THE LOCAL APPROACH TO THE EFFECT OF NOTCH DEPTH ON FRACTURE TOUGHNESS

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The assessment of notch depth dependence on fracture toughness, of a high strength steel characterized by the critical CTOD value, was made in terms of the local approach. The Weibull stress was evaluated by taking into account the gradient in the triaxial stress field ahead of the crack tip. The Weibull parameters obtained were shown to be independent of notch depth, which is in agreement with the local approach theory. An application of the local approach follows on the prediction of notch depth dependence of CTOD results.

INTRODUCTION

Recent progresses on the fracture mechanics assessment of flawed structures have been made by using the local approach [1,2]. Under the assumption of unstable crack propagation being stress controlled, the local approach gives a local parameter, called the Weibull stress, which combines the weakest link model with the stress gradient in the vicinity of the crack tip. The probability distribution of the Weibull stress obeys a two-parameter Weibull distribution which is independent of geometric parameters governing crack tip stress conditions.

In this paper, this approach was used to assess the effect of notch depth on critical CTOD values of a high strength steel. Previous work [3] has demonstrated that deep and shallow notch specimens exhibit large differences in the crack tip stress fields at the same CTOD level, which results in the notch depth dependence on critical CTOD values at cleavage fracture initiation. By taking into account the triaxial stress field ahead of the crack tip, however, the local approach is found to be an effective method for analysing toughness results for specimens with different geometry. An application of the local approach is also made to predict the notch depth dependence of CTOD results.

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LOCAL APPROACH TO NOTCHED BODIES

For a notched body subjected to an arbitrary stress state, the Weibull stress σ_w is given by [4]

$$\sigma_w^m = \frac{1}{V_0} \int_{V_f} \sigma_{eff}^m \, dV_f \tag{1}$$

where V_f is the volume of the fracture process zone and V_0 is a reference volume. For multiaxial stress states, the effective stress σ_{eff} in spherical coordinates (r,θ,φ) is evaluated by

$$\sigma_{eff}^m = \frac{1}{4\pi} \int_0^{2\pi} \int_0^{\pi} \sigma_{eq}^m \sin\theta \, d\theta \, d\varphi \tag{2}$$

where σ_{eq} is an equivalent stress corresponding to mode I loading.

By using a finite element analysis to determine the crack tip stress fields, the numerical evaluation of Eq. (1) can be made by considering the transformation of the global coordinates (x, y, z) of the deformed element into the local coordinates (ξ, η, ζ) [5]. The mapping of the nodal displacements through the shape function of the element then gives

$$\sigma_w^m = \frac{1}{V_0} \sum_n \int_{-1}^{1} \int_{-1}^{1} \int_{-1}^{1} [\sigma_{eff}(\xi,\eta,\zeta)]^m \, |J| \, d\xi \, d\eta \, d\zeta \tag{3}$$

where $|J|$ is the determinant of the Jacobian matrix of the mapping. This equation enables easy integration of the stress tensor over the deformed shape of the yielded elements.

The probability distribution of the Weibull stress follows an extreme value distribution in the form

$$F(\sigma_w) = 1 - exp\left[-\left(\frac{\sigma_w}{\sigma_u}\right)^m \right] \tag{4}$$

where m and σ_u are the Weibull shape and scale parameters, respectively, which are assumed to be material property independent of specimen geometry.

EXPERIMENTAL RESULTS

Fracture toughness data were obtained by three-point bend CTOD tests using full-thickness specimens with different notch depths extracted from a 15 mm thick high strength steel with 778 MPa tensile strength [6]. Tests were conducted at -120°C, which corresponds to the lower shelf of ductile-brittle transition temperature for this steel. Figure 1 presents the effect of the *a*/W-ratio on the critical CTOD value at cleavage fracture initiation. Most of the specimens with *a*/W=0.1 failed with significant ductile crack extension prior to cleavage fracture. Specimens with *a*/W=0.5 exhibited completely brittle behaviour with negligible crack extension. A statistical analysis based on a Weibull distribution was conducted to assess the scatter of experimental data. Table 1 presents the Weibull parameters for critical CTOD distributions for all *a*/W-ratios. Although the shape parameter m_δ does not show significant variation, the scale parameter b_δ largely depends on the notch depth.

TABLE 1 - Weibull parameters for critical CTOD distributions

Weibull Parameter	*a*/W=0.1	*a*/W=0.3	*a*/W=0.5
Shape, m_δ	1.87	1.48	2.26
Scale, b_δ (mm)	1.10	0.13	0.05

LOCAL APPROACH TO THE EFFECT OF NOTCH DEPTH

Crack tip stress fields were obtained through three-dimensional finite element analyses using 8-nodes isoparametric elements. Crack tip elements were degenerated into triangular prisms in order to allow blunting of the crack tip. Because of symmetry, only one quarter of the specimen was modelled by employing 1256 elements and 1665 nodes. The side length of degenerated elements at crack tip is 0.2 mm. Crack tip opening displacements in the finite element model were determined by the 90° intercept method.

The Weibull stress σ_w and the Weibull parameters m and σ_u were calculated according to an iterative procedure [4] using Eq. (3), being the equation solved by Gaussian quadrature. The equivalent stress σ_{eq} was determined on the basis of the coplanar energy release rate criterion [7]. Figure 2 gives the cumulative distribution of the Weibull stress for each *a*/W-ratio. Table 2 presents the Weibull parameters m and σ_u estimated by the maximum likelihood method. Because of occurrence of stable crack growth Δa prior to cleavage fracture in some specimens with *a*/W=0.1, a statistical analysis based on a censoring model was applied [8]. All *a*/W-ratios exhibit very similar Weibull parameters, irrespective of notch depth, which is in good agreement with theoretical predictions. These results indicate that the characterization of crack tip conditions based on the new parameter σ_w is valid to the fracture mechanics assessment of specimens with different notch depths.

TABLE 2 - Weibull parameters for σ_w-distributions

Weibull Parameters	a/W=0.1	a/W=0.3	a/W=0.5
Shape, m	18.8	19.0	21.7
Scale, σ_u (MPa)	1906	2040	1959

As an application of the local approach, the effect of notch depth on critical CTOD values was predicted. Figure 3 gives the predicted scatter bands at 90% confidence level for critical CTOD values of specimens with a/W=0.1 and a/W=0.3, obtained from the correlation with the σ_w-distribution for specimens with a/W=0.5. The results show reasonable agreement with experimental data, especially for specimens with a/W=0.3. For specimens with a/W=0.1, only the distribution of experimental data exhibiting small crack extension could be predicted, since the change in fracture mode could not be described by a local stress-based criterion.

CONCLUSION

Independence of the Weibull parameters on the notch depth was confirmed by the local approach. Assessment of notch depth dependence of CTOD results through the local approach also gave good agreement with experimental data, provided that the stable crack growth prior to cleavage is small.

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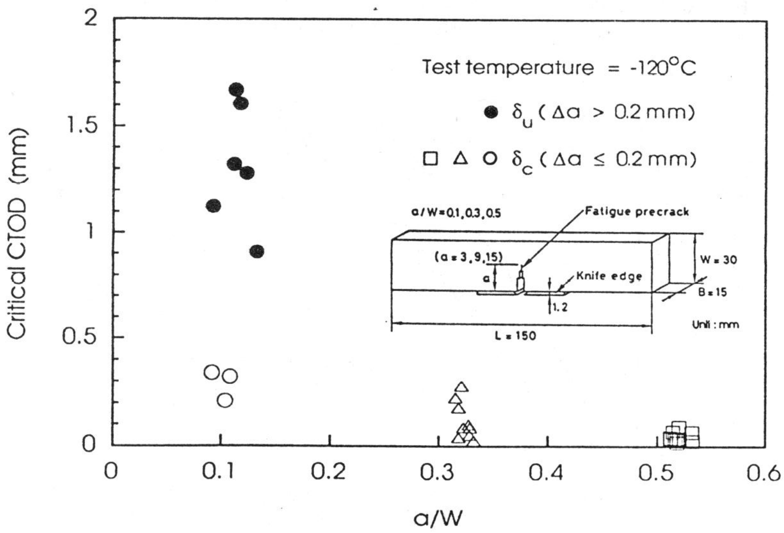

Figure 1 - Effect of *a*/W-ratio on the critical CTOD value at cleavage fracture initiation.

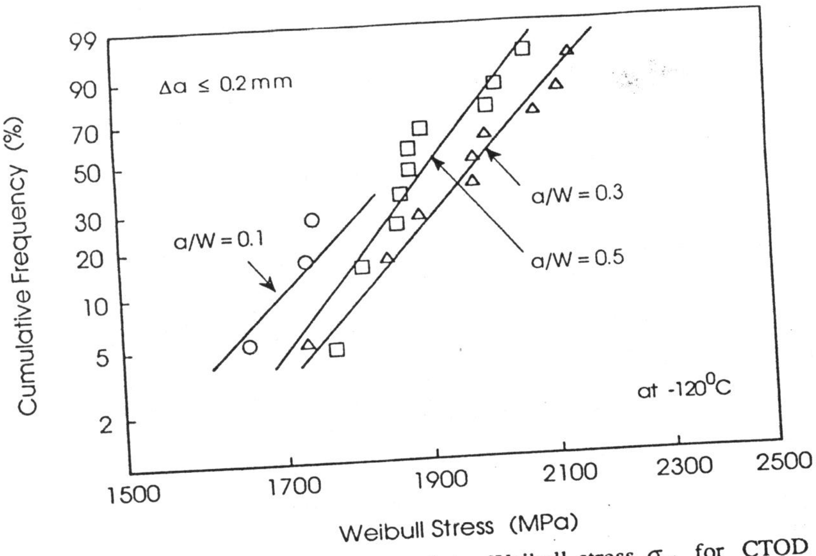

Figure 2 - Cumulative distributions of the Weibull stress σ_w for CTOD specimens with different *a*/W-ratios.

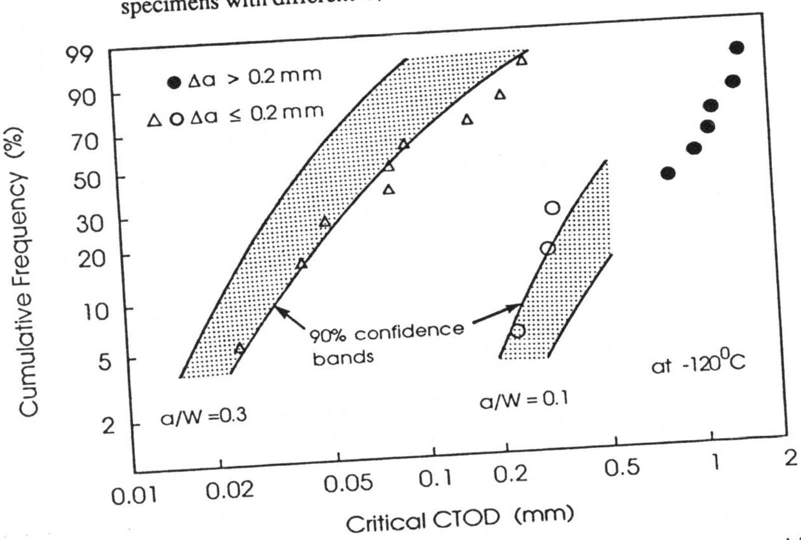

Figure 3 - Predicted scatter bands at 90% confidence level for specimens with a/W=0.3 and a/W=0.1.