18th International Conference
ENGINEERING MECHANICS 2012
Svratka, Czech Republic, May 14 – 17, 2012

pp. 1253–1258
Paper #108

MODELLING OF DUCTILE FRACTURE FOR SUB-SIZED THREE-POINT-BEND GEOMETRY

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Abstract: *The contribution deals with the simulation of R-curve using complete Gurson model of ductile fracture. The R-curve was experimentally determined for a Eurofer97 steel on sub-sized three-point-bend geometry in previous study. To apply complete Gurson model the parameters describing the voids´ behaviour and characteristic length parameter need to be determined. The nucleation parameters were identified by single specimen method of smooth tensile test specimen and from metallographic examination of fracture micro-mechanism. The characteristic length parameter was derived by fitting load versus deflection curves of sub-sized specimens. The simulations of the tests were carried out by FEM software ABAQUS 6.11 in Standard and Explicit modules. The identification was supported by parametric studies. Comparing experimental and simulated R-curve the ductile tearing was not successfully achieved. Insufficient calibrated parameters as a result non-uniqueness problem of single specimen method were found.*

Keywords: ***complete Gurson model, single specimen approach, Eurofer97, R-curve***

1. Introduction

Generally, the macroscopic parameters for ductile fracture for example ductility or crack resistance curve cannot be directly transferred from one geometry to another. Because of this one if the important tasks is to separate parameters describing the ductile fracture from the parameters which describe geometry and size effect. Ductile fracture is for the most engineering materials driven by nucleation of microvoids, their growth and subsequently in certain cases by their coalescence. From that point of view is convenient to obtain the parameters describing the micro-ductile fracture. The failure will be then connected with the material behaviour and that could be used for separation of geometry and size effect. It is not that case when ductile fracture is connected with macroscopic pseudo fracture parameters, because those parameters are evidently influenced by above mentioned effects.

In the paper (Ødegård et al., 2000) the authors propose a method for determining void nucleation parameter. They pursue an idea that for the same material, complete Gurson model should work both at low stress triaxiality case (tensile specimens) and high triaxiality case (cracked specimens). The void nucleation parameter can therefore be determined from tensile specimens where the mesh size has no significant effect. There are two different approaches for application of introduced method namely single specimen approach and multispecimen approach. Within these approaches smooth and both smooth and notched tensile specimens are used, respectively. Once the void nucleation parameters are determined, the remaining characteristic length parameter which describes the strain gradient effect can be fitted from fracture mechanics tests. If these parameters are known and verified, they can be used as transferable parameters between different components.

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The contribution deals with determination of ductile fracture parameters for advanced Eurofer97 steel developed for fusion/fission power generation using complete Gurson model. Apart from getting be familiar with Gurson model, the possibility to derive the Gurson parameters from smooth tensile specimens was verified. The identified parameters were used for simulation of R-curves which were measured by single and multispecimen method using sub-sized three-point-bend specimen type of KLST by Dlouhý et al. (2011) in previous study.

In the following, the complete Gurson model is described first. Next the applied procedure of parameters identification from tensile test is introduced. Then the results of R-curve simulation are compared and discussed with experimentally determined ones. At the end the conclusion of the study is presented.

2. Complete Gurson model

The Gurson model describes the plasticity of material via behaviour of void in ideal-plastic Mises material (Ødegård et al., 2000). The material described by Gurson model behaves like continuum within it is the void effect averaged. That connects the microscopic and macroscopic behaviour of the material. The yield function of the Gurson model has the following form:

$$\phi(q,\bar{\sigma},f,\sigma_m)=\frac{q^2}{\bar{\sigma}^2}+2q_1 f^*\cosh\left(\frac{3q_2\sigma_m}{2\bar{\varsigma}}\right)-1-\left(q_1 f^*\right)^2=0 \quad (1)$$

where f is the void volume fraction, σ_m is the mean normal stress, q is conventional von Mises equivalent stress, $\bar{\sigma}$ is the flow stress of the matrix material, q_1, q_2 are constants introduced by Tvergaard (1981, 1982). The function $f^*(f)$ was applied by Needleman & Tvergaard (1984) to model rapid loss of the material stress-carrying capacity after the occurrence of void coalescence as observed during the test. This function is expressed as follows:

$$f^* = f \text{ for } f < f_c \quad (2)$$

$$f^* = f_c + \frac{f_u^* - f_c}{f_f - f_c} \text{ for } f \geq f_c, \quad (3)$$

where $f_u^* = 1/q_1$. The complete loss of load-carrying capacity occurs at $f = f_F$ i.e. ultimate void volume fraction.

The function becomes more predominant once the void volume fraction f exceeds a critical value f_c.

The increase in void volume fraction consists of two terms: the nucleation of new voids and growth of existing voids. It can be written as:

$$\Delta f = \Delta f_{nucl} + \Delta f_{gr}. \quad (4)$$

The symbol Δ represents the increment in the quantity.

The complete Gurson model can simulate microvoid nucleation, growth and by introducing empirical void coalescence criterion the void coalescence. For existing voids the model can describe the softening effect caused by the voids on material behaviour and at the same time can predict the void growth rate during plastic deformation. Void nucleation can be stress controlled or strain controlled. In the literature, strain controlled nucleation has been preferred, because it is easier to handle in the finite element implementation. Different materials may have different nucleation laws. For many engineering materials which contain large inclusion voids can be nucleated during the early stage of plastic deformation. For such a materials, a cluster mode may be used to simulate the void nucleation (parameter f_0). For materials where voids are nucleated from carbides or intermetallic phases a continuous or statistical void nucleation model (parameter f_n) may be applied. For material, where neither one of models is suitable, complex model consisting of their combination should be used. Because the laws describing voids growth and nucleation cannot itself treat void coalescence, the complete Gurson models contains one empirical treatment of it called critical volume fraction (f_c). The coalescence occurs via faster growth rate when a critical void volume fraction has been reached. The void coalescence will be finished (material load carrying capacity becomes zero) when the void volume fraction reaches another value – the volume fraction at final failure (f_F).

When the Gurson model is applied to the ductile fracture problem, the void nucleation parameter and crack tip mesh size need to be determined. The void nucleation parameters can therefore be determined from tensile specimen, where the mesh size has no significant effect. The crack tip mesh size, which is described by the characteristic length l_c, can be then determined from fracture mechanics tests, where the effect of mesh size is significant (Ødegård et al., 2000).

The ductile behaviour of the material is described by its stress-strain curve and ductile fracture behaviour is in the case of complete Gurson model characterized by eight parameters: q_1, q_2, f_0, ε_n, s_n, f_n, f_c, f_F. Parameters q_1 and q_2 describe growth of voids, ε_n and s_n together with f_n describe the statistical nucleation model.

Abaqus explicit module can be used for simulation of damage of material. Its benefit is also lower computational cost comparing with standard module. But certain issues should be resolved before its application i.e. the effect of applied velocity and its comparison with solution of standard module.

2.1. Derivation of Gurson parameters

To derive the Gurson parameters the single specimen approach was applied. This methodology involves the description of ductility of the material from smooth tensile test (trace load-elongation or load-diameter reduction). When ductility of the material is known, the optimal nucleation parameters (f_0, f_n), which give the best fit to the experimental results, can be obtained. The results of tensile tests were used from study (Dlouhý et al., 2011). Only smooth tensile specimen results as a load vs. elongation were available.

To choose which nucleation model, if cluster or continuous nucleation, should be applied, metallographic study of micro-void nucleation mechanism was performed. The broken parts of tensile specimens were longitudinally cut and specimens were prepared by standard metallographic processes. The voids were revealed by mechanical-chemical polishing with OPS suspension (colloidal solution with fine particles of silicon carbide). The specimens were then studied using scanning electron microscopy (JSM 6460, Jeol) and quantification of voids fraction was performed by image analysis. The images from the corresponding sites of specimens were acquired at different magnification. The examination revealed that voids nucleate just in the neck region and no voids were observed in uniformly deformed part of specimen. This fact exclude the cluster nucleation model as a possible description of void nucleation mechanism and leaving its value f_0=0. The value of void volume fraction from region near to the fracture surface 0.011 was chosen as f_c. It is important to note that the values of void volume fraction were magnification dependent. With higher magnification, the void volume fraction was higher. The void volume fraction was determined at value of magnification which was the most relevant also for observation of precipitates in studied steel thus 2500 times. The value of void volume fraction f_F and the values of parameters describing void growth q_1 and q_2 were chosen as recommended in literature (Ødegård et al., 2000; Dutta et al., 2008) thus 0.15, 1.5 and 1.0, respectively. The statistical nucleation model was applied by choosing recommended values of ε_n=0.3, s_n=0.1 (Ødegård et al., 2000) and parameter f_n was fitted to experimentally determined trace load-elongation. The axisymmetric model of tensile specimen was created consisted from 1160 elements type of CAX4 (4 nodes, reduced integration) using ABAQUS 6.11 software. The loading was displacement driven. The stress-strain curve of the steel prior to necking was given by the true strain and true stress computed from experiments. In order to obtain true response in the post-necking regime up to final failure the relevant part of true stress-true strain curve was fitted by iterations, until the response load vs. elongation from finite element simulation was comparable with experimental results. It was found that f_n=0.001 gives good fit to the experimental data Fig. 1. By obtaining parameter f_n the process of their identification has finished.

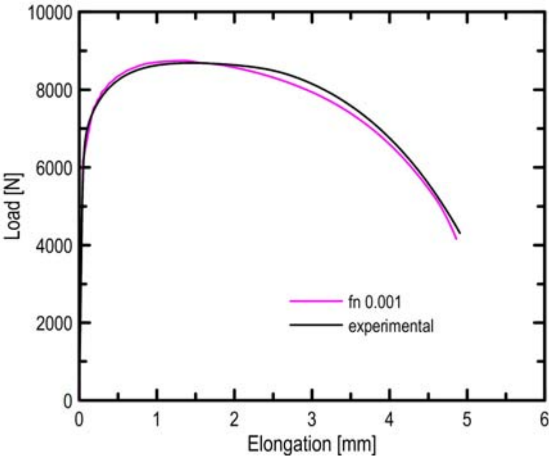

Fig. 1: Experimental and computed tensile curves.

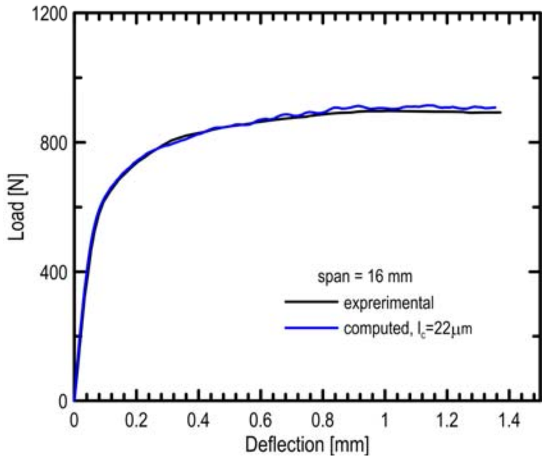

Fig. 2: Experimental and computed three-point-bend traces load-deflection.

2.2. Determination of characteristic length parameter

The 3D models of the tested KLST specimens were built according to (Dlouhý et al., 2011). Using symmetry only one quarter of specimen was modelled. The meshes with various elements´ size in process zone, where the crack propagation was prescribed, were created using the elements with square cross-section and with size ranging from 10 µm to 100 µm. In dependence on the specimen mesh the models consisted from 20.10^3 to 45.10^3 elements of C3D8R (8 nodes, reduced integration). From comparison of experimental and simulated curves the mesh with element size 22 µm fits the best to the results Fig. 2. Based on that element size characteristic length parameter l_c=22 µm was obtained.

3. Comparison of computed and experimental R-curves

The explicit module in ABAQUS naturally does not allow determination of the J-integral. Its values were determined from load-displacement curve according to the standard determination like for fracture mechanics test (ISO 12135:2002). The ductile tearing at different deflection was determined by counting the elements, where void volume fraction reached value of f_F. Comparison of experimental and computed R-curves is shown in Fig. 3.

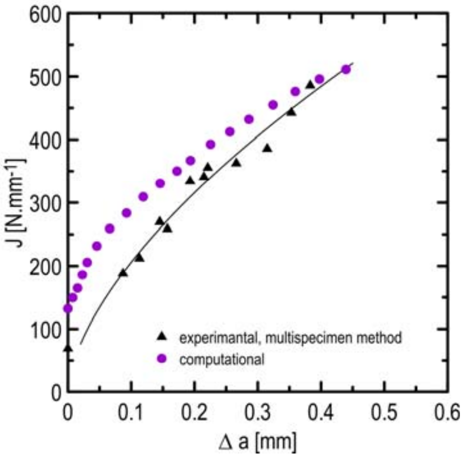

Fig. 3: Computed and experimentally determined R-curves.

4. Discussion of results

The simulated R-curve fits with experimental one within its upper parts. However, the J-initiation values and values of J-integral up to about 0.2 mm of crack extension are considerably overestimated. That is not problem of values of J-integral counted from load-displacement curve but of crack extension. The crack propagation up to 0.2 mm is slow because model behaviour is too stiff. The slope of R-curve seems to be right, but the curve should be turned or shaped. It could be changed just by parameters of Gurson model. Thus it seems to be that the parameters were not successfully identified. In fact it is disadvantage of single specimen approach of nucleation parameter identification, which is non-uniqueness problem. The same fit to the tensile test data can be obtained by fitting parameter of nucleation model and at the same time by fitting parameter of cluster model (Dutta et al., 2008). But the latter was reliably excluded on the basis of metallographic examination. However, this above mentioned non-uniqueness problem can be resolved by using multispecimen approach. Both smooth and notched tensile specimens are used. The results from those tests serve for construction of a ductility diagram (fracture strain vs. a representative stress triaxility from specimen center). Within that approach various geometries of specimens cover a wide range of stress triaxiality. If two nucleation models yield same results at smooth specimen (low triaxiality), they will certainly give different results at notched specimens (high triaxiality), vice versa.

The shape of R-curve predicted by using the nucleation parameter from tensile tests may be different to the experimentally one. There are several factors which may contribute to this discrepancy (Ødegård et al., 2000). Also appropriate choice of Gurson model parameter values, which were treated as fixed in present study, is questionable. In this contribution, fixed values of Tvergaard parameters q_1 and q_2 are applied. In general, q_1 and q_2 are also dependent on the hardening exponent n. In the study (Faleskog et al., 1998) values of $q_1$and q_2 was tabulated as a function of n. The question is if the Gurson model is suitable for Eurofer97 steel. The problem could be also Gurson model itself. It is known that this model works well for many engineering material but certainly not for all.

5. Conclusion

In this study the process of identification of complete Gurson model parameters was carried out. The parameters describing the voids´ behaviour and characteristic length parameter need to be determined. In first, the identification process of nucleation parameters was applied using single specimen approach from results of smooth tensile specimen. The identification procedure was supported by examination of fracture mechanism via micro-void nucleation. Next, the characteristic length parameter was derived by fitting load versus deflection curves of sub-sized three-point-bend geometry. Difficulty was encountered while computing R-curve of fracture specimens using identified parameters in agreement with the experimental data. Insufficient calibrated parameters as a result non-uniqueness problem of single specimen method were found. The possibility of multispecimen approach of nucleation parameters identification and also performance of Gurson model for Eurofer97 steel will be studied further.

Acknowledgement

The authors gratefully thank for the financial support of projects of the Czech Science Foundation No. 106/09/H035 and 107/10/0361.

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