# PREDICTION OF CLEAVAGE FRACTURE IN WELDED WIDE PLATES BY THE J-Q-M APPROACH

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The effect of geometry and strength mismatch on brittle fracture initiated from cracks located at the fusion line of weldments is investigated. The scope has been to derive expressions for the crack tip constraint, and thereby open for transferability schemes from one geometry/mismatch condition to another. The procedure has been phrased the J-Q-M approach, where Q quantifies the geometrical effects and M the material mismatch effects. In the paper the J-Q-M approach is applied to predict the fracture of 70 mm thick surface notched wide plates with a yield strength of 500 MPa.

## INTRODUCTION

The Kr parameter in the failure assessment diagram given in PD 6493 , Kr = $K_I$/Kmat, is based on single parameter fracture mechanics and the validity range is restricted. It is often experienced that tensile testing of wide plates can tolerate higher loads than predicted from deeply notched fracture mechanics specimens, Hauge et al (1). The reason is that the reduced constraint in wide plates is not correctly treated by the FAD procedures. Recent publications have proposed to extend the validity range by introducing the T-stress and the Q-parameter, Ainsworth and O'Dowd (2).

In addition to the geometry effects, also the effect of material mismatch must be included in the analysis. Predictive capability is needed such that the influence of strength mismatch can be forecasted in dependence of geometry, notch location, depth and mode of loading.

In the present paper focus is on brittle fracture initiated from cracks located at the fusion line of weldments. The scope of this research has been to derive expressions for the crack tip constraint, and thereby open for transferability schemes from one geometry/mismatch condition to another. The procedure has been phrased the J-Q-M Approach, where Q quantifies the geometrical effects and M the material mismatch effects (Zhang et al (3,4), Thaulow and Toyoda (5) and Zhang et al (6)).

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## THE J-Q-M APPROACH

The J-Q-M Approach quantifies the crack tip stress fields in dependence of geometry (size, crack depth, global geometry and mode of loading), represented by Q, and material strength mismatch, represented by M. The Approach is based on the J-Q theory, O'Dowd and Shih (7), the RKR failure criterion, Dodds et al (8), and a parallel theory developed to take material mismatch into account (3-6).

The J-Q-M Approach is related to the prediction of unstable fracture and allows only limited plasticity before the onset of the fracture. But the range of application is increased compared with the excisting practice, relying on one parameter J or CTOD. The competing failure criteria, related to ductile crack growth and plastic collapse, are not discussed in this paper.

The application of the approach is schematically illustrated in Figure 1. J is used both for the energy induced on the specimen from external forces, $J_{applied}$, and the corresponding material resistance, $J_{resistance}$. $J_{resistance}$ is determined from standard fracture mechanics testing, and unstable fracture will take place when the available energy exceeds the material resistance.

$J_{reference}$ is a defined reference case, referring to a homogeneous specimen $(M = 0)$ that is infinitely large $(Q = 0)$. All other cases are compared to this reference.

$J_{applied}$ expresses the crack tip loading of a given specimen/component, and is directly related to the applied global load or displacement.

The 1:1 line in Figure 1 refers to a condition where the real case has exactly the same constraint, or crack tip stress field, as the reference case.

The CTOD specimen in the figure refers to deeply notched bending, giving a high geometrical constraint. In the case of weld metal overmatch with respect to the HAZ, an extra constraint is induced on the HAZ because of the mismatch. As indicated in Figure 1 this can result in a situation where the specimen reaches higher constraint than the reference case in the initial phase of loading. As the size of the plastic zone increases the curve will fall below the 1:1 line. Evenmatch will result in lower constraint and the slope of the curve decreases compared with the overmatch case. Over- and evenmatch can now be compared with reference to the same $J_{reference}$. In order to obtain the same reference value, indicated with the horizontal dotted line in Figure 1, the even-match case must be loaded to a higher J than the over-match, e.g. the specimen can tolerate a higher load before it «fails».

The wide plates can be treated in the same way as the fracture mechanics specimens. The wide plates in tension represent a much lower geometrical constraint level than the CTOD specimen, and higher applied J is necessary to reach the same $J_{reference}$, Figure 1.

In order to relate $J_{reference}$ to fracture, an approach where the fracture is related to the weld thermal simulation of CTOD specimens has been applied. These specimens represent a homogenous microstructure of the most brittle part of the HAZ, hence the mismatch constraint, M, will be zero. For the examined steels, fracture after weld thermal simulation was experienced at a low CTOD, giving only a limited size of the plastic zone and little relaxation from the initial high constraint in small scale yielding. Increased plasticity can, however, be corrected for by a simple Q- correction through FE calculations. In this way, $J_{reference}$ can be related to the failure of homogeneous CGHAZ (or ICCGHAZ) microstructures and a specimen size where valid J results are obtained (e.g. under small scale yielding). The horizontal dotted line in Figure 1 can be chosen to represent the J experienced in weld thermal simulation testing, and the J-Q-M Approach is then used to transfer from this «ideal» situation to the realistic cases under consideration.

Figure 1 refers to a micromechanic approach, and does not include the remote load necessary to reach $J_{applied}$. In order to relate the fracture to the global load, we also need a relationship between $J_{applied}$ and load.

## FRACTURE MECHANICS AND WIDE PLATE TESTING

A 70 mm thick TMCP steel plate was sub-merged arc welded with consumables to give yield strength over- and evenmatch (weld metal vs. base material), see Table 1. The tensile properties for the HAZ were set equal to the coarse grained zone, and were obtained from weld thermal simulation testing.

Fracture mechanics three point bend specimens, 13*26 mm, were extracted from the weld thermal simulated specimens in order to provide lower bound fracture toughness data. The test temperature was 10°C and the average of three tests was J=60 N/mm.

Twelve wide plates with a width of 1300 mm, were tested. The surface notch was aimed to hit the fusion line. Both over- and evenmatched weldments, with a notch depth of a/W=0.1 and 0.3, were tested.

## 2D FE CALCULATIONS

The next step is to examine the transferability from the small-scale fracture mechanics specimens to structural components. The three point bend specimen and the wide plate geometry was first modeled in 2D plain strain. The thickness of HAZ was 2 mm with the crack tip located at the fusion line. The initial notch radius was 0.005 mm and non-singular 20-node elements with small strain formulation were used.

The yield strength and the hardening exponent from the Ramberg-Osgood relationship were 506 MPa/15.5 for the base material, 566 MPa/14 for HAZ, 643 MPa/14 for weld metal overmatch and 566MPa/14 for weld metal evenmatch. The effect of going from three point bend specimen to the wide plate results in a dramatic decrease in constraint, see Figure 2.

If $J_{reference}$ is above 75 N/mm, no brittle fracture is expected even if the structure is loaded up to J=400 N/mm.

At a reference value of $J_{reference}$ =60 N/mm, overmatch bending will fracture at an applied load of J=60 N/mm while the evenmatched wide plate can be loaded to about J=380

N/mm. So, even if very brittle behavior is recorded with CTOD testing, the structural component can tolerate high loads before it theoretically reaches the necessary stress level to initiate brittle fracture. In practice extended yielding and ductile crack growth will often take place before the critical stage is reached, and the assumptions behind the J-Q-M calculations will not be valid any more.

## WIDE PLATE 3D FE CALCULATIONS

A complete 3D FE analysis of the wide plate has been performed. The conditions were similar to the 2D model, except that the 20 node elements were substituted with 8 node elements and a "semielliptical" surface crack with extended flat bottom was introduced, see Figure 3.

At the bottom of the elliptical surface crack a higher constraint was experienced than in the 2 D plane strain FE calculations, Figure 4. However, at positions along the crack front closer to the surface, the 3D model gives lower constraint.

When we compare with the remote loading, however, the 3D plate must be loaded to a higher load than the 2D plate to obtain the same $J_{applied}$, Figure 5.
These two opposite relationships are nearly cancelled out when $J_{reference}$ is plotted vs. global load, Figure 6.

The results indicates that 2D plane strain simulates the 3D situation fairly well, but care must be exercised depending on the location along the crack and the kind of analysis performed (local or global).

## COMPARISON BETWEEN WIDE PLATE TESTING AND FE CALCULATIONS

The wide plate test specimen with the shortest ductile crack growth before the onset of brittle fracture, 0.72 mm, was selected to be compared with the J-Q-M calculations. The specimen was overmatched and experienced brittle fracture at a gross load of 478 MPa at a measured CMOD of 1.39 mm.

The relationship between CMOD and $J_{applied}$ was established by the FE calculations, and the CMOD of 1.39 mm corresponded to J=700 N/mm.

By introducing this J-value in Figure 5, the 2D calculations give a load of about 465 MPa and the 3D about 500 MPa. In average, this is rather close to the recorded fracture load of 478 MPa. At this global level, minor changes at the crack tip such as limited ductile crack growth, seems to have no influence.

If we, however assume that fracture will take place at $J_{reference}$=60 N/mm, established on the basis of weld thermal simulation CTOD testing, a fracture load of about 415 MPa should be expected according to Figure 6. At this micromechanic level the reason for the conservative estimate can be related to 1) the calculations does not take ductile crack growth into account, 2) the model assumes that the whole crack tip hits the fusion line (100% hit) and 3) the weld thermal simulation CTOD represents a lower bound estimate.

The influence of ductile crack growth will be of major interest to explore, since most brittle fractures are preceded by some ductile crack growth.

## CONCLUSIONS

- The J-Q-M Assessment has proved to give a realistic estimate of the constraint for cracks located at the fusion line of weldments, including both the geometry and mismatch constraint effects.
- In order to reach the same reference constraint for deeply notched specimens in bending and tension, the tensile specimen could be loaded to J=380 N/mm while the bend specimen reached the same constraint at J=60 N/mm.
- A close correspondence between the J-Q-M predictions and wide plate testing was found for estimating the failure load from the calculated $J_{applied}$. However, a conservative prediction of the failure load was obtained by using the $J_{reference}$ value obtained from weld thermal simulated testing.

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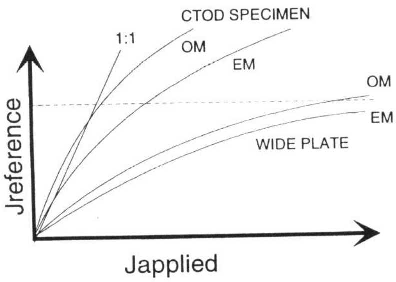


Figure 1 Schematic illustration of the J-Q-M Approach. Deeply notched CTOD bend specimens, with weld metal overmatch and evenmatch, compared with surface notched wide plates loaded in tension.

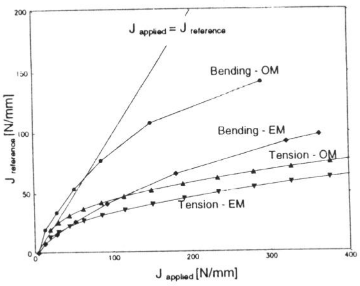


Figure 2 J-Q-M Approach assessment diagram. 2D FE calculations of specimens in bending (small scale fracture mechanics specimens) and tension. (wide plates).

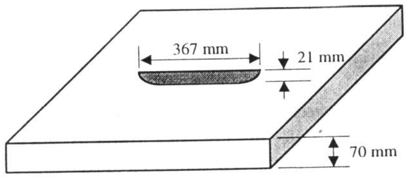


Figure 3 Schematic plot of the wide plate model. The width of the plate is 1300 mm and the length is 1500 mm.

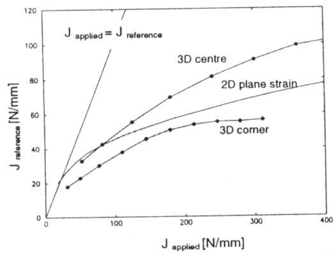


Figure 4 Relationship between $J_{reference}$ and $J_{applied}$ for wide plate in tension. Steel D overmatch and a/W=0.3.

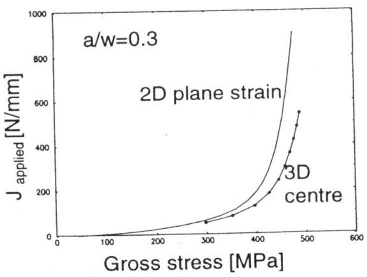


Figure 5 Relationship between $J_{applied}$ and remote load (gross stress) for wide plate in tension. Results from 2D plane strain and 3D at the center of the crack.

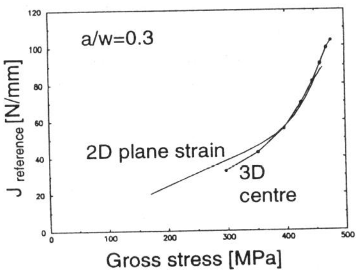


Figure 6 Relationship between $J_{reference}$ and remote load (gross stress) for wide plate in tension. Steel D overmatch and a/W=0.3.