NUMERICAL SIMULATION OF DUCTILE FRACTURE INITIATION BY APPLICATION OF RICE-TRACEY VOID GROWTH MODEL

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ABSTRACT

The standard tensile specimen, made of steel 22 NiMoCr 3 7, has been numerically analyzed to simulate the initiation of ductile failure, in the scope of ESIS TC8 Numerical Round Robin on Micromechanical Models, Phase II, Task A. The large strain (updated Lagrangian) finite element formulation was used to simulate expected level of strains. Material non-linearity was modeled by true stress-strain curve, employing Von Mises yield criterion with isotropic hardening. The results obtained in this way were in good agreement with the experimental results, in particular for the force-contraction relation. Using results for strains and stresses, obtained for the standard tensile specimen, further numerical analysis has been performed to evaluate critical void growth ratio $(R/R_0)_c$, as the maximum value of (R/R_0), obtained according to the Rice-Tracey model. The critical void growth ratio value was then used for the analysis of crack growth initiation in CT25 specimen, as the further step in the scope of numerical modeling of ductile fracture initiation. The criterion for crack growth initiation evaluation was the critical void growth ratio value, $(R/R_0)_c$, obtained for the smooth round specimen, compared with the void growth ratio value, obtained in the element ahead of crack tip. For the load level at which $(R/R_0)_c$ has been reached, the corresponding J integral was evaluated and compared with the experimentally determined J_i value. Since these two values turned out to be in good agreement, it was concluded that the Rice-Tracey model can be applied for numerical simulation of ductile fracture initiation in the scope of the procedure employed here.

INTRODUCTION

According to the uncoupled micromechanical damage model, the damage parameter is calculated in postprocessing phase of the finite element analysis. Using the Rice-Tracey model [1] and taking into account material hardening proposed by Beremin [2], critical void growth ratio $(R/R_0)_c$ can be written as:

$$\ln\left(\frac{R}{R_0}\right)_c = \int_{\varepsilon_0=0}^{\varepsilon_c} 0.283 \cdot \exp\left(\frac{3\sigma_m}{2\sigma_{eq}}\right) d\varepsilon_{eq}^p \tag{1}$$

where R stands for the actual mean void radius, R_0 is its initial value, the ratio σ_m/σ_{eq} represents stress state triaxiality, and $d\varepsilon_{eq}^p$ is the equivalent plastic strain increment. In order to simplify evaluation, one can neglect strain which corresponds to the void initiation, as done in eqn. 1. The upper limit, ε_c, in the integral in eqn. 1 corresponds to the critical void growth ratio, i.e. when their coalescence initiate a crack in material. According to the applied model, damage does not alter the behaviour of the material [8], so the damage parameter is not represented in the yield criterion.

In the coupled models, the finite element (FE) analysis takes into account damage parameter, most often void volume fraction f. In some papers [8,9,10], these two micromechanical modeling approaches have been compared and the following could be concluded:

- the uncoupled models can simulate the crack initiation (for geometries without initial crack) or its stable growth initiation (for precracked geometries), but problems arise if the stable crack growth simulation should be done;
- coupled models can simulate also the stable crack growth.

Therefore, if the aim of simulation is initiation of crack, one can use the uncoupled model as simpler one, that the result of a single FE calculation may be used for many postprocessing routines [10]. On the other hand, one should keep in mind that significant simplifications of void initiation and coalescence mechanisms are made in this way, which coupled models can represent more adequate. However, experimental investigations on reactor pressure vessel steel indicates that the void growth is dominant phase of ductile fracture initiation [9], verifying application of void growth model, although mechanisms of void initiation and coalescence should be taken into account in more accurate analysis.

One should also keep in mind that corrections of the original value of parameter 0.283, as given by Rice & Tracey in eqn. 1, might be necessary, [11,12].

NUMERICAL MODELING AND RESULTS

The calculations are performed in the scope of round robin organized by the European Structural Integrity Society (ESIS) TC8 as the Phase II Task A [3,4,5].

In the Phase II Task A1 numerical simulation of standard smooth tensile specimen was performed (Fig. 1a) in order to characterize material and evaluate critical values of damage parameter. The input data were obtained by tensile testing of steel 22 NiMoCr 3 7 at 0°C [3].

Having in mind symmetry, only one quarter of the specimen was modeled (Fig. 1b) in two different ways: in the first case small radial imperfection ($\Delta D=0.005D_0$) was introduced over four finite element rows (Fig. 1c), so that necking is 'enforced', whereas in the second case the specimen was modeled without it. Isoparametric quadratic eight noded finite elements with reduced (2x2) integration were used. The large strain formulation with updated Lagrange procedure was applied. Material non-linearity was taken into account by using the true stress - true (logarithmic) strain curve, employing von Mises yield criterion with isotropic hardening. The loading was imposed by prescribed displacements, in eight 0.5 mm steps.

As the relevant output results the specimen elongation ΔL (for reference length 25 mm) and necking contraction ΔD were followed.

The obtained results for F-ΔL curve (Fig. 2) indicate relatively large difference (after reaching maximal loading) between experimental and numerical results, specially for the model with the initial radial imperfection. Contrary to that, the results obtained for F-ΔD are in good agreement with the experimental one, both for the model with initial imperfection and for the model without it. Therefore, for the following analysis of the cracked specimen, only the model without initial imperfection was used.

According to obtained results, specimen fails when the numerical obtained loading is in-between last two steps, that corresponds to experimental obtained contraction of the specimen 2.63 mm, i. e. prescribed displacement approximately ~3.8 mm [5]. The corresponding critical value $(R/R_0)_c$=2.73 in the specimen center, is obtained by using eqn. 1 adopted for postprocessing calculation [6]:

$$\ln\left(\frac{R}{R_0}\right)_{i+1} = \ln\left(\frac{R}{R_0}\right)_i + 0.283\,\Delta\varepsilon_{eq}^{p}\,\exp\left(\frac{3\sigma_m}{2\sigma_{eq}}\right) \qquad (2)$$

where $(R/R_0)_i$ is the void growth ratio in 'i-th' step of loading with the 'zero-th' value $(R/R_0)_0$=1. So, the crack initiates when the critical value of damage parameter has been reached, and its location can be identified according to the critical value $(R/R_0)_c$.

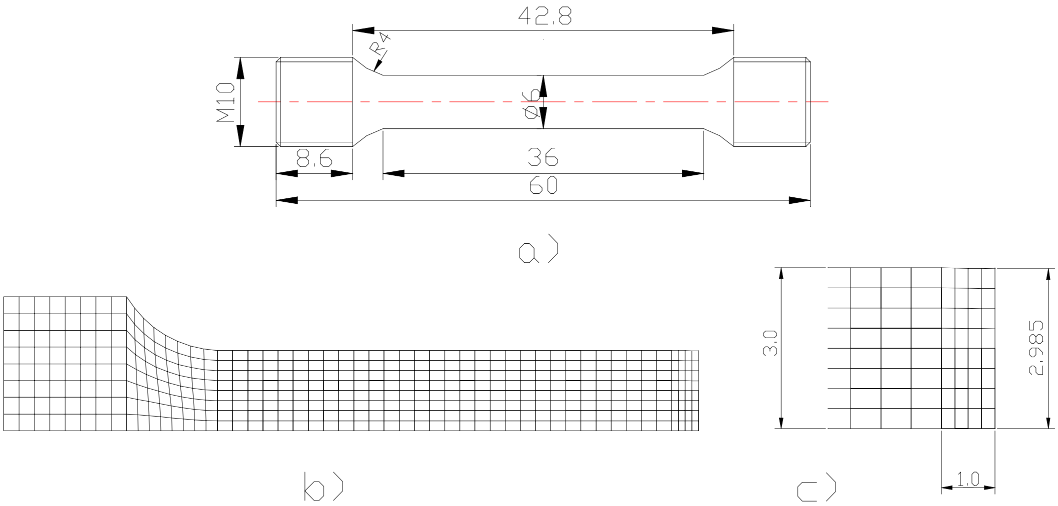


Figure 1: Cylindrical smooth specimen: a) dimensions b) finite element mesh
c) imperfection of the diameter in the center plane

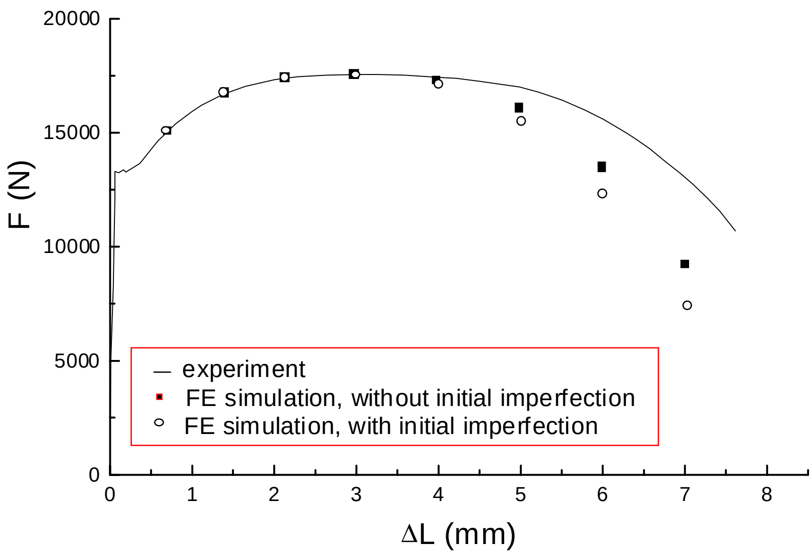


Figure 2: Load F, vs. elongation ΔL for smooth specimen

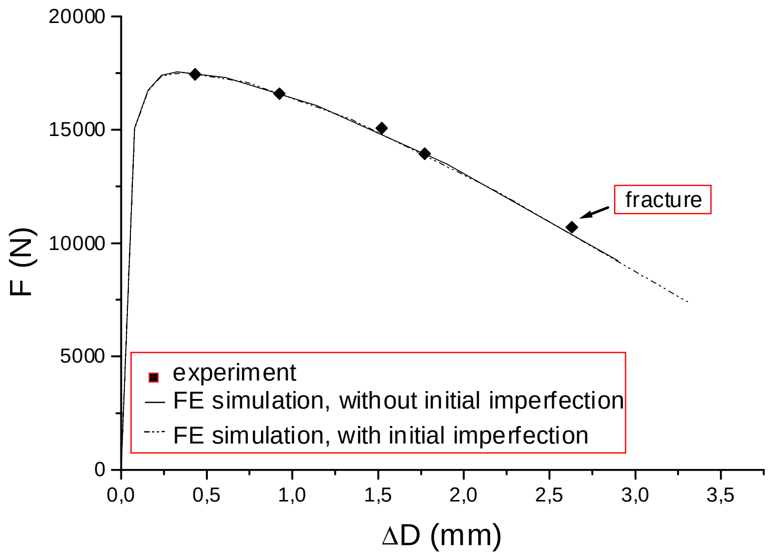
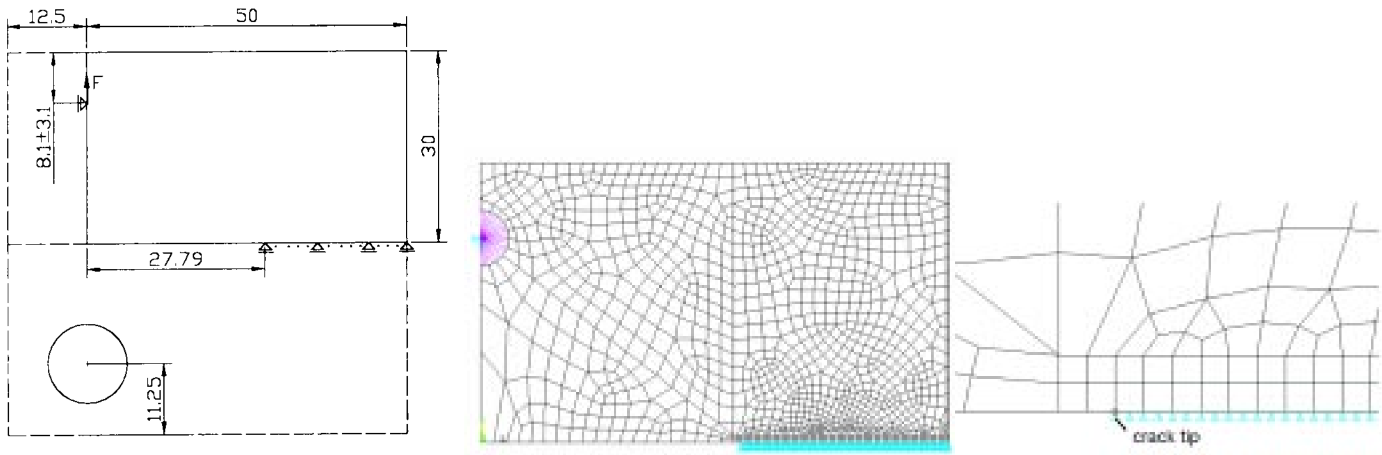


Figure 3: Load F, vs. reduction of diameter ΔD for smooth specimen

In the second part of the paper, crack growth initiation was analyzed for the standard CT25 specimen (Fig. 4a) according to the recommendations of the round robin organizer [4] for the FEM modeling. Isoparametric two-dimensional plane strain finite elements (8 node) were used (Fig. 4b), including large strain formulation. Crack tip singularity was modeled only by refining the mesh. The size of crack tip elements was 0.4 x 0.4 mm (Fig. 4c).



a) b) c)

Figure 4: CT25 specimen a) dimensions and boundary conditions
b) finite element mesh c) finite element mesh around crack tip

Since the uncoupled model was used, only the J integral at crack initiation, J_i was calculated, without further crack growth analysis. Toward this end, the critical value of void growth parameter $(R/R_0)_c$, as estimated on smooth specimen, was used for the comparison with calculated values of (R/R_0) ratio in elements around crack tip. J integral was evaluated using the area below numerically determined curve force - load line displacement. Such a procedure is valid only up to the crack initiation in accordance with the applied uncoupled model.

The initiation point was evaluated according to Fig. 5, where the void growth parameter in the finite element just ahead of crack tip is given vs. load line displacement for the first three loading steps. The crossing point with the critical value $(R/R_0)_c$ provides the corresponding value for load line displacement v_{LL}. By introducing this value to F-v_{LL} diagram, the J_i can be evaluated according to the proposed procedure given in [7].

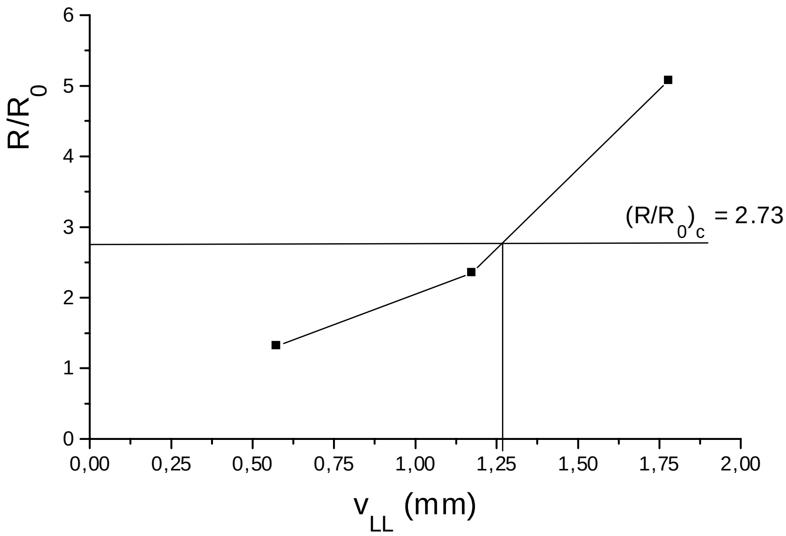


Figure 5: Void growth ratio (R/R_0), vs. load line displacement v_{LL} ahead of the crack tip

The J integral at crack initiation, J_i = 230.7 N/mm, evaluated by applying this procedure, is within range of numerical results calculated by other participants of round robin (121 - 311 N/mm), and is in excellent agreement with the experimental value, J_i = 229 N/mm, as reported in [5].

CONCLUSION

Based on the results of numerical analysis of ductile fracture initiation, obtained by the application of Rice-Tracey void growth model and performed on standard and precracked CT25 specimens, one can conclude the following:

- Excellent agreement between the experimental and numerical results was obtained for F-ΔD curve for both applied meshes (with the initial radial imperfection and without it);
- Significant differences between the experimental and numerical results for F-ΔL curve occurred after maximal loading, specially for the mesh with the initial radial imperfection;
- Critical value of damage parameter $(R/R_0)_c$, evaluated on standard smooth specimen and used for crack growth initiation analysis on precracked CT25 specimen, provided excellent agreement between J_i value calculated by applying this numerical procedure with experimental one.

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