value is $R_{eL} = 467$ MPa. At this temperature the CCT-plate failed below the transition temperature $T_{gy}$ at a net cross-section stress of $\sigma_n = 403$ MPa by cleavage. The CNT-plate reached general yield and failed at a net cross-section stress of $\sigma_n = 489$ MPa.

The elastic-plastic displacement controlled computations were performed by the general purpose finite element program ABAQUS by Hibbitt et al. (5) regarding the von Mises yield condition and isotropic strain hardening. Small strain theory (J-analysis) as well as large strain theory (stress analysis) have been used. The uniaxial stress-strain curves were represented by multilinear approaches. Herein the experimentally observed Lueders-strain regions were taken into account. Young's modulus and Poisson's ratio were taken to be $E = 210$ GPa and $\nu = 0.3$, respectively.

For the three-dimensional calculations isoparametric 20-noded elements with reduced integration were used. Around the crack tip these elements were collapsed to produce a 1/r-singularity in the strains. Compared to an only J-integral aimed FE-analysis the two-dimensional basic mesh for the wide plate is substantially refined especially in the crack tip region, see the inserts in Figure 3. The mesh for the CT-specimen represents a part of this wide plate mesh and is thus in this part nearly identical to it. For the notched versions of the investigated geometries this holds true. By reason of symmetry conditions only one eighth of the wide plate and a quarter of the CT-specimen have to be modelled in the 3-D case using 5 element layers for half the thickness. This fine division is identical for both geometries in the near surface region with element thicknesses of 0.5 mm, 1.0 mm and 1.5 mm.

## RESULTS

Subsequently the global response of the investigated geometries will be discussed in terms of loads and J-integral values, which can be obtained experimentally, too. These J-integral values $J_m$ represent, of course, mean values of the distributions along the defect fronts across the thickness evaluated by 3-D FE-computations. The local behaviour of the different geometries will be discussed using such distributions as well as the defect opening stresses and the constraint in the ligament at fracture.

### Fracture Mechanics Loading Parameter J-integral

A first comparison of the cracked and the notched type of the analysed geometries is shown in Figure 1 by plotting $J_m$ as a function of the load up to fracture. In the WP-case $J_m$-values of about 37 N/mm (CCT) and 290 N/mm (CNT) have been calculated. Except the CCT-plate all geometries were loaded up beyond general yield before fracture whereby the plastic deformation in the notched type is much greater. As expected no influence of the flaw sharpness on this kind of global behaviour can be observed.

In Figure 2 the J-distributions along the defect fronts are presented. Besides the state of fracture for all structures additional solutions for the notched type at lower load levels, viz. at fracture of the cracked type, are given. Also for this local J-behaviour the curves for the cracked and the notched geometries coincide at a given load level.

From the first two figures it appears that the 'applied side' of a J-integral based safety assessment is independent of the real defect tip geometry. As e.g. even locally no higher J-values can be observed in the cracked geometries no explanation can be given for the different 'material reaction' expressed by different $J_c$-values or fracture loads.

### Local Stresses and Constraint

As a further result the distributions of the opening stress $\sigma_y$ along the defect fronts are presented in Figure 3 for the same load levels as in the previous figure. These curves are plotted at those x-positions, at which $\sigma_y=\sigma_y(x)$ in the mid-plane reaches its maximum value. Due to the different defect tip geometries and the different amounts of plastic deformation these positions are not identical for all the solutions. In contrast to the J-solutions the $\sigma_y$-curves for the cracked and the notched geometries do not coincide at a given load level. As expected the cracked geometries lead to higher opening stresses. This result means that cleavage is promoted in the cracked structures. In the notched structures a higher fracture mechanics load $J_m$ is necessary to reach nearly the same $\sigma_y^{max}$-values. The amount of plastic deformation is greater and thus the transition temperatures are shifted to lower values.

In order to describe the multiaxiality of the stress state there exist different measures of the local constraint which may be used conveniently for different fracture mechanisms. For brevity only the so-called q-value after Clausmeyer (6) is discussed in this paper. The distributions along the defect fronts for the state of fracture in Figure 4 show that at least near the midplane the q-values of the cracked and the notched geometries are lying very close together. Qualitatively this is the same result as for the $\sigma_y$-distribution. The oscillation of the CT-solution near the free surface has to be assessed as a numerical problem.

## SUMMARY AND CONCLUSION

The results of detailed 3-D J-integral and stress analyses show that only the local stress and stress state provide an explanation for the influence of flaw sharpness on $J_c$-values and transition temperatures. For that reason the local stress state has to be taken into account for a safety assessment of a structural component.

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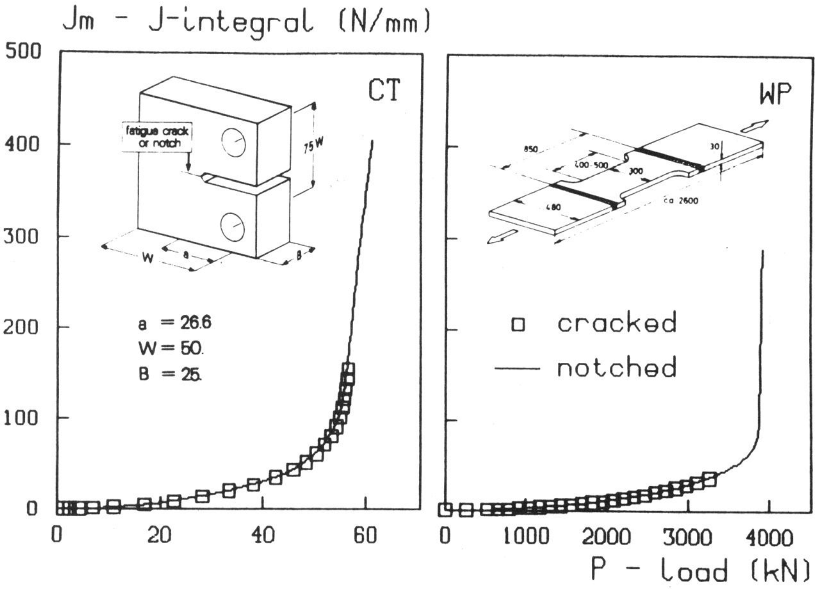

Figure 1. Global J-behaviour of cracked and notched geometries

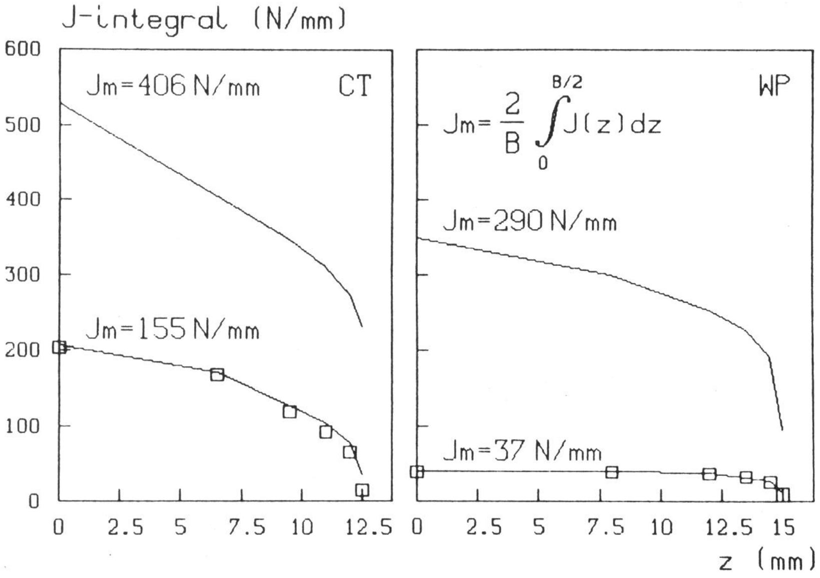

Figure 2. Local J-behaviour of cracked and notched geometries

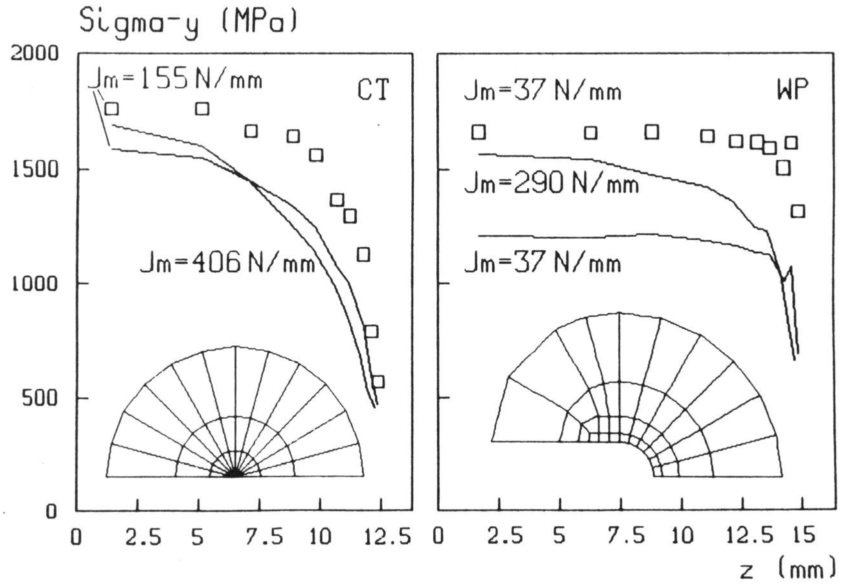

Figure 3. Defect opening stress across the thickness of cracked and notched geometries

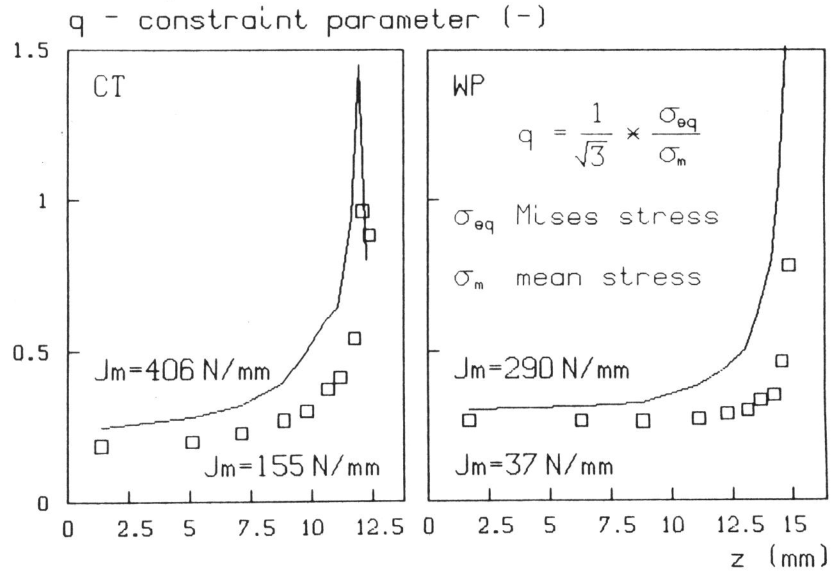

Figure 4. Multiaxiality of stress state across the thickness of cracked and notched geometries