An investigation on the capability of different constraint parameters for characterizing in-plane and out-of-plane constraints

Zeng Chen[1,2], Mahmoud Mostafavi[1], Rob Kulka[2]

[1]Department of Mechanical Engineering, University of Bristol, Bristol BS8 1TR, UK

[2]NSIRC, TWI Ltd, Granta Park, Great Abington, Cambridge, CB21 6AL, UK

Abstract. In-plane constraint and out-of-plane constraint have significant effects on the materials' fracture toughness. Currently, there are many effective parameters, including T-stress, T_z, Q, triaxiality and other unified parameters, proposed to characterize crack-tip constraints. In this work, a series of numerical simulations of previous fracture experiment of A533B steel are conducted to investigate those methods. The constraint parameters corresponding to the critical toughness of each specimen are calculated and the correlations of them with J-integral are compared. The results are used to discuss the advantages and disadvantages of each constraint parameter.

Numerical modelling

The finite element analysis (FEA) was conducted with ABAQUS 6.14. The material is A533B steel. The fracture test data can be found in [1]. The material property is shown in Table 1 and the true stress-strain curve are plotted in Fig. 1. Nine SEN(B) specimens with different thicknesses and a/W were modelled. C3D8R type elements were used. The rollers were created as rigid bodies, and the contact condition between them and the specimen was defined as Surface-to-surface frictionless contact. For the reference specimen (see next section), displacement was applied to the load roller in the Y direction until the experientially measured fracture load is achieved as reaction force on the support roller. Other specimens are loaded in the same manner but RKR was used as fracture criterion. An example of the models is shown in Fig. 2. All outputs were extracted at the midplane.

Parameter	Value
Temperature [℃]	-150
Elastic Modulus, E [MPa]	220000
Poisson's Ratio, υ	0.294
Yield Stress, σ_y [MPa]	626

Table 1. Material property of A533B steel

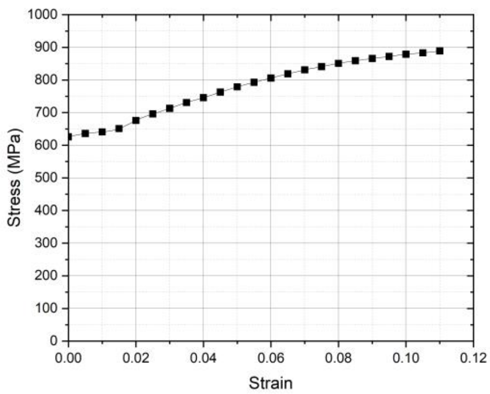


Fig. 1. True stress vs. strain curve of A533B steel under -150℃

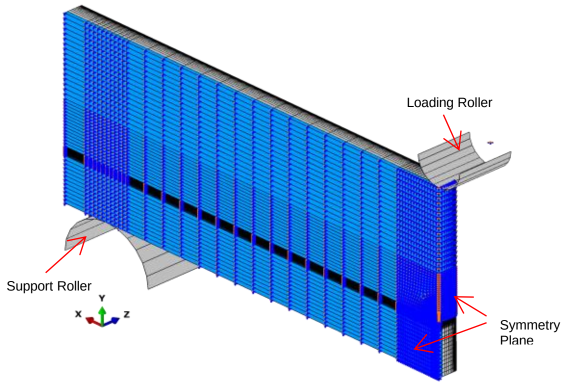


Fig. 2. Finite element model for the SEN(B) specimen with B=10mm and a/W=0.3

Prediction of the fracture toughness

The J-integral was extracted at the 10th contour of the midplane. The critical J-integral of the specimen with B=10mm and a/W=0.3 was chosen as the reference value to predict other specimens' critical J-integral by the RKR criterion (reference stress and critical value as identified by the reference specimen). All estimated J-integral values are listed in Table 2.

Geometry [mm] (W=50mm)	J-integral [N/mm]
B=10mm, a/W=0.3	16.4
B=10mm, a/W=0.5	11.9
B=10mm, a/W=0.7	9.8
B=15mm, a/W=0.3	15.2
B=15mm, a/W=0.5	10.1
B=15mm, a/W=0.7	9.1
B=25mm, a/W=0.3	13.9
B=25mm, a/W=0.5	9.3
B=25mm, a/W=0.7	8.1

Table 2. Estimated J-integral values

Results and discussion

Here mainly present the evaluation of Q and three unified parameters.

Parameter Q is defined as the deviation between the crack-tip stress field and a reference stress field at a point ahead of the crack tip [2, 3]:

$$Q = \frac{\sigma_{\theta\theta} - \sigma_{\theta\theta}^{ref}}{\sigma_{\theta\theta}}, at\ r = \frac{2J}{\sigma_0}\ and\ \theta = 0 \qquad (1)$$

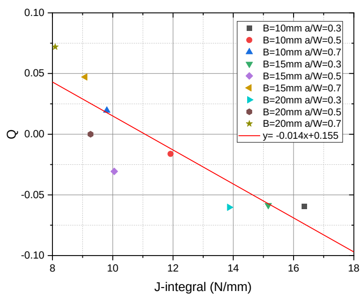
Where $\sigma_{\theta\theta}$ is the opening stress.
Three unified parameters, φ, A_p, A_d, which can be defined as follows [4-6], are calculated and compared with Q. The comparison can be seen in Fig. 3.

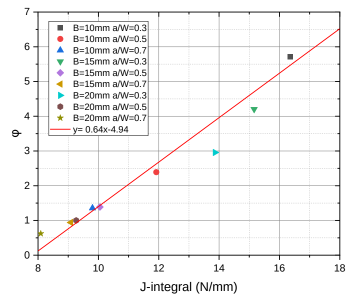
$$\varphi = \frac{A_c}{A_{ref}} \qquad (2)$$

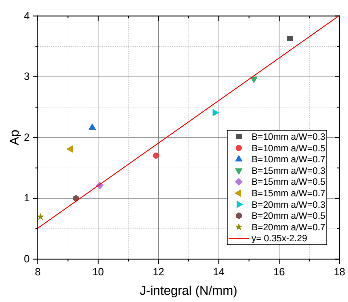
$$A_p = \frac{A_{PEEQ}}{A_{pref}} \qquad (3)$$

$$A_d = \frac{\delta}{\delta_{ref}} \qquad (4)$$

where A_c is the area of the plastic region, A_{PEEQ} is the area surrounded by the equivalent plastic strain isoline around crack tip, δ_c is the CTOD, they are measured from a given specimen at fracture. A_{ref}, A_{pref} and δ_{ref} are the same as A_c, A_{PEEQ}, and δ_c but in the reference specimen which was standard.







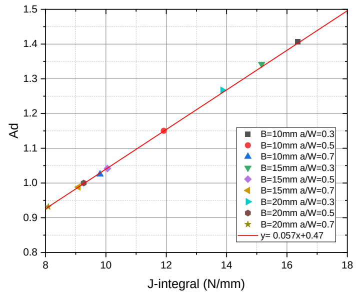


Fig. 3. The correlations between Q, φ, A_p, A_d and J-integral for different specimens

Fig. 3 shows three constraint parameters that are all sensitive to both in. and out of plane constraints, Q can partially quantify both constraints but not sensitive to the out-of-plane constraint of the shallow crack specimen. The points of Q scatter more significantly than the points of three unified parameters. It indicates it is easier to use the unified parameter to establish a good monotonic correlation with the J-integral.

Conclusions

1. Q can partially characterize both constraints. However, they cannot characterize the out-of-plane constraint for shallow crack specimens.
2. The unified parameters work better than Q and are sensitive to both constraints. Compared with Q they show a more linear correlation with the fracture toughness so that it is easier to establish a prediction model.

Reference

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