Assessment of ductile fracture resistance of structural steel using a simple numerical approach

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Abstract

The local approach method has been the subject of much investigation in recent years as an alternative method to assess ductile fracture resistance. Often, a model suggested by Rice and Tracey (R&T) was used due to its simplicity and ease of interface with finite element analysis (FEA). In this work, the R&T model suitability to estimate ductile fracture of structural steel was assessed by employing an automated iterative calculations combined with elastic-plastic FEA analysis. The sensitivity of this approach was examined by using several different modelling techniques, such as element removal or nodal release, several time integration methods and critical element mesh sizes at the crack front. The apparent fair correlation between the experimental results and the numerical results indicated that the R&T model is probably adequate to estimate crack initiation and initial growth, but it may not be capable to estimate the ductile fracture and further growth of long cracks. This work was part of a larger investigation to examine implementation of several local fracture models and methods in design of components fracture tolerance.

Introduction

Ductile fracture of steel, often regarded as a process of nucleation, growth and coalescence of voids that initiate at inclusions or second phase particles. The void growth around the particles is usually related to the plastic strain and the hydrostatic stress. Coalescence may occur between adjacent voids in the material critical area. The coalescence is accompanied by reduction in localised load-bearing capacity of the surrounding material. Several past theories describe this behaviour. Rice and Rosengren [1] developed a simplistic micro-mechanical ductile fracture model in which the matrix fracture of the material was considered by assuming an idealised, spherical void. Later, exponential relationship was used to correlate the rate of void growth, Rice and Tracey [2]. This paper examines the suitability of the R&T model to describe structural steel fracture. It is part of a larger investigation to implement local fracture models in component design for fracture tolerance [3].

In this work, crack tip initiation was assumed to occur when the void growth ratio (R/R_0) reached a critical value $(R/R_0)_c$. Further crack propagation was simulated using the ABAQUS code elastic-plastic analysis and the crack growth process was automated by employing Unix shell scripts. Using the calibrated constitutive parameters, results from the crack growth simulation of compact tension C(T) specimens were in fair agreement with experimental resistance curves of the EN8 (BS080M40) structural steel.

Different modelling techniques were used to assess the dependency of the numerical results on several parameters. Those included element removal or nodal release; several time integration methods and variation in critical elements mesh size at the crack front.

The R&T Model

Rice and Tracey [2] developed a relationship between void growth and stress triaxiality to a mathematical model. The general rule for growth rate of voids was written as:

$$\frac{dR}{R} = \alpha \exp(\frac{3}{2}\xi) d\varepsilon_{eq}{}^{p} \tag{1}$$

where α is a material constant, taken to be 0.283 in the original model, ε_{eq}^{p} is the equivalent plastic strain, ξ is the triaxiality ratio: $\xi=\sigma_m/\sigma_0$ (σ_m is the hydrostatic stress and σ_0 is the yield stress). To take into account the strain hardening of the material, Beremin [4] suggested replacing the yield stress by the actual flow stress (σ_{eq}). This allows a straightforward integration of Eqn. 1:

$$\ln\frac{R}{R_0} = \int \alpha \exp\left(\frac{3\sigma_m}{2\sigma_{eq}}\right) d\varepsilon_{eq}{}^{p} \tag{2}$$

Since the Rice and Tracey model is based on a single void, it does not take into account the interface between voids, nor does it predict ultimate failure. A separate failure criterion must be applied to characterize microvoid coalescence. For instance, when a void ratio (R/R_0) reaches a critical value $(R/R_0)_c$.

Material and Experimental Programme

The material investigated in this work was medium carbon steel, BS080M40 (EN8), with the following chemical composition (wt/%): C 0.42, Si 0.23, Mn 0.074, S 0.03, and P 0.01. The material was supplied in a rolled bar form, of cross-section 75mm × 26mm and about 3m in length. The metalographic inspection showed that the material contains non-metallic inclusions elongated in the rolling direction. They were rod-like, but elliptical in cross-section. The material was normalised by heating to 860^{o}C and air-cooled. Vickers hardness results obtained from the material before and after heat-treatment were 205 and 184 kg/mm^2, respectively.

The tests were performed using an Instron 250 kN servo-hydraulic testing machine, employing displacement control, according to ESIS [5] and BS 7448 [6]. Axial and radial extensometers were used to measure the extensions of the hourglass and the notched specimens. The C(T) specimen load line displacement was measured by using clip gauge extensometers.

Tensile tests were carried out using solid hourglass specimens and round specimens with different notch radii (r =10, 4, 2mm), and fracture tests conducted using compact tension (C(T)) side-grooved specimens [6]. The smooth hourglass specimens were used in static tests to obtain elastic and elastic-plastic stress-strain response of the material. The notched specimens with different radii were used in uniaxial tension tests to obtain calibration curves of the load versus the reduction of the radial displacement. Crack resistance curves of the material according to BS7448 [6] were obtained from C(T) tests, and compared with the fracture simulation results.

Calibration and Determination of the Material Parameters

The cavity growth (R/R_0) was calculated for each element by using the average values of the stresses and strains obtained from the FEA element's Gauss points at successive increments in the analysis. The following incremental equation was used in the calculation:

$$\ln\left(\frac{R}{R_0}\right)_{n+1} = \ln\left(\frac{R}{R_0}\right)_n + 0.283\Delta\varepsilon_{eq}^p \exp\left(\frac{3\sigma_m}{2\sigma_{eq}}\right) \tag{4}$$

where $\ln(R/R_0)_{n+1}$ is the cavity growth rate at increment number (n+1), $\ln(R/R_0)_n$ at increment number *n*. At the start of the analysis, $R=R_0$ and $\ln(R/R_0) = 0$. The calculation was carried out in ABAQUS user subroutine, USDFLD.

This calculation of the critical value, $\ln(R/R_0)_c$, was based on the evolution of the plastic strain and stress triaxiality within elements at the critical location. For the notched tensile specimens, this is maximum at the centre line of the specimen below the notch root, where ductile cracks initiate. The true strain was calculated using:

$$\varepsilon = 2 * \ln\left[\frac{r_N}{r_N - U_r(node\,at\,the\,tip)}\right] \tag{5}$$

where r_N is the initial length of the minimum section and U_r is the radial displacement of the node at the tip.

A void diameter at fracture, ϕ_F, was determined from the experimental load vs. radial displacement curve, whilest the experimental "mean ductility" at fracture (engineering fracture strain) was defined as:

$$\varepsilon_F = 2 * \ln\left(\frac{\phi_0}{\phi_F}\right) \tag{6}$$

where ϕ_0 is the initial value of the void diameter at the minimum section.

Calculated void growth ratios, (R/R_0), are shown in Fig. 1, using values from centre elements, versus the true strain curves. The experimental average mean ductility at fracture for three notches was used to obtain the values of the critical parameter $(R/R_0)_c$. It was found to be $(R/R_0)_c = 1.548$ for notch radius 10mm, 1.465 for notch radius 4mm and 1.448 for notch radius 2mm, as shown in Fig. 1. The average value of $(R/R_0)_c$ from the three calibrations is 1.487.

Previously it was shown that the finite element mesh size, L_c, ahead of the crack tip might influence the analysis [7, 8]. To examine the effect of the element size on the critical void calibration values, a refined mesh was applied to all the notches at net section. Results were obtained from separate FEA analyses by changing the number of elements (from 10 to 100) across the minimum net section, and also using a range of element sizes, from 0.05mm to 0.5mm. The critical values of the void growth ratio versus element mesh size are shown for different notches in Fig. 2. It appears that mesh size has little effect on the calculation of the critical void growth ratio, $(R/R_0)_c$, for mesh sizes that are less than 0.3mm. Based on the calibration work, the two material parameters for the R&T model, i.e. the mesh size and the critical void growth ratio, $(R/R_0)_c$, were taken as 0.25mm and 1.487 respectively, and were used for the simulation of the ductile fracture tests of C(T) specimens.

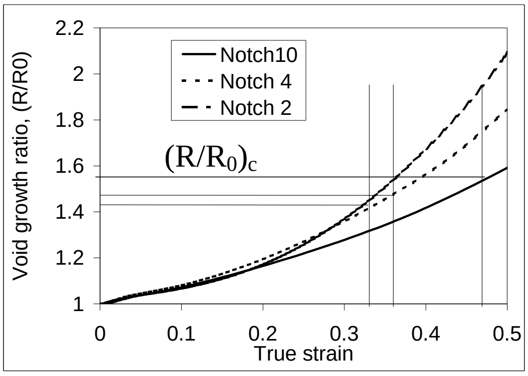

FIGURE 1. The R&T model critical void growth ratio $(R/R_0)_c$ for different notch radii.

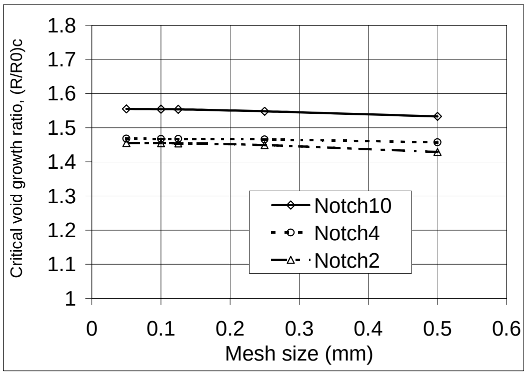

FIGURE 2. The R&T model critical void growth ratio $(R/R_0)_c$ variation with mesh size.

Simulation of Ductile Fracture of C(T) Specimens

FEA Simulation

The R&T model and the FEA analysis were used to estimate the crack propagation rate of C(T) specimens as follows. If the void growth ratio (R/R_0) in the element in front of the crack tip reached a critical value, the element was judged to have failed; it was therefore removed from the model, or alternatively the node at the crack tip was released. Element removal was performed using the ABAQUS command-line MODEL CHANGE and the nodal release was performed by modifying the boundary conditions. Instantaneous crack length was measured as distance from the original crack tip to the most recently failed element edge.

Ductile failure of specimens involves the progressive reduction of load carrying capacity at the crack tip elements. In the crack propagation analysis, a field variable was defined as damage parameter (β) using the USDFLD subroutine within ABAQUS. The material modulus, *E*, was modified as function of this damage parameter, β, and was solution dependent property. The elastic modulus decreased with the damage until a total element failure has been reached and the element was removed.

The simulation procedure included iterative post-processing of FEA results using a UNIX shell script. Each new incremental fracture involved the current FEA results, updating of the FEA model and a 'restart' of the FEA analysis with the modified model. This was obtained by combining the ABAQUS/Standard FEA analysis with ABAQUS user subroutine (USDFLD), ABAQUS/Make (results) subroutine and a separate Fortran programme. Fig. 3 illustrates a flow chart of the automated UNIX shell developed for the simulation of crack growth with the R&T model for ductile fracture. The procedure propagates the cracks by either using the 'node release' technique of 'failed' elements or by using the 'elements removal' technique at the crack tip

Time-increment in FEA analysis commonly referred to, as the size of step required to increase the load in a piece-wise non-linear elastic-plastic simulation, where the total time-increments refer to the total applied load. For each load step, it was found that a better overall convergence was achieved at the point of the analysis 'restart' if the initial time-increment used for the current (restart) load step was similar to the time-increment that was used in the last load step. To assess increment dependency, three different time-incrementations were used. All three employed ABAQUS automated time-incrementation facility with initial increment size of 0.01. In the first case the maximum increment size was not defined. For the two other cases a maximum increment size of 0.01 and 0.001 were used, respectively. This way progressively smaller time-increments were obtained, from cases 1 to 3.

Using the method of the element removal for propagating cracks, the maximum allowed crack length was about 0.5mm. This was due to convergence limitation. Two different crack tip element mesh sizes were used for the C(T) specimens crack growth simulations; 0.5mm and 0.125mm. For mesh size of 0.5mm the crack growth was simulated using both element removal and node release techniques (without convergence problem), while only the node release technique was applied to the mesh size of 0.125mm.

Results and Discussion

Typical results from releasing nodes at the crack tip when the void growth ratio reaches the critical value, $(R/R_0)_c$, are shown in Fig. 4 for ductile crack growth of 0.99 mm, and a load line displacement (LLD) of 0.88 mm. Fig. 4 show a crack that is propagating along the specimen ligament. The opening stress (σ_{22}), triaxiality (σ_{eq}/σ_m) (Fig. 4 a) and the effective plastic strain rate ($\dot{\varepsilon}_{eff}$)(Fig. 4 b) have maximum values at the crack tip.

Consequently, the calculated void growth rate, $\left(\frac{\dot{R}}{R_0}\right)$ (Fig. 4 c), is higher at the current crack tip than at any other part of the model (Fig.4 d). The void growth ratio, (R/R_0), is an accumulated quantity, which increases from load step to load step at every integration point. However, its absolute maximum value is always at the initial crack tip, independent of the load step.

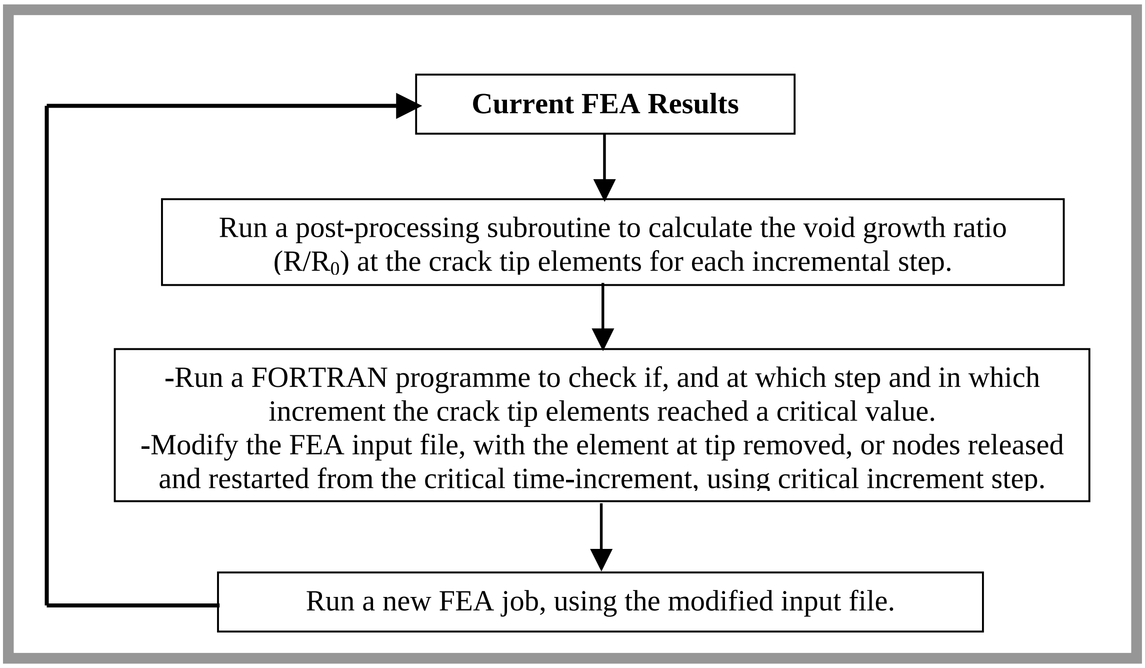

FIGURE 3. Automated UNIX shell procedure to simulate ductile crack growth in FEA elastic-plastic analysis.

To simulate ductile fracture resistance in the C(T) specimens, 20 contours of *J*-integral were calculated from the FEA results, establishing domain dependency. The computed *J*-*R* curves using three different time-increments are compared in Fig. 5 with the experimental results. It is shown that the computed values of the *J*-integral increases as the maximum time allowed in the time-increment is reduced. This is related to the incremental dependency of this analysis, the smaller the time increment, the smaller the load increment. For smaller load increment, the void ratio (R/R_0) can be correlated with the critical value more closely and with less overshoot. Consequently, the nodes can be released earlier. In general, decrease in the time-increment appeared to increase the accuracy of the results, but more computer time and memory is required. A separate study has also shown that constant time-increment size in the FEA programme may not be recommended for crack growth analysis using the R&T model.

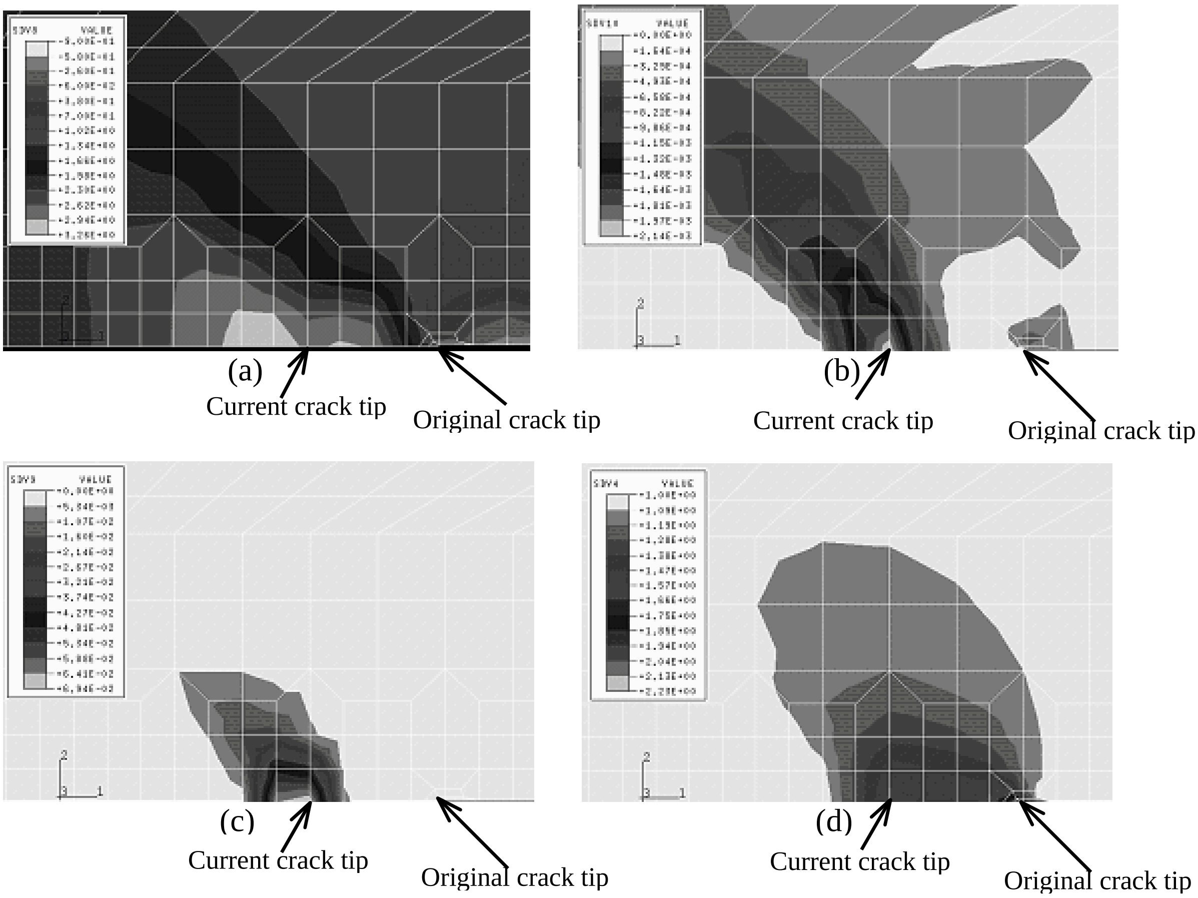

FIGURE 4. FEA results using the R&T model: (a) the distribution of the triaxiality (σ_{eq}/σ_m), (b) the distribution of the effective plastic strain rate, (c) the distribution of the void growth rate, (d) the distribution of the void growth ratio, (R/R_0).

The results obtained using different element mesh sizes (0.5mm, 0.25mm and 0.125mm) are shown in Fig. 6. It is shown that the numerical values of the *J*-integral are higher when using larger elements. For the mesh size of 0.5mm, both element removal and node release techniques were used for the crack propagation. Comparing the two different crack growth techniques, the *J*-integral values obtained from element removal are lower than that of the nodal release method. This could be due to the fact that failed elements were eliminated in the first case (one element each step), while in the later case the element remains in the model (with the node released). The study also shows some dependency of the predicted *J-R* curve on the element mesh size. In general the analysis indicated that the results obtained from the local approach method might be dependent on the detailed techniques used in the simulation stage and that standards should be applied for consistency.

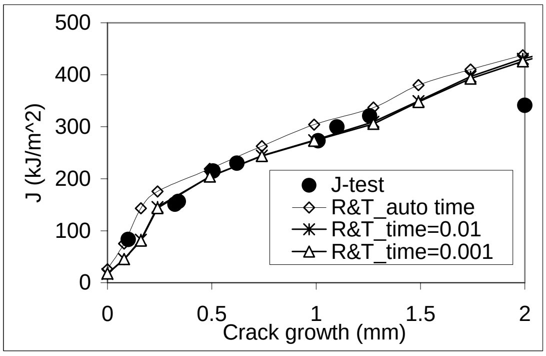

FIGURE 5. Structural steel resistance curves - effect of time increment.

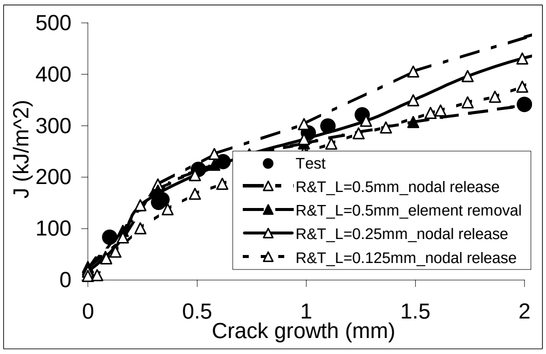

FIGURE 6. Structural steel resistance curves - effect of mesh size.

Conclusions

The determination and calibration of material parameters from the laboratory tests for the R&T model is fairly straightforward. However, the uncoupled model was found to be adequate for the initiation stage but limited in use for the crack growth stage.

The present work indicates that the simulation results using the R&T model could be dependent on the crack growth simulation technique. For example: time step incrementation, mesh size at crack front and crack propagation method. A typical cell size for the modelling, defined as the mesh size in the finite element analysis, was about 0.25mm for the investigated steel. This was determined by metallurgical observations and confirmed in the simulation of axial tension of notched specimens.

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