ANALYSIS OF FRACTURE BEHAVIOUR OF UNDERMATCHED WELDS ON TENSILE PANELS

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Summary

An experimental and numerical study of fracture characteristics in undermatched weld joints is reported in this paper. The centre cracked tensile panels with transverse welds were tested at room temperature for short (a/W=0,1) and long (a/W=0,3 and 0,5) through thickness notches located at the weld metal. Elastic-plastic 3-D finite element solutions have been obtained for three a/W ratios. Experimentally measured near crack tip fracture parameters (i.e CTOD and CMOD) showed linear relationship to the remote overall deformation. In addition to the usual crack tip plastic zone developments, the occurence of the secondary strain build-up at the fusion boundaries of the undermatched weld did not disturb this relationship. The numerical verification showed the geometry independent nature of the CTOD measurements on these highly heterogeneous tensile panels.

Introduction

Almost all weld joints are of bimaterial nature. In many cases, the yield strength levels of the weld, heat affected zone (HAZ) and base metals can differ significantly (under- or overmatching). It is common practice, however, to deposit weld metals which display higher strength (overmatching) than the steels used in offshore structures. If the weld metal is considered as a potential location for defects or cracks to be present or develop, the higher yield strength of the weld metal (defective region) compared to the base plate may in fact provide an optimum weld joint performance by shielding a crack from imposed strains. However, nominally identical applied stress/strain levels cause different amounts of strain concentrations at the respective parts of the weld joints depending on the strength levels, crack size and weld geometry. The structural integrity of the cracked mis-matched weld joint therefore mainly depends on the fracture toughness of the cracked zone and complex stress/strain condition of the crack tip due to the heteregeneous interface at the finite vicinity of the crack tip. An extreme interaction should be expected between the crack tip strain and the neighboring heterogeneity in case of HAZ cracked components or specimens.

Numerous experimental and numerical studies have recently been carried out in the fields of fracture mechanics of mismatched weldments or bi-material interface cracks [1-19]. However, the effect of strength heterogeneity of the welded joints (under- and overmatched welds) on deformation characteristics of various fracture mechanics specimen types/parameters needs some further consideration.

A research program at GKSS Research Center to study the fracture characteristics of the mismatched weld joints is currently being carried out. The experimental part of this program contains both CTOD and centre cracked tensile (CCT) panel tests with matched, over- and undermatched welds and various crack configurations. This paper however, reports only some results of this program together with elastic-plastic finite element analyses of the centre cracked tensile panels with undermatched transverse welds. The FE-analyses of the panels were carried out at the Technical Research Centre of Finland (VTT).

Material and Experimental procedure

The base plate used in this program is 30 mm thick C-Mn high strength steel, type StE 460. Bead-on-plate welds were produced by submerged arc welding with special care to obtain a straight-sided weld bead profile (penetration depth is 13 mm) as shown in Figure 1.

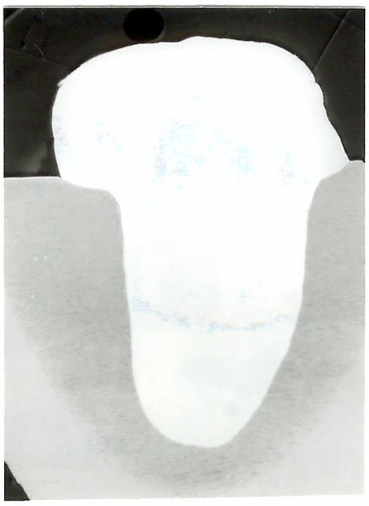


Figure 1. The bead on plate weld profile

The welding procedure and Ni-based wire were chosen with the intention to produce an undermatched weld deposit. The mechanical properties of the base, weld metals and their relative strength ratio are given in Table 1. The high level of weld metal undermatching enabled us to clearly determine the effect of undermatching on fracture behaviour of welded joints.

Table 1. The mechanical properties of the base and weld metals

Material	σ_y [MPa]	σ_{uts} [MPa]	Matching Ratio, M
Base Metal	458	625	0,54
Weld Metal	248	540	

$M = \sigma_y^{WM}/\sigma_y^{BM}$

The CCT panels (10 mm thick) were prepared from 30 mm thick plates with a through thickness notch and tested at room temperature. Figure 2 shows the specimen details with the HAZ and weld metal notch. The "Step-wise High R-ratio fatigue precracking procedure" [20] was used for CTOD and CCT specimens to obtain a straight fatigue crack front. The shallow and deep notched (at HAZ and undermatched weld metal with a/W =0,1-0,3 and 0,5 ratios) CTOD and CCT specimens were tested and detailed experimental results have been reported in Refs. [11-13].

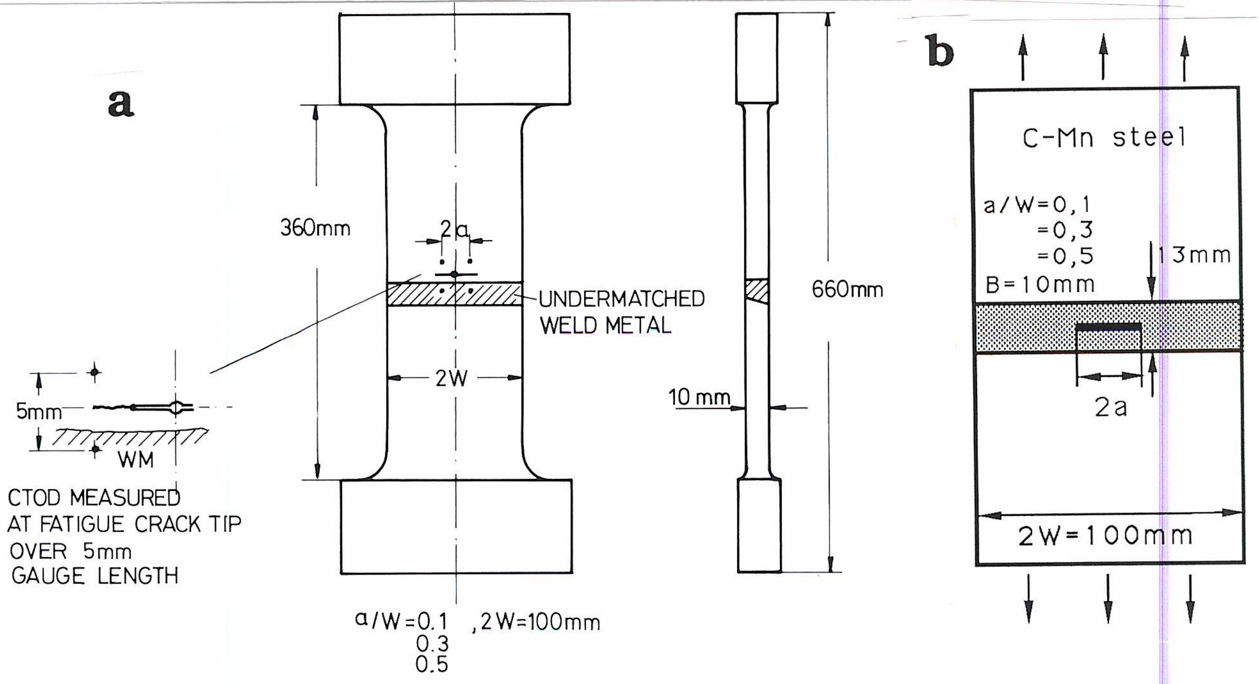


Figure 2. CCT panel with transverse undermatched weld.
a) HAZ notched, b) weld metal notched CCT panel

The experimental and numerical results of only three weld metal notched CCT panels as shown schematically in Figure 2b, will be discussed in this paper to keep the manuscript short.

The experimental approach used in tensile panel tests was to measure the CTOD (with two or four GKSS made δ_5 clip-on gauges [21] at the original fatigue crack tip over a gauge length of 5 mm), CMOD and overall elongation, ΔV_{LL} (with linear transducer over a gauge length of 160 mm) as a function of the applied load for three crack sizes. The DC potential drop technique was also applied for monitoring stable crack growth. On the back surface of some of the tensile panels, deformation patterns were obtained by photoelastic coating.

Numerical Solutions

The elastic-plastic finite element analyses were carried out using the 85-version of the ADINA code [22]. In crack growth analyses a separate subroutine package IWM-CRACK [23] linked with ADINA was used. In the calculation the full Newton iteration process with line search was adopted for the solution of equilibrium equations.

Finite element model

The mesh A shown in Figure 3a was used in elastic-plastic analyses for the case a/W=0,5. Due to symmetry only one quarter of the specimen was modelled. There are two symmetry planes, i.e. the XY- and XZ-plane. Displacements at the end of the specimen (Y=180 mm) were forced to be equal by constraint equations. For two- and three-dimensional elastic-plastic analyses the mesh was similar. There was only one element layer through the specimen. The two-dimensional case was modelled with 110 isoparametric 8-noded plane elements. In the three-dimensional case the mesh consisted of 110 20-noded isoparametric solid elements. The total number of degrees of freedom was 738 in the two dimensional model and 2556 in the three-dimensional, respectively.

In order to model the crack front area, collapsed elements causing an 1/r-singularity in the strains near the crack front, were adopted. The three dimensional mesh used in the crack growth analyses is shown in Figure 3b. In this model, the middle plane of the specimen (YZ-plane) is also a symmetry plane. Thus only one eighth of the specimen is modelled.

The model consists of 177 20-noded solid elements and the number of degrees of freedom is 3422.

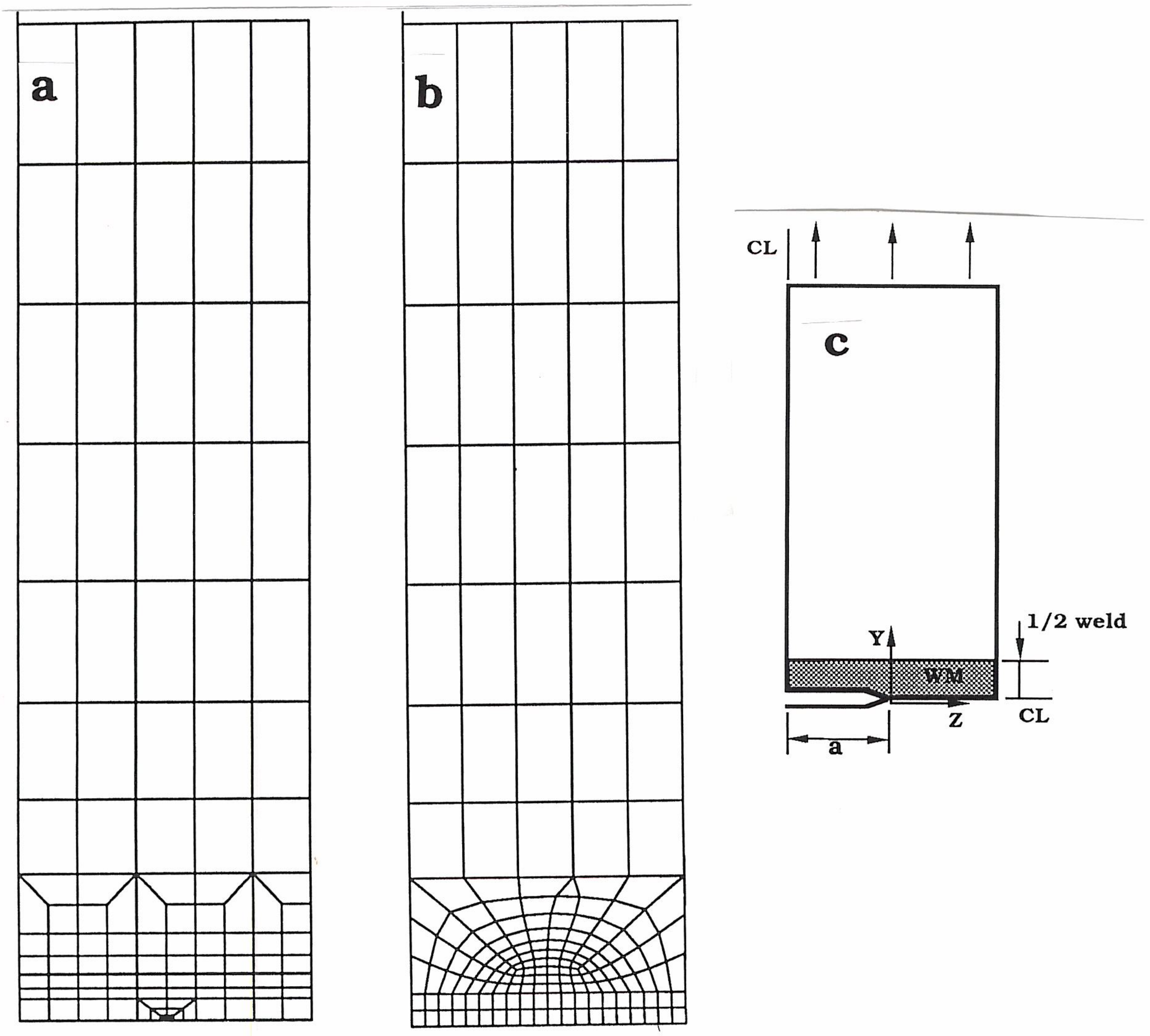


Figure 3. Finite element mesh designs for CCT panels
a) Mesh for stationary crack, b) Mesh for crack growth analyses.
c) Schematic showing the part of the panel used in the FE-model.

Material properties, loading and crack growth criteria

Material nonlinearities were taken into consideration by using the von Mises yield function and isotrophic hardening. Piece-wise linear stress-strain curves were used for base and weld materials as shown in Figure 4. In both models the two lowest element layers constitute the weld metal. The prescribed displacement at the end of the specimen was increased step by step (each step 0,1 mm) 14 times. In crack growth analyses the crack growth, Δa was controlled by the CTOD(δ_5). For all a/W ratios the same R-curve was used (as shown in Figure 9). At each step the calculated

CTOD(δ_5) value was compared to the given CTOD R-curve, and the nodes at the ligament were released (sequentially releasing the constrained nodes adjacent to the crack tip) according to the crack growth criteria.

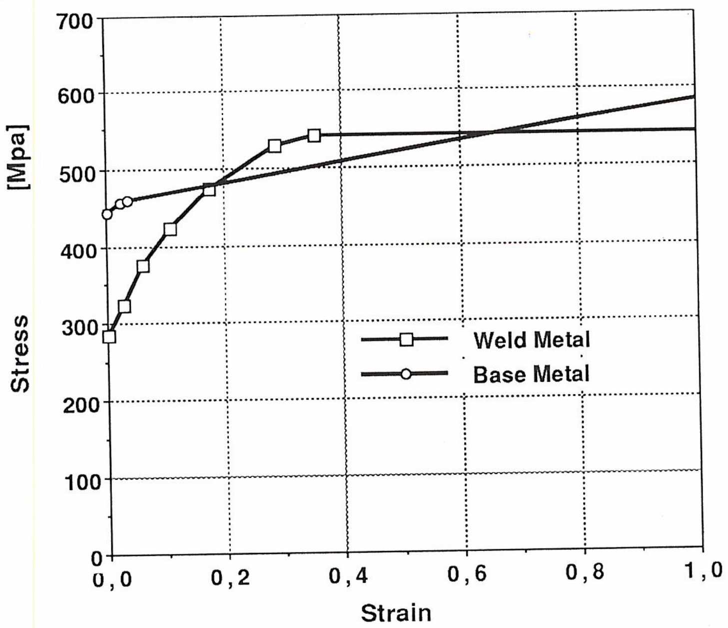


Figure 4. Material stress-strain curves used in numerical analyses

Experimental and Numerical Results

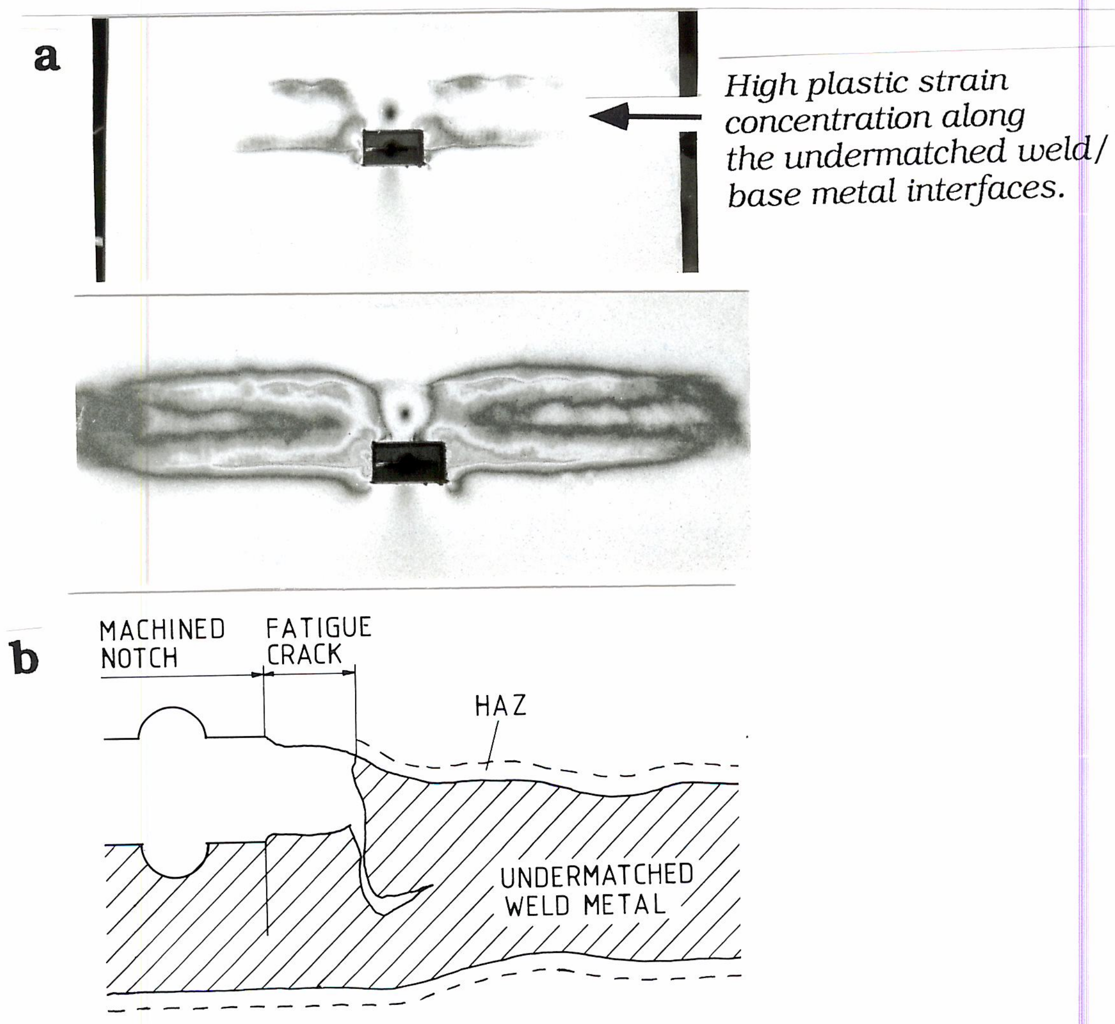
Before discussing the results of the experimental and the finite element analyses, it should be mentioned that the results of the three weld metal notched panels shown in this paper present only a small part of an extensive research program. The finite element analyses of the HAZ/fusion line notched panels with matched, under- and overmatched welds are in progress.

Experimental Observations

Complete experimental results of the undermatched weld metal and HAZ notched CTOD and CCT panels with various a/W ratios have been reported in the literature [13]. These studies revealed that the lower strength weld metal side of the HAZ notched CTOD and CCT specimens caused localized plastic deformation which led to a relaxed stress state at the crack tip and subsequently prevented a cleavage crack initiation at the fusion line-coarse grained heat affected zone (CGHAZ). Due to the unsymmetric spread of plasticity (localized yielding) towards the weld metal, ductile crack initiation occured in the weld metal and this caused a crack path deviation into the weld metal for both shallow and deep notched CTOD and CCT specimens as shown schematically in Figure 5. A numerical investigation of deformation process of interface crack tip has been carried out by C. F. Shih and R.J. Asaro [5] and they have reported that large shear stresses and strains can develop (due to different angular distribution of the stresses for interface crack from those for crack in a homogeneous medium) near the bond line of an interface crack despite the tensile nature of the remote stresses. This explains the experimentally observed crack path deviation into the soft weld metal in HAZ notched panels (Fig. 5b).

An examination of the strain patterns obtained with photoelastic coating of the HAZ notched panel (a/W=0,1) indicates strain concentrations at the fusion boundaries of the weld. With the applied load increasing, the intensity of strain bands mainly increased at these regions by leaving the mid -weld part in an almost unstrained condition. In the course of this process, extensive plastic strain concentrated in the whole width of the transverse weld and the specimen remained in this net section yielding condition till the end of the test (Figure 5a). The base plate portions of the weld metal notched panels did not deform plastically (i.e. the base metal behaved like a rigid body). Extensive confined plastic deformation in weld metal and crack growth have exhausted the specimen`s load carrying capacity before the base metal started to deform plastically.

The occurence of plastic zones at two different parts of the panels (usual crack tip plastic zone development and remote plastic zones at the fusion boundaries of the weld) is a unique feature of undermatched welds or bimaterial interfaces of materials with different Poisson ratios. The possible effect of this phenomenon on the crack driving forces (CTOD or J-integral) should be carefully analysed. One may expect the development of a higher crack driving force for cracks in undermatched welds due to the plastic strain concentration caused by its lower strength.



High plastic strain concentration along the undermatched weld/ base metal interfaces.

Figure 5. Photoelastic coating shows plastic strain concentration in undermatched weld with HAZ crack (a/W=0,1).
a) Extensive plastic strain built-up at the fusion boundaries.
b) Crack deviation from HAZ into undermatched weld.

Comparison of the experimental and numerical results

The calculated and measured load-load line displacement (ΔV_{LL}) curves are shown in Figure 6. The load-displacement curve, where the crack growth is taken into consideration 3D-FE (crack growth) shows the best agreement with the measured results. The 2D-plane strain and 3D-stationary crack models are not able to simulate complex deformation (i.e. crack growth and local necking in thickness direction etc.) in weld metal. Thus the specimens with shorter cracks, a/W=0,3 and 0,1 were further analyzed numerically with only simulating crack growth. The measured and calculated load-displacement curves for all the three panels (a/W=0,5, 0,3 and 0,1) are shown in Figure 6. It is apparent that the agreement between experiment and simulation is not as good in the descending part of the load-displacement curve as in the ascending part.

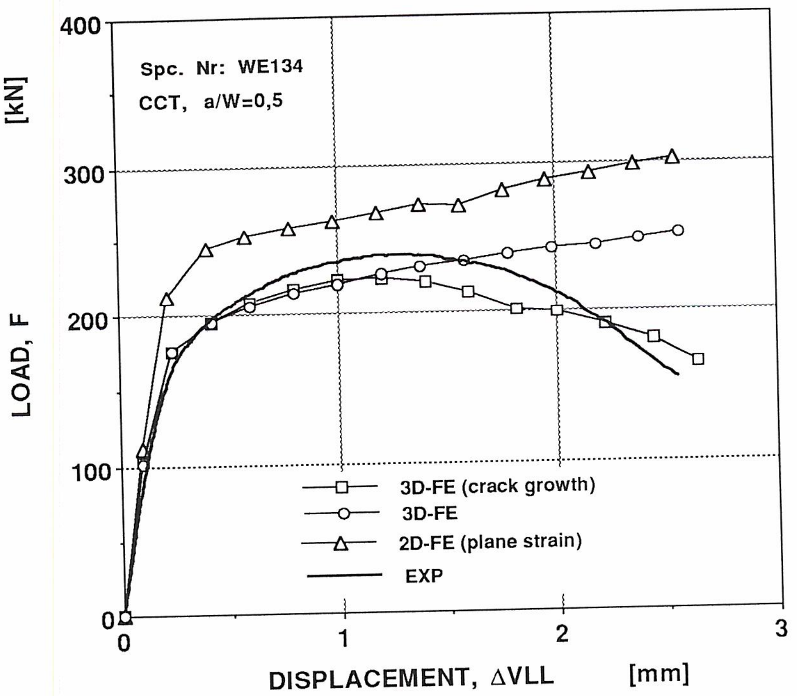


Figure 6. Calculated and measured load-displacement curves for the specimen of a/W=0,5 with 2D and 3D FE-analyses.

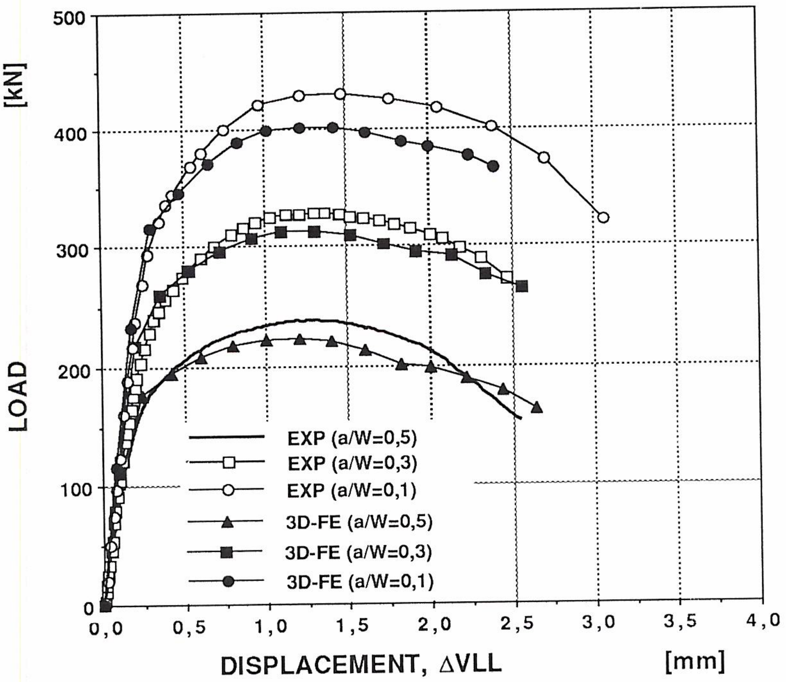


Figure 7. Calculated and measured load-displacement curves for all three a/W ratios.

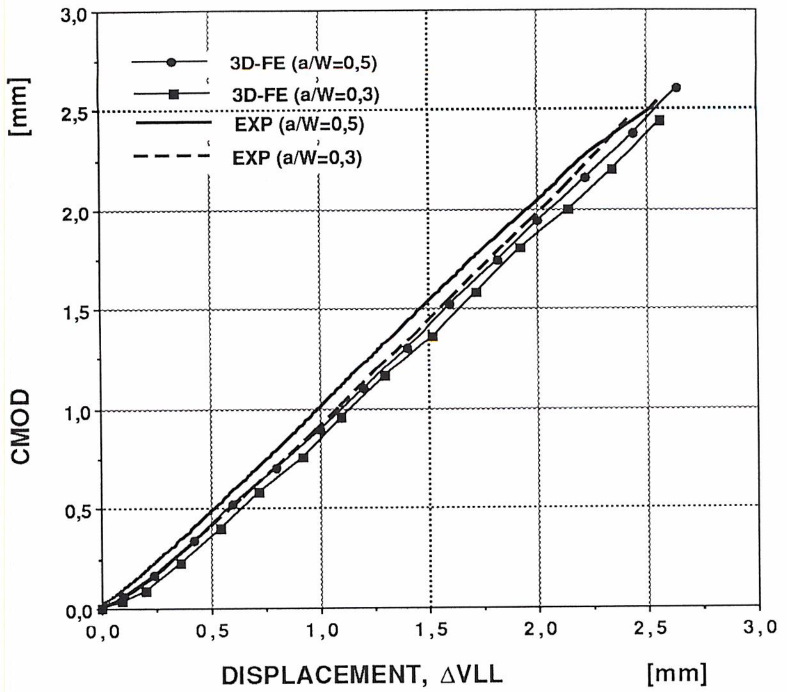


Figure 8. Calculated and measured CMOD-displacement curves

Also the calculated dependence in Figure 8 between crack mouth opening displacement, CMOD and ΔV_{LL} shows a good agreement with the measured one. The occurence of an extensive plastic zone at the weld/base metal interface apparently does not affect (depress) the measured CMOD values. A similar observation was also made with regard to CTOD(δ_5) mesurements.

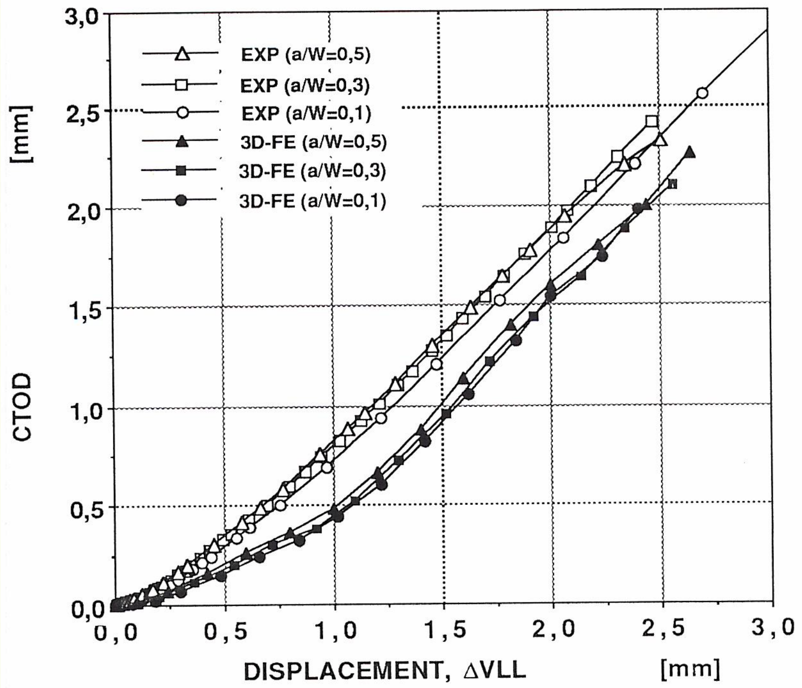


Figure 9. Calculated and measured CTOD(δ_5)-displacement curves

The experimental and calculated CTOD(δ_5) vs. applied displacement curves are presented in Figure 9. At first the measured and calculated values agree well and the discrepancy can easily be understood by looking at the calculated load vs. displacement curves (Figure 7), because the calculation sligthly overestimates the displacement for a given applied load. Due to the rather coarse mesh, the FE-model is not able to simulate the near vicinity of the crack tip quite well. Hence, the calculated CTOD(δ_5)-VLL dependence shows a moderate deviation from 1:1 linear relationship as it was observed in Figure 8 in a perfect manner. A finer mesh with more layers in thicknessis direction is planned to be used particularly in the analyses of the HAZ notched panels. It is known that, at net section yielding stages of the homogeneous CCT panels, the CMOD or CTOD show usually 1:1 linear dependence on applied displacement.

An extensive strain build-up at the outer boundaries of the undermatched weld as mentioned earlier, has important implications due to its possible effect on crack tip fracture parameters (CTOD or J-Integral). The development of intense plastic strains at the fusion boundaries will in fact shield the small crack in the central region from the applied displacement. Luxmoore et al [17] have obtained the reduction of calculated J-Integral for 15% and 30% undermatched welds compared to matched CTOD specimen. However, our experimental and calculated crack driving force parameter- CTOD(δ_5) -values have shown identical behaviour with applied displacement for all a/W ratios as shown in Figure 9. Therefore, one can conclude that the CTOD(δ_5) concept is still a valid fracture characterizing parameter for the fracture analyses of these highly undermatched welds.

The CTOD(δ_5) R-curves of the panels for extensive crack growth are shown in Figure 10. As is usually observed in homogeneous materials, CTOD(δ_5) values monotonically rise as the ductile crack grows. The calculated R-curves for all a/W ratios show as expected a single R-curve, since numerical calculations used the same R-curve as an input data for all a/W ratios. However, FE-results still exhibit some discrepancy with experimental results at the beginning of the R-curves. This discrepancy remains within a relatively constant range with FE-results during the subsequent crack growth in the short crack (a/W=0,1) specimen but expected good agreement with the a/W=0,3 and 0,5 specimens for larger crack growth range.

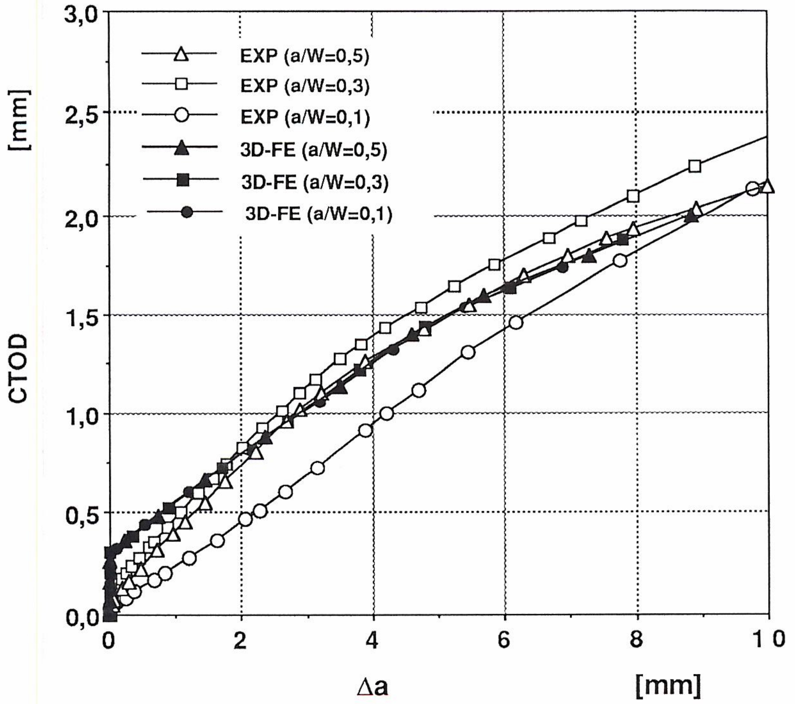


Figure 10. Calculated and measured CTOD(δ_5)- Δa curves.

Conclusions

In this paper an experimental and numerical investigation on center cracked tensile panels with undermatched welds was conducted.

In the light of the above experimental and numerical results and their comparisons, it can be concluded that CMOD and CTOD(δ_5) adequately characterize the deformation and fracture process (the amount of crack tip opening scales linearly with the remote applied strain) at the crack tip of transverse undermatched welds under tensile loading.
Complex plastic zone developments confined to the weld metal apparently do not affect the locally measured and calculated crack driving force, CTOD(δ_5) values. The correlation between remotely applied displacement and near crack tip parameters exhibit identical behaviour similar to the specimens with uniform mechanical properties.

The displacements calculated using the crack growth analyses showed a good agreement with the measured ones. The crack growth model does not simulate the descending part of the load-displacement curve as well as the ascending part. The main reason is probably that the crack growth was controlled in the calculation by only one displacement component and thus no tunneling effect was allowed. This also caused an increasing difference between crack driving force CTOD (δ_5) value in the crack front with increasing ΔV_{LL}.

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