APPLICATION OF THE LOCAL APPROACH TO PREDICT BRITTLE FRACTURE FOLLOWING LOCAL COMPRESSION

A Mirzaee-Sisan, S Hadidi-Moud, C E Truman[1], D J Smith
Department of Mechanical Engineering, University of Bristol,
Queen's Building, University Walk, BS8 1TR, UK
C.E.Truman@Bristol.ac.uk

Abstract

In this paper application of the local approach to predict the fracture behaviour of A533B ferritic steel at low temperature, in presence of a residual stress field, is investigated. The local approach assumes a Weibull probability distribution for the fracture toughness data and is based on the work of the Beremin group [1]. In the work presented here, the Weibull parameters are calibrated to fracture data obtained at low temperature for specimens containing no residual stress fields. The same parameters are then used to predict the fracture behaviour of specimens containing a residual stress field which has been introduced by the local compression technique. Local approach predictions obtained using finite element analysis and experiments demonstrated a reduction in the low temperature fracture toughness of laboratory specimens following local compression. However, the decrease in experimental fracture toughness data is not as high as predicted by numerical simulations using the local approach.

Introduction

Prediction of brittle fracture is major concern in structural integrity assessments. If a residual stress field is present in a structure, predictions become more complicated to make. Residual stress fields are conventionally incorporated into assessments by superposing the stress intensity factors for the residual stress field and the applied loading in what is commonly referred to as the global approach [2]. In this paper, however, a local approach is used which considers the crack tip stress field in a statistical manner. Recently, Hadidi-Moud et al [3] have used a modified Beremin model to predict brittle fracture at low temperature in the presence of a residual stress field created by warm pre-stressing. The study described in this paper is a continuation of this work and investigates the effect of a residual stress field, introduced by local compression, on brittle fracture. Local compression, in this context, is taken to mean punching the two opposite sides of a specimen with rigid punching tools. This generates plastic yielding and a subsequent residual stress field in the region between the two punches. A companion paper describes the method in more detail [13].

To explore the influence of the residual stress field generated by local compression on fracture toughness, a series of experiments were conducted. First, a number of specimens were fractured at -170^{o}C in the as-received (AR) condition. Then another set of specimens were subjected to local compression at room temperature and then fractured at -170^{o}C in order to investigate the influence of residual stresses on the fracture toughness distribution. A local approach, based on the Beremin model, was then used to predict the experimental data.

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[1] Corresponding author: Tel +44 (0) 1179289737, FAX +44 (0) 1179294423.

The paper ends with a discussion of the results and compares predictions based on the local approach with experimental data.

Beremin described a statistical model to predict cleavage fracture [3] in which the local stress field at the crack tip was used to characterise the fracture. A Weibull probability distribution was assumed and the fracture process was considered a weakest link phenomenon. In essence, failure of a body of material was assumed to commence when the weakest reference volume failed. A modified Beremin model [3], which includes a minimum threshold stress, $\sigma_{\min}$, is given by

$$P_f\left[\sigma_f\right] = 1 - \exp\left[-\left(\frac{\sigma_w - \sigma_{\min}}{\sigma_u - \sigma_{\min}}\right)^m\right], \tag{1}$$

where σ_w, the Weibull stress, is defined as

$$\sigma_w = \left[\frac{1}{V_0}\int \sigma_1^m dV\right]^{1/m} . \tag{2}$$

The Weibull stress, σ_w, encapsulates the failure condition and is a function of a reference volume, V_0 , shape parameter, m, and maximum principal stress, σ_1, determined within a volume of material which has undergone plastic deformation. Use of the local approach requires calibration of the Weibull parameters m, V_0 and σ_u. A large number of studies have been conducted which use the Beremin or modified Beremin models to predict failure in the ductile to brittle regime [4]. However, no strict guidelines currently exist for the calibration of the Weibull parameters. Whether these parameters are geometry or temperature dependent is an ongoing debate. The Weibull parameters are usually determined from experimental data, and Beremin [1] proposed calibrating the Weibull parameters to round notched bar test data. Hojo [5] demonstrated an independency of the calibration of Weibull parameters to the specimen geometries, while Wiesner [6] indicated differences between the parameters when determined from different specimen geometries. Gao has addressed the non-uniqueness issue of the Weibull parameters [7]. He employed a method in which the Weibull parameters were calibrated using fracture toughness data from two specimens of different constraint. Bakkers [8] proposed a threshold parameter, σ_{min}, in addition to the original Beremin model parameters. This additional parameter, which may be allowed to vary [3], is used to obtain a better calibration. If the threshold parameter is considered to be constant, it equates to a Weibull stress corresponding to a toughness of 20 MPa $m^{0.5}$ for common ferritic steel [7]. Hadidi-Moud et al also showed the non-uniqueness of Wiebull parameters and differences in Weibull parameters calibrated to round notched bar specimens and compact tension, C(T), specimens [3]. This study [3] showed that the local approach could predict brittle fracture in specimens with residual stresses generated by warm pre-stressing when a compressive residual stress was present at the crack tip. Kordisch [9] and Lefevre [10] also used a local approach to predict the warm pre-stressing effect.

The aim of this paper is to study the application of a modified Beremin model to predict the effect of residual stresses introduced by local compression. Local compression can create a tensile residual stress field ahead of a crack tip. Results of the application of the local approach are evaluated by comparison to experimental data. The key point in this model is that the Weibull parameters were calibrated to fracture toughness data obtained in the (AR) condition at -170°C. The same parameters were then used to predict the effect of a residual stress field introduced by local compression. In the following, the experimental programme and the local compression method are summarised.

Experimental programme

The material used in this study was a typical pressure vessel ferritic steel, A533B. The mechanical properties of this steel are tabulated in Table 1. Decreasing the temperature promotes brittle fracture in the lower shelf region. Because of the scatter in the fracture toughness data of ferritic steels, which fail by cleavage fracture at low temperature, the test programme consisted of a number of tests. Half of the specimens were fractured in the AR condition and the remaining half were fractured after local compression. Standard compact tension, C(T), specimens were used. They were oriented in the T-L direction. The specimens had dimensions W=50mm and B=25mm. An EDM wire of dimension 0.1mm was used to fabricate a very sharp notch of length to width ratio a/W=23.7/50. The specimens were then subjected to fatigue loading to achieve an a/W ratio of 0.5. The fatigue pre-cracking procedure met the requirements of the ASTM E399 standard. The C(T) specimens containing fatigue pre-cracks were then tested at -170°C in the AR condition and following local compression.

In the next section the local compression method is described briefly and the experimental results presented. The model used to implement the local approach is explained and the results of finite element simulations are presented. Finally, local approach predictions are compared with experimental data.

TABLE 1. Material properties of A533B steel

E =220 GPa, ν=0.3												
True strain	5.0 E-03	1.0 E-02	1.5 E-02	2.5 E-02	3.5 E-02	4.5 E-02	5.5 E-02	6.5 E-02	7.5 E-02	8.5 E-02	9.5 E-02	1.0 E-01
True Stress-MPa (20°C)	455	460	475	520	557	585	607	625	637	650	610	613
True Stress-MPa (-170°C)	661	666	676	721	756	788	818	844	866	884	897	904

Local compression

Local compression can introduce a tensile residual stress field ahead of the crack tip in laboratory specimens [11,13]. A schematic diagram of the local compression technique is shown in Figure 1. Compact tension, C(T), specimens are punched from both sides at room temperature. Local compression was performed using a pair of rigid punching tools. The relative position of the punch and the specimen has been characterized by a dimensionless parameter, X/r, where X represents the distance between the centre of the punching tool and crack tip, and r is the radius of the punch. Mahmoudi [12] used finite element analysis to examine the effect of punch size and position on the development of residual stresses. He found that the position X/r =1 provided the greatest tensile region ahead of crack tip. Two hardened cylinders of radius 12.5 mm were used to apply a compressive load to the specimens. This preloading was performed at room temperature. A compressive load of 340 kN was applied using a 400kN servo-hydraulic rig at room temperature. The specimens were then unloaded after the attainment of 0.02*B (where B is the thickness of the specimen) permanent surface indentation. This cycle of loading generated a tensile stress field ahead of the crack. The specimens were then fractured at -170^{o}C and the data compared to the AR data. This will be explained in the next section.

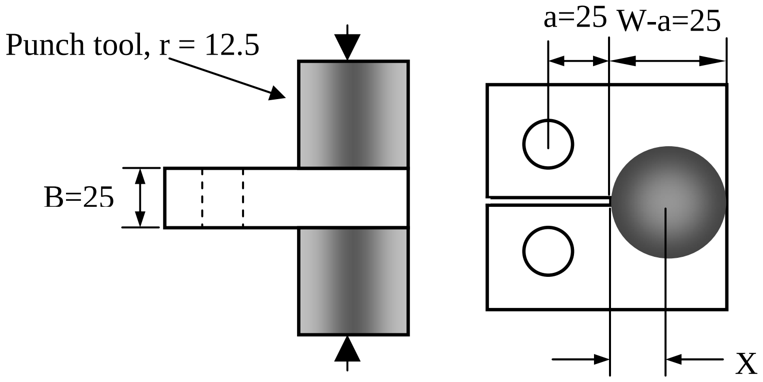

FIGURE 1: Schematic diagram showing the local compression technique.

Dimensions are in mm.

Test results

In order to examine the effect of residual stresses introduced by local compression, two series of tests were performed on C(T) specimens at $-170\ ^{o}$C. A total of twelve specimens were fractured in the AR condition at -170°C. The quasi-static fracture toughness tests were conducted using an Instron 250 kN serve-hydraulic rig under displacement control. A loading rate of 0.003 mm/sec was used while the specimen was cooled by liquid nitrogen. The test results were plotted against the probability of failure, given by [13]

$$P_f = \frac{i - 0.5}{N}, \tag{3}$$

where N is the total number of specimens, and i the order number. Figure 4 shows this distribution.

Twelve A533B C(T) specimens with a fatigue pre-crack, which had previously been subjected to local compression at room temperature, were reloaded to fracture at -170^{o}C. The results are expressed as apparent toughness against probability of failure. The statistical distribution, equation 3, is illustrated in Figure 3. Experimental results show that the lower shelf toughness of punched specimens decreased by approximately 12% compared to the as-received data.

Failure probability predictions

To estimate the probability of fracture using the local approach a numerical subroutine [3] was used in conjunction with the results from the 3D FE analyses. The commercial code

ABAQUS [14] was used to create the finite element models. Two different parts were created in ABAQUS/CAE, one representing a C(T) specimen and the other a punching tool. The punching tool was modelled as a rigid body and the 3D C(T) model was meshed using 8-noded reduced integration elements, C3D8R. Figure 2 shows a typical mesh used for the analysis. Due to the existence of two planes of symmetry (see Figure 2), only a quarter of the C(T) was meshed. An elastic-plastic material model with isotopic hardening was used in the simulation. The smallest size of the element at the crack tip was X=0.1mm, Y=0.1mm and Z=1.57mm. The local compression simulation consisted of a cycle of punching, unloading, cooling and loading to fracture. The cycle was simulated in three distinct steps. The first step modelled punching the specimen, i.e. moving the punch tool towards the specimen and punching it while using room temperature material properties for the C(T). The second step consisted of unloading, or removing the punching tool from the C(T). The third step of the finite element simulation was a static analysis, loading the C(T) to fracture using low temperature material properties. For AR specimens, only step 3 was simulated.

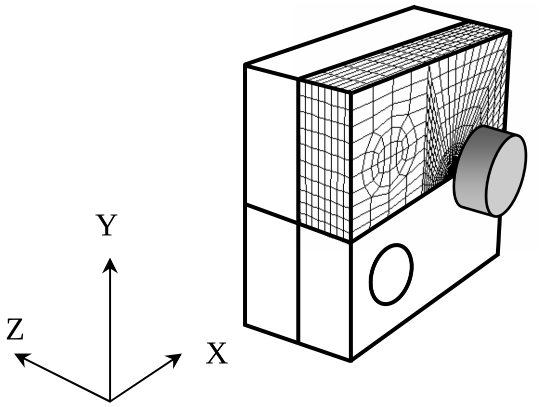

FIGURE 2: Typical 3-D mesh of C(T) for modelling of local compression

The Weibull stresses were evaluated from post processing the finite element analysis results and the Weibull parameters were calibrated to the experimental AR data. The magnitude of Weibull exponent, m, was chosen to be 4 [3] and the other parameters σ_{min} and σ_u were varied to find a best fit to the data. *Vo* was also considered as a free parameter and selected as 0.01 mm^3 [3]. A subroutine was used to calculate the Weibull stresses at different increments of the finite element analysis and each element was monitored by the routine. When the stress exceeded the yield limit, the Weibull stress was calculated using equation 2. The probability of failure was then calculated using equation 1. The calibrated parameters were σ_u =7.9 GPa and σ_{min} = 2.85 GPa. Figure 3 shows the experimental results and the local approach predictions. The results are presented as apparent toughness against probability of failure. The predictions based on the local approach indicated that the effect of local compression was larger than that observed in the test programme. This may be explained by considering the microstructural aspects of the cleavage fracture. It has been hypothesised that local compression may redistribute the population of cleavage initiators at the crack tip during the compression step.

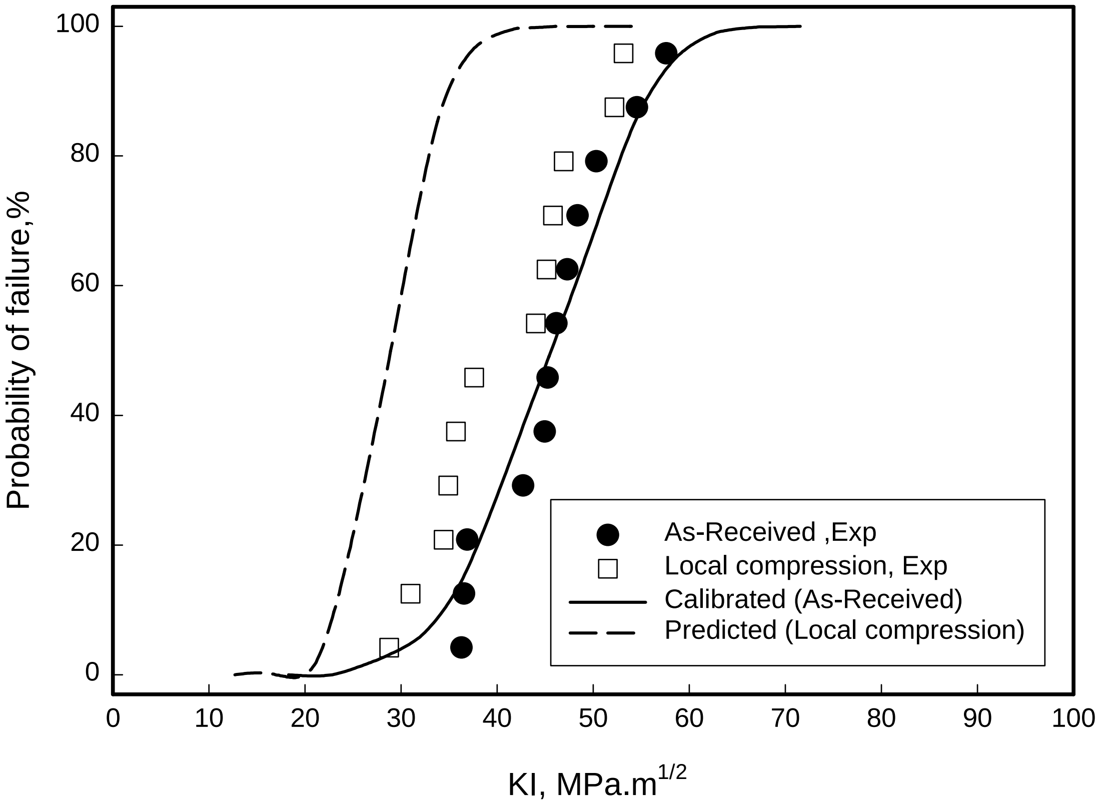

FIGURE 3: Prediction of failure probability in for A533B steel at -170°C

Conclusion

This paper has described the applicability of a modified local approach to predict brittle fracture in the presence of residual stresses. The study included numerical simulations and experimental measurements. A tensile residual stress field was created ahead of the crack tip in compact tension specimens by local compression. Experimental results showed that the residual stress field introduced by local compression decreased the apparent toughness of A533B steel at -170°C by approximately 12%. Numerical simulations using a local approach overestimated the effect of local compression compared to experimental results. The inconsistency may arise from the local approach taking into account only stresses ahead of the crack tip to predict failure. Local compression may also change the microstructural properties ahead of the crack, although this has not been considered in this work and will require further investigation.

Acknowledgment

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