# FINITE ELEMENT PREDICTION OF DUCTILE FRACTURE IN AUTOMOTIVE PANEL FORMING: COMPARISON BETWEEN FLD AND LEMAITRE DAMAGE MODELS

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Received: 26/6/2011 Accepted: 29/8/2011 Online: 11/9/2011

**ABSTRACT**
In sheet metal forming processes with complex strain paths, a part is subjected to large plastic deformation. This severe plastic deformation leads to high plastic strain localization zones and subsequent accumulation of those strains. Then internal and superficial micro-defects and in other words ductile damage is created. This damage causes quality problems such as fracture. Therefore, design engineers need to accurately estimate the damage initiation and its growth. In this paper, initiation and evolution of damage has been predicted using Lemaitre's damage and forming limit diagram (FLD) damage models for automotive panel forming, because of its nonlinear strain paths. Lemaitre's damage criterion has been implemented as a subroutine for an elastic-plastic material and plane stress and finite strain theories. Using this subroutine in explicit finite element code, damage initiation and evolution is predicted for the above mentioned process and the results obtained by FLD and Lemaitre models are compared. In this paper, FLD and Lemaitre damage models results show the fact that the damage localization zones are corresponding to the equivalent plastic strain distributions. Comparison of the FLD damage and Lemaitre damage results show that in an automotive panel forming process, both models predict initiation of cracks in the edges of a sheet. Hence, it is concluded that finite element method combined with continuum damage mechanics can be used as a reliable and rapid tool to predict damage evolution in sheet metal forming processes with nonlinear and complex strain paths such as automotive panel forming.

**KEYWORDS:** Prediction of damage evolution, FLD damage, Lemaitre damage, Automotive panel forming, Nonlinear strain paths

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**NOMENCLATURE**

$D$ Damage variable
$\varepsilon_{major}$ Maximum principle strain
$\sigma$ cauchy stress tensor
$\tilde{\sigma}$ effective stress tensor
$\Psi$ potential of dissipation
$\varepsilon_e$ elastic strain tensor
$\varepsilon_p$ plastic strain tensor
$T$ temperature
$r$ damage accumulated plastic strain
$\alpha$ back strain tensor
$Y$ damage energy release rate
$W_e$ elastic strain energy
$E$ Young's modulus
$\sigma_{eq}$ Von Mises equivalent stress
$R_v$ function of triaxiality ratio
$\nu$ Poisson's ratio
$\sigma_H$ hydrostatic stress
$\dot{D}$ damage evolution
$\dot{\gamma}$ plastic consistency parameter
$s$ damage parameter

**INTRODUCTION**

Continuum damage mechanics (CDM), as one of the new branches of mechanical engineering, is a powerful complementary for fracture mechanics. Microstructure of materials includes some crack and voids. These defects can be created during loading or manufacturing of material [1]. The main goal of damage mechanics is investigation of damage evolution and its effect on the mechanical strength of material. Definition of microstructure defects by continuous field variables are common practice in all of the CDM models. According to CDM, in the existing constitutive equations, the effect of damage evolution in material is considered as deterioration of mechanical properties such as strength and stiffness [2]. Prediction of rupture modes is a major challenge in metal forming processes.

Each car contains between the 200 and 300 sheet metal formed parts. Finite element simulations have been developed to move the trial-and-error procedure from the factory to the computer which makes the process design much faster and cheaper [3]. The implemented numerical model must deal with the fact that the onset of rupture is strongly dependent on the strain paths imposed on the parts [2]. The use of numerical methods, such as the finite-element method, to predict the damage initiation and evolution has created the possibility to analyze with relative success a forming process during its development stage. This numerical prediction can provide a faster and more cost-effective development of high quality products, imperative in today's strong competition.

**FLD DAMAGE MODEL**

A forming limit diagram (FLD) is a plot of the forming limit strains in the space of principal (in-plane) logarithmic strains. The FLD damage initiation criterion is intended to predict the onset of necking instability in sheet metal forming. The maximum strains that a sheet material can sustain prior to the onset of necking are referred to as the forming limit strains. According to Fig. (1), under the following condition, general FLD damage initiation criteria will be satisfied:

$$D = \frac{\varepsilon_{major}^{A}}{\varepsilon_{major}^{B}} = 1 \qquad (1)$$

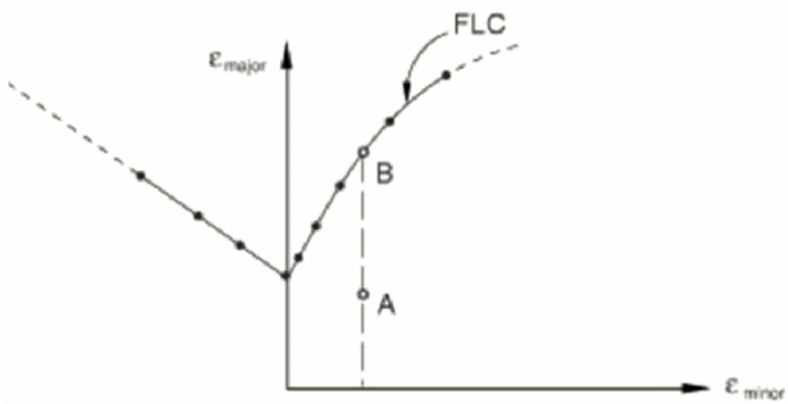


Fig. 1. Forming limit diagram.

**LEMAITRE DAMAGE MODEL**

The principles of CDM are first reviewed for the case of uniaxial stress. In this case, isotropic damage, $D$, is assumed throughout the represented volume element (RVE). Based on the concept of effective stress and the hypothesis of strain equivalence, the effective stress tensor, $\tilde{\sigma}$, can be represented as [4]:

$$\tilde{\sigma} = \frac{\sigma}{1-D} \tag{2}$$

where $\sigma$ is the true stress in the undamaged RVE. In addition, for the undamaged state, $D=0$ and complete failure, $D=1$. Hence:

$$0 \le D \le 1 \tag{3}$$

The evolution law for the internal variables can be derived from a potential of dissipation. Now the Helmholtz free energy, $\Psi$, can be considered as a scalar function of state variables:

$$\Psi = \Psi(\varepsilon_e, \varepsilon_p, T, r, \alpha, D) \tag{4}$$

In which $\varepsilon_e$ and $\varepsilon_p$ are the elastic and plastic strain tensors associated with the stress tensor, $T$ is the temperature associated with the entropy density, $r$ is the damage accumulated plastic strain associated with isotropic strain hardening, and $\alpha$ is the back strain tensor associated with kinematic hardening.
Lemaitre showed that the strain energy release rate $Y$ may be related to the elastic strain energy $W_e$ through the following equations:

$$Y = \frac{1}{2}\frac{dW_e}{dD}\bigg|_{\sigma=const} = \frac{W_e}{1-D} \tag{5}$$

Considering the Von Mises equivalent stress for plasticity, $Y$ will be equal to:

$$Y = \frac{\sigma_{eq}^2}{2E(1-D)^2} R_\nu \tag{6}$$

In which $E$ is the Young's modulus, $\sigma_{eq}$ is the Von Mises equivalent stress. $R_\nu$ is a function of triaxiality ratio defined as:

$$R_\nu = \frac{2}{3}(1+\nu) + 3(1-2\nu)\left(\frac{\sigma_H}{\sigma_{eq}}\right)^2 \quad (7)$$

Where $\nu$ is the Poisson's ratio and $\sigma_H$ is hydrostatic stress. Considering Lemaitre's damage criterion, equations of damage evolution in terms of internal variables are:

$$\dot{D} = \dot{\gamma}\frac{1}{1-D}\left(\frac{Y}{r}\right)^s ; \dot{\gamma} = \dot{\varepsilon}_{eq}^{p} \quad (8)$$

Where $\dot{\gamma}$ is the plastic consistency parameter and $r$ and $s$ are the damage parameters of the material [1, 5].

## NUMERICAL SIMULATION

This example considers the simulation of automotive panel forming process. Blank was modeled with a total of 4743 elements using reduced integration 4-node; bilinear finite strain elements (type S4R). Tool surfaces were considered rigid bodies and discretization was performed using 3-node rigid elements (type R3D3). In this process during stamping, the rectangular blank is formed to the shape of a matrix. Concerning material modeling, the sheet material has been assumed as isotropic St14 steel. The elastic- plastic- damage material properties are presented in table (1).

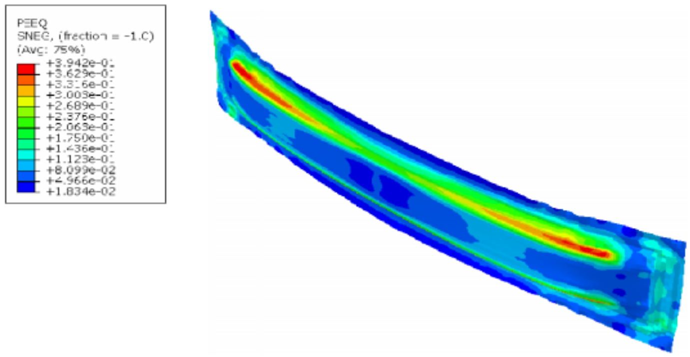
Table 1. Material properties of St14 [6].

| | |
|---|---|
| Young's modulus, $E(GPa)$ | 180 |
| Initial yield stress, $\sigma_{y0}(MPa)$ | 159 |
| Ultimate stress, $\sigma_u(MPa)$ | 283 |
| Hardening coefficient, $K(MPa)$ | 630 |
| Hardening power, $n$ | 0.36 |
| Damage parameter, $s$ | 1 |
| Damage parameter, $r(MPa)$ | 2.532 |
| Critical damage parameter, $D_{cr}$ | 0.434 |

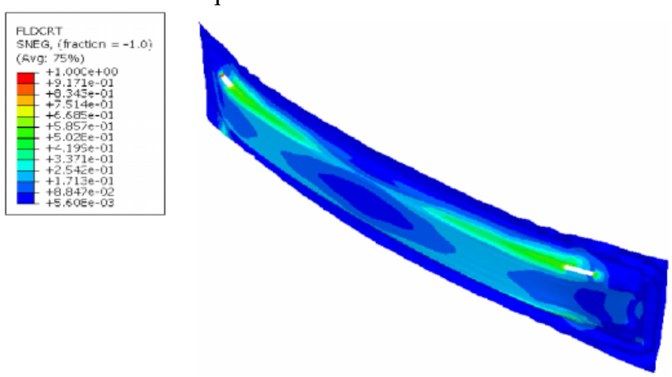
The initial flat sheet blank dimensions are 1.38m×0.28m×0.00147m. Penalty friction law was assumed and μ=0.15 was used for the friction coefficient between blank and tools.

**RESULTS AND DISCUSSION**

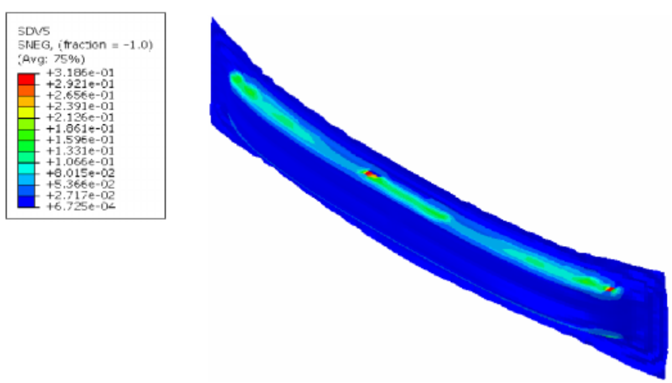
Multiple simulations were performed in order to investigate the development of damage in the work piece during the stamping process. Fig. (2) shows the distribution of both equivalent plastic strain and damage for various punch travels. It can be seen from Fig. (2a) that the region of maximum equivalent plastic strain is located at the zones which come in contact with the sharp matrix corners. It appears that both damage models predict the crack initiation in these sites. In Fig. (2b), by increasing of punch travel, these fracture bonds propagate along the sheet edges. In Fig. (2c), it is observed that in the last step of forming, these fracture bonds are highly pronounced along the sheet walls. On the other hand, rupture will appear in the sheet metal.




Equivalent Plastic Strain

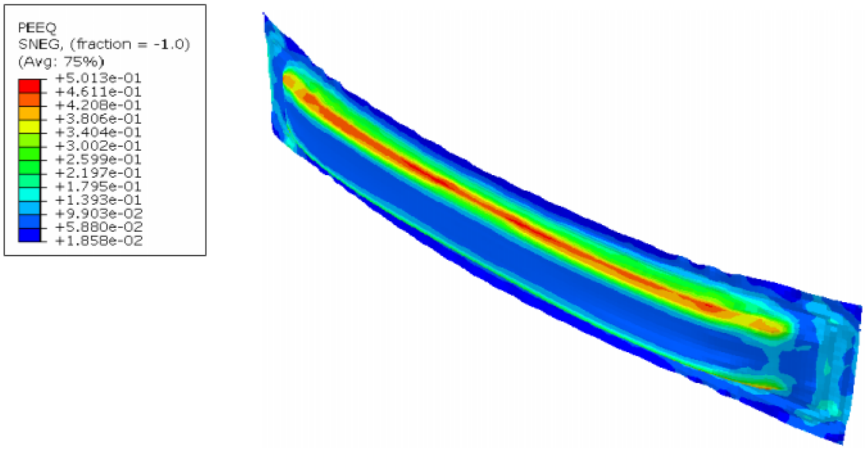



FLD damage

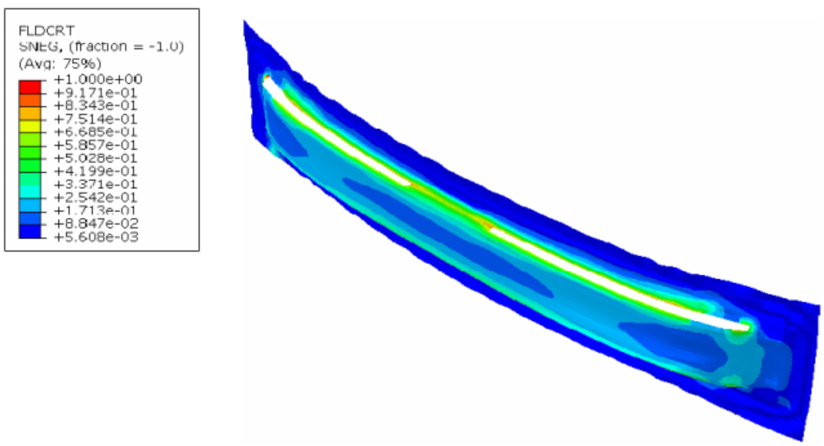



Lemaitre damage

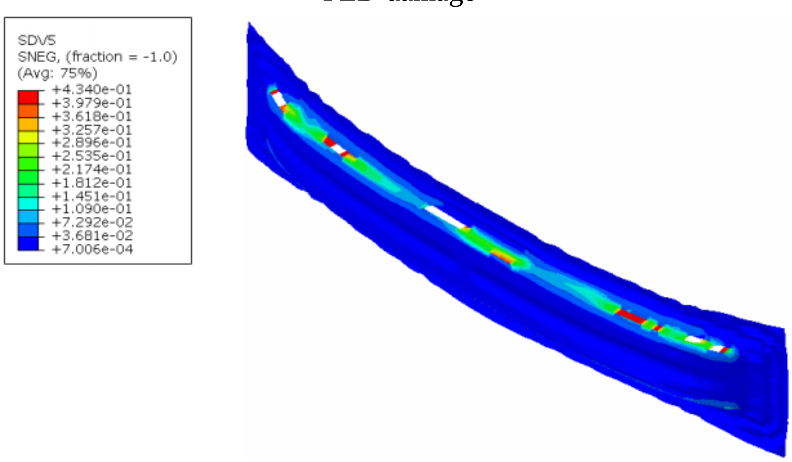
(a)



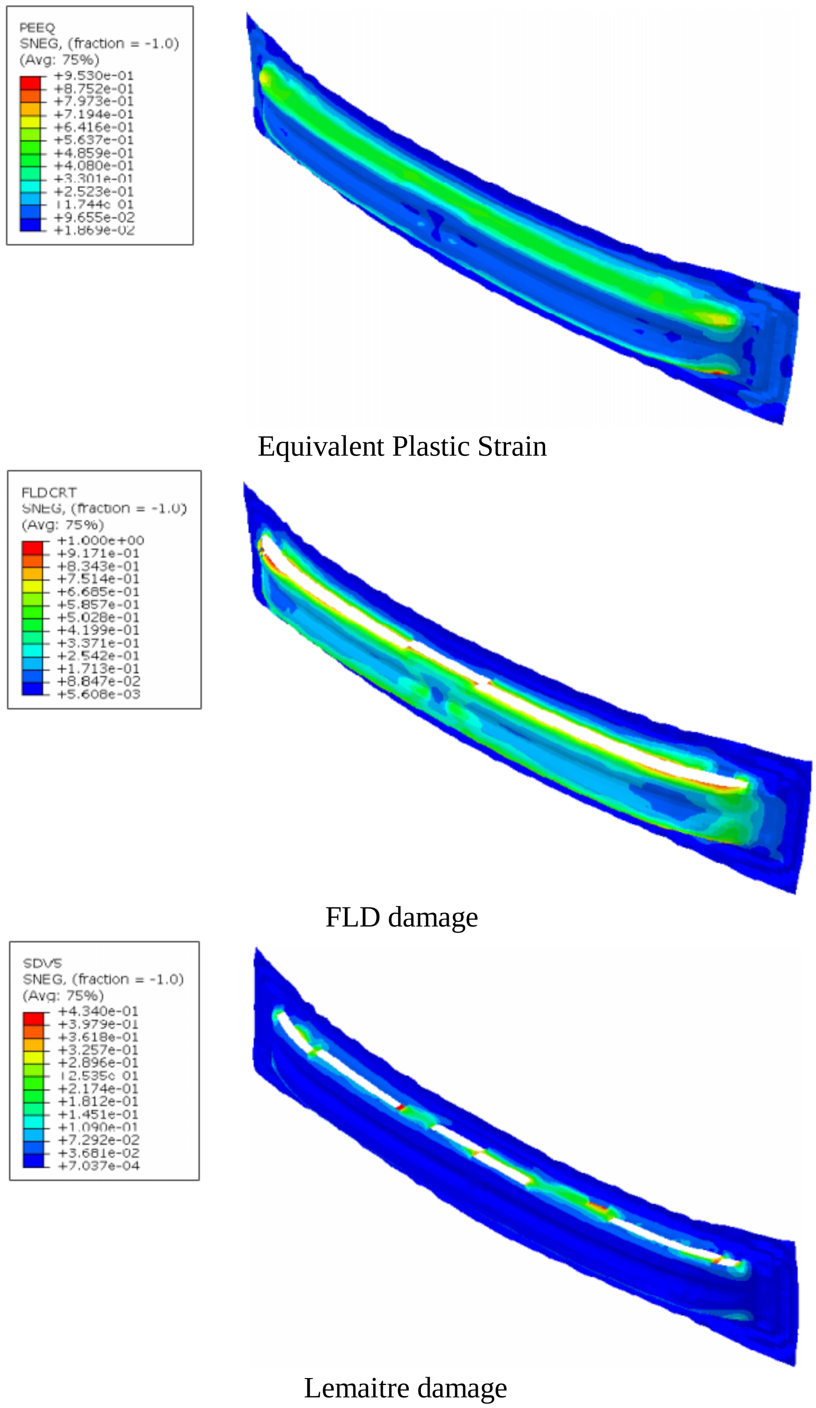

Equivalent Plastic Strain




FLD damage




Lemaitre damage
(b)




(c)

Fig. 2. Equivalent plastic strain and damage distribution for various punch travel, (a) crack initiation, (b) crack evolution and (c) rupture.

Fig. (3) shows the strain paths for three different nodes. According to this figure, strain paths are nonlinear and complex in this process.

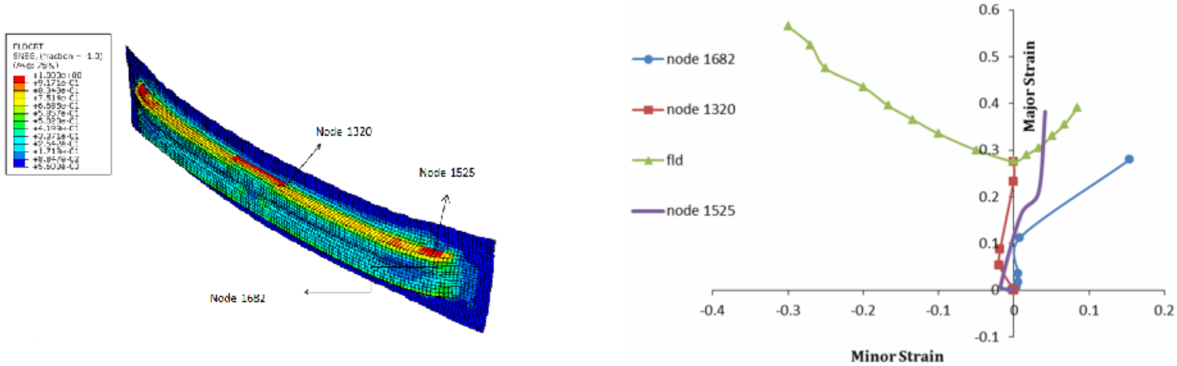



Fig. 3. Strain paths for three different nodes.

The results show that, in the automotive panel forming with complex strain paths, the sheet metal is subjected to large plastic deformation. Both models predict that the initiation of crack will appear at the zones with the maximum localization of equivalent plastic strain. By increasing the punch travel, these fracture bonds progress along the sheet walls and are inclined closer to each other. In addition, the equivalent plastic strain in these regions will reach the maximum amplitude.

## CONCLUSIONS

Comparison between FLD damage and Lemaitre damage models for prediction of fracture in automotive panel forming shows that both models predict damage initiation, its growth and fracture in walls of the panel. In these sites, the equivalent plastic strain accumulation is obseved much higher than the safe zones. The location of crack initiation in this part with nonlinear and complex strain paths was successfully identified from the prediction of damage evolution and verified by the equivalent plastic strain distribution. Therefore, it is concluded that finite element analysis, in conjunction with damage continuum mechanics, is a rapid and reliable tool for predicting the damage evolution and rupture in sheet metal forming processes with nonlinear and complex strain paths.

## ACKNOWLEDGMENTS

The authors would like to thank Iran Khodro Industrial Dies (IKID) managers, for their generous cooperation.

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