XII International Conference on Computational Plasticity. Fundamentals and Applications
COMPLAS XII
E. Oñate, D.R.J. Owen, D. Peric and B. Suárez (Eds)

A METHOD FOR POST-PROCESSING OF FINITE ELEMENT ANALYSES TO ASSESS CRITICAL MACROSCOPIC VOIDS

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Key words: finite element analysis, pressure dependent damage, critical void, post-processing

Abstract. A method for post-processing of finite element analyses to assess critical macroscopic voids is presented. One single, global analysis of the structure or component is carried out and then post-processed. By using a template model and the same constitutive model as for the global model, a damage scaling function is defined once and then applied to the result from the global model. The result is a database with critical relative sizes for different void rotations at the integrations points in the global model.

1 INTRODUCTION

The presence of voids in metallic materials reduces its macroscopic mechanical strength. Voids in materials are a result of the manufacturing processes and the strength reduction is mainly due to two things: Increase in mean stress due to the reduction of solid material, i.e. less load carrying section area, and; local increase in strains and stresses on the boundary of the voids. Voids can exist at different spatial scales. In an engineering finite element analysis the relative size of the voids are typically too small to be explicitly modelled and discretized. Instead, the effects of the voids has to be incorporated in constitutive equations and considered indirectly through test data on macroscopic properties. Publication for ductile metals in this area seems to have started with for example [1], [2] and [3] and has since grown vast. Since such constitutive models treat voids collectively and in an averaging, homogenized fashion, they do not give any information about the characteristics of individual voids. If one needs to formulate and supply specific acceptance criteria, for example to be used for non-destructive testing of components, for individual voids another route has to be followed. There are alternatives to be used in this case, cf. for example [4], but a more general methodology is presented here which is easier to automatize in a finite element context.

Commonly, in an engineering finite element analysis of a structure or component it is assumed that there are no extraordinary voids present in the material. Only smaller, i.e. for a given material and manufacturing process ordinary ones, whos effect on the mechanical properties of the material are considered indirectly. Typically via tensile test data in which these ordinary voids grow, coalesce and new ones nucleate until the specimen is completely fractured.

In Fig. 1 a simple simulation of such a process, however without nucleation, is shown. From the pictures it can be seen how plastic strains are accumulated at the void boundaries and in bands between closest neighbours. When the stress dependent failure stress is reached, cracks are initiated and propagated until the plate is separated into two parts, i.e. it fractures.

The focus of the presented study has been to develop methods with an engineering approach, using finite element tools, to determine criteria for relative size and configuration of individual voids with elliptical shape in a steel structure. The expected void sizes are in the order of 10^{-3} mm.

The basic idea here is to run one single standard finite element analysis of a structure of interest and corresponding loads, and then apply a scaling function to the result to find the critical void configuration in a material/integration point that matches the weakest link, in a macroscopic sense, of the void-free structure.

2 COMPUTING THE SCALING FUNCTION

First, the scaling function needs to be determined. This function will be dependent on the constitutive model used, which needs to be the same used for the base model. However, once the scaling function has been determined for a given constitutive model it can be applied to any problem.

Here a standard isotropic elasto-plastic model with yield criteria according to Von Mises and piecewise linear deformation hardening is used, and a stress triaxiality dependent failure model. The Young's modulus and Poisson's ratio were set to 210 GPa and 0.3, respectively. The constitutive parameters for the deformation hardening to necking were fitted against test data and the result is shown in Fig. 2.

Due to lack of data for the specific material on the failure strain ϵ_{f} at different levels of stress triaxiality χ, typical values were chosen and shown in Tab. 1. However, the choice of constitutive parameters here is not important since the purpose of the present paper is to present the method. It is only important that the constitutive model and parameter values can distinguish between compressive and tensile stress states, which here is embodied in the damage parameter.

Damage D is assumed to be accumulated according to the linear evolution law

$$\dot{D} = \frac{\dot{\epsilon_{\mathrm{p}}}}{\epsilon_{\mathrm{f}}} \tag{1}$$

where the dot represents time derivative or increment. The material fails, i.e. a crack initiates, when the damage D reaches unity.

Table 1: Failure strain at different levels of triaxiality

χ	$-\frac{1}{3}$	0	$\frac{1}{3}$	$\frac{2}{3}$	1
ϵ_{f}	3	0.5	1	0.5	0.5

The scaling function is determined by numerical analyses of a template model, see Fig. 3, for which the displacement based boundary conditions Δx and Δy, the ratio k between the minor and major axis of the elliptic void and the rotation v is varied. Here the dimensions of the template model is chosen as $h = 1$ and $r = 0.2$. The intervals for the variables are chosen as $\{k|0.1 \leq k \leq 1\}$, $\{v|0° \leq k \leq 180°\}$, $\{\Delta x| -0.002 \leq \Delta x \leq 0.002\}$ and $\{\Delta y| -0.002 \leq \Delta y \leq 0.002\}$. Contact was defined for the void boundary to eliminate material penetration. Based on these intervals, a total of 3402 template models were set up and analyzed and in Fig. 5 the result is shown for the case $v = 0°$ and $k = 0.3$. The strains ϵ_x and ϵ_y are the linear global strains over the template model, ie. for the case where no void is present.

3 APPLICATION TO BOLTED CONNECTION

The scaling function is applied to the results from a finite element analysis of a bolted connection, see Fig. 6. In the analysis double symmetry is exploited when creating the mesh. The weakest link in the base model is the bolt. So, the analysis is carried out until failure of the bolt, and it is this stress state in the plates to which we'll apply the scaling function. Further, the strain state on the vertical symmetry plane is here assumed to be in a state of plane strain. When the bolt fails, some of the integrations points or elements in the plates has started to yield, and some are still in the elastic domain. To exemplify the method of scaling the local solution, an element that is in elastic domain is chosen from the plate. The position of the chosen element and the damage scaling function corresponding to the elements stress state at bolt failure is shown in Fig. 7.

The final step in the procedure is to choose a critical damage level. A conservative choice would be $D < 1$. Since $D = 0$ corresponds to elastic domain and yielding in both compression and tension, it is recommended that a value larger than zero is choosen. This way we allow the pressure dependent damage evolution come into play, and we're able to better separate compressive and tensile stress states. Here $D = 0.025$ is choosen as the treshold value, and the result for the choosen element is plotted in Fig. 8. From this plot the minimum ratio between the minor and major axis of the critical elliptic void can be seen, for different rotation of the major axis from the global x-axis.

4 DISCUSSION

An engineering method to post-process results from a finite element analysis in order to determine critical size and rotation of elliptical voids has been developed. The method allows for assessment of critical voids for any integration point, or element, in the model and is far less costly than sub-modelling techniques. In the paper the method is applied to one single element, but all elements in the model can be evaluated in the same manner and the results visualized on the mesh as documentation to be used when performing non-destructive testing such as ultrasonic testing or computed tomography scanning.

Extension of the method to three dimensions is straight forward. In the paper it is the relative size of the voids that is determined. Further development of the method should include the determination of absolute void sizes, by for example relating the template model to a characteristic element size. Or, if element sizes are small in comparison with the critical voids and boundary effects can't be ruled out, some kind of moving representative elementary volume. Finally, the effect of interaction between voids should also be incorporated into the model.

5 ACKNOWLEDGEMENT

The research leading to these results has received funding from the European Union's Seventh Framework Programme managed by REA-Research Executive Agency http://ec.europa.eu/research/rea ([FP7/2007-2013] [FP7/2007-2011]) under grant agreement no. 286603.

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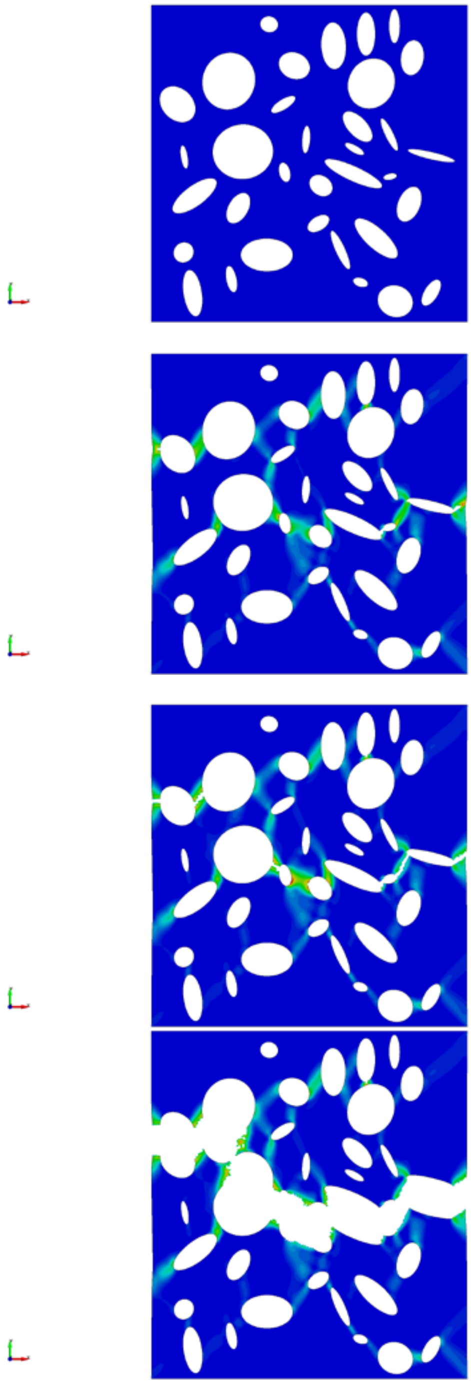

Figure 1: Plastic straining and fracture of plate with voids at different stages of loading.

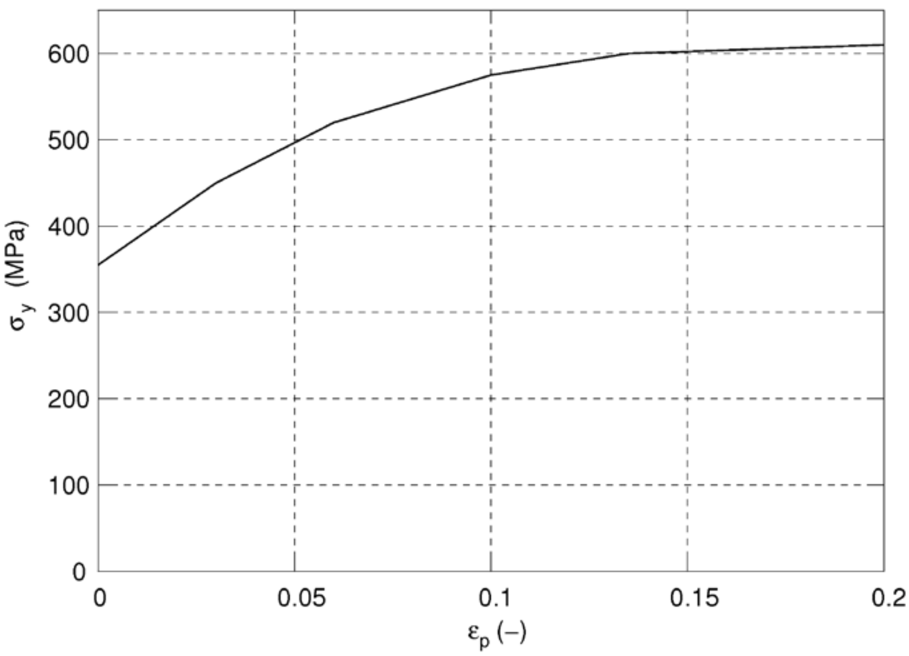

Figure 2: Deformation hardening.

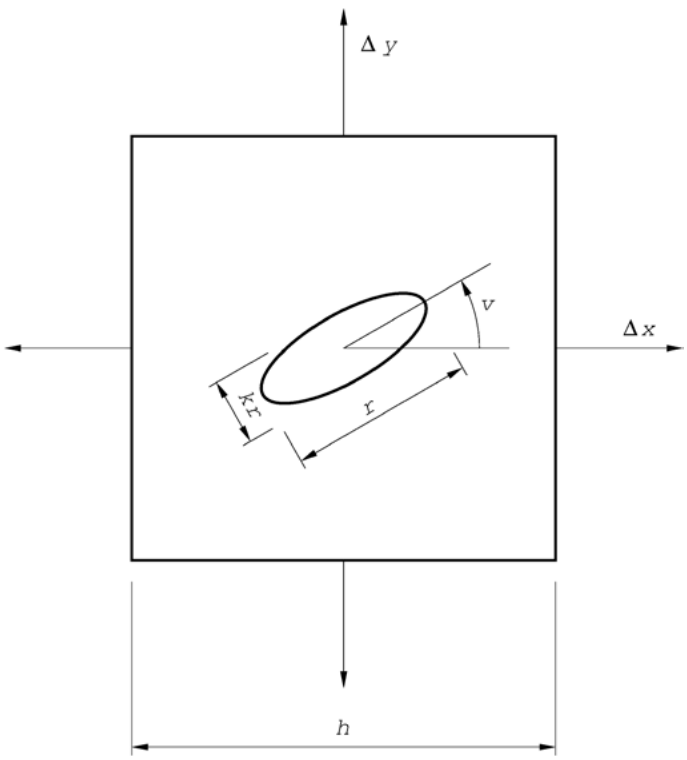

Figure 3: Template element for numerical computation of scale function.

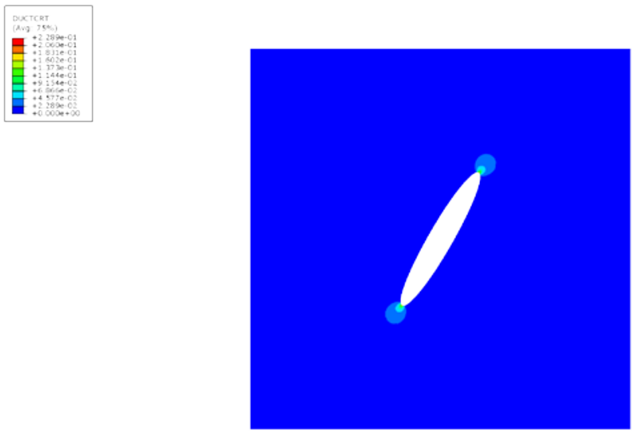

Figure 4: Resulting damage D for $v = 60°$, $k = 0.15$, $\epsilon_x = \epsilon_y = 0.002$.

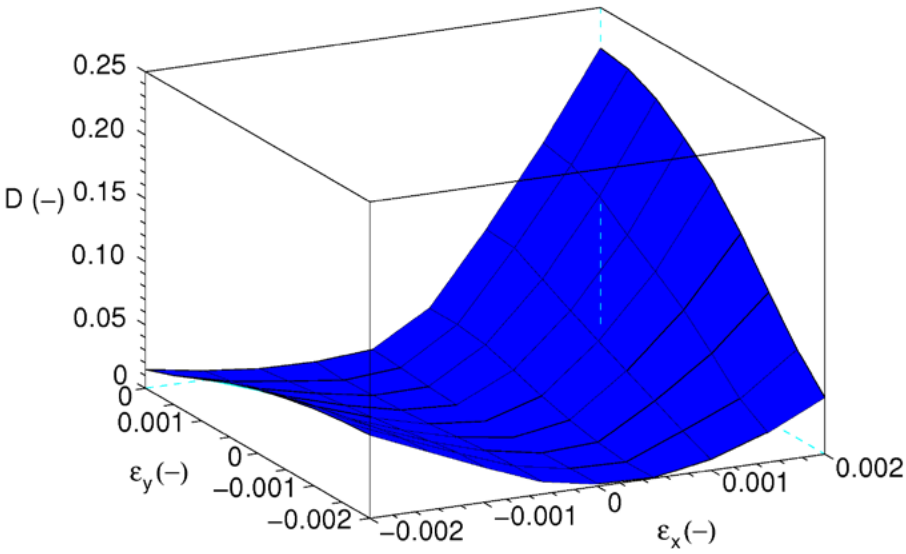

Figure 5: Scaling function for $v = 0°$ and $k = 0.15$.

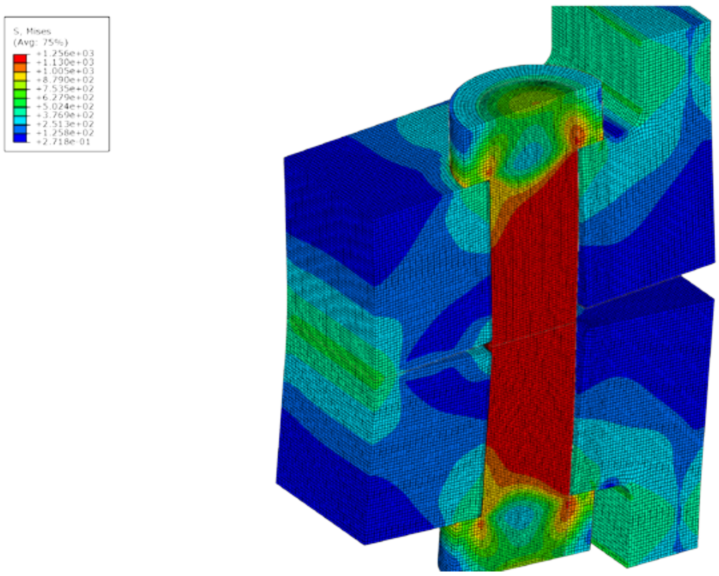

Figure 6: Equivalent Von Mises stress (MPa) at bolt failure.

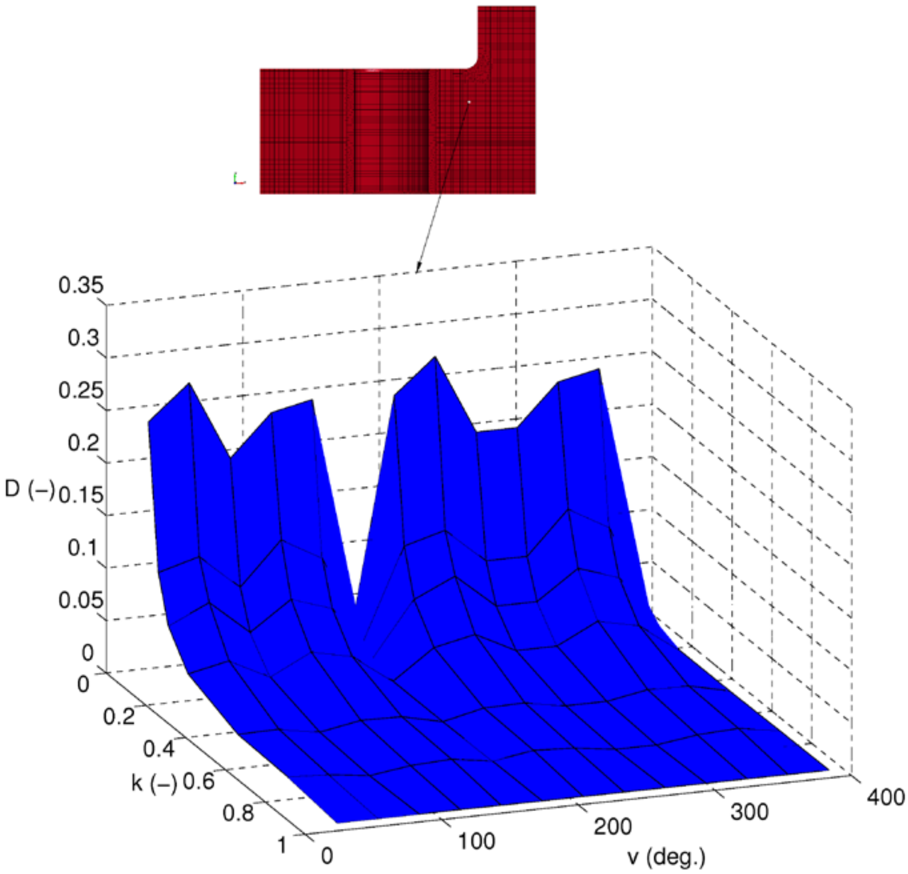

Figure 7: Damage for an element in the finite element model when scaling function is applied.

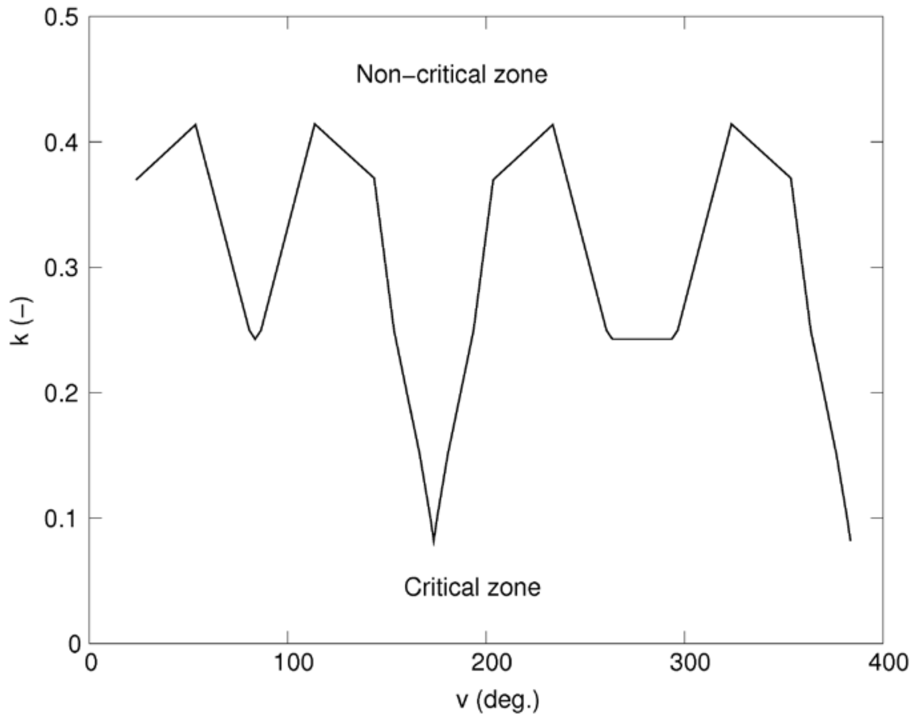

Figure 8: Critical and non-critical voids for $D = 0.025$.