EVALUATION OF GEOMETRY INDEPENDENT SZW_C VALUE FOR J_{SZW} PREDICTION

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ABSTRACT

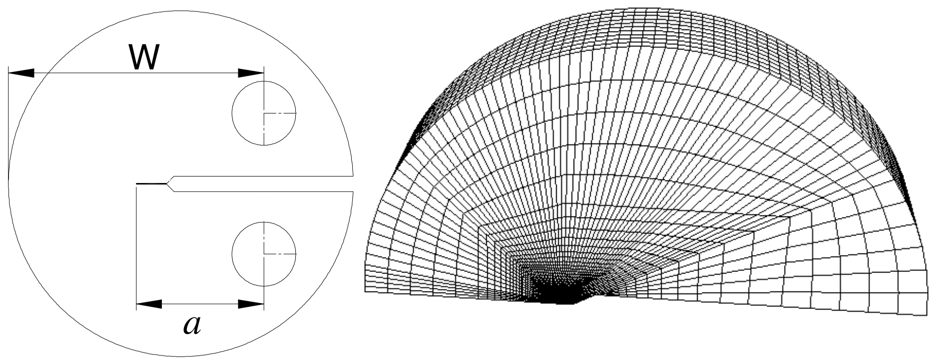
The problem in critical stretch zone width (SZWc) experimental evaluation is in identifying the size of stretch zone on a blunted crack front, as this requires a high degree of precision and expertise in measuring the SZW. Recently, the dependency of SZWc on the fracture specimen thickness has been numerically predicted. Thus to obtain geometry independent SZWc based evaluation of initiation fracture toughness (J_{SZW}) value, there is a need to understand the variation of SZWc with geometry which may includes fracture specimen thickness, initial crack size, fracture specimen geometry and the type of loading. The present work attempts to predict numerically this variation using the newly developed energy based numerical evaluation method of SZW prediction. To have better understanding of the variation of fracture parameter across the thickness three-dimensional (3D) finite element method (FEM) model of fracture specimens have been used. The experimentally obtained properties of SA333 Gr.6 carbon steel material are used as the effective properties of the homogeneous continuum. The minimum thickness fracture specimen criteria available in the literature are also evaluated for determining the geometry independent J_{SZW} value. To measure valid elastic-plastic fracture toughness value, the present study also showed the possibility of further improving the minimum thickness criterion of fracture specimen.

INTRODUCTION

Industries like nuclear power plants are increasingly demanding highly tough ductile materials to optimize the component dimensions without reducing the safety margins. Thus it is indispensable that the nonlinear properties of the used materials be known and modeled precisely, and especially the material crack initiation behaviour frequently governs by elastic-plastic initiation fracture toughness (J). Among several other definitions, the crack initiation fracture toughness (J_i) based on critical stretch zone width (SZWc), called J_{SZW}, and has received much attention. The problem in SZWc experimental evaluation is in identifying the size of stretch zone on a blunted crack front, as this requires a high degree of precision and expertise in measuring the SZW. Recently, the dependency of SZWc on the fracture specimen thickness has been numerically predicted [1]. Thus to obtain geometry independent SZWc based evaluation of initiation fracture toughness (J_{SZW}) value, there is a need to understand the variation of SZWc with geometry which may includes fracture specimen thickness, initial crack size, fracture specimen geometry and the type of loading. The present work attempts to predict numerically this variation using the newly developed energy based numerical evaluation method of SZW prediction. To have better understanding of the variation of fracture parameter across the thickness three-dimensional (3D) finite element method (FEM) model of fracture specimens have been used. The present study has been conducted on SA333Gr.6 carbon steel material used in the PHT system of Indian nuclear power plant. The experimentally obtained properties of SA333 Gr.6 carbon steel material are used as the effective properties of the homogeneous continuum. The minimum thickness fracture specimen criteria available in the literature are also evaluated for determining the geometry independent J_{SZW} value. The present study tries to establish the methodology to numerically determine SZWc using experimentally tested tensile test data. The presented work focuses on understanding the effect of specimen geometry on the numerically predicted magnitude of SZWc. The objective is to investigate the effects of specimen thickness, crack size, loading type and geometric variation on the formation of SZW during the blunting process in a ductile material. This has been done to understand the role of stress-tri-axiality on the determination of SZWc and $J_{SZW.}$ The conclusions are finally presented based on the present study.

SZW NUMERICAL EVALUATION

To have better understanding of the variation of fracture parameter across the thickness three-dimensional (3D) FEM model of fracture specimens have been used. Different standard (compact tension (CT) specimen, disk shape specimen and three point bend specimen) and non-standard (single edge crack plate) fracture specimen geometries are considered in the present study. Fig. 1 shows the disk shape specimen and its FEM model.



(a) Disk shape fracture specimen (b) FEM mesh of one-fourth model

Fig.1: Schematic view of Disk shape fracture specimen and its FEM model

The investigation was limited to fracture specimen analysis subjected to mode-I type of loading. The symmetry in this case permits consideration of only one fourth of the specimen geometry for computational economy. The mesh was constructed with eight noded brick elements with reduced integration and hourglass control option available in commercial FEM software ABAQUS code version 6.6 [2]. The details of mesh finalization criteria and applied boundary condition can be seen in references [3, 4]. In the finite element model load is applied under displacement control. The study has been conducted on SA333 Gr. 6 carbon steel material. The tensile test data used as an input in the prediction of SZWc using FEM analysis is given in Table 1.

Table 1: Experimentally tested results for SA333 Gr. 6 carbon steel [4]

Young's modulus		203 GPa
Poison's ratio		0.3
Yield strength		288 MPa
Ultimate tensile strength		420 MPa
% area in reduction		76.64
% Total elongation		36.2
Power law ($\sigma = K\,\varepsilon^{n}$) parameters	K	750
	n	0.23
Experimental SZWc		192μm
Experimental J_{SZW}		220 N/mm

Table 1 also showed the experimentally obtained critical SZW and SZWc based fracture toughness value for the material. On the blunted crack front the *critical energy density* used to delineate the highly stretched region denoted as SZW, is defined on the material's true stress-strain curve as the energy density integral up-to critical strain ($\boldsymbol{\varepsilon}_{\mathbf{c}}$) equals to strain hardening exponent (n), for the specific case of power law variation of material's true stress-strain curve [3]:

$$E_{Critical} = \int_{0}^{\varepsilon_c} \sigma \, d\varepsilon \tag{1}$$

With further increase in load, the energy density accumulated near the blunted crack and finally reaches a value associated with fracture. It is defined on the true stress-strain material curve as the energy density integral up-to fracture strain (ε_f) or the numerically determined strain value in tensile test simulation corresponding to experimental total percentage elongation (if it is greater), obtained in tensile test specimen when fracture occurs, given as [1]:

$$E_{Fract.} = \int_0^{\varepsilon_f} \sigma \, d\varepsilon \tag{2}$$

For the material, *critical energy density* is 100MJ/m^3 and *fracture energy density* is 1550MJ/m^3 used for defining the critical load line displacement (LLD) and critical SZW, where the crack initiation occurs in standard fracture specimen. Fig 2 showed the variation of SZW predicted on the disk shape specimen geometry. The average predicted critical SZW near the mid thickness of disk shape fracture specimen is 190μm, which compares reasonably well with the experimentally obtained critical SZW value as given in Table 1.

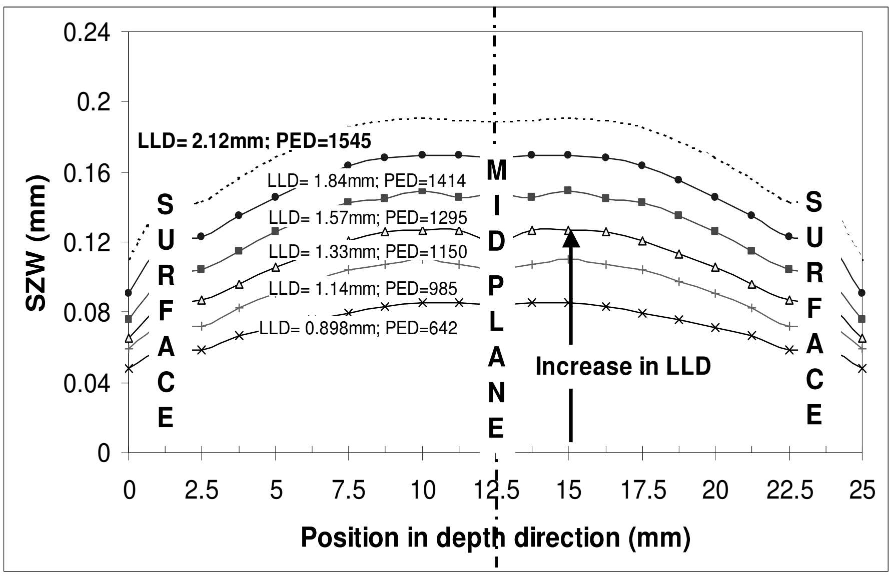


Fig.2: Variation of SZW in Disk shape fracture specimen

VARIATION OF SZW DUE TO *a*/W ratio

The standard experimental fracture toughness test method [5] has dimensional requirements for fracture specimens which govern mainly on the basis of plastic zone size relative to the specimen's geometrical dimensions. The data that meet these requirements are qualified for the measurement of valid fracture toughness parameter (*J*) and the determined value is considered least affected by specimen dimensions. To determine valid elastic-plastic fracture toughness value there is a requirement for the initial crack size to be satisfied in the standard fracture specimen. Using CT specimen fracture geometry having eleven different crack size(a)/Width(W) ratios (varies from 0.2 to 0.7), the variation of SZWc with change in *a*/W ratio is numerically studied using the proposed [6] energy based numerical SZW prediction methodology. In Fig. 3, it can be seen that for *a*/W ratio of 0.4 and above, the predicted SZWc value is almost constant. There is a gradual increase in SZW value with the decrease in *a*/W value below 0.4. In these cases the predicted plastic zone size is found to be greater than un-cracked ligament (W-*a*) and the crack size and therefore these *a*/W (value below 0.4) ratios geometries do not fulfill the code requirement. Therefore, it is concluded that the proposed numerical method of SZW prediction can predict the variation of critical SZW variation with the change in *a*/W ratio.

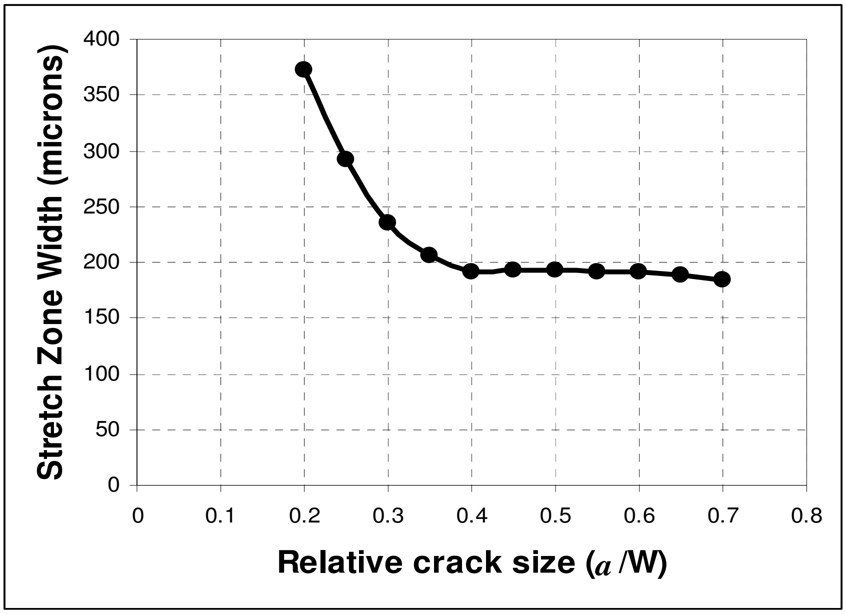


Fig.3: Variation of SZW with the change in initial crack size in CT specimen

VARIATION OF SZW DUE TO FRACTURE SPECIMEN THICKNESS

Generally the width (W)/Thickness (B) ratio of compact tension specimen is taken as 2. However in certain cases if required the ASTM code [5] suggested this ratio to be $2 \le W / B \le 4$ for compact tension specimen. It is also recommended that any specimen thickness can be used as long as the qualification requirements are fulfilled. As per ASTM-E1820, the thickness (B) of the specimen should be:

$$B \ge 25 \frac{J_Q}{\sigma_f} \tag{6}$$

where σ_f is the flow strength of the material defined as average of yield and ultimate strength, J_Q is provisional elastic plastic fracture toughness value. For the material, considering the *J*szw as J_Q, the fracture specimen minimum thickness as per Eqn. 6 is $B \ge 15.54\ mm$. This is the minimum thickness requirement for the standard fracture specimen as per the ASTM code for the measurement of valid elastic-plastic fracture parameter value. Similarly, using the yield strength (σ_y) material parameter, Broek [7] and Kikuchi [8], define the minimum thickness requirement of standard fracture specimen for measuring geometry independent elastic-plastic fracture toughness as:

$$B \ge 25 \frac{J_Q}{\sigma_y} \tag{7}$$

For the material, considering the *J*szw as J_Q, the fracture specimen minimum thickness as per Eqn. 7 is $B \ge 19.09\ mm$. In the present study, seven different thickness (100mm, 50mm, 25mm, 18mm, 12.5mm, 6.25mm and 3.125mm) of compact tension specimens were considered keeping W = 50mm as constant. The individual variation of width (W) of the specimen for the same W/B ratio is not included in the present study. It is to be note that though the W/B ratio of 12.5mm thick specimen comes under the ASTM specified range ($2 \le W / B \le 4$); it does not fulfill the fracture specimen minimum thickness requirement (Eqns. 6) for the material. The mesh and the number of elements used in different thickness model are same. The effect of variation of element size in the thickness direction is also checked to be negligible. Using different thickness of the fracture specimen, SZWc is determined using the proposed method of critical SZW measurement. The variation of critical stretch zone width with fracture specimen thickness as predicted by the proposed numerical SZWc method is shown in Fig. 4. Comparing the limiting thickness values given by Eqns 6 and 7 with Fig. 4 results, it comes out that the value of SZWc converges when using fracture specimens having thickness greater than that given by Eqn. 7. Thus the present study showed that fracture specimen thickness greater than the specified is to be used for numerical prediction of valid critical SZW. The present numerical study also showed the possibility of further improving the minimum thickness criterion given in ASTM code.

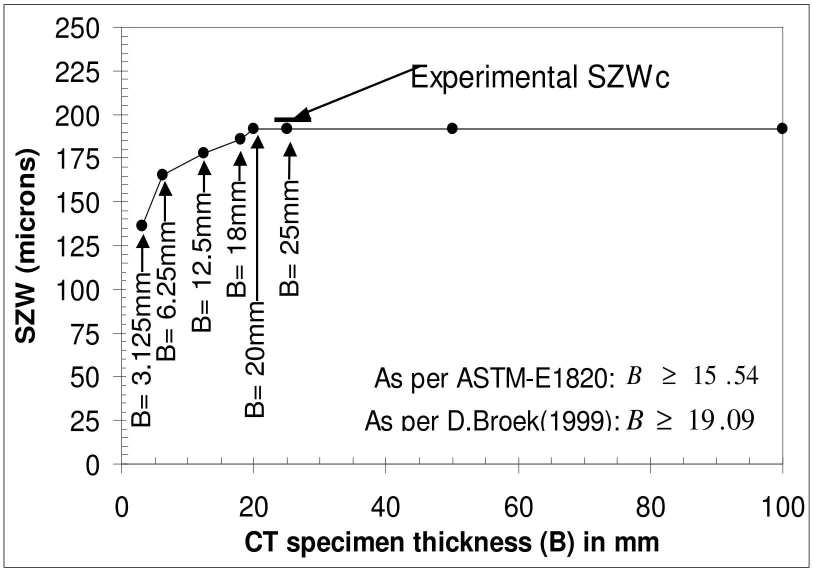


Fig.4: Variation of SZW with the change in CT specimen thickness

VARIATION OF SZW DUE TO FRACTURE SPECIMEN GEOMETRY AND LOADING CONDITION

Constraint effects on fracture toughness have been the subjects of a number of recent studies. Using ASTM- E1820 recommendations, different initiation fracture toughness (*J*) values have been found in different geometries of fracture specimens. The different levels of crack tip constraint of bend and tension specimens can affect the magnitude of crack growth or *J*-integral or the development of stretch zone and SZW. The variation of SZWc with the change in fracture specimen geometry and loading would be interesting to explore numerically. Standard fracture specimen geometries such as the compact tension specimen, Disk shape specimen and three point bend specimen and also non-standard fracture specimen geometry like single edge cracked plate subjected to tensile load have been considered in the present study with having constant *a*/W ratio of 0.55. A detailed 3D finite element analyses are performed on all the different geometry of fracture specimens. The predicted results of SZWc in different fracture specimen geometries are shown in Fig. 5.

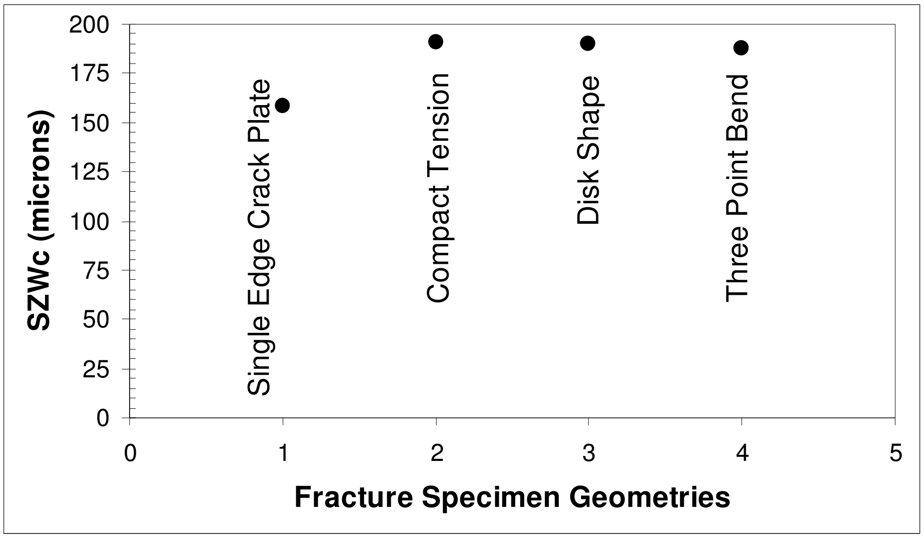


Fig.5: Variation of SZWc with fracture specimen geometry

The numerically predicted SZWc in single edge cracked plate subjected to tensile load is comparatively lower than that predicted in standard fracture specimen geometries considered in the present study. It comes out that the predicted critical SZW in single edge cracked plate is nearly 17% lower compared to SZWc value predicted in other fracture specimens. It is also found that the proposed numerical method of SZW evaluation predicted same magnitude of SZWc in the standard fracture specimens considered in the present study.

Once the valid critical SZW is obtained numerically, using the standard fracture specimen that fulfils the geometry requirements, the geometry independent initiation fracture toughness (J_{SZW}) can be predicted using the equation [3]:

$$J_{SZW} = m\,\sigma\,\left(2\,SZW_C\right) \tag{8}$$

where m $\approx$ 1.25 [3], σ is the integral average stress measure [3], which is 434.86 MPa for the material. Using Eqn 8, the fracture toughness value for the material, using compact tension specimen (a/W= 0.55; B = 25mm and W= 50mm) is 209N/mm, which compares reasonably well with experimentally determined value.

CONCLUSION

In the present investigation, the variation of SZWc is numerically predicted in standard and nonstandard fracture specimens. In fracture specimens, the initial crack size, thickness and the geometry of fracture specimens are varied numerically. Three dimensional FEM models are used to predict the variation of SZWc value due the change in fracture specimens dimensions and loading conditions. The present study showed that fracture specimen thickness and a/W ratio greater than the specified size is to be used for numerical prediction of valid SZWc value. It is also found that the proposed numerical method of SZW evaluation predicted same magnitude of SZWc in the standard fracture specimens considered in the present study. The numerically predicted SZWc value in single edge cracked plate under tensile loading is 17 percentage lower than that its value predicted in other three standard fracture specimen geometry considered in the present study. The numerically predicted valid SZWc finally leads to J_{SZW} that matches well with experimental value.

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