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# Numerical investigation of ductile damage parameters identification: benefit of local measurements

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## Abstract

Identification of material parameters is an important issue to improve the accuracy of finite element computations. Identification of these parameters by inverse analysis is based on experimental observables coming from mechanical experiments. In this paper, a simple tensile test is used. Two types of observables are investigated to identify ductile damage law parameters. The first one is a global measurement, such as the load-displacement curve. The second is a local observable based on full field measurements. Our approach, based on response surfaces, allows an efficient analysis of identification issues. Ill conditioned problems and multi-minima can be obtained using only a global observable. Full field measurements are a good way to improve the identification of plastic hardening and damage law parameters. In fact, local measurements combined with global ones, lead to a better formulation of the inverse problem.

**Key Words:** Parameters identification, inverse analysis, global optimization, sensitivity analysis, ductile damage, full field measurements

## 1. Introduction

Identification of material parameters is an important issue to improve the accuracy of finite element computations. Some mechanical joining processes, such as riveting or clinching are based on materials plastic deformation ability. The mechanical strength of these joining points is linked to the plastic hardening and damage history of materials during the joining process [1]. To predict the assembly final mechanical strength, reliable damage law parameters have to be identified.

Identification by inverse analysis of damage law parameters can be achieved using different kind of mechanical tests. Local or global measurements can be done on these tests for the identification procedure. These different choices - local or global measurements - can be illustrated by two papers. Abendroth et al. [2] make the identification of damage law parameters using global measurement on small punch tests, and Springmann et al. [3] make the identification of damage law parameters using local field measurement on tensile tests. Therefore, in this paper, we present an approach based on response surfaces to detail the benefit of local measurements.

First, we describe the inverse analysis issue. This description details the direct model, the mechanical test, the objective function definition and briefly the minimization algorithm. The minimization algorithm used here is able to construct a response surface. This response surface gives the evolution of the objective function all over the design space. In the second part of this paper, we present response surfaces constructed with different objective functions, computed using different observables. The final goal is to evaluate the benefit of each kind of observable to solve the identification issue for ductile damage parameters.

## 2. Inverse analysis issues

### Experimental observable - Virtual measurement

Identification by inverse analysis of material parameters is done using a tensile test. In our study, this tensile test is a virtual tensile test. In other words, experimental measurements come from a tensile test finite element modeling. This methodology allows controlling all parameters and avoids experimental uncertainties. Material parameters values which are used to generate the virtual measurement are given in Table 1.

Two different measurements are done on this tensile test: the tensile load-displacement curve, and the displacement field on one side of the sample. Our goal is to show the ability of each observable to make the identification procedure of ductile damage parameters as accurate as possible.

### Direct Model

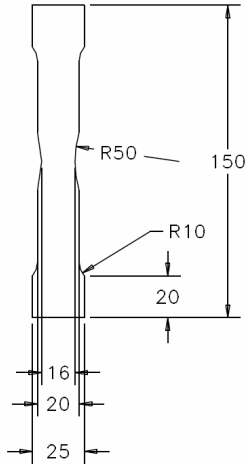


Figure 1 : Sample dimensions (mm), thickness is 2 mm - The sample is notched in order to localize strain in the centre

Parameters	Value
$\sigma_y$	46 MPa
$K$	430MPa
$n$	0.34
$b$	1
$S_0$	0.7
$\bar{\epsilon}_d$	0.16

Table 1 : value of material parameters used to generate the virtual tensile test observable

The direct model is obtained using the finite element library CIMLib® developed at CEMEF.. Dimensions of the sample are given in Figure 1. To describe the material behavior used for cold material forming applications, an elastic-plastic law coupled with a ductile damage model has been chosen. The main equations describing the elastic-plastic behavior and ductile Lemaitre damage model are given here:

- Hardening law:

$$\sigma_0 = \sigma_y + K \bar{\epsilon}^n \quad (1)$$

- Damage evolution law:

$$\dot{w} = \begin{cases} 0 & \text{if } \bar{\epsilon} < \bar{\epsilon}_d \\ \frac{\lambda^{pl}}{1-w} \left( \frac{-Y}{S_0} \right)^b & \text{if } \bar{\epsilon} \geq \bar{\epsilon}_d \end{cases} \quad (2)$$

The flow stress  $\sigma_0$  is described by a hardening law equation(1), based on the yield stress  $\sigma_y$ , the consistency  $K$ , the equivalent plastic strain  $\bar{\epsilon}$ , and the hardening exponent  $n$ . The evolution law for the damage parameter  $w$  is given by equation (2), where  $\bar{\epsilon}_d$  is the plastic strain threshold for damage growth,  $\lambda^{pl}$  is the plastic multiplier,  $Y$  the strain energy release rate,  $S_0$  and  $b$  are material damage parameters. More details about this model are given in [4]. The mechanical behavior is coupled with

the damage parameter by computing an effective stress  $\tilde{\sigma}$ , as shown in equation (3).

$$\tilde{\sigma} = \frac{\sigma}{1-w} \quad (3)$$

$w$  equals zero for an undamaged material and grows toward 1 which is reached for complete fracture.

The objective of the identification procedure is to determine the parameters values for the plastic hardening and damage laws.

### Objective functions

To solve the identification issue, an objective function has to be minimized. The formulation of this objective function is specific to each observable. Equation (4) defines how the objective function is defined using the load-displacement observable.  $P$  is the set of parameters to identify,  $F^{num}$  and  $F^{exp}$  are respectively the numerical and experimental forces, and  $d$  is the tool displacement. More details about this formulation and about how to deal with the softening part of the load-displacement curve can be found in [5]. Accounting accurately for this softening part and for the breaking instant (Load and displacement at fracture) is a key point to obtain a smooth and valuable cost function to identify damage parameters.

Equation (5) evaluates the objective function when the observable is the displacement field in the tensile direction.  $Ux^{num}$  and  $Ux^{exp}$  are respectively the numerical and experimental displacement fields in the tensile direction  $x$ . The same formulation is used to compute the objective function  $fc_y(P)$  for transverse displacement fields.

$$\left\{ \begin{array}{l} fc_F(P) = \sqrt{\frac{\sum_{i=1}^n [(F_i^{num}(P) - F_i^{exp})]^2 \Delta d_i}{\min\left(\sum_{i=1}^n (F_i^{exp})^2 \Delta d_i, \sum_{i=1}^n (F_i^{num}(P))^2 \Delta d_i\right)}} \\ \Delta d_i = d_i - d_{i-1} \end{array} \right. \quad (4)$$

$$fc_x(P) = \sum_{i=1}^T \left( \sqrt{\frac{\sum_{i=1}^n [\delta_i \cdot (Ux_i^{num}(P) - Ux_i^{exp})]^2}{\sum_{i=1}^n \delta_i}} \right) \quad (5)$$

At the end, we obtain 3 objective functions. This 3 objective functions can be added up in order to obtain one single global objective function (equation (6)). Each objective function is weighted by a weight coefficient  $\omega$ .

$$fc(P) = \omega_x fc_x(P) + \omega_y fc_y(P) + \omega_F fc_F(P) \quad (6)$$

### Resolution strategy / Sensitivity analysis

To minimize the objective function, a minimization algorithm is used. A flowchart of the parallel Efficient Global Optimization [6] algorithm is presented in Figure 2. This algorithm is implemented in the MOOPI (MOdular Optimization software for Parameters Identification) software developed in the CIMLIB library. This algorithm deals with an iterative building of a kriging response surface thanks to the maximization of the expected improvement technique. In this paper, we analyze these response surfaces to evaluate the efficiency of each kind of observable.

The Efficient Global Optimization (EGO) algorithm is a global algorithm. The EGO algorithm is dedicated to time consuming objective functions. In fact, each evaluation of the objective function usually needs a finite element computation. This is extremely time consuming, in particular for highly non linear problems such as elastic-plastic and ductile damage mechanical behavior. So an adapted algorithm must be used. In order to increase the efficiency of this algorithm, we have developed a parallel version of the EGO algorithm (Figure 2). Our developments are based on a virtual enrichment method. This virtual enrichment technique sets, temporarily, the objective function value to a virtual

value. This virtual value is set by the kriging response surface.

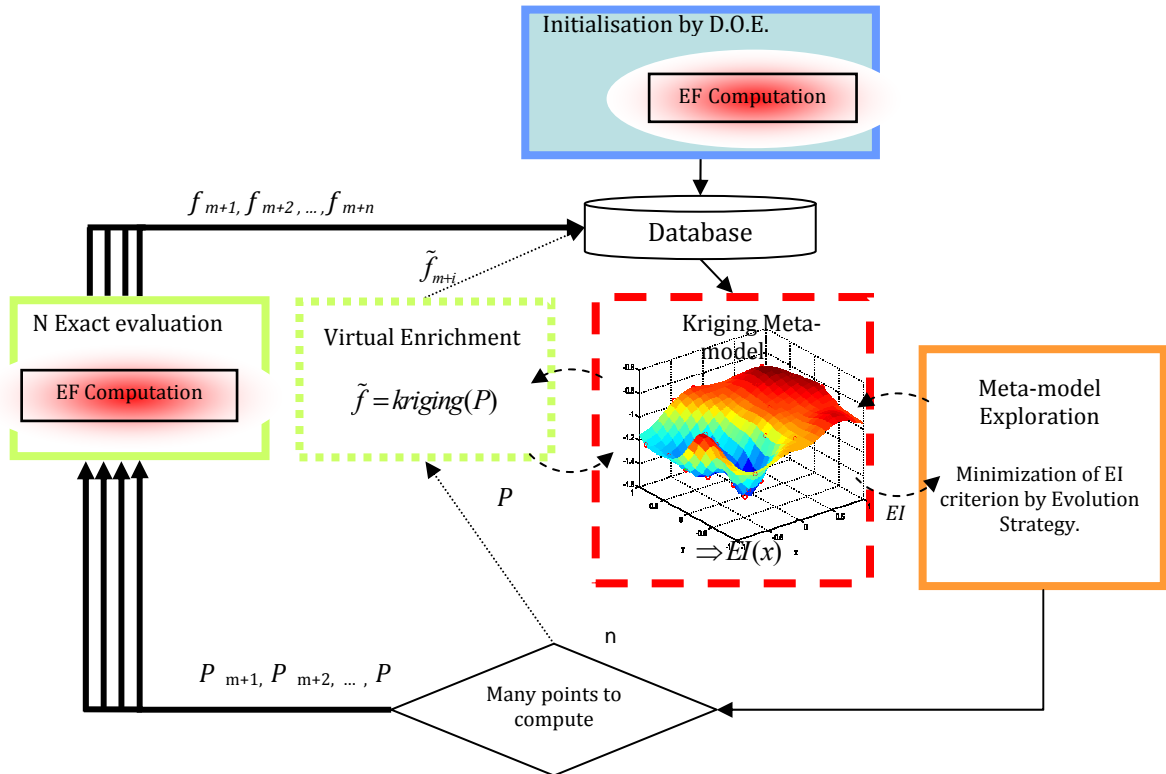


Figure 2: Flowchart of parallel extension of the EGO algorithm implemented in the MOOPI software  
 - This algorithm is well suited to time consuming identification issues, and is able to take advantages of parallel computation capabilities

### 3. Results and discussions

The whole identification of materials parameters require the identification of six parameters (equation (1) and (2)). However, to illustrate the methodology and the influence of the observables choice, only two couples of parameters are selected. For these two couples, response surfaces are plotted in Figure 3 and Figure 4.

#### Hardening parameters identification

Figure 3 shows the evolution of objective functions evaluated using different observables. To plot the surfaces, parameter  $K$  ranges from 200 to 1000 MPa, and parameter  $n$  ranges from 0.1 to 0.6. Figure 3a exhibits an ill conditioned problem. According to the load-displacement curves, a set of  $K$ - $n$  couples represent a good solution of the identification issue; i.e. objective function value is low. This set of couples values is illustrated by the red-dash line on Figure 3a. Figure 3c exhibits the same specificity; a set of  $K$ - $n$  couples gives good results according to the objective function computed using transverse displacement fields (red-dash line on Figure 3c). Therefore, this two figures show an ill conditioned problem. However, the most interesting remark is that the two valleys (red-dash lines) have not the same orientation. So, adding these 2 objective functions enables to obtain a well conditioned identification problem. An illustration of the added up objective function is shown in Figure 3d. On this surface the minimum is well defined. Note that the use of the longitudinal displacement field (Figure 3b) also enables to converge towards a single minimum.

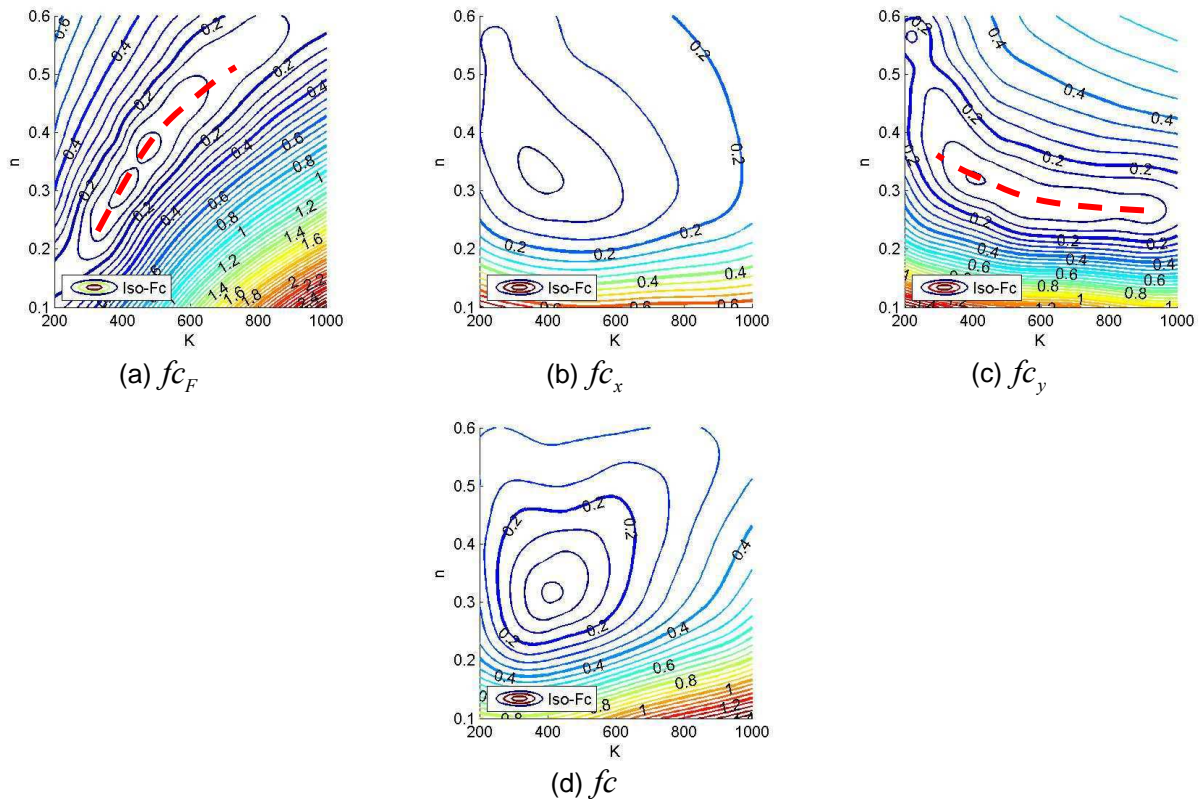


Figure 3 : sensitivity analysis of hardening parameters by kriging response surfaces, evolution of the four objective functions based on: (a) load-displacement, (b) displacement field  $U_x$  in the tensile direction, (c) displacement field  $U_y$  in the transverse direction, (d) total objective function

### Damage law parameters identification

Figure 4 shows the evolution of the objective functions evaluated with different observables. To plot the surfaces, parameters  $b$  of the Lemaitre damage model ranges from 0.5 to 3, and parameter  $S_0$  ranges from 0.1 to 1.5. The surface presented in Figure 4a is computed using the load-displacement curve objective function. This surface exhibits two minima. The global one ( $b=1$ ,  $S_0=0.7$ ) and a local one (red cross on Figure 4a). Same minima appear on the surface computed with the transverse displacement field (Figure 4c). However, the local wrong minimum is not observed on the surface computed with the tension direction displacement field (Figure 4b). of the use of local measurements, such as full field measurements, allow the suppression of local minima for ductile damage parameters identification.

Figure 4d shows the surface obtains by adding the three objective functions (equation(6)). This surface still exhibit two minima. This highlights one remaining difficulty with this methodology: the choice of the weight coefficients  $\omega$  in equation(6) is important to obtain a single minimum.

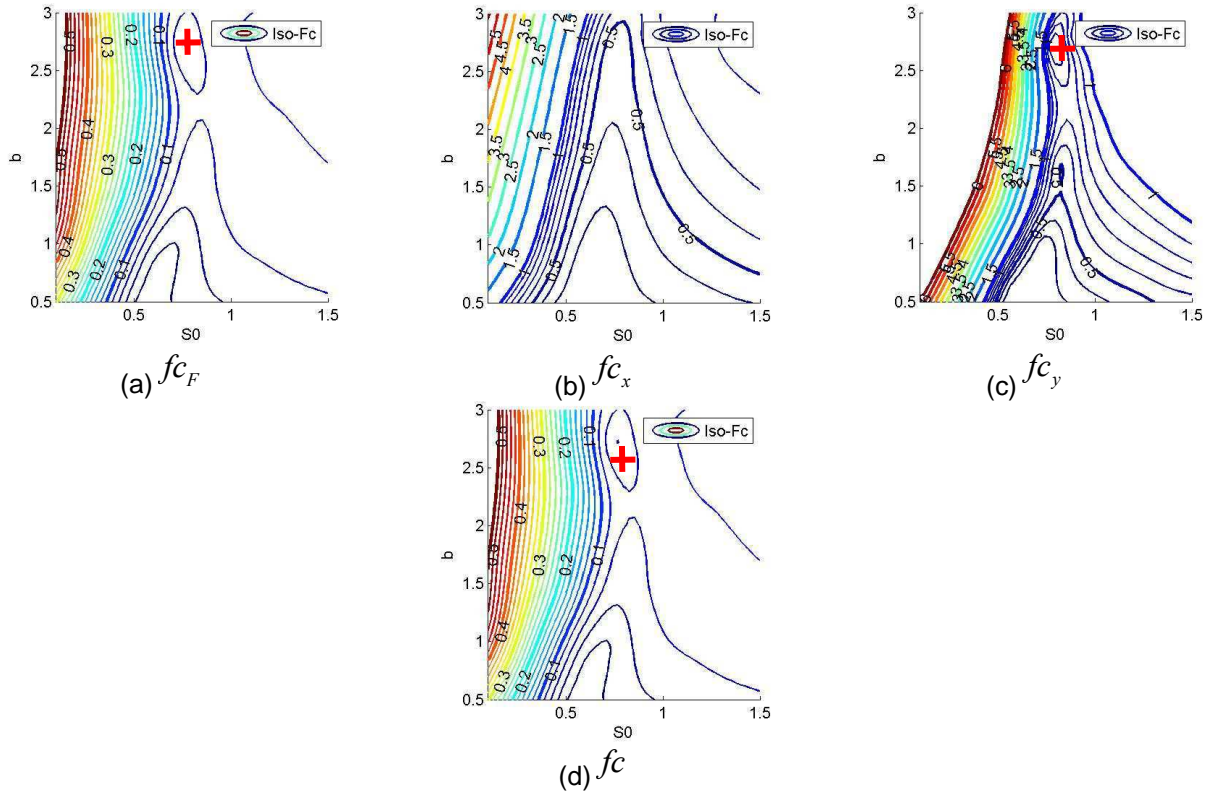


Figure 4 : sensitivity analysis of damage law parameters by kriging response surfaces, evolution of the three objective functions based on: (a) load-displacement, (b) displacement field  $U_x$  in the tensile direction, (c) displacement field  $U_y$  in the transverse direction, (d) total objective function

## 4. Conclusion

Response surfaces obtained with a parallel version of the EGO algorithm show that the use of local measurements is very efficient to improve the identification of material parameters. Two couples of parameters have been studied in order to show this improvement. On the one hand, full field measurements suppress ill conditioned problems that can be observed for the hardening law identification. On the other hand, full field measurements limit the numbers of spurious local minima.

One difficulty of this methodology is to set the weight parameters of equation (6) in order to construct a mono-objective minimization problem. However, plotting the different response surfaces is a good way to evaluate and set these weight parameters.

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