Consideration of the Effect of Reduced Out-of-Plane Constraint in Thin Section Components

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Summary

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Introduction

- The use of plane strain fracture toughness in structural integrity assessments is generally considered conservative.
- Conventionally derived from deeply cracked specimens using recommended testing standards and validity criteria.
- These criteria were designed to ensure plane strain conditions and high hydrostatic stresses near the crack tip.
- The effective toughness of thin section components is generally observed to be greater than that used in standard assessment. This can be due to the loss of out-of-plane constraint.
- Generally, there is no guidance for accounting for out-of-plane constraint loss, aside from testing specific geometries.
Thin Specimen Testing

- This work has focussed on the effects associated with the loss of out-of-plane constraint within thin, straight notch, Compact Tension (CT) specimens.
- The understanding gained through analysis of this specimen type will assist future study of other geometries.

http://www-materials.eng.cam.ac.uk/mpsite/properties/non-IE/toughness.html
Thin Specimen Testing

- Fracture toughness may be derived from the specimen tests, through calculation of the $J$-integral from a load-displacement curve of the specimen.
- In general, the $J$-integral for a variety of configurations can be written in the following form:

$$J = \frac{K_I^2}{E'} + \frac{\eta_p U_p}{Bb}$$

- $\eta_p$ may be derived for a particular geometry using FE modelling, given that the elastic-plastic $J$-integral may be derived with elastic-plastic finite element analyses.
Finite Element Analysis

- A series of finite element analyses were performed to identify if recommendations could be made to correct toughness for the loss of constraint in CT specimens, using Abaqus.
- The specimens were modelled in three dimensions, to capture through-thickness variations of fracture mechanics parameters and stress fields.
- A range of specimen thicknesses were modelled ($B = 19\text{mm}, 10\text{mm}, 5\text{mm}, 4\text{mm}, 3\text{mm}, 2\text{mm}$). Each specimen thickness was modelled with different crack depths ($a/W = 0.4, 0.5, 0.6, 0.7$).
- The Ramberg-Osgood form of deformation plasticity was used in the analyses. A hardening exponent of $n = 5$ was assumed.
Finite Element Analysis

- Focussed crack tip meshes were used to generate accurate fracture parameters.
- For sharp cracks, the strain field becomes singular at the crack tip.
- Including the singularity improves the accuracy of the $J$-integral and the stress and strain calculations.
Finite Element Analysis

- Nodal force applied to a reference point, constrained to all nodes in the model representing the loading pin.
- The magnitude of the applied load uniquely defined for each geometry, depending on the calculated limit load.
- This range of loading was chosen to allow appropriate load-displacement curves to be produced.
- Twenty loading steps were defined for each elastic-plastic analysis, in equal increments.
Constraint

- Interaction of crack-tip plastic zones with traction-free surfaces and global plastic zones affects crack tip stress triaxiality which can modify the apparent fracture toughness.
- The $J$-integral becomes invalid as a crack tip characterising parameter on its own, when the large strain region reaches a finite size relative to in-plane dimensions.
- In this instance, two-parameter fracture mechanics is often used to characterise the stress-strain fields.
- Where out-of-plane dimensions become important, a three-parameter fracture model may be required.
R6 currently takes account of the level of constraint in a particular specimen geometry using a normalised parameter, $\beta$, defined in terms of the constraint parameters $T$ (elastic) and $Q$ (elastic-plastic).

$$\beta_T = \frac{T}{L_r \sigma_y} \quad \beta_Q = \frac{Q}{L_r} \quad L_r = \frac{\sigma_{ref}}{\sigma_y}$$

R6 contains a compendium of $\beta$ solutions for various geometries, although only $\beta_T$ solutions are currently included.

There are currently no out-of-plane constraint solutions in R6.

‘Assessment of the Integrity of Structures Containing Defects’, R6 - Revision 4, EDF Energy.
A triaxial stress constraint parameter that has been suggested by Guo, amongst others, is the $T_Z$ parameter.

$$T_Z = \frac{\sigma_{33}}{\sigma_{11} + \sigma_{22}}$$

This parameter has been investigated in this study to identify if it can provide a reasonable description of the out-of-plane constraint loss, as well as a means of prediction of increased toughness in thinner specimens.

Finite Element Analysis

- Good contour independence in the analyses.
- Variation of elastic $J$-integral across the specimen thickness for a 3mm thick specimen ($x/B = 0$ at the surface).
Finite Element Analysis

- Variation of \( T \)-stress across the specimen thickness for a 3mm thick specimen.
Finite Element Analysis

- Variation of elastic $J$-integral with crack depth (weighted through-thickness average), for different specimen thicknesses.
- Validated against SIF solution in R6 Section IV.3.6.3.
The variation of $\beta_T$ with crack depth (weighted through-thickness average) for different specimen thicknesses (derived using a plane stress limit load solution, R6 Section IV.1.5.1).
Finite Element Analysis

- Variation of elastic-plastic $J$-integral across specimen thickness for a 3mm thick specimen, $a/W = 0.5$, illustrating position-dependence.
Finite Element Analysis

- Load-displacement curves derived with displacements extracted at the load line, $B = 3\text{mm}$.
- Validated against fully-plastic solutions in the literature.

Finite Element Analysis

- The variation of plastic eta ($\eta_p$) factor for different thicknesses. Compared to advice in ASTM, from 2D plane strain analysis.

Some modified boundary layer analysis has been carried out to study the effects of elastic-plastic in-plane constraint.

The $Q$ parameter is calculated based upon the normalised difference between the small scale yielding stress and the stress from the configuration of interest.

$$Q = \frac{\sigma - (\sigma)_{SSY, T=0}}{\sigma_y}$$
Modified Boundary Layer Analysis

- Normalised stresses, $B = 3\text{mm}$, $a/W = 0.5$, mid-plane position.
- Increased deviation from small scale yielding stresses for the thinner specimens observed.
Modified Boundary Layer Analysis

- Normalised $T$-stress vs. $Q$ for different thicknesses, $a/W = 0.5$. 

![Graph showing normalised $T$-stress vs. $Q$ for different thicknesses](image)
Out-of-Plane Constraint Analysis

- $T_Z$ for $B = 3\text{mm}$, $a/W = 0.5$, mid-plane position.
- Increased deviation from initial $T_Z$ field for thinner specimens.
Damage Modelling

- It was assumed for this analysis that ductile fracture initiation can be described through a ductility exhaustion approach.
- Accumulated plastic equivalent strain eventually leads to sufficient ductility exhaustion to initiate failure (corresponding to the critical growth and coalescence of voids in the material).
- The incremental damage, \( \Delta D \), for a given incremental load, is calculated using a fracture ductility model, based upon a Rice and Tracey formulation.

\[
\Delta D = \frac{\Delta \varepsilon_p}{\varepsilon_f} \quad \varepsilon_f = C_1 + C_2 \exp\left( C_3 \frac{\sigma_m}{\sigma_e} \right)
\]
Triaxiality reduces as loading increases \((B = 3\text{mm}, \ a/W = 0.5)\). Increased reduction in thinner specimens.
Future work will allow calibration of the material constants, based on data from testing of thin C(T) specimens.

By tuning the failure prediction model to match the test failure, the model would predict accumulated damage of 1 at a loading equivalent to a calculated critical $J$-integral from a specimen.

The triaxiality vs. ductility curve used in this indicative analysis used material constants of $C_1 = 0.0$, $C_2 = 2.0$, $C_3 = -1.5$. 
Damage Modelling

- Accumulated damage with loading, $B = 19\text{mm}$, $a/W = 0.5$.
- Damage accumulates more readily at the mid-plane (where out-of-plane constraint is higher).

![Graph showing damage accumulation]

- Damage (All Paths)
  - $x/B = 0.125$
  - $x/B = 0.25$
  - $x/B = 0.5$

- $J (\text{N/mm})$

- $0.0$ $0.2$ $0.4$ $0.6$ $0.8$ $1.0$

- $0.0$ $30.0$ $60.0$ $90.0$ $120.0$ $150.0$
Damage Modelling

- Accumulated damage with loading, $B = 3\text{mm}$, $a/W = 0.5$.
- Higher critical $J$-integral predicted for thinner specimens.

![Graph showing damage vs. J (N/mm) for different x/B ratios](image)
The variation in accumulated damage due to thickness, can be used to derive simple toughness scaling models.

Critical $J$-integral values were derived from the various analyses ($a/W = 0.5$), and toughness vs. thickness curves were derived.

![Graph showing the variation in toughness with thickness.](image)
Conclusions

- Fracture mechanics parameters have been derived for CT specimens under various loading configurations.
- $\eta_p$ factors were derived for different specimen thicknesses. Revised $\eta_p$ values could be used in fracture mechanics testing of thinner CT specimens to derive $J$-integral values at fracture and hence effective toughness values for a given configuration.
- The $\beta_T$ and $Q$ constraint factors were derived for different specimen thicknesses. The analysis showed that thinner width specimens generally have lower in-plane geometric constraint.
- The proposed $T_Z$ parameter was shown to provide a reasonable description of the out-of-plane constraint loss in the thinner specimens, for the different configurations.
Conclusions

- Damage model employed to estimate the critical $J$-integral value, at the initiation of ductile fracture in the various configurations, through a ductility exhaustion approach.
- For an assumed set of damage model constants, a relationship exists between the thickness of the specimens and the predicted critical value of $J$-integral. There is an indication that thinner CT specimens will have a higher effective toughness.
- Further work will calibrate the damage model developed for these analyses, to estimate different material responses and subsequent apparent fracture toughness values.
- Important to appreciate that whilst thinner specimens may exhibit higher apparent toughness, there is also the potential for failure by plastic collapse or elastic buckling.
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Any Questions?