*MAT_TRANSVERSELY_ANISOTROPIC_ELASTIC_PLASTIC_{*OPTION*}

Available option allows the change of Young's Modulus during the simulation:

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ECHANGE

A new option is available to allow for the calculation of the Formability Index (F.I.) which accounts for sheet metal forming problems with non-linear strain path:

NLP_FAILURE

This is Material Type 37. This model is for simulating sheet forming processes with anisotropic material. Only transverse anisotropy can be considered. Optionally an arbitrary dependency of stress and effective plastic strain can be defined via a load curve. This plasticity model is fully iterative and is available only for shell elements. Also see the notes below.

Card 1	1	2	3	4	5	6	7	8
Variable	MID	RO	E	PR	SIGY	ETAN	R	HLCID
Type	A	F	F	F	F	F	F	F

Define the following card if option ECHANGE or NLP_FAILURE is used

Card opt.	1	2	3	4	5	6	7	8
Variable	IDSCALE	EA	COE	ICFLD		STRAINLT		
Type	I	F	F	F		F		

VARIABLE	DESCRIPTION
MID	Material identification. A unique number or label not exceeding 8 characters must be specified.
RO	Mass density.
E	Young's modulus.
PR	Poisson's ratio.
SIGY	Yield stress.

VARIABLE	DESCRIPTION
ETAN	Plastic hardening modulus.
R	Anisotropic hardening parameter. When it is set to a negative value, normal stresses (either from contact or applied pressure) are considered and *LOAD_SURFACE_STRESS must be used to capture the stresses. It is found in some cases this inclusion can improve forming simulation accuracy, and it applies to ELFORM of 2 and 16. The result of an example of using this feature is provided in Remark #3 and Figure 0-3.
HLCID	Load curve ID defining effective yield stress versus effective plastic strain.
IDSCALE	Load curve ID defining the scale factor for the Young's modulus change with respect to effective strain (if EA and COE are defined), this curve is not necessary).
EA, COE	Coefficients defining the Young's modulus with respect to the effective strain, EA is E^A and Coe is ζ(if IDSCALE is defined, these two parameters are not necessary).
ICFLD	Load curve ID for Forming Limit Diagram (FLD) definition.
STRAINLT	Critical strain value at which strain averaging is activated

Remarks:

1. Consider Cartesian reference axes which are parallel to the three symmetry planes of anisotropic behavior. Then, the yield function suggested by Hill [1948] can be written

$$F(\sigma_{22}-\sigma_{33})^2+G(\sigma_{33}-\sigma_{11})^2+H(\sigma_{11}-\sigma_{22})^2+2L\sigma_{23}^2+2M\sigma_{31}^2+2N\sigma_{12}^2-1=0$$

where σ_{y1}, σ_{y2}, and σ_{y3}, are the tensile yield stresses and σ_{y12}, σ_{y23}, and σ_{y31} are the shear yield stresses. The constants F, G H, L, M, and N are related to the yield stress by

$$2L=\frac{1}{\sigma_{y23}^2}$$

$$2M=\frac{1}{\sigma_{y31}^2}$$

$$2N=\frac{1}{\sigma_{y12}^2}$$

$$2F = \frac{1}{\sigma_{y2}^2} + \frac{1}{\sigma_{y3}^2} - \frac{1}{\sigma_{y1}^2}$$
$$2G = \frac{1}{\sigma_{y3}^2} + \frac{1}{\sigma_{y1}^2} - \frac{1}{\sigma_{y2}^2}$$
$$2H = \frac{1}{\sigma_{y1}^2} + \frac{1}{\sigma_{y2}^2} - \frac{1}{\sigma_{y3}^2} \ .$$

The isotropic case of von Mises plasticity can be recovered by setting $F = G = H = \frac{1}{2\sigma_y^2}$

and $L = M = N = \frac{3}{2\sigma_y^2}$

For the particular case of transverse anisotropy, where properties do not vary in the x_1-x_2 plane, the following relations hold:

$$2F = 2G = \frac{1}{\sigma_{y3}^2}$$
$$2H = \frac{2}{\sigma_y^2} - \frac{1}{\sigma_{y3}^2}$$
$$N = \frac{2}{\sigma_y^2} - \frac{1}{2}\frac{1}{\sigma_{y3}^2}$$

where it has been assumed that $\sigma_{y1} = \sigma_{y2} = \sigma_y$.

Letting $K = \frac{\sigma_y}{\sigma_{y3}}$, the yield criteria can be written

$$F(\sigma) = \sigma_e = \sigma_y,$$

where

$$F(\sigma) \equiv \Big[\sigma_{11}^2 + \sigma_{22}^2 + K^2\sigma_{33}^2 - K^2\sigma_{33}(\sigma_{11} + \sigma_{22}) - (2 - K^2)\sigma_{11}\sigma_{22} \\ +2L\sigma_y^2(\sigma_{23}^2 + \sigma_{31}^2) + 2\left(2 - \tfrac{1}{2}K^2\right)\sigma_{12}^2\Big]^{1/2}$$

The rate of plastic strain is assumed to be normal to the yield surface so $\dot{\varepsilon}_{ij}^p$ is found from

$$\dot{\varepsilon}_{ij}^p = \lambda \frac{\partial F}{\partial \sigma_{ij}}.$$

Now consider the case of plane stress, where $\sigma_{33} = 0$. Also, define the anisotropy input parameter, R, as the ratio of the in-plane plastic strain rate to the out-of-plane plastic strain rate,

$$R = \frac{\dot{\varepsilon}_{22}^p}{\dot{\varepsilon}_{33}^p}.$$

It then follows that

$$R = \frac{2}{K^2} - 1.$$

Using the plane stress assumption and the definition of R, the yield function may now be written

$$F(\sigma) = \left[\sigma_{11}^2 + \sigma_{22}^2 - \frac{2R}{R+1}\sigma_{11}\sigma_{22} + 2\frac{2R+1}{R+1}\sigma_{12}^2\right]^{1/2}.$$

Note that there are several differences between this model and other plasticity models for shell elements such as the model, MAT_PIECEWISE_LINEAR_PLASTICITY. First, the yield function for plane stress does not include the transverse shear stress components which are updated elastically, and, secondly, this model is always fully iterative. Consequently, in comparing results for the isotropic case where R=1.0 with other isotropic model, differences in the results are expected, even though they are usually insignificant.

The Young's modulus has been assumed to be constant. Recently, some researchers have found that Young's modulus decreases with respect to the increase of effective strain. To accommodate this new observation, a new option of_ECHANGE is added. There are two methods defining the change of Young's modulus change:

The first method is to use a curve to define the scale factor with respect to the effective strain. The value of this scale factor should decrease from 1 to 0 with the increase of effective strain.

The second method is to use a function as proposed by Yoshida [2003]:

$$E = E^0 - (E^0 - E^A)(1 - \exp(-\zeta\bar{\varepsilon})).$$

2. When option NLP_FAULURE is used, a necking failure criterion independent of strain path changes is activated. In sheet metal forming, as strain path history (plotted on in-plane major and minor strain space) of an element becomes non-linear, the position and shape of a traditional strain-based Forming Limit Diagram (FLD) changes. This option provides a simple formability index (F.I.) which remains invariant regardless of the presence of the non-linear strain path, and can be used to identify if the element has reached its necking limit.

Formability index (F.I) is calculated, as illustrated in Figure 0-1, for every element throughout the simulation duration. The value of F.I. is 0.0 for virgin material and reaches maximum of 1.0 when the material fails. The theoretical background can be found in two papers: 1) T.B. Stoughton, X. Zhu, "Review of Theoretical Models of the Strain-Based FLD and their Relevance to the Stress-Based FLD, International Journal of Plasticity", V. 20, Issues 8-9, P. 1463-1486, 2003; and 2) Danielle Zeng, Xinhai Zhu, Laurent B. Chappuis, Z. Cedric Xia, "A Path Independent Forming Limited Criterion for Sheet Metal Forming Simulations", 2008 SAE Proceedings, Detroit MI, April, 2008.

Load curve input for FLD (ICFLD) follows keyword format in *DEFINE_CURVE, with abscissa values as minor strains and ordinate values as major strains.

Input of FLD can also be done using keyword *DEFINE_CURVE_FLC, where sheet metal thickness and strain hardening value 'n' are used. Detailed usage information can be found in the manual pages describing the keyword.

The formability index is output as a history variable #1 in D3PLOT files. It is activated by setting NEIPS to 1, in the second field of card 1 in keyword *DATABASE_EXTENT_BINARY. The history variable can be plotted in LS-PrePost2.4, accessible in *FCOMP* (page 1), under 'Fringe Component' *MISC*.

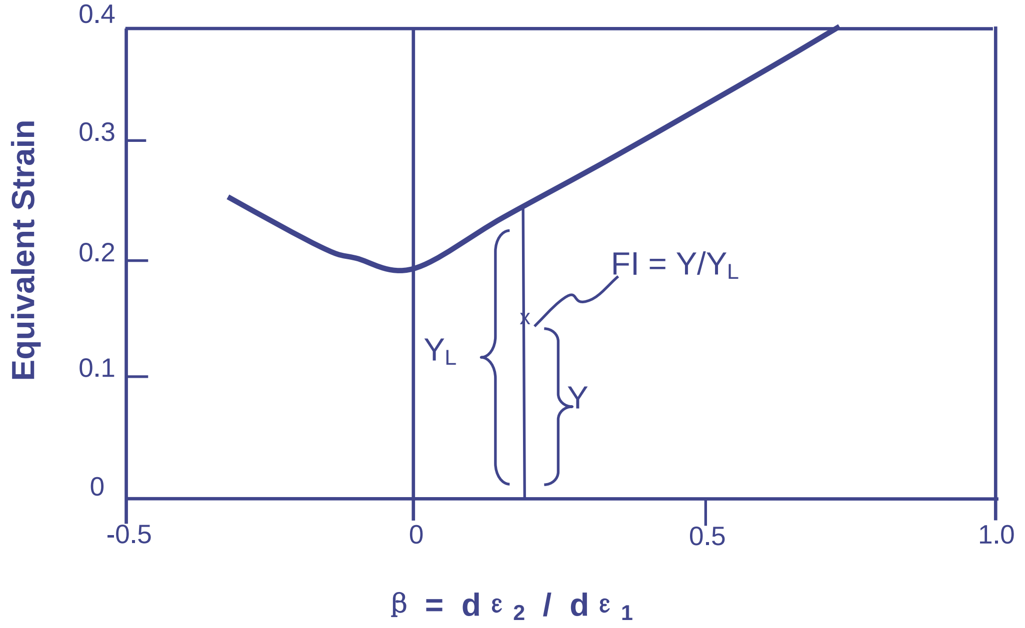


Figure 0-1. Calculation of F.I. based on critical effective strain method.

When plotting the formability index, the pull-down menu under *FCOMP* can be used to select minimum value '*Min*' for necking failure determination. In *RANGE* (page 1), the option *None* is to be selected in the pull-down menu next to *Avg*. The index has a default range between 0.0 and 1.0. The non-linear forming limit is reached when the index reaches 1.0.

In addition, the evolution of the index throughout the simulation can be plotted in LS-PrePost under *HISTORY* (page 1) by *Element*, using the scroll bar to roll down the bottom to select *history var#1*. Furthermore, the strain path of an element can be plotted in FLD (page 1), using option *Tracer*, by selecting corresponding integration point representing the '*Min*' index value in the *Position* pull-down menu.

Strains (and strain ratios) can be averaged to reduce noises, which in turn affect the calculation of the formability index. This is done through the variable STRAINLT. Under this user input value, various strains of every element are averaged through the calculation time and these averaged values are used to calculate the index. A reasonable STRAINLT value could be ranged from 5.0E-3 to 1.0E-2. Averaged strain ratios (minor/major) for every element are output through history variable #2, accessible through LS-PrePost under *HISTORY* (page 1) by *Element*, also through *FCOMP* (page 1), under 'Fringe Component' *MISC*. It is therefore necessary to set the value of NEIPS to 2 to have the variable written into D3PLOT files.

It is suggested that variable 'MAXINT' in *DATABASE_EXTENT_BINARY is set to the same value of variable 'NIP' in *SECTION_SHELL.

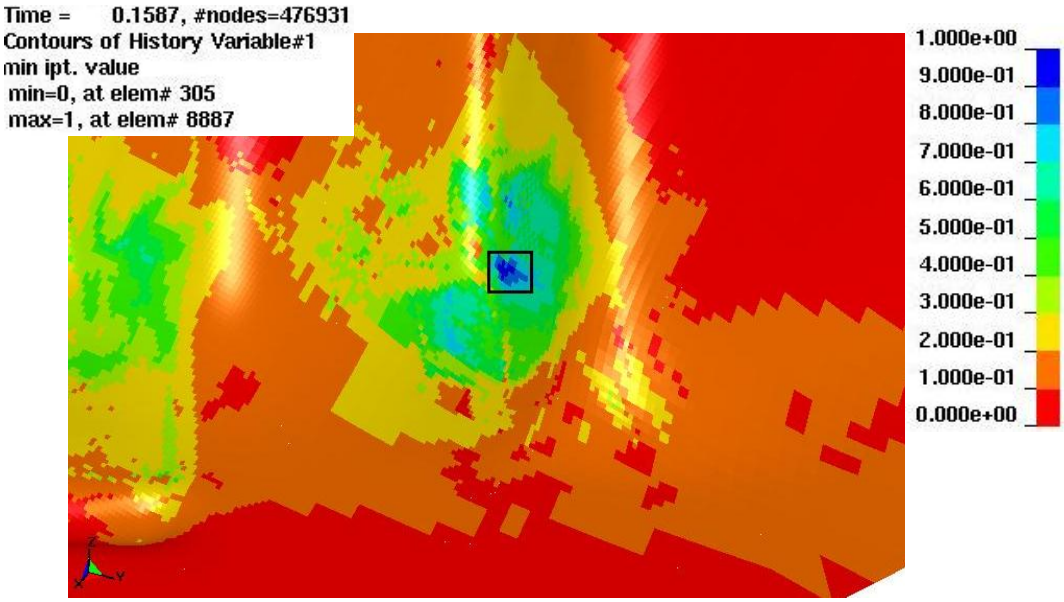
An example of the keyword input (partial) using this non-linear strain path failure criterion is provided below:

```
*MAT_TRANSVERSELY_ANISOTROPIC_ELASTIC_PLASTIC_NLP_FAILURE
$      MID        RO         E        PR      SIGY      ETAN         R  HLCID
         1 7.830E-09 2.070E+05      0.28       0.0       0.0     0.864    200
$      IDY        EA       COE     ICFLD           STRAINLT
                                     891            1.0E-02
*DEFINE_CURVE
891
$ minor, major strains for FLD definition
       -3.375000e-01        4.965000e-01
       -2.750000e-01        4.340000e-01
       -2.250000e-01        3.840000e-01
       -1.840909e-01        3.430909e-01
       -1.500000e-01        3.090000e-01
       -1.211539e-01        2.801539e-01
       -9.642858e-02        2.554286e-01
       -7.500000e-02        2.340000e-01
       -5.625001e-02        2.152500e-01
       -3.970589e-02        1.987059e-01
       -2.500000e-02        1.840000e-01
……
$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$
$ load curve  200: Mat_037 property, DP600 NUMISHEET'05 Xmbr, Power law fit
$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$
*DEFINE_CURVE
200
0.000,395.000
0.001,425.200
0.003,440.300
0.004,452.000
0.005,462.400
0.006,472.100
……
```

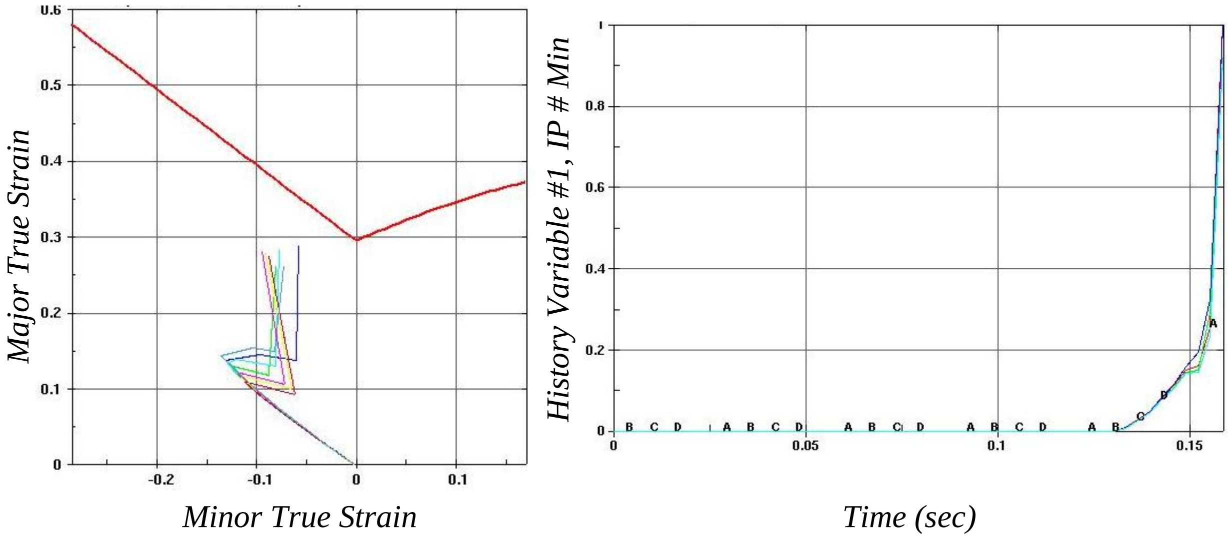
As shown in Figure 0-2 (top), typically, F.I contour can be plotted in *FCOMP/Misc*, in LS-PrePost. Strain paths of an individual element, or elements in an area can be plotted using the "*Tracer*" feature in the *FLD* menu. Finally, time history plot of the F.I. for elements selected can be plotted in *History* menu, Figure 0-2 (bottom).

The NLP_FAILURE option is implemented in explicit dynamic and is available in LS-DYNA R5 Revision 60925 and later releases. This option is also available in implicit static in R6 Revision 73241 and later releases.

3. In Figure 0-3, a comparison of thinning contour is shown on a simple U-channel forming (one-half model) using negative and positive R values. Maximum thinning on the draw wall is slight higher in the negative R case than that in the positive R case.



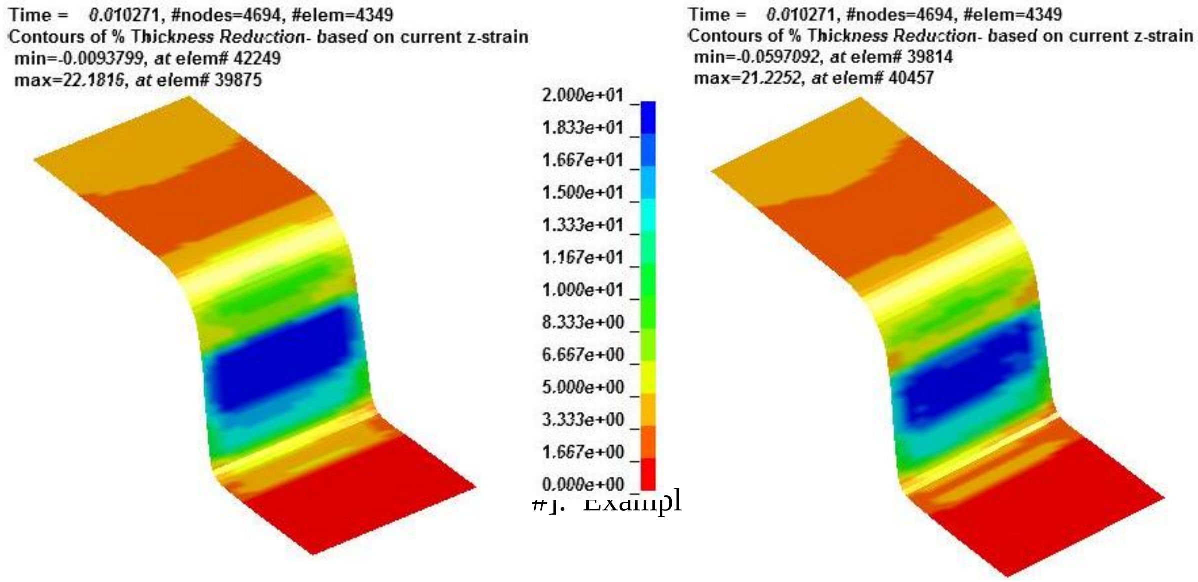
F.I. contour plot (min IP value, non-averaged)



Non Linear Strain Path

F I time histroy plot

Figure 0-2. Plotting F.I. values



#1. Exampl

With negative R-value

With positive R-value

Figure 0-3. Thinning contour comparison