

# A user-friendly programme for calculating Forming Limit Diagrams

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**ABSTRACT:** The paper presents a computer programme used for interactive calculation of Forming Limit Diagrams. The programme is based on a Hutchinson-Neale model. Different yield criteria (Hill 1948, Barlat-Lian and BBC 2003) are implemented in this model. The programme consists in four modules: a graphical interface for input, a module for the identification and visualization of the yield surfaces, a module for the identification and visualization of the strain hardening laws and a module for calculating and visualizing the forming limit curves. A useful facility offered by the programme is the possibility to perform the sensitivity analysis both for the yield surface and the forming limit curves. The numerical results can be compared with experimental data, using the import/export facilities included in the programme. The programme may be incorporated in finite element codes.

**Key words:** Forming Limit Diagrams, yield criterion, strain hardening law

## 1 INTRODUCTION

During the last years, numerical simulation of the sheet metal forming processes has become more and more attractive for industry. Its main advantage consists in shortening the time needed for the design of the technological processes and, consequently, in reducing the overall price of the products. The accuracy of the results obtained in a “virtual” design environment is an important element conditioning the efficient use of the simulation techniques. One way to improve the quality of the numerical results provided by the simulation programmes is to refine the constitutive models. Some of the most recent models able to describe the anisotropic behaviour of sheet metals are presented in [1,2,3].

The formability of the sheet metals is another important factor that should be taken into account when designing a forming process. This information is useful both for the producer and the user of the thin rolled products. In order to assess the formability of sheet metals, several methods based on simulative or mechanical tests have been

developed. At the beginning of 1960’s, a more general and realistic concept was proposed, namely the Forming Limit Diagram – FLD [3,4,5]. This concept is now used by almost all industrial laboratories for evaluating the limit strains of the sheet metals. The forming limit diagrams are also used by commercial finite-element codes as a limiting criterion of the forming process.

One of the most important advantages of the FLD concept is the possibility to develop mathematical models for calculating the limit strains [3]. This fact allows a more consistent connection between the FLD modules and the FE code in a “virtual manufacturing” environment.

It is well known the fact that the position and shape of the FLD is influenced by the shape of the yield surface adopted in the computational model [6]. A sensitivity analysis regarding the influence of different material parameters and constitutive laws upon the limit strains is needed in the pre-processing stage. Such an analysis is also useful for the sheet metal producers when trying to obtain materials having desired formability characteristics.

Aiming to meet these requirements, the authors have

developed a software package named FORM-CERT able to calculate FLD's. One of the most important facilities offered by FORM-CERT consists in the possibility to adopt different yield criteria (Hill'48 [7], Barlat'89 [6], BBC2003 [8] etc.) and strain hardening laws (Swift and Voce) when computing the FLD's. The programme is based on the Hutchinson-Neale [9] model of the necking process. This choice is made by the user via a graphical interface. The interface allows the input of the data, but also offers detailed diagrams of the results obtained during different steps of the calculations (yield locus, hardening law and, finally, the FLD).

## 2 DESCRIPTION OF THE PROGRAMME

The programme FORM-CERT developed by the authors consists in the following modules:

- Identification module associated to the yield criterion (responsible for evaluating the coefficients of the yield criterion, as well as for the graphical output of the yield locus and planar distribution of the yield stress and r-coefficient)
- Module for calculating and displaying the strain hardening law
- Module for calculating and displaying the forming limit diagram.

Figure 1 shows a structural diagram of the programme. This diagram presents the modules mentioned above, as well as their interaction. We shall describe next the functionality of each module.

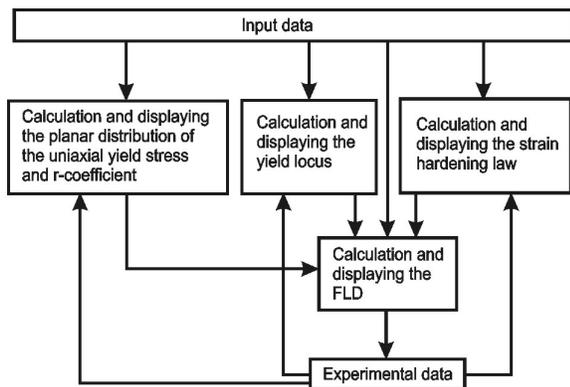


Fig. 1. Structure of the FORM-CERT programme

### 2.1 Identification module associated to the yield criterion

The yield surface is described in a general manner using the BBC2003 yield criterion [8]. This formulation contains 8 independent coefficients. For

evaluating these coefficients, 8 mechanical parameters of the sheet metal are normally needed: uniaxial yield stresses and r-coefficients associated to three planar directions (defined by 0°, 45° and 90° angles measured from the rolling directions) together with the biaxial yield stress and biaxial r-coefficient. The BBC2003 yield criterion can be reduced to simpler formulations (Hill'48, Barlat'89, etc.) by enforcing equalities between some of its coefficients [10]. In this way, the general yield criterion can be also used in the situations when only 2, 4, 5, 6, or 7 mechanical constants are available [11]. The performances of the BBC2003 yield criterion for different identification strategies have been evaluated and presented in [10, 12]. Figure 2 shows the user graphical interface of this module. Here is the place where the user can choose the identification strategy by specifying the number of mechanical parameters available for input. The input boxes can be filled from keyboard but the programme also offers the possibility to import data from an ASCII file. The module performs the identification, displays the values of the coefficients and stores them into an ASCII output file. Optionally, the values of the coefficients can be passed to the FLD calculation module. The identification module also offers the possibility to plot the computed yield locus. Different yield loci obtained from different identification strategies (with more or less coefficients) can be superimposed on the same diagram. A separate panel of the graphical interface ("Experimental data") can be accessed for importing experimental points from ASCII files. This data is also shown on the same diagram. In this way, the user has the possibility to evaluate the performances of the yield criterion in

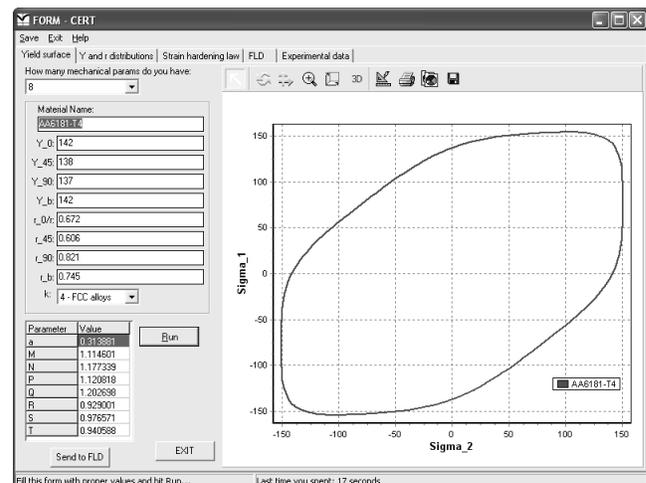


Fig. 2. Graphical user interface of the identification module

different identification cases and to select the best formulation. The identification module also allows to study the sensitivity of the yield locus to the variation of the input data.

### 2.2 Calculation and displaying the planar distribution of the uniaxial yield stress and r-coefficient

As it is well known [1, 4, 13], the knowledge of the yield locus is not sufficient for evaluating the performances of a yield criterion. The planar distribution of the uniaxial yield stress and r-coefficient offers useful information related to this aspect. The accuracy of the constitutive models is strongly dependent on their capability to describe such variations. In fact, the residual stresses, the springback and the thickness distribution obtained from FE calculations is closely connected to the performances of the yield criterion.

As a consequence, the programme developed by the authors includes a module that computes and displays the distribution of the uniaxial yield stress and r-coefficient in the plane of the sheet metal (see Figure 3).

Of course, the diagrams are calculated using the type of the yield criterion selected in the identification module. A detailed description of the computational procedure is given in [8, 14]. Again, experimental points can be superimposed on the same diagram by accessing the panel “Experimental data”. The module also offers the possibility to perform a sensitivity analysis of the curves to the variation of the input data (coefficients of the yield criterion).

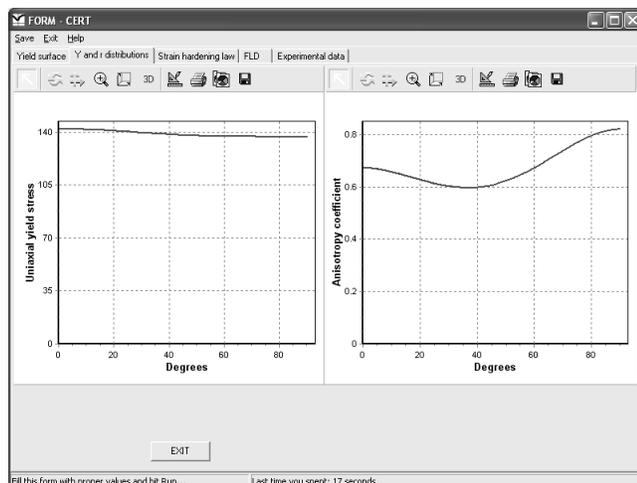


Fig. 3. Graphical user interface of the module used for displaying uniaxial yield stresses and r-coefficient distributions

### 2.3 Calculation and displaying the strain hardening law

A separate module of the programme has been developed for calculating and displaying to types of hardening laws: Swift and Voce, respectively. The graphical interface allows the user to choose the type of the hardening law and plots the associated curve (see Figure 4). The predictions offered by different hardening laws can be superimposed on the same graph and also compared with experimental data (acquired via the “Experimental data” panel). This module offers the possibility to adopt the most accurate hardening law.

### 2.4 Calculation and displaying the FLD

This is the main module of the programme. The graphical user interface provided by this module is divided in two regions (Figure 5). The first one receives the input data: coefficients of the yield criterion and strain hardening law calculated by the modules mentioned in §2.1 and §2.3, a parameter specifying the thickness non-homogeneity factor and also the value of the strain increment used for computing the FLD. The Hutchinson-Neale model of the strain localization process has been implemented in the FORM-CERT programme. The mathematical formulation and the solution procedure of the model are presented in [15]. At present, the FLD module works only for linear strain paths. The second region of the graphical user interface is used for plotting the FLD obtained from calculations. Several curves can be superimposed on the same diagram and also compared with experimental data

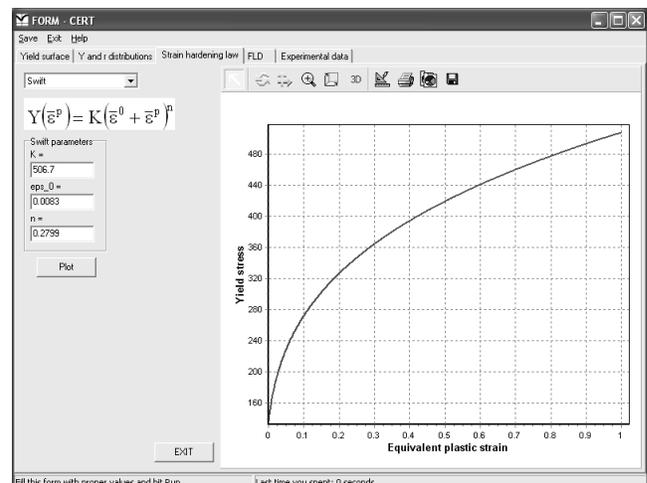


Fig. 4. Graphical user interface of the module used for calculating and displaying the strain hardening rule

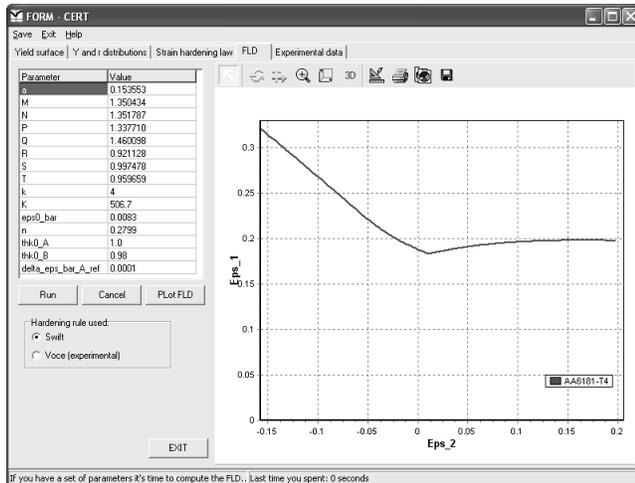


Figure 5. Graphical user interface of the FLD module (imported from ASCII files via the “Experimental data” panel).

### 2.5 “Experimental data” module

This module is structured as a panel for acquiring input data. The user has the possibility to type this data or to import it from ASCII files. The data can be plotted on diagrams or exported to other modules of the FORM-CERT programme.

All the diagrams generated by the modules mentioned above can be processed and also exported in different graphical formats (Bitmap, Windows Metafile, GIF, JPEG, Postscript, PDF, etc.). In addition, the results of the computations can be exported in a numerical format (via ASCII, XML, Excel, and HTML files).

## 3 CONCLUSIONS

This paper describes the programme FORM-CERT developed in the frame of the Research Centre in Sheet Metal Forming (CERTETA). The main functionality of the programme is related to the calculation of Forming Limit Diagrams. In addition, FORM-CERT provides identification facilities (for yield criteria and strain hardening laws). The use of the programme is very simple due to its user-friendly graphical interface. FORM-CERT can be used as a standalone application for calculating FLD’s and comparing them with experimental data, or as an auxiliary tool for the finite-element simulation of sheet metal forming processes. In its current structure, the programme offers useful functionalities both for research and industrial laboratories.

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