A MODIFIED CTOD DESIGN CURVE IN CONSIDERATION OF MECHANICAL HETEROGENEITY IN WELDS

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ABSTRACT

Although the current CTOD design curve has been widely used for the welded structure integrity evaluation, the influence of welds strength mis-matching on crack driving force is not in consideration In the present studies, an attempt is made at modifying the CTOD design curve, in which effect of the weld strength mis-matching and weld geometrical factors is included. The modified CTOD design curve proposed for the welds is compatible with the current CTOD design curve for homogeneous material structures. In addition, if the weld strength mis-matching factor M or the normalized strength mis-matching factor M' is equal to one, the modified CTOD design curve becomes the current CTOD design curve.

Moreover, tests on electron beam welded bimaterial single-edge cracked tension specimens were carried out. From the experimental results and the modified CTOD design curve, it is indicated that the use of the current design curve is conservative for the overmatched welds, when directly applying the current CTOD design curve to the welds.

KEYWORDS

CTOD driving force, design curve, mechanical heterogeneity, welds

INTRODUCTION

It is relatively common for weld metal and base metal to have different mechanical properties often with different chemical compositions and microstructures. Nowadays, ones believe that weld metal over-matching is beneficial if the weld metal must be shielded from plastic strains. For undermatched weld metal, however, the overall deformation capacity is small because the weld metal is only a small part of the welds, especially when some kind of weld metal or heat affected zone(HAZ) defect occurs.

It is true that significant progress has been made during the last decade in understanding the fracture behaviour of welded joints with respect to their mechanical heterogeneity(Burdekin et al., 1994; Kirk et al., 1994; Toyoda, 1989; Zhang et al., 1989; Smith, 1992), but till now only relatively little research has been devoted to the study on the effect of weld strength mis-matching on the fitness-for-purpose defect assessment procedures(Schwalbe,1992). In the present paper an attempt will be made at a modification on the CTOD design curve with consideration of welds heterogeneity, which includes the effects of strength mis-matching and weld geometry factors.

CTOD DESIGN CURVE

CTOD design curve is based on fracture mechanics relationships between applied strain, required fracture toughness of the material and defect size. For the revised version of BSI PD6493(BSI, 1991), the level 1 treatment now gives the CTOD formulation in terms of applied stress, as follows:

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for $\sigma/\sigma_y \le 0.5$

$$\delta = \frac{\sigma^2 \pi a F^2(a/W)}{\sigma_y E} \tag{1}$$

for $\sigma/\sigma_y \ge 0.5$

$$\delta = \frac{\sigma^2 \pi a F^2(a/W)}{\sigma_y E}\left(\frac{\sigma_y}{\sigma}\right)^2\left(\frac{\sigma}{\sigma_y} - 0.25\right) \tag{2}$$

where δ is the CTOD, σ is the applied stress, σ_y is the yield strength of material, E is the Young's modulus, a is the half crack length, and F(a/W) is the correct geometrical parameter. To assess the significance of a defect in the welded structures by using the current CTOD design curve, the mechanical properties of the material where the defect lies can be used, or it may be assumed that the strength mis-matching may be neglected due to the small size of the weld compared to the size of the base metal.

MODIFIED CTOD DESIGN CURVE

The difference between weld and base metals yield strength is an important factor in protecting any pre-existing weld metal defect from severe plastic strains. This must be considered if the weld metal overmatches when gross-section yielding is likely to occur. If the weld undermatches, gross-section yielding may not occur and most of the plastic deformation is concentrated in the weld metal. In fact the use of the current design curve may be conservative for overmatched welds, and non-conservative for undermatched ones. Thus, it is necessary to consider the effect of the local strain on the crack driving force.

Effect of Strength Mis-Matching

It is assumed that both the weld metal and base metal have the same Young's modulus; σ_y^b and σ_y^w are the yield strength of base and weld metals, respectively. If it is defined that the strength mis-matching factor of welds $M=\sigma_y^w/\sigma_y^b$, Eqs(1) and (2) may be rewritten as:

for $\sigma/\sigma_y^b \le 0.5$

$$\delta_w = \frac{\sigma^2 \pi a F^2(a/W)}{M \sigma_y^b E} \tag{3}$$

for $\sigma/\sigma_y^b \ge 0.5$

$$\delta_w = \frac{M \sigma_y^b \pi a F^2(a/W)}{E}\left(\frac{\sigma}{M\sigma_y^b} - 0.25\right) \tag{4}$$

where δ_w is the CTOD when the crack lies in the weld metal. Thus, in the modified CTOD formulations given by Eqs(3) and (4), the effect of weld strength mis-matching may be included. It follows from Eqs(3) and (4), the non-dimensional relations can be given,

for $\sigma/\sigma_y^b \le 0.5$

$$\frac{\delta_w E}{\sigma_y^b a F^2(a/W)} = \frac{\pi}{M}\left(\frac{\sigma}{\sigma_y^b}\right)^2 \tag{5}$$

for $\sigma/\sigma_y^b \ge 0.5$

$$\frac{\delta_w E}{\sigma_y^b a F^2(a/W)} = \pi M\left(\frac{\sigma}{\sigma_y^b} - 0.25\right) \tag{6}$$

When it is assumed that M=0.7, 1.0, and 1.3, respectively, the above non-dimensional relations are shown in Fig.1. It is clear that the CTOD design curve for the undermatched welds is higher than the evenmatched welds or homogeneous material structure, and the CTOD design curve for the overmatched welds is lower than the homogeneous material structure. That is the δ_w value is increased with the decrease in the M value. In addition, if M-1.0, Eqs(3) and (4) are identical with the Eqs(1) and (2), respectively.

Effect of Geometrical Factors

Yielding behaviour of welds is obviously influenced by the crack depth and strength mis-matching. When loading a crack which lies in the weld metal, the yielding may extend out to the base metal through the weld boundaries, or may be confined in the weld metal itself(Tang et al., 1994, 1995). In order to consider the interaction of the crack depth and strength mis-matching, a factor M' is defined as a normalized strength mis-matching factor. If M' is substituted for M in the Eqs(3) and (4), it follows that

for $\sigma/\sigma_y^b \le 0.5$

$$\delta_w = \frac{\sigma^2 \pi a F^2(a/W)}{M' \sigma_y^b E} \tag{7}$$

for $\sigma/\sigma_y^b \ge 0.5$

$$\delta_w = \frac{M' \sigma_y^b \pi a F^2(a/W)}{E}\left(\frac{\sigma}{M'\sigma_y^b} - 0.25\right) \tag{8}$$

where it is assumed that

for $M \le 1$

$$M' = M^{(h/c)} \tag{9}$$

for $M \ge 1$

$$M' = 2M(h/c) - 2(h/c) + 2 - M^{(h/c)} \tag{10}$$

where h is the half width of the weld metal, and c is the uncracked ligament. If h/c=0, i.e. there does not exist weld metal. If h/c=1, the Eqs(7) and (8) become Eqs(3) and (4). Practically the value of M' reflects the effect of the ratio of weld width to uncracked ligament on the weld strength mis-matching. That is, M'=1, if h/c=0, and M'=M, if h/c=1. As M' is a normalized strength mis-matching factor, the Eqs(7) and (8) represent the CTOD design curve with consideration of the comprehensive effect of strength mis-matching and geometrical factors of welds.

EXPERIMENTS

Two pipeline steels API X52 and X60 were used to fabricate a 4 mm thick electron beam welded bimaterial single-edge cracked tension panels. In the welds API X52 steel was used as the base metal, and API X60 steel as the weld metal. The welded joints fabricated were in strength overmatching. Table 1 gives the mechanical properties of the test steels. The material constant α and n following the Ramberg-Osgood relation are also listed in Table 1.

Table 1 Mechanical properties of the test steels

	σ_y(MPa)	σ_{uts}(MPa)	α	n
API X52	358	515	1.103	7.99
API X60	533	575	1.078	14.01

The size of the specimens was that length 2L=200 mm, weld width 2h=8, 15, 21 mm, specimen thickness B=4 mm, and specimen width W=30 mm. Moreover, a/W=0.25, h/c=0.33; when a/W=0.40, h/c=0.22 and 0.58. Specimen numbering is given in Table 2.

Table 2 Specimen numbering and related parameters

Specimen	a/W	h/c	M	M'	F(a/W)
A	0.40	0.22	1.49	1.130	2.104
B	0.25	0.33	1.49	1.201	1.501
C	0.40	0.58	1.49	1.296	2.104

Tensile test was carried out in an Instron 1342 testing machine with a crosshead speed of 0.5 mm/min at room temperature. During the testing the load(P) vs crack mouth opening displacement(CMOD) was recorded.

Fig.2 shows the results of the testing. It is indicated that the CMOD-σ curve of the welds are located between the two base metal specimens, in which the API X60 steel specimens may also be regarded as the all weld metal specimen, and the CMOD-σ curves of the welded specimens more approach to that of the API X60 base metal specimen in the same a/W condition when the weld width is increased. That is, the effect of the base metal on the crack driving force of the weld metal is reduced.

In the table 2 the values of M' are computed from the Eq.(10), and the values of F(a/W) are computed from

$$F(a/W) = 1.12 - 0.231(a/W) + 10.55(a/W)^2 - 21.72(a/W)^3 + 30.39(a/W)^4 \quad (11)$$

From Eqs(1),(2), (7), and (8), the CTOD design curves of the base metals and the welds specimens tested can be shown in Fig.3 for a/W of 0.4. Obviously, the CTOD design curves of the welded specimens are located between the two base metal specimens, and the CTOD-σ curves of the welded specimens more approach to that of the API X60 base metal specimen in the same a/W value with the increase in the weld width. It is clear that the effect of strength mis-matching, and weld geometrical factor on the CTOD design curves is evident. From the experimental results and the modified CTOD design curve, it is indicated that the use of the current design curve is conservative for the overmatched welds, when directly applying the current CTOD design curve to the welds.

It should be noted that the tested CMOD values are increased more rapidly with the increase in the applied stress, when the value of $\sigma/\sigma_y^b>0.5$. It is inferred that the

CTOD design curve appears to be non-conservative at high stress(Harrison et al., 1988). Moreover, it is indicated that the CTOD turning point is shifted to the higher applied stress when the yield strength of base metal is higher. As the equivalent yield strength of the tested welds is located between the two base steels(Zhang et al., 1995), the turning point of the welds specimen is located between the two base metal specimens.

CONCLUSIONS

(1) A modified CTOD design curve has been proposed for the welds. In the CTOD formulations the effect of the weld strength mis-matching and the weld geometrical factors is in consideration.
(2) The modified CTOD design curve proposed for the welds is compatible with the current CTOD design curve. If the weld strength mis-matching factor M or M' is equal to unit, the modified CTOD design curve becomes the current CTOD design curve for the homogeneous material structures.
(3) If directly applying the current CTOD design curve to the welds, a proper prediction may not be obtained. From the experimental results and the modified CTOD design curve proposed, it is indicated that the use of the current design curve is conservative for the overmatched welds.
(4) Compared to the experimental results, the CTOD design curve appears to be non-conservative at high stress region.

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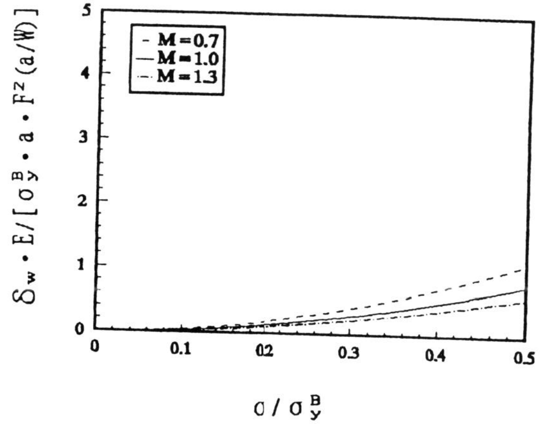
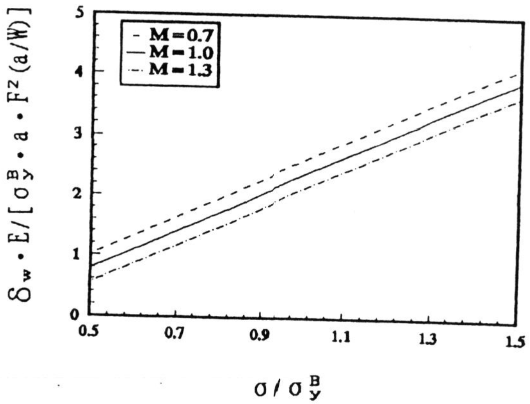
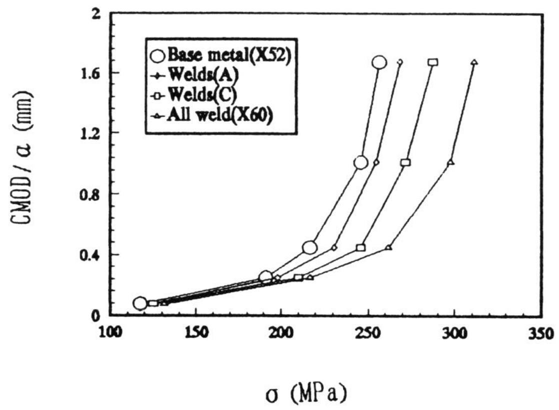


(a) $\sigma/\sigma_y^b \leq 0.5$

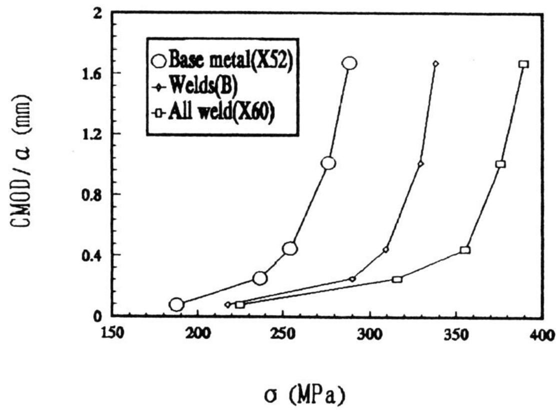


(b) $\sigma/\sigma_y^b \geq 0.5$

Fig.1 Modified CTOD design curve with consideration of weld strength mis- matching

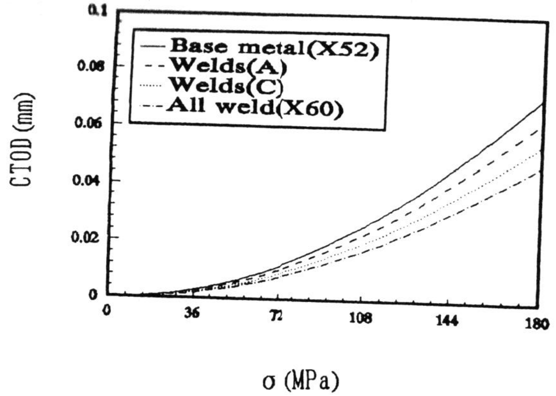


(a) a/W=0.40

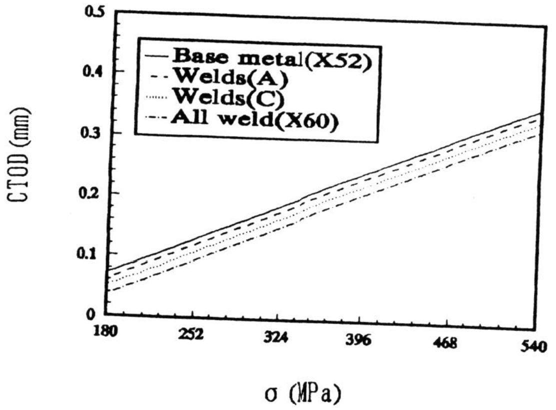


(b) a/W=0.25

Fig.2 Effect of weld width on crack mouth displacement for the welds specimens



(a) $\sigma/\sigma_y^b \leq 0.5$



(b) $\sigma/\sigma_y^b \geq 0.5$

Fig.3 CTOD design curves of the base metals and welds specimens tested (a/W=0.40)