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# Implementation of a nonlocal damage model – mesh dependence in sheet metal forming

Nicolas Pernin, Jérôme Chambert and Philippe Picart

The aim of the present work is to propose a micromechanical nonlocal damage model in order to predict the damage evolution in metal forming processes, especially in cold forging of small components. The modelling considered here is based on a Gurson model [1] modified by Tvergaard and Needleman [2], where the nonlocal damage has been defined in the same manner as Pijaudier-Cabot and Bazant [3]. The nonlocal void volume fraction is determined from an average of the usual local porosity at the neighbouring points using a weighting function. Two different weighting functions are used, the first one is defined by a Gaussian distribution function, the second one is defined in the same manner as Tvergaard and Needleman [4] ; the use of these two different functions is compared. The neighbourhood is determined by a material length  $l_c$ . The influence of the value of the parameter  $l_c$  is studied. The ability of such nonlocal damage modelling to reduce the mesh-size dependency is investigated for the case of a 2D tensile specimen with a centred hole. Numerical results show that nonlocal extension trends to lower the mesh dependence.

The ductile fracture of metallic materials is widely described by three main stages: nucleation, growth and coalescence of micro-voids. The local damage approaches, such as continuum damage mechanics [5] or micromechanical modelling [1,2,6], have been developed successfully to analyze the ductile fracture of materials. These models can predict the softening response of most engineering structures until strain localization occurs. However, the local damage formulation does not describe precisely the post-localization regime of deformation neither in a mathematical nor in a physical point of view. Mathematically, the constitutive partial differential equations suffer from a loss of ellipticity in the case of static loading. Consequently, the finite element results depend on the mesh resolution. The predicted localization width tends to zero when the mesh is more and more refined. Physically, this means that no energy is dissipated and the numerical solutions become meaningless. Actually, the strain localization width is determined by a microstructural parameter such as the average void spacing or size. In order to overcome these drawbacks, several approaches have been proposed in literature. The nonlocal damage formulation [3] related to material length scale is widely used. Many studies have been devoted to a nonlocal damage modelling based on the Lemaître – Chaboche theory [5]. On the contrary, few authors have introduced a nonlocal damage concept into the modified Gurson model [2,7,8].

## Non local Gurson-type model

Gurson's model [1] for ductile porous metals has been modified by Tvergaard and Needleman [2] to take into account matrix hardening and void coalescence process. In this paper, a nonlocal version of this modelling is formulated by averaging the damage variable with a weighting function. The flow potential, used here, is of the following form :

$$\Phi = \frac{\sigma_{eq}^2}{\bar{\sigma}^2} + 2q_1 f^* \cosh\left(\frac{3}{2} q_2 \frac{\sigma_m}{\bar{\sigma}}\right) - 1 - q_1^2 f^{*2} = 0$$

in which  $\sigma_{eq} = \sqrt{3 \boldsymbol{\sigma}' : \boldsymbol{\sigma}' / 2}$  is the von Mises equivalent stress,  $\boldsymbol{\sigma}'$  the deviatoric part of the Cauchy stress tensor  $\boldsymbol{\sigma}$ ,  $\sigma_m = \boldsymbol{\sigma} : \mathbf{I} / 3$  the hydrostatic stress,  $\mathbf{I}$  the second order identity tensor,  $\bar{\sigma}$  the yield stress of the matrix material and  $f$  the current void volume fraction. The coefficients  $q_1$  and  $q_2$  are constitutive parameters introduced by Tvergaard [9,10] to better represent the effects of porosity in plastically deforming materials. Following Tvergaard and Needleman [11], the effective void volume fraction  $f^*$  is introduced to account for void coalescence:

$$f^*(f) = \begin{cases} f & \text{if } f < f_c \\ f_c + \frac{f_U^* - f_c}{f_F - f_c} (f - f_c) & \text{if } f \geq f_c \end{cases}$$

Here,  $f_c$  is the critical value of porosity at which void coalescence occurs and  $f_U^* = 1/q_1$ . The material loses its stress carrying capacity at Gauss points from which the porosity reaches the final void volume fraction  $f_F$ .

The local porosity rate comes partly from the growth of existing voids and partly from the nucleation of new voids, which are controlled by the plastic strain:

$$\begin{cases} \dot{f}_{local} = (1-f) \mathbf{D}^p : \mathbf{I} + A \dot{\bar{\epsilon}} \\ A = \frac{1}{h_M} \frac{f_N}{s_N \sqrt{2\pi}} \exp\left[-\frac{1}{2} \left(\frac{\bar{\epsilon}^p - \epsilon_N}{s_N}\right)^2\right] \end{cases}$$

Here,  $\mathbf{D}^p$  is the plastic strain rate tensor,  $f_N$  the volume fraction of void nucleating particles,  $\epsilon_N$  the mean strain for nucleation and  $s_N$  the standard deviation. The tangent modulus of the matrix material is defined by  $h_M = d\bar{\sigma} / d\bar{\epsilon}^p$  where  $\bar{\epsilon}^p$  is the equivalent plastic strain. The nonlocal porosity  $f$  is obtained by averaging the local

damage  $f_{local}$  with some weighting function  $\psi_i$  with  $i = 1$  or 2.

$$\begin{cases} f(\mathbf{x}) = \frac{1}{W(\mathbf{x})} \int_V f_{local}(\mathbf{y}) \psi_i(\mathbf{x} - \mathbf{y}) dV(\mathbf{y}) \\ W(\mathbf{x}) = \int_V \psi_i(\mathbf{x} - \mathbf{y}) dV(\mathbf{y}), i = 1 \text{ or } 2 \end{cases}$$

where  $V$  is the considered volume,  $\mathbf{x}$  and  $\mathbf{y}$  denote the coordinate vectors.  $\psi_i$  represent weighting functions, the first one used is defined by a Gaussian distribution function following Bazant and Pijaudier-Cabot [3]

$$\psi_1(\mathbf{x}) = \exp\left(-|\mathbf{x}|^2/l_c^2\right)$$

Secondly, in the same manner as Tvergaard and Needleman [4], another delocalization function is used, it is defined by :

$$\psi_2(\mathbf{x}) = \left(1/\left(1 + (|\mathbf{x}|/l_c)^8\right)\right)^2$$

See figure 1.

### Finite element implementation

The proposed formulation has been implemented in the finite element code POLYFORM developed by our laboratory for large strain elastic-plastic problems. Considering a non linear behaviour, one difficulty is to evaluate the averaged value of  $f$  at iteration ( $k$ ) for each integration point

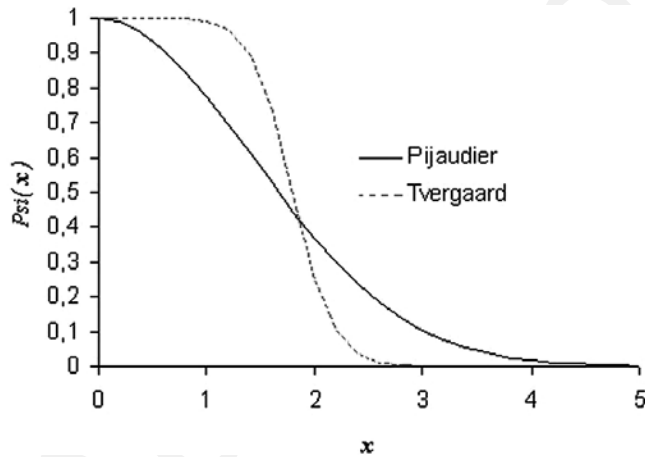


Fig. 1: Two different weighting functions.

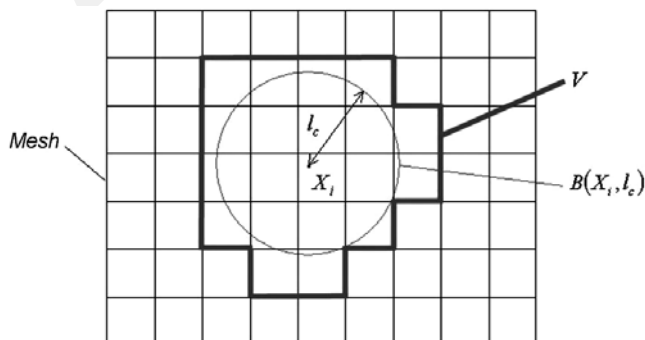


Fig. 2: Determination of the volume  $V$  around the point  $X_i$ .

at time  $t + \Delta t$  because it needs the local values at the neighbouring points which are not yet necessary determined. In that case, the nonlocal values of  $f^{t+\Delta t}$  are computed from the values computed at iteration ( $k-1$ ). For  $k=1$ , we use the nonlocal values computed for the convergent iteration at time  $t$ .

To take into account the nonlocal aspect we have to define a neighbourhood for each integration point  $X_i$ . So, we use a material length parameter  $l_c$  and the sphere  $B(X_i, l_c)$  centred on the considered integration point  $X_i$  with a radius  $l_c$ . This neighbourhood represents the smallest recovery of the sphere  $B(X_i, l_c)$  denoted  $V$ . Let  $N_i$  be the number of the integration points included in the volume  $V$  (see figure 2).

### Set-up test

In order to validate the proposed formulation, a 2D tensile specimen with a centred hole was simulated using both local and nonlocal models in plane strain conditions. Dimensions of specimen are  $200 \text{ mm} \times 200 \text{ mm}$ . Due to symmetry only a quarter of the specimen is discretized using 4-node elements with 4 integration points. The loading conditions consist of applying a prescribed displacement  $u$  of 2.6 mm in the vertical direction using 65 equal loading increments at the top of the mesh (see figure 3 and figure 4).

Values for Young's modulus and Poisson's ratio are 200 GPa and 0.3, respectively. The matrix yield stress is given by  $\bar{\sigma} = 500(1 + \bar{\epsilon})^{0.2}$ . The value of the internal length parameter  $l_c$  ranges from 0.1 mm to 8 mm.

The set of simulations uses the following values for the Gurson model parameters:

$q_1 = 1.5$ ,  $q_2 = 1$ ,  $f_0 = 0.02$ ,  $f_C = 0.05$ ,  $f_F = 0.25$ ,  $f_N = 0.04$ ,  $s_N = 0.1$  and  $\epsilon_N = 0.2$ .  $f_0$  is the initial void volume fraction.

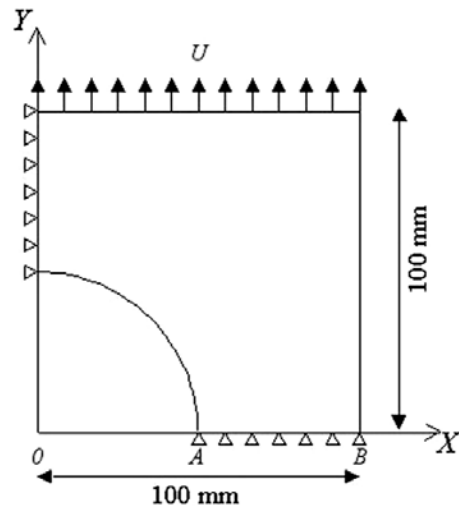
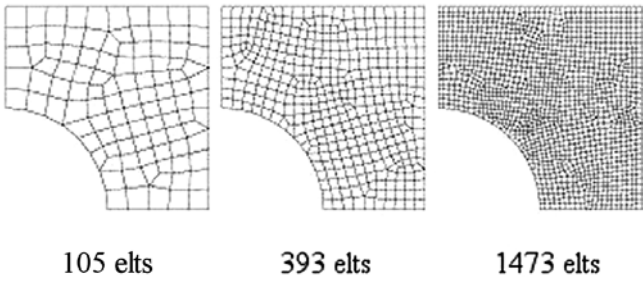
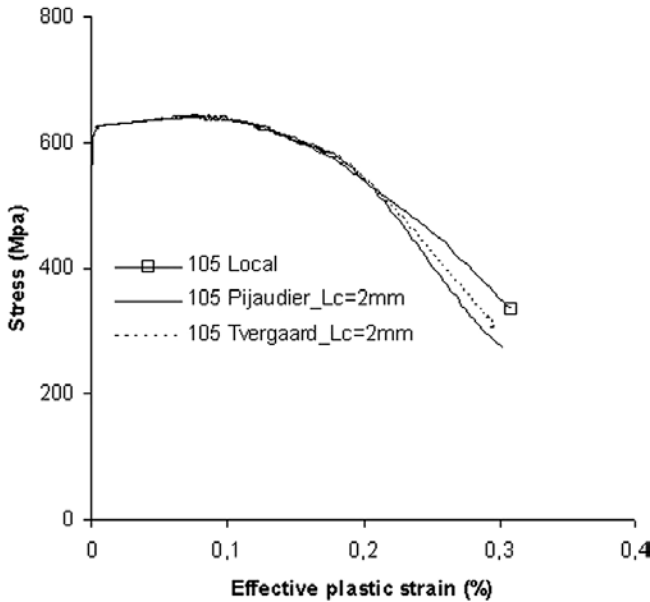


Fig. 3: Geometry and loading conditions.

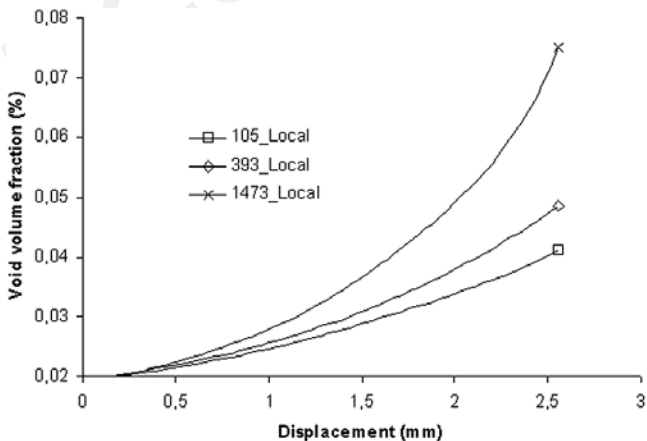


**Fig. 4:** Finite element meshes for a tensile specimen with a centred hole. To study mesh-dependency in strain softening, three meshes with 105 (element edge length  $l_e = 10$  mm), 393 ( $l_e = 5$  mm) and 1473 ( $l_e = 2.5$  mm) elements, respectively, are used.

**Figure 5** shows equivalent stress-strain curves at point A for local model and nonlocal models ( $l_c = 2\text{mm}$ ) with Pi-



**Fig. 5:** Evolution of the equivalent stress versus the effective plastic strain predicted using elastic-plastic modelling with damage at point A with local model and nonlocal models (using two weighting functions).



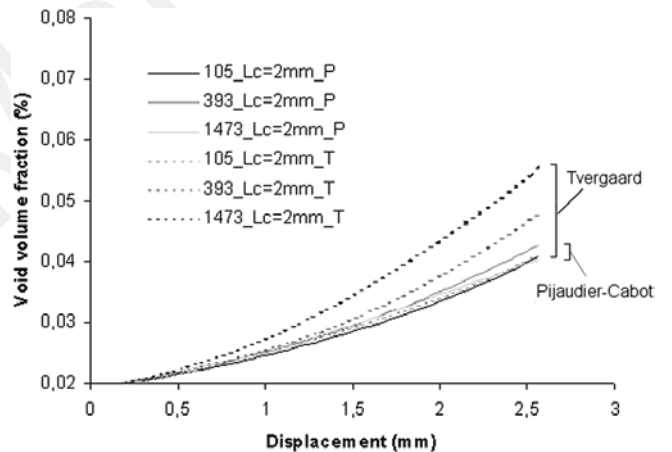
**Fig. 6:** Evolution of void volume fraction versus displacement for the three meshes using local model at point A.

jaudier-Cabot  $\psi_1$  function and Tvergaard  $\psi_2$  function.

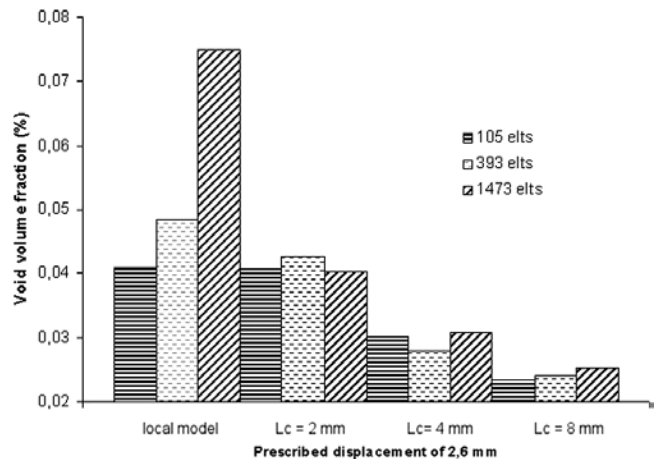
The decrease of the stress carrying capacity of the matrix material is correctly described by the local and non local GTN models.

Now the influence of the nonlocal formulation on the mesh-dependency through the analysis of the void volume fraction evolution and distribution is evaluated. As shown in **figure 6**, the evolution curve of the local damage versus the prescribed displacement is strongly affected by the mesh size. Against for the nonlocal approach the evolution of the void volume fraction-displacement curves is similar whatever the mesh refinement ; results seem to be better using Gaussian weighting function  $\psi_1$  than using Tvergaard and Needleman's delocalization function  $\psi_2$  (see **figure 7**). So  $\psi_1$  function is presently applied in the following of this paper.

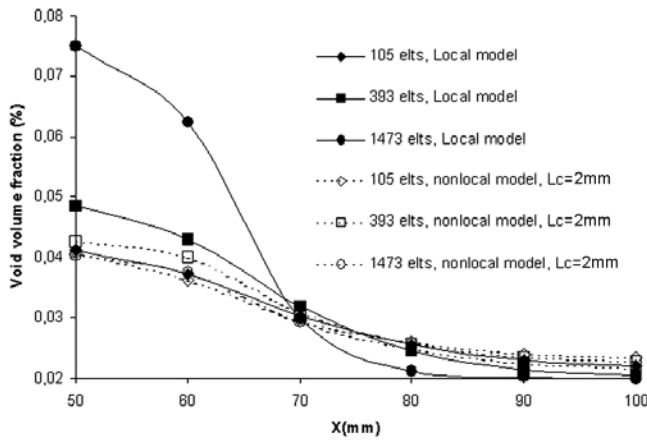
Concerning the distribution of the void volume fraction, more the length parameter  $l_c$  is important, more void volume fraction prediction tends to the initial porosity  $f_0$  (see **figure 8**). Besides results with an internal length parameter equal to 2 mm seems to be more realistic, so  $l_c$  is now fixed to 2 mm.



**Fig. 7:** Evolution of the void volume fraction versus displacement predicted by nonlocal modelling using two different weighting functions at point A, for three meshes with 105, 393 and 1473 elements respectively.



**Fig. 8:** Distribution of the void volume fraction at point A using different values for the length parameter  $l_c$  with the three meshes.



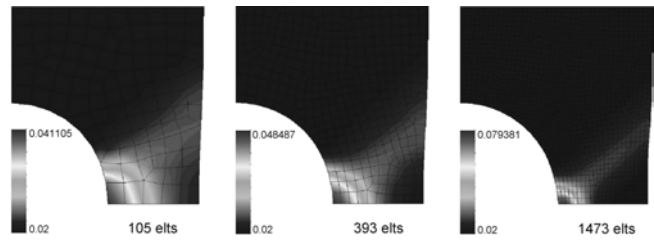
**Fig. 9:** Evolution of the void volume fraction along the symmetry axis  $\vec{Ox}$  between point  $A$  and point  $B$  predicted by local and nonlocal modelling ( $l_c = 2mm$ ) for three different meshes with 105, 393 and 1473 elements respectively.

The variation of void volume fraction across the specimen for local and nonlocal models is plotted in **figure 9**. The nonlocal approach allows to reduce in significant way the gradient of void volume fraction between fine mesh and coarse mesh.

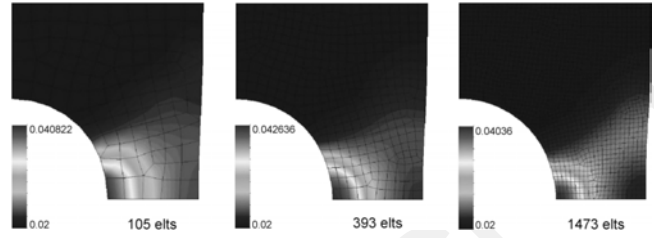
**Figure 10 and 11** show contours of void volume fraction for 2.6 mm prescribed displacement. In figure 10, for the local model, maximum void volume fraction is about 4.1 % for the coarse mesh with 105 elements, whereas it reaches 7.9 % for the fine mesh with 1473 elements. In figure 11, for the nonlocal model, void volume fraction reaches a value about 4 % for each mesh. The mesh dependency is clearly less sensible for the nonlocal approach.

## Conclusion

A nonlocal elastic-plastic GTN model, using nonlocal damage variable has been implemented in the context of a two-dimensional model problem in the FE code POLYFORM for quasi-static loading conditions. These results show that the nonlocal approach could reduce significantly the problem of mesh dependency. Our future prospects are to apply this formulation to metal forming processes such as precision blanking or micro cold forging.



**Fig. 10:** Evolution of the local void volume fraction.



**Fig. 11:** Evolution of the nonlocal void volume fraction.

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