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NUMERICAL MODELING OF DUCTILE FRACTURE INITIATION IN STRUCTURAL STEEL

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Abstract. *Numerical modeling of ductile fracture initiation on a precracked geometry, taking into account the behaviour of simple uncracked material, has been done in the scope of micromecanical analysis. Numerical simulation has been applied in two steps: first, a tensile smooth cylindrical specimen and then, the standard CT specimen. Analysis was performed on a structural steel 22 NiMoCr 3 7, in the scope of ESIS TC8 Numerical Round Robin on Micromechanical Models, Phase II, Task A. The large strain (updated Lagrangian) finite element (FE) 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/R0)c, as the maximum value of (R/R0), obtained according to the Rice-Tracey micromechanical 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/R0)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/R0)c has been reached, the corresponding J integral was evaluated and compared with the experimentally determined Ji 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.*

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INTRODUCTION

Micromechanical models have been used extensively in the last decade in order to analyze and predict ductile fracture initiation of alloys by simulating void initiation, growth and coalescence. Two basic approaches are: coupled and uncoupled damage. In the first one or more damage parameters are calculated to model ductile fracture initiation. Thus, the FE analysis must include procedure for calculation of these parameters and optionally, fracture initiation criterion. The most used damage parameter is void volume fraction. Anyhow, this is not good enough; evaluated damage parameter should correspond to experimental values at the point of fracture initiation and sudden drop of force at the diagram force-contraction. This is the weak point in all coupled numerical models, which is still under investigation [6,7]. Besides, the FE analysis according to coupled models can be time-consuming and convergence dependent, specially if more complicated geometry is involved. The main advantage is a possibility to follow crack growth in a cracked body and to evaluate J-Δa curve.

According to the uncoupled micromechanical damage models, the damage parameter is calculated in postprocessing phase of the finite element analysis. Here, the Rice-Tracey void growth model has been applied, evaluating void growth ratio R/R_0 by postprocessing of conventional elastic-plastic FE results. R stands for the actual mean void radius, R_0 is its initial value. The application of these models is simple and fast, and 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 structural steel which is numerically analyzed here, 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.

BASIC EQUATIONS OF THE RICE-TRACEY VOID GROWTH MODEL

The Rice-Tracey model considers growth of an isolated spherical void in infinite space, where von Mises yield criterion applies. The stresses σ_1, σ_2 and σ_3 act remote from a void, while the strain rates are $\dot{\varepsilon}_1$, $\dot{\varepsilon}_2$ i $\dot{\varepsilon}_3$. Under the load voids are deform into the ellipsoidal shape. Rice and Tracey have shown that the void radius rate can be expressed as [1]:

$$\dot{R}_i = \left[(1+G)\,\dot{\varepsilon}_i + D\sqrt{\frac{2}{3}\dot{\varepsilon}_j\dot{\varepsilon}_j} \right] R_0 \quad (i, j = 1, 2, 3) \tag{1}$$

where D and G are constants depending on stress state, while R_0 represent the initial radius of spherical void. Taking into account the incompressibility assumption $(\dot{\varepsilon}_1 + \dot{\varepsilon}_2 + \dot{\varepsilon}_3 = 0)$, there are two independent strains. Rice and Tracey have expressed $\dot{\varepsilon}_2$ i $\dot{\varepsilon}_3$ depending on $\dot{\varepsilon}_1$ and parameter Φ, as follows:

$$\dot{\varepsilon}_2 = -\frac{2\Phi}{3+\Phi}\dot{\varepsilon}_1 ; \quad \dot{\varepsilon}_3 = \frac{\Phi - 3}{3+\Phi}\dot{\varepsilon}_1 ; \quad \Phi = -\frac{3\dot{\varepsilon}_2}{\dot{\varepsilon}_1 - \dot{\varepsilon}_3} \tag{2}$$

Using the Rice-Tracey model and taking into account material hardening proposed by Beremin [2], critical void growth ratio $(R/R_0)_c$ where ductile fracture initiation has been occurred, can be written as:

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

where σ_m is hydrostatic stress and

$$\sigma_{eq} = \sqrt{\frac{3}{2}\sigma'_{ij}\sigma'_{ij}} \tag{4}$$

equivalent stress with σ'_{ij} the deviator of the Causchy stress tensor. The ratio σ_m/σ_{eq} represents stress state triaxiality, and d ε_{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. 3. The upper limit, ε_c, in the integral in eqn. 3 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 [10], so the damage parameter is not represented in the yield criterion.

NUMERICAL MODELING AND RESULTS

The identification and determination of the so called micromechanical parameters require a hybrid methodology of combined testing and numerical simulation. Different from classical fracture mechanics, this procedure is not subject to any size requirements for the specimens as long as the same fracture phenomena occur. Recent investigations in this field of elastic-plastic fracture mechanics should give answer: are damage parameters of respective models only material and not geometry dependent. That could be a general advantage compared with the classical fracture mechanics, and such parameters could be easy transfer from geometry to geometry.

The aim of this investigation was to evaluate damage parameters on a simple uncracked geometry (smooth cylindrical specimen) using Rice-Tracey model to define ductile fracture initiation point, and then to model crack growth initiation in a cracked body (CT specimen). 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]. Round robin organizer has supplied participants with experimental results.

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). Isoparametric quadrangular eight noded finite elements with reduced (2×2) 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. The possible reason is that the analysis was done on the quarter of the specimen, so the necking in the center is eventually different from the real one. This should be clarified by model of the specimen half or even the whole specimen. Contrary to that, the results obtained for F-ΔD are in good agreement with the experimental one.

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 (Fig. 3), 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. 3 adopted for postprocessing calculation:

$$\ln\left(\frac{R}{R_0}\right)_{i+1} = \ln\left(\frac{R}{R_0}\right)_i + 0.283\,\Delta\varepsilon_{eq}^{p} \exp\left(\frac{3\sigma_m}{2\sigma_{eq}}\right) \quad (5)$$

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 $(R/R_0)_c$.

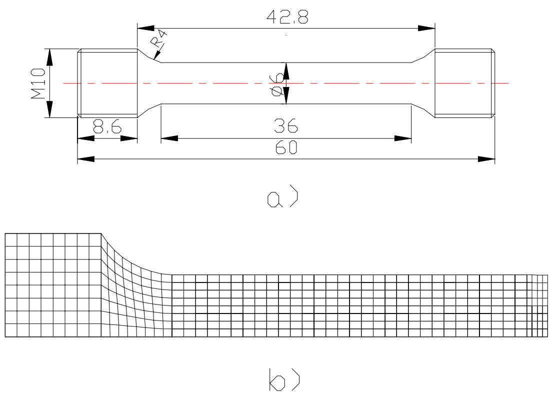

Fig. 1. Cylindrical smooth specimen: a) dimensions b) finite element mesh

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 FE 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 × 0.4 mm (Fig. 4c).

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.

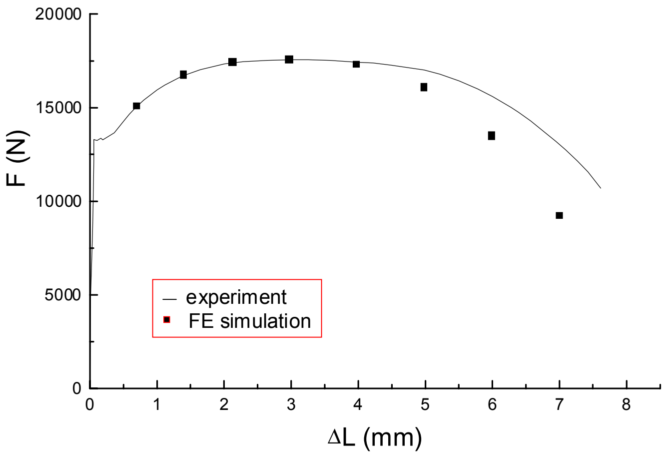

Fig. 2. Load F vs. elongation ΔL for smooth specimen

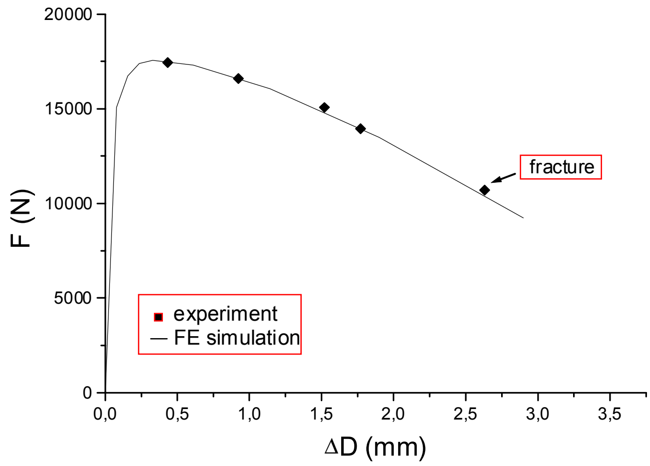

Fig. 3. Load F vs. reduction of diameter ΔD for smooth specimen

J integral was evaluated from the external work U according to the load line displacement curve [13,14]:

$$J_0 = \frac{\eta U}{B_n (W - a_0)} \quad \text{and} \quad \eta = 2 + 0.522\left(1 - \frac{a_0}{W}\right) \tag{6}$$

Such a procedure is valid only up to the crack initiation in accordance with the applied uncoupled model. If crack growth is analyzed, J integral evaluation according to (6) should be corrected due to the changed crack length by [13,14]:

$$J = J_0\left[1 - \frac{(0.75\eta - 1)\Delta a}{W - a_0}\right] \tag{7}$$

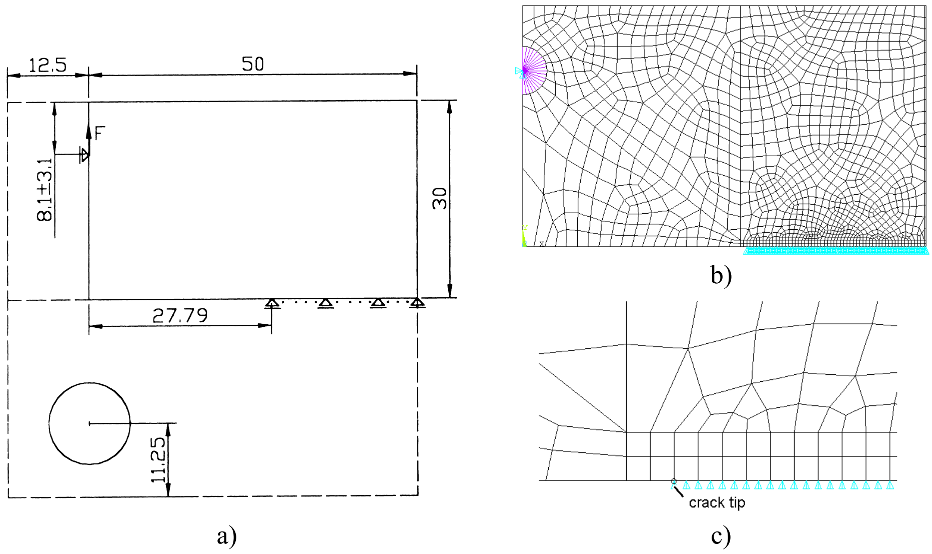

Fig. 4. CT25 specimen a) dimensions and boundary conditions
b) finite element mesh c) finite element mesh around crack tip

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 [14].

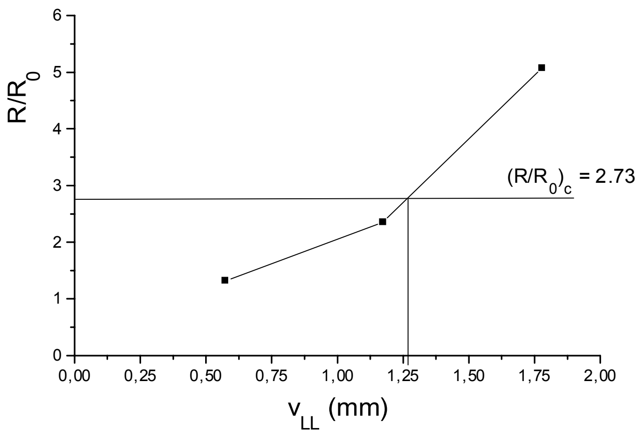

Fig. 5. Void growth ratio (R/R_0), vs. load line displacement v_{LL} ahead of the crack tip

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 The Rice-Tracey void growth model and performed on standard and precracked CT25 specimens, one can conclude the following:

- For the geometries involved one can use 2D elastic-plastic FE analysis;
- Excellent agreement between the experimental and numerical results was obtained for F-ΔD curve;
- Significant differences between the experimental and numerical results for F-ΔL curve occurred after maximal loading;
- 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.

According to obtained results, damage parameter determined on simple geometry without initial crack, can be used for ductile crack initiation on precracked geometry. Further investigations should be done on different geometries without and with initial crack, in order to better understand behaviour of real structures with cracks, under external load.

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NUMERIČKO MODELISANJE INICIJALIZACIJE DAKTILNE FRAKTURE U STRUKTURNOM ČELIKU

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U radu je dato numeričko modelisanje inicijalizacije daktilne frakture u strukturnom čeliku na geometriji pre loma uzimanjem u obzir ponašanje jednostavnog neslomljenog materijala uz pomoć mikromehaničke analize. Numerička simulacija bazirana je na metodi konačnih elemenata. Zaključuje se da Rice-Tracey model može da bude primenjen za numeričku simulaciju inicijalizacije daktilne frakture.