ANALYSIS OF THE FRACTURE BEHAVIOUR OF SURFACE CRACKED WIDE PLATES CONTAINING OVERMATCHING WELD METAL

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The structural significance of weld defects or cracks has to be assessed for safe and economic operation of welded structures. In comparison to other defects assessment procedure, the Engineering Treatment Model for Mis-Matched welded joints (ETM-MM) takes into account the mechanical properties of base and weld metal as well as the weld width. The ETM-MM estimates have already been compared with experimental and numerical results of wide plates containing through thickness cracks. In this work, the ETM-MM was validated for surface cracked wide plates containing overmatched weld metal by comparing the experimentally obtained CTOD(δ_5) results with the ETM-MM predictions. The observed deformation and fracture characteristics of wide plates with various notch positions were found to be useful for the application.

INTRODUCTION

The structural performance of a component containing welds is influenced by the mechanical properties of the participitating regions (base metal, weld metal and HAZ). The yield strength mis-match, M, (= yield strength ratio weld metal / base metal) affects the deformation and fracture behaviour of the welded joints significantly under both bending and tension loadings. Other important influencing parameters are strain hardening exponents of base and weld metals (N_B, N_W), weld metal width (2H), joint configuration, applied strain definition as well as crack size/location. However, defect assessment procedures such as BS PD6493 (1) assume that defects are present in a material of uniform mechanical and microstructural properties and do not consider any interaction between mechanical properties of the various regions of weldments and subsequent influence on structural performance. Therefore, these procedures may provide overconservative or unsafe predictions of load or critical crack size for mis-matched welded joints particularly for significantly mis-matched weldments. Schwalbe et al (2,3) have recently developed the ETM-MM defect assessment procedure which takes into account the influence of M, strain hardening behaviour of the cracked configuration

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(mis-match strain hardening exponent N_M), and weld metal width (2H) on structural behaviour. The ETM-MM provides formulae for predicting the crack tip opening displacement, CTOD(δ_5), on a basis of 5 mm in the weld metal for the loading ranges of "elastic", "small scale yielding" and "fully plastic", for undermatching and overmatching weld. The CTOD(δ_5) is expressed as a function of applied load, F, or applied global strain, ε, and is calculated as an absolute or normalized value or in a design curve manner (2,3). Concern has to be given to the determination of the yield load for which numerous solutions are available for homogeneous specimens but only a few solutions for mis-match configuration. The present test results were used to provide further validation of ETM-MM and identify areas which need further development to accomodate the effects of mis-match and surface crack in this procedure appropriately.

EXPERIMENTAL PROCEDURE

Specimen preparation and testing

The dimensions of the wide plates tested were: total length = 1580 mm, total gauge length = 700 mm, B = 25 mm, 2W = 180 mm. A semi elliptical surface crack was made by spark erosion, Fig. 1. This notch was then extended by fatigue with the plate loaded in tension to the specified depth of about 10 mm. The wide plate tests were conducted at -10°C in tension and unloaded after attaining the maximum load. The plates were refatigued for marking the amount of stable crack growth obtained from the tension testing. During testing, the applied load, crack mouth opening displacement (CMOD), CTOD(δ_5), overall extension using linear variable differential transducer (LVDT) and extension of stable crack growth were monitored. The local deformation (or opening) at the surface crack was measured with three δ_5-clip gauges at both ends of the fatigue crack tips and at the middle of the surface crack, all over a gauge length of 5 mm, Fig. 1. The overall extension of the plate was measured over a gauge length of 270 mm, from which the gauge length strain, GLS, was derived.

RESULTS AND DISCUSSION

The mechanical properties and the engineering stress-strain curves for the base and weld metals are given in Table 1 and Fig. 2, respectively. Both base and weld metals exhibited a Lüders straining behaviour. Weld metal overmatching of 50% was achieved.

CTOD(δ_5) vs. applied strain relationship

In this paper, the crack driving force will be discussed in terms of CTOD(δ_5) vs. normalized applied strain curves, Fig. 3. The applied strain (GLS) was normalized with the base metal yield strain. All wide plates tested failed in a ductile manner (in the Gross Section Yielding mode, GSY). The comparison of the curves obtained for base metal wide plate and for wide plates containing welds with surface crack position in weld metal and HAZ shows a potential advantage of the overmatching weld metal for protection of surface cracks located in the weld metal and HAZ of the weld joint compared to the base metal by lower CTOD(δ_5) levels during the entire deformation of the plates. The highest strains are assumed to occur at regions about ±45 deg. from the crack emanating towards the back side of the specimen (4,5). The plasticity development in 45° deg. direction is then influenced by the mechanical properties of the area which the 45° deg. yielding pattern has to penetrate (6). Therefore, the shielding effect of the overmatching weld metal particularly occurs for a surface defect located in the weld metal which is shown by the obtained CTOD(δ_5) level which is lowest for the weld metal notched wide plate in comparison to the other wide plates tested. The crack tip is shielded from the applied deformation due to the (higher strength) weld metal which results in plasticity development primarly at remote base metal. For a defect located at the HAZ, the degree of protection of overmatching weld metal is apparently less than for a defect in the weld metal. This is due to the easier plasticity development (presence of the softer base metal near the crack tip) towards the base metal. Obviously, the presence of high strength weld metal on one side of the HAZ crack will prevent development of a symmetrical plastic zone and hence the plastic zone will primarily develop at the lower strength base metal side which is shown by the increase of CTOD(δ_5) for HAZ notched panels. In comparison to the three point bend specimens (4,5), for the surface cracked wide plates the presence of local brittle zones (LBZs) at the crack tip did not lead to a brittle fracture initiation because the critical condition along the fusion line is mitigated by the (asymmetrical) development of 45° yielding pattern into the base metal.

Predictions of the ETM-MM

For calculation of the net section yield load, F_{YM}, and N_M the formulae according to (2,3) were applied which take into account yielding from the weld metal strip penetrating into the base metal, and 2H:

$$F_{YM} = 2\cdot\sigma_{YW}\cdot\left\{1.41\cdot H+\left(W-a-1.41\cdot H)\cdot\frac{\sigma_{YB}}{\sigma_{YW}}\right)\right\}\cdot B \qquad (1)$$

for deformation under plane stress condition, and

$$N_M = \frac{W-a}{\dfrac{H}{N_W} + \dfrac{(W-a-H)}{N_B}} \qquad (2)$$

with N_B and N_W obtained from tensile testing, Table 1.

According to the ETM-MM procedure F_{YM} has to be calculated either with the yield stress $\sigma_Y = 0.9 * R_{p0.2}$ for continuously hardening materials (see Fig. 2), and with $\sigma_Y = R_{p0.2}$ for steels with a Lüders plateau. The ETM-MM assumes a "local yield load", F_{YL}, which for overmatching equals $0.9 * F_{YM}$. In order to use these formulae (developed for through thickness cracks) to the crack configuration used, the surface crack was replaced with an equivalent through thickness crack length a* calculated according to BS PD6493. For determining 2H an idealized rectangular weld was assumed representing the same amount of weld metal volume as the real weld metal (→ $2H_{average}$ = 22 mm). With these assumptions the prediction of the CTOD(δ_5) as a function of applied load F with notch position in overmatching weld metal was made using the ETM-MM-formulae according to (2,3):

Stage 1: $F \leq F_{YL}$
(elastic regime)

$$\delta_5 = \frac{K^2}{E \cdot \sigma_{YW}} \qquad (3)$$

Stage 2: $F_{YL} \leq F \leq F_{YM}$
(regime of local yielding)

$$\delta_5 = \delta_{5YL} \cdot \left(\frac{F}{F_{YL}}\right)^{\frac{4}{1+N_W}} \qquad (4)$$

In order to investigate the sensitivity of the procedure, the regime of local yielding was expressed using an alternative formulation which accounts for a contribution of the base metal to the hardening behaviour:

Stage 2:
(alternative)

$$\delta_5 = \delta_{5YL} \cdot \left(\frac{F}{F_{YL}}\right)^{\frac{1}{N_M}} \qquad (4a)$$

Stage 3: $F \geq F_{YM}$
(fully plastic regime)

$$\delta_5 = \delta_{5YM} \cdot \left(\frac{F}{F_{YM}}\right)^{\frac{1}{N_M}} \qquad (5)$$

With the alternative solution for the regime of local yielding the strain hardening around the surface crack which takes place at the beginning of plastic deformation is underestimated which therefore should result in more conservative predictions. For HAZ, stage 2 was calculated with $N_W = N_B$. Stage 3 for BM and HAZ was calculated with $N_M = N_B$. The stress intensity factor, K, was calculated for the crack tip position at the surface according to Newman and Raju. For the all base metal wide plate the ETM-MM formulae were applied by setting 2H to zero, and N_M being N_B, which leads to the ETM formulae valid for homogeneous material. Then (according to the ETM) no regime of local yielding is assumed and "stage 2" does not apply. For the notch position in the HAZ for the calculation of the yield load an all-base metal wide plate was assumed because in an earlier investigation the ETM-MM prediction using weld metal properties was found to be unsafe (5). For the fully plastic regime it was assumed that the base metal has to accomodate the entire deformation and strain hardening. Therefore, stage 3 was calculated with the strain hardening exponent for base metal.

Figures 4 to 6 show the comparison between experimental results (obtained from testing of base metal wide plate and wide plates containing welds) and ETM-MM predictions, expressed in CTOD(δ_5) vs. normalized load curves. For the base metal wide plate (Fig. 4) the ETM prediction shows for the Lüders straining regime some nonconservatism whereas the later fully plastic regime is close to the experiment. The presence of the extensive Lüders plateau obviously increases the difficulty of more accurate crack driving force prediction. Up to maximum load, the slope of the predicted curve is very similar to the experimentally obtained curve which prooves the adequate description of the strain hardening behaviour with N_B. The comparison between the test conducted on weld metal notched panel and ETM-MM estimation reveals slight nonconservatism at the beginning of the plastic regime with the original stage 2 solution whereas in the fully plastic regime, the prediction turns to be clearly conservative, Fig. 5. With the alternate solution for stage 2 the onset of small scale yielding can be predicted very close with slight conservatism. With N_M according to eqn. 2 the slope of the curve is underestimated which contributes to the conservatism of the prediction in the fully plastic regime. For the notch position in the HAZ, Fig. 6, with the original stage 2 solution the onset of plastic yielding is predicted well with only very little nonconservatism. The alternate solution leads to a clear conservative prediction. In comparison to the base metal wide plate and the weld metal notched wide plate which both exhibit a transition from the elastic regime to the plastic regime with a Lüders plateau similar to the tensile test, the HAZ notched wide plate exhibits a transition which resembles more a steady curve. This may be caused by the asymmetrical development of 45° yielding pattern and the constraint state of the HAZ which interfere with the Lüders straining regime. The slope of the fully plastic part is underestimated again with N_M.

Summarizing, with the simple equations and the input assumptions used (yield load calculated with $\sigma_Y = R_{p0.2}$) the quality of the predictions is very satisfactory. The regime influenced by the Lüders strain can be described more or less satisfactory with the alternate solution for stage 2 (eqn. 4a), whereas the fully plastic regime is better predicted with the original solution. A more accurate prediction of the onset of plastic deformation is not possible because the ETM-MM (and comparable defect assessment procedures) had been developed for power-law hardening materials. Therefore, further work will concentrate on an alternative way to handle materials exhibiting Lüders straining behaviour and on modification of the mis-match strain hardening exponent N_M. The use of an equivalent crack length a* according to PD6493 seems to be adequate for ETM-MM estimation.

CONCLUSIONS

The CTOD(δ_5) vs. normalized applied strain relationships clearly revealed the beneficial effect of weld metal strength overmatching on both weld and HAZ part through defects. With the simple equations and the input assumptions used the ETM-MM estimates give satisfactory, mostly conservative, predictions of the CTOD(δ_5) for base metal, weld metal and HAZ notched cases. The Lüders straining behaviour of the materials causes some loss in accuracy for ETM-MM predictions in the Lüders straining regime. The ETM-MM estimates may be improved if a solution can be deduced which takes into account the Lüders straining behaviour.

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TABLE 1 Mechanical properties of the base and weld metals

	yield strength [MPa]	tensile strength [MPa]	strain hardening exponent N	1/N	mis-match factor M	elongation [%]
BM	449	568	0.065	15.5	-	28
WM	675	728	0.026	37.8	1.50	23

$M = \sigma_{YW} / \sigma_{YB}$; $\varepsilon_{YB} = 0.38\ \%$

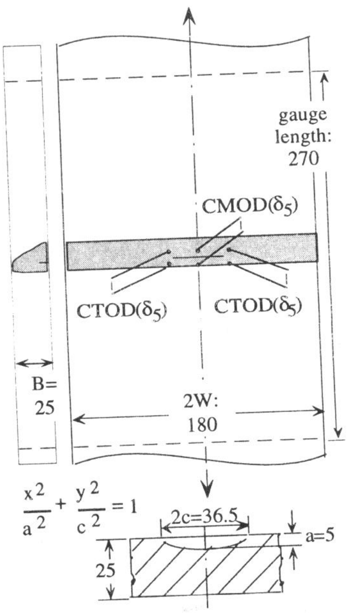

Fig. 1: Instrumentation and surface crack dimension

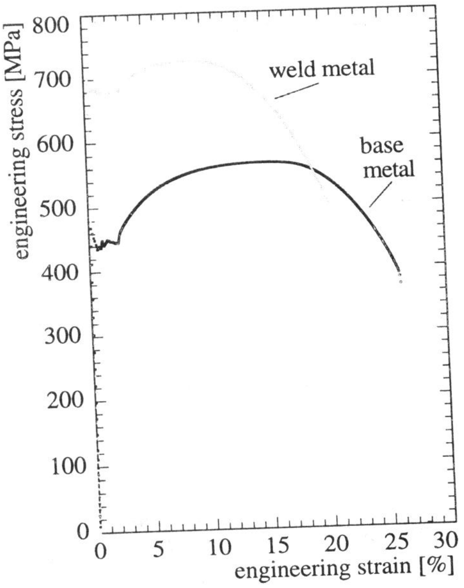

Fig. 2: Engineering stress-strain curves obtained for base metal and weld metal

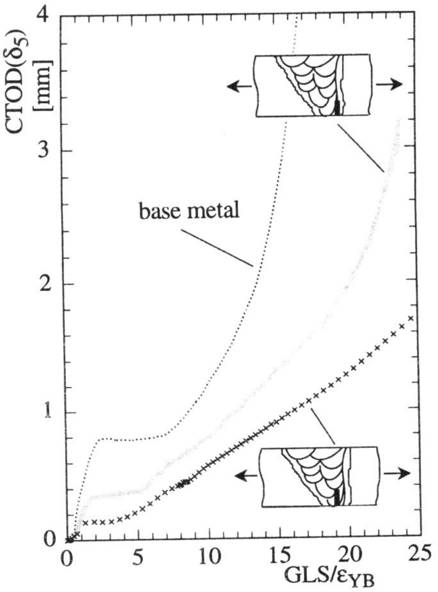

Fig. 3: Comparison of CTOD vs. GLS curves of base metal wide plate and three welded wide plates

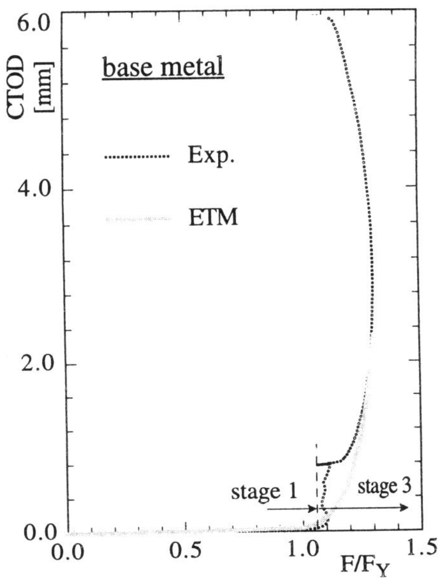

Fig. 4: ETM prediction and from test result obtained for the base metal wide plate.

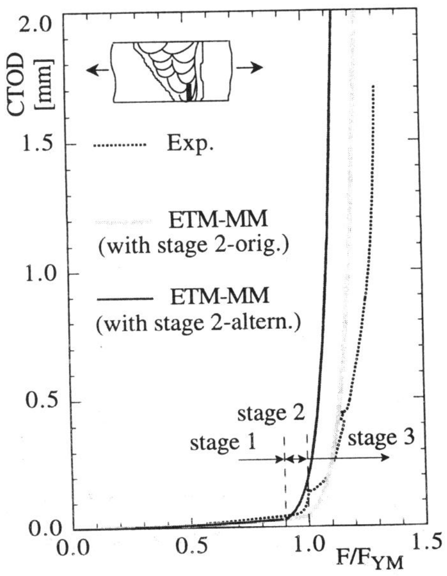

Fig. 5: ETM-MM prediction and test result obtained for notch position in weld metal root

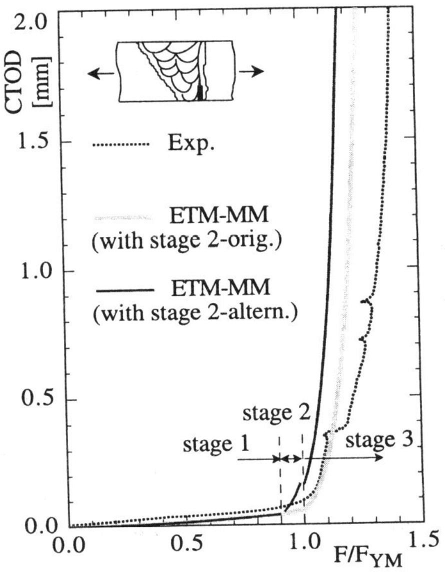

Fig. 6: ETM-MM prediction and test result obtained for notch position in HAZ.