A new versatile tool for simulation of failure in LS-DYNA and the application to aluminium extrusions

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Presentation Contents

quote from a research department manager :

- We do not need geniuses here, we need dedicated engineers that solve many little problems every day in the fastest and cheapest way possible

- sometime in the 90's (but nothing changed)

Today’s little problem : Anisotropic failure

- Failure strains for a 7000 series extruded aluminium :

	tension	shear	biaxial
00 degree	0.19	0.48	0.26
45 degree	0.65	0.20	0.26
90 degree	0.31	0.32	0.26

- Determined for DIC, linked to the VSGL
- 3 measurements with good repeatability
- Shear direction is defined as the direction of the first principal stress
- Experiments were NOT proportional

- How to match these data in a numerical model ?

Strengths and Limitations of GISSMO

- End 2007 Frieder Neukamm defended his Diplomarbeit at the university of Stuttgart
- His failure model was implemented in LS-DYNA as *MAT_ADD_EROSION_GISSMO, development continued until early 2009
- Since then, the GISSMO model has been successfully used for the predictive simulation of failure in metals as far as they can be considered isotropic and exhibit good ductility

- GISSMO was never intended to be used for non-isochoric materials such as thermoplastics
- Nor did it have any capability to deal with material anisotropy
- Not could it be used to simulate directional crack propagation or load induced anisotropy

Generalisation of GISSMO

DMGTYP

For GISSMO damage type the following applies.

DMGTYP is interpreted digit-wise as follows:

$$\text{DMGTYP} = [NM] = M + 10 \times N$$

Active or passive mode

M.EQ.0: Damage is accumulated, no coupling to flow stress, no failure.

M.EQ.1: Damage is accumulated, element failure occurs for $D = 1$. Coupling of damage to flow stress depending on parameters, see remarks below.

Choice of damage driver

N.EQ.0: Equivalent plastic strain is the driving quantity for the damage. (To be more precise, it's the history variable that LS-PrePost blindly labels as "plastic strain". What this history variable actually represents depends on the material model.)

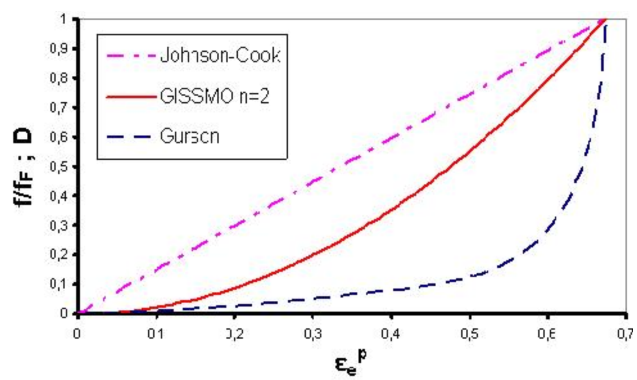
N.GT.0: The Nth additional history variable is the driving quantity for damage. These additional history varriables are the same ones flagged by the *DATABASE_EXTENT_BINARY keyword's NEIPS and NEIPH fields. For example, for solid elements with *MAT_187 setting $N = 6$ chooses volumetric plastic strain as the driving quantity for the GISSMO damage.

Recall : damage accumulation in GISSMO

- The GISSMO damage accumulation is given by :

$$\dot{d} = n d^{1-\frac{1}{n}} \frac{\pounds_p}{\pounds_{pf}} \qquad \pounds_p \geq 0 \Rightarrow d \geq 0$$

- The parameter n controls the damage growth under proportional loading (= constant failure strain)



Potential problem with history variables

- If we base the damage accumulation on volumetric strain rather then equivalent plastic strain we get :

$$\dot{d} = n d^{1-\frac{1}{n}} \frac{\dot{\pounds}_v}{\pounds_{vf}}$$

- Clearly, as the volumetric strain may take on negative values (in compression) , a positive damage value is no longer guaranteed

- Negative damage values may result in error terminations, consider for example the damage accumulation with n=2 :

$$\dot{d} = n d^{1-\frac{1}{n}} \frac{\dot{\pounds}_v}{\pounds_{vf}} \Rightarrow \dot{d} = 2\sqrt{d}\, \frac{\dot{\pounds}_v}{\pounds_{vf}}$$

Macaulay bracket or Foeppl symbol :

- The history variable is modified internally to avoid negative damage rates :

$$\dot{d} = n d^{1-\frac{1}{n}} \frac{\pounds_v}{\pounds_{vf}} \Rightarrow \dot{d} = n d^{1-\frac{1}{n}} \frac{\langle \pounds_v \rangle}{\pounds_{vf}}$$

- Negative damage rates (self healing) is controversial

- Avoiding negative damage values renders the implementation robust

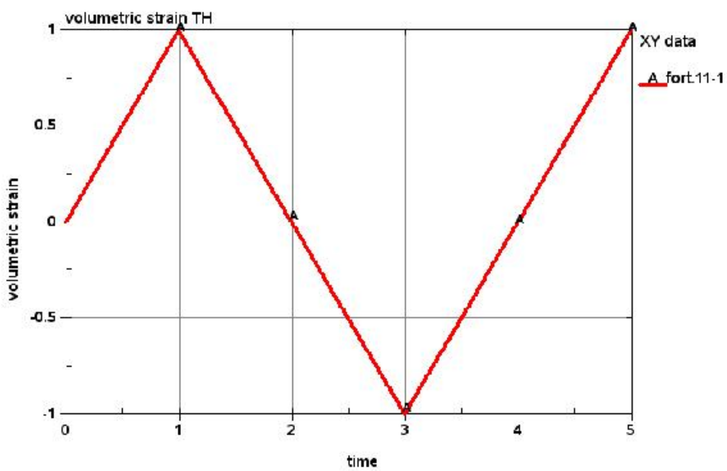
- Note that other choices are possible, i.e. :

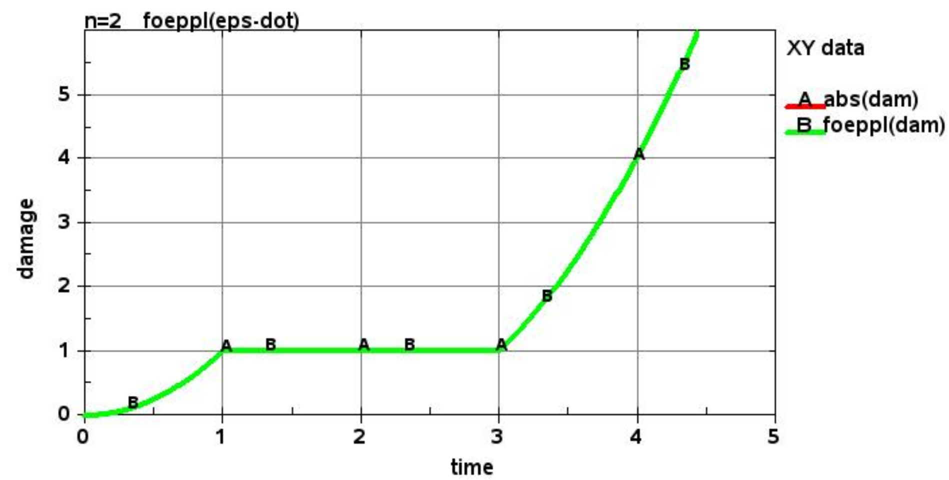
$$\dot{d} = n d^{1-\frac{1}{n}} \frac{\left| \pounds_v \right|}{\pounds_{vf}}$$

example

- As an example consider an element under cyclic volumetric loading :

$$\dot{d} = n d^{1-\frac{1}{n}} \frac{\langle \pounds_v \rangle}{\pounds_{vf}}$$





- The damage evolution is monotonically increasing
- Damage remains constant when volumetric strain rate <0

Summary

- GISSMO was generalized in the sense that the user now has control over the quantity that drives the damage

- For shell elements it is often argued that damage accumulation due to inplane and OOP deformation should be treated separately

- This could be achieved by splitting the equivalent plastic strain in 2 components :

$$£_p^{oop} = \int \sqrt{\frac{2}{3}\left[2\left(£_{yz}^{p}\right)^2 + 2\left(£_{zx}^{p}\right)^2\right]}dt$$

$$£_p^{inplane} = \int \sqrt{\frac{2}{3}\left[\left(£_{xx}^{p}\right)^2 + \left(£_{yy}^{p}\right)^2 + \left(£_{zz}^{p}\right)^2 + 2\left(£_{xy}^{p}\right)^2\right]}dt$$

- But it requires 2 GISSMO models !

Introducing *MAT_ADD_GENERALIZED_DAMAGE

- Idea conceived at Mercedes-Benz, Sindelfingen early 2015
- Simultaneous accumulation of multiple damage variables in up to 3 GISSMO models added to a single material model
- Damage driven by history variables that can be manipulated through *DEFINE_FUNCTION
- Damage coupling with a user defined damage tensor

- Like GISSMO , MAGD remains primarily a failure model and the purpose of damage coupling is regularisation
- However the capabilities of the damage coupling in MAGD are quite extensive

MAT_ADD_GENERALIZED_DAMAGE or MAGD for shells

```
*MAT_ADD_GENERALIZED_DAMAGE
$       pid       idam    dmgtyp      refsz     numfip                              nhis
          1          1         1                   -80                                 3
$      his1       his2      his3      iflg1      iflg2      iflg3
                                          2          1          1
$     dam11      dam22     dam33      dam44      dam55      dam66
         41         42        44         43         44         44
$     dam12      dam21     dam24      dam42      dam14      dam41
$     lcsdg      ecrit    dmgexp      dcrit     fadexp     lcregd
        997      -1097       2.0                   8.0
$     lcsrs       shrf     biaxf

$     lcsdg      ecrit    dmgexp      dcrit     fadexp     lcregd
        999      -1099       2.0                   8.0
$     lcsrs       shrf     biaxf

$     lcsdg      ecrit    dmgexp      dcrit     fadexp     lcregd
        998      -1098       2.0                   8.0
$     lcsrs       shrf     biaxf

$---+----1----+----2----+----3----+----4----+----5----+----6----+----7----+---
*DEFINE_FUNCTION
        41
func41(d1,d2,d3,a,x)=1.-d1
*DEFINE_FUNCTION
        42
func42(d1,d2,d3,a,x)=1.-d2
*DEFINE_FUNCTION
        43
func43(d1,d2,d3,a,x)=1.-d3
*DEFINE_FUNCTION
        44
func44(d1,d2,d3,a,x)=1.
```

$$\begin{pmatrix} \pm_{xx} \\ \pm_{yy} \\ \pm_{xy} \end{pmatrix} = \begin{pmatrix} D_{11} & D_{12} & D_{14} \\ D_{21} & D_{22} & D_{24} \\ D_{41} & D_{42} & D_{44} \end{pmatrix} \begin{pmatrix} \pm_{xx}^{eff} \\ \pm_{yy}^{eff} \\ \pm_{xy}^{eff} \end{pmatrix}$$

$$\begin{pmatrix} \pm_{xx} \\ \pm_{yy} \\ \pm_{xy} \end{pmatrix} = \begin{pmatrix} 1-d & 0 & 0 \\ 0 & 1-d & 0 \\ 0 & 0 & 1-d \end{pmatrix} \begin{pmatrix} \pm_{xx}^{eff} \\ \pm_{yy}^{eff} \\ \pm_{xy}^{eff} \end{pmatrix}$$

1 limitation :
Single value of NUMFIP

MAGD : history variables

		MAT_024	MAT_036	MAT_187
ND+1	triax	6	9	23
ND+2	Lode	7	10	24
ND+3	d	8	11	25
ND+4	d1	9	12	26
ND+5	d2	10	13	27
ND+6	d3	11	14	28
ND+13	his1	18	21	35
ND+14	his2	19	22	36
ND+15	his3	20	23	37

Combined shear/volumetric damage with MAT_187

- A first application of MAGD is fully isotropic
- SAMP allows to model permanent change in volume or volumetric plastic strain by setting the plastic Poisson coefficient to a value different from 0.5
- The volumetric plastic strain is stored as history variable #6
- Physically the phenomenon of decreasing density is observed as a change in color (crazing) and preceeds failure
- It seems logical to use the volumetric plastic strain as a driver for volumetric damage
- Classical shear damage driven by equivalent plastic strain can be considered additionally

Damage tensor following Lemaitre :

Define deviatoric and Volumetric damage

$$\mathbf{s}^{eff} = \frac{\mathbf{s}}{1-d_1} \qquad p^{eff} = \frac{p}{1-d_2}$$

Derive damage tensor

$$\begin{pmatrix} \pm^{eff}_{xx} \\ \pm^{eff}_{yy} \\ \pm^{eff}_{xy} \end{pmatrix} = \begin{pmatrix} \frac{2}{3(1-d_1)} + \frac{1}{3(1-d_2)} & -\frac{1}{3(1-d_1)} + \frac{1}{3(1-d_2)} & 0 \\ -\frac{1}{3(1-d_1)} + \frac{1}{3(1-d_2)} & \frac{2}{3(1-d_1)} + \frac{1}{3(1-d_2)} & 0 \\ 0 & 0 & \frac{1}{1-d_1} \end{pmatrix} \begin{pmatrix} \pm_{xx} \\ \pm_{yy} \\ \pm_{xy} \end{pmatrix}$$

$$\begin{pmatrix} D_{11} & D_{12} & D_{14} \\ D_{21} & D_{22} & D_{24} \\ D_{41} & D_{42} & D_{44} \end{pmatrix} = \begin{pmatrix} \frac{2}{3(1-d_1)} + \frac{1}{3(1-d_2)} & -\frac{1}{3(1-d_1)} + \frac{1}{3(1-d_2)} & 0 \\ -\frac{1}{3(1-d_1)} + \frac{1}{3(1-d_2)} & \frac{2}{3(1-d_1)} + \frac{1}{3(1-d_2)} & 0 \\ 0 & 0 & \frac{1}{1-d_1} \end{pmatrix}^{-1} = \begin{pmatrix} 1-\frac{2}{3}d_1 - \frac{1}{3}d_2 & \frac{1}{3}d_1 - \frac{1}{3}d_2 & 0 \\ \frac{1}{3}d_1 - \frac{1}{3}d_2 & 1-\frac{2}{3}d_1 - \frac{1}{3}d_2 & 0 \\ 0 & 0 & 1-d_1 \end{pmatrix}$$

Invert damage tensor

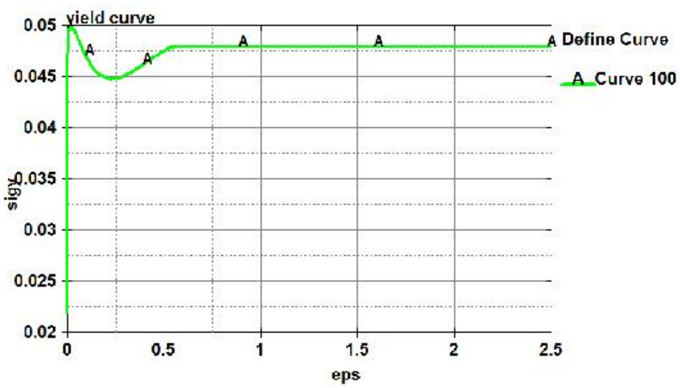
$$\begin{pmatrix} \pm_{xx} \\ \pm_{yy} \\ \pm_{xy} \end{pmatrix} = \begin{pmatrix} D_{11} & D_{12} & D_{14} \\ D_{21} & D_{22} & D_{24} \\ D_{41} & D_{42} & D_{44} \end{pmatrix} \begin{pmatrix} \pm^{eff}_{xx} \\ \pm^{eff}_{yy} \\ \pm^{eff}_{xy} \end{pmatrix}$$

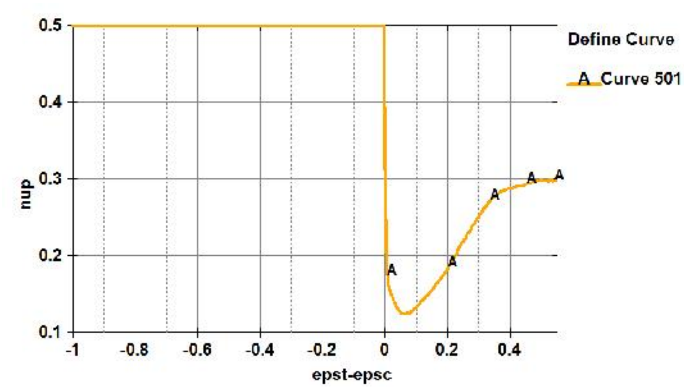
Obtain damage functions for MAGD

Example :

- SAMP material input with volumetric plastic strain

```
$
*MAT_SAMP-1_TITLE
ABS TERLURAN LCIP
$       MID        RO      BULK     SHEAR      EMOD       NUE    RBCFAC
          1    1.0E-6       4.0       1.2       2.4       0.4         0         0
$    LCID_T    LCID_C    LCID-S    LCID-B    RNUEP    LCID-P    INCDAM
$       100         0         0         0       0.0       501         0         0
        100         0         0         0       0.3         0         0         0
$    LCID_D    EPFAIL    DEPRPT  LCID_TRI   LCID_LC
          0       0.0       0.0         0         0
$   MAXITER      MIPS             INCFAIL     ICONV      ASAF    IPRINT     NHISV
          0        20         0         0         0       0.0
$
```

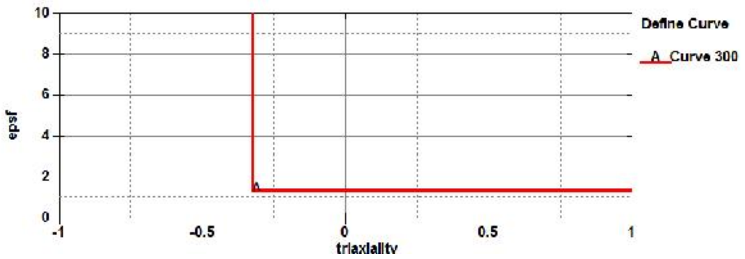




Example :

- Deviatoric damage only : GISSMO equivalent

```
$
*MAT_ADD_GENERALIZED_DAMAGE
$      pid      idam    dmgtyp     refsz    numfip                        nhis
         1         1         1                   1                           1
$     his1      his2      his3    iflg1     iflg2     iflg3
         0         0                   0         0         0
$    dam11     dam22     dam33     dam44     dam55     dam66
        42        42        44        42        44        44
$    dam12     dam21     dam24     dam42     dam14     dam41
         0         0
$    lcsdg     ecrit    dmgexp     dcrit    fadexp    lcregd
       300      0.00       1.0     0.333       1.0
$    lcsrs      shrf     biaxf

$
```



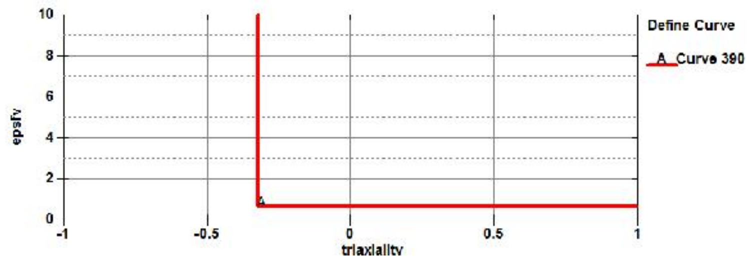
- Damage functions with *DEFINE_FUNCTION :

$$f42 = 1 - d_1 \qquad f44 = 1$$

Example :

- Deviatoric AND volumetric damage :

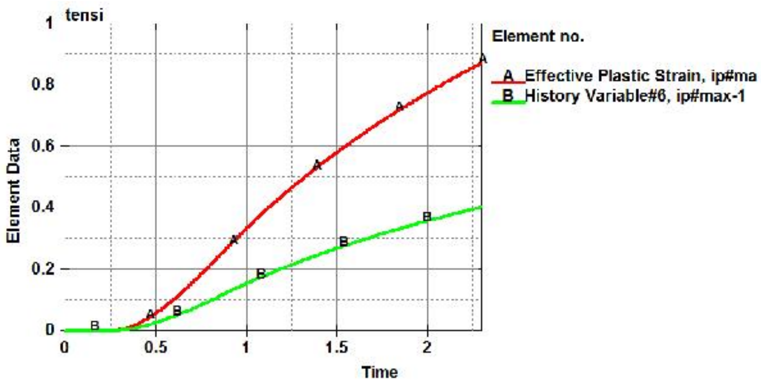
```
*MAT_ADD_GENERALIZED_DAMAGE
$      pid      idam    dmgtyp     refsz    numfip                          nhis
         2         1         1                   1                             2
$     his1      his2      his3    iflg1     iflg2     iflg3
         0         6                   0         0         0
$    dam11     dam22     dam33     dam44     dam55     dam66
        41        41        44        42        44        44
$       44        44        44        44        44        44
$    dam12     dam21     dam24     dam42     dam14     dam41
        43        43
$
$    lcsdg     ecrit    dmgexp     dcrit    fadexp    lcregd
       300      0.00       1.0     0.333       1.0
$    lcsrs      shrf     biaxf

$    lcsdg     ecrit    dmgexp     dcrit    fadexp    lcregd
       390      0.00       1.0     0.111       1.0
$    lcsrs      shrf     biaxf

$--------1---------2---------3---------4---------5---------6---------7---------8
```

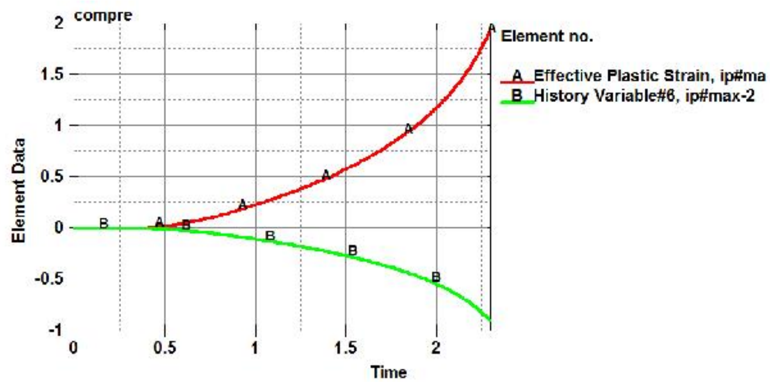


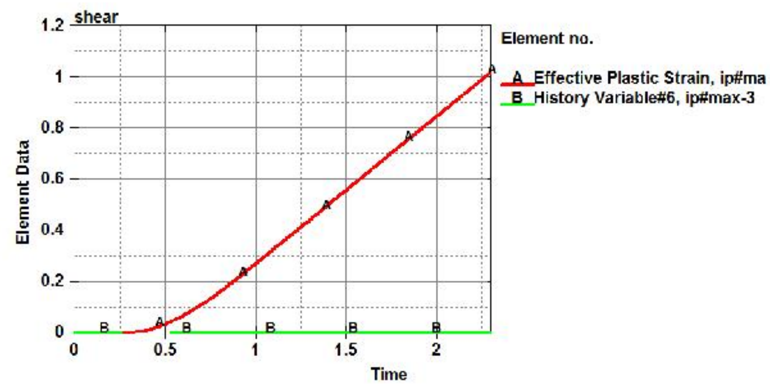
- Damage functions with *DEFINE_FUNCTION :

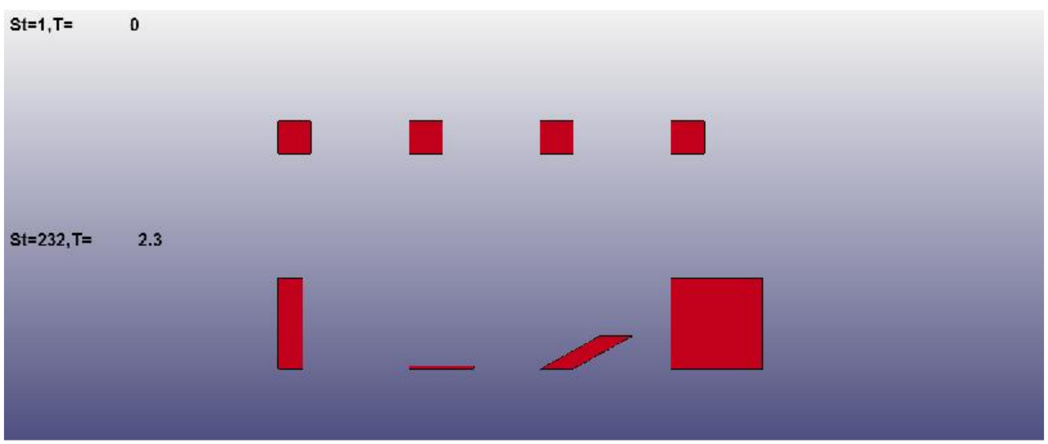
$$f41 = 1 - \frac{2}{3}d_1 - \frac{1}{3}d_2 \qquad f43 = \frac{1}{3}d_1 - \frac{1}{3}d_2 \qquad f42 = 1 - d_1 \qquad f44 = 1$$

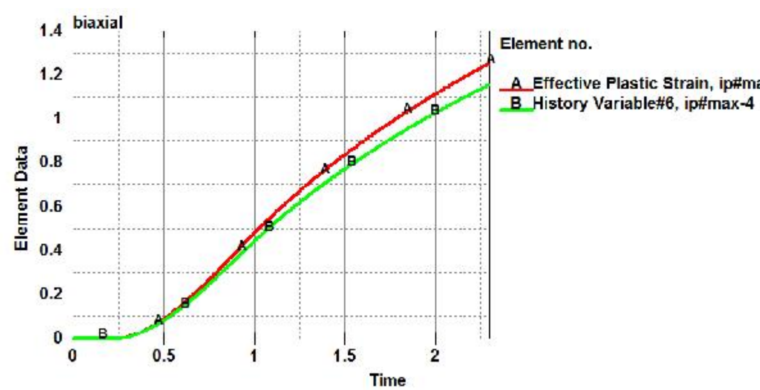
example


tensi
Element no.
A Effective Plastic Strain, ip#ma
B History Variable#6, ip#max-1
Element Data
Time

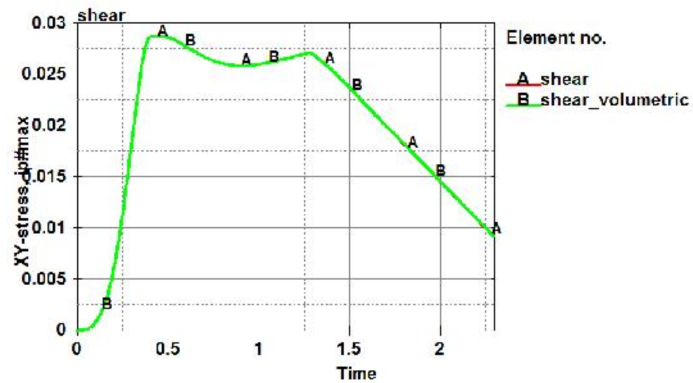

compre
Element no.
A Effective Plastic Strain, ip#ma
B History Variable#6, ip#max-2
Element Data
Time

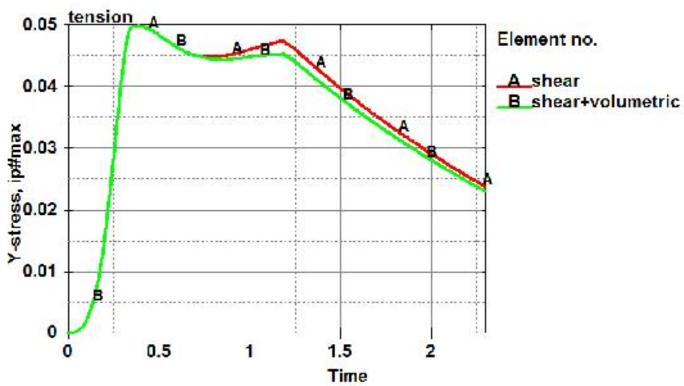

shear
Element no.
A Effective Plastic Strain, ip#ma
B History Variable#6, ip#max-3
Element Data
Time

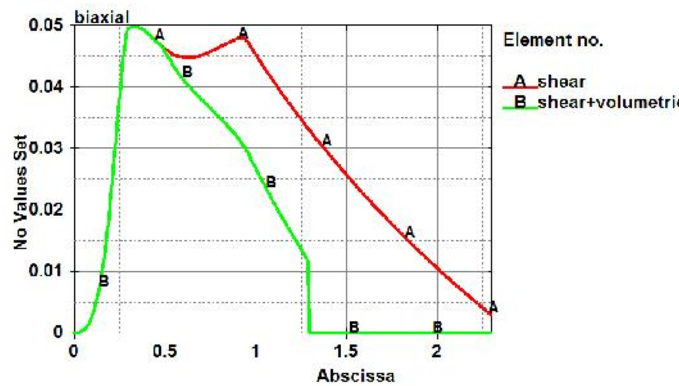

St=1,T= 0
St=232,T= 2.3

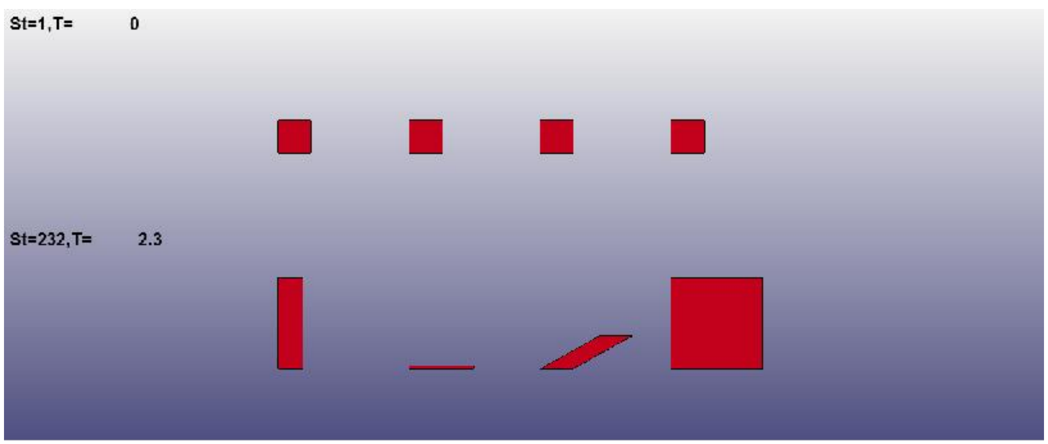

biaxial
Element no.
A Effective Plastic Strain, ip#ma
B History Variable#6, ip#max-4
Element Data
Time

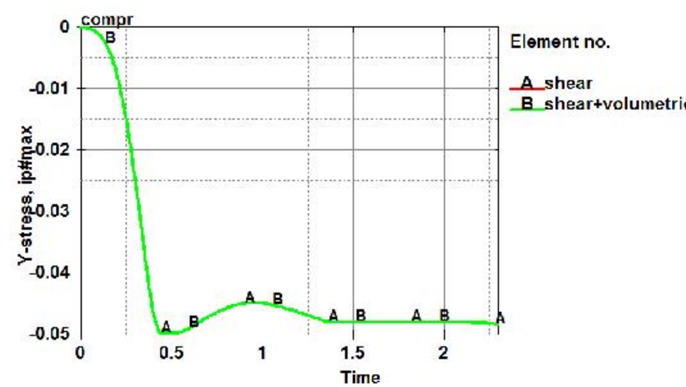
example


shear
XY-stress, ip#max
Time
Element no.
A shear
B shear_volumetric


tension
Y-stress, ip#max
Time
Element no.
A shear
B shear+volumetric


biaxial
No Values Set
Abscissa
Element no.
A shear
B shear+volumetric


St=1,T= 0
St=232,T= 2.3


compr
Y-stress, ip#max
Time
Element no.
A shear
B shear+volumetric

Plastic strain rate tensor as a damage driver

- Optionally (IFLAG1=1) we can use the components of the plastic strain rate tensor as the incremental damage drivers
- The plastic strain rate tensor is not always available in the material law and is estimated as :

$$\dot{\boldsymbol{\varepsilon}}_p = \frac{\pounds_p}{\pounds_{eff}} \dot{\mathbf{e}} = \frac{\pounds_p}{\pounds_{eff}} \left[\dot{\boldsymbol{\varepsilon}} - \frac{\pounds_v}{3} \boldsymbol{\delta} \right]$$

- This is a good approximation for isochoric materials with small elastic strains (metals) and correct for J2 plasticity

- The damage increment is driven by :

$$IFLAG2 = 0 \quad \langle \pounds^p_{xx} \rangle \; \langle \pounds^p_{yy} \rangle \; \langle \pounds^p_{xy} \rangle \quad element \; system$$

$$IFLAG2 = 1 \quad \langle \pounds^p_{aa} \rangle \; \langle \pounds^p_{bb} \rangle \; \langle \pounds^p_{ab} \rangle \quad material \; system$$

$$IFLAG2 = 2 \quad \langle \pounds^p_{1} \rangle \; \langle \pounds^p_{2} \rangle \quad principal \; system$$

A reference : orthotropic damage in principal system

- Lemaitre assumes that the principal directions of damage coincide with the principal directions of the plastic strain tensor, so first we compute the principal directions and principal values of the plastic strain tensor :

$$\begin{pmatrix} \pounds_1^p & 0 \\ 0 & \pounds_2^p \end{pmatrix} = \mathbf{Q}^T \begin{pmatrix} \pounds_{xx}^p & \pounds_{xy}^p \\ \pounds_{xy}^p & \pounds_{yy}^p \end{pmatrix} \mathbf{Q}$$

- Then we accumulate the damage in this frame, note that the damage evolution can be linear or non-linear but is independent of both direction and state of stress (if the first principal stress is positive) :

$$d_1 = \max\left(d_1, \frac{\pounds_1^p - \pounds_f}{\pounds_r - \pounds_f} \right)$$

$$d_2 = \max\left(d_2, \frac{\pounds_2^p - \pounds_f}{\pounds_r - \pounds_f} \right) \qquad \dot{d}_i = \dot{d}_i \frac{\langle \pm_1 \rangle}{\pm_1}$$

A reference : orthotropic damage in principal system

- Then the stress tensor is transformed from the material reference frame in the principal damage frame, damage is applied , and the damaged stress transformed back into the material frame :

$$\boldsymbol{\sigma}_{eff}^{p} = \mathbf{Q}^{T}\boldsymbol{\sigma}_{eff}\mathbf{Q}$$

$$\boldsymbol{\sigma}^{p} = \mathbf{M}\boldsymbol{\sigma}_{eff}^{p}$$

$$\boldsymbol{\sigma} = \mathbf{Q}\boldsymbol{\sigma}^{p}\mathbf{Q}^{T}$$

- Where the damage tensor in the principal system is very simple :

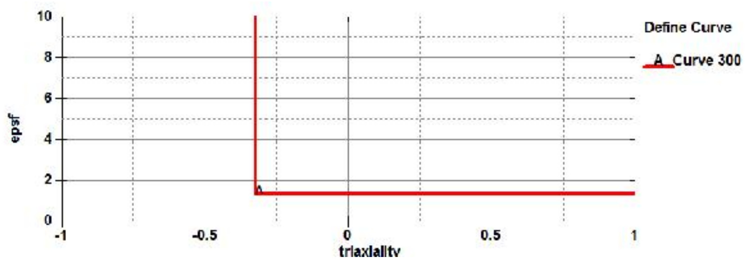
$$\pm_{xx} = (1 - d_1)\pm_{xx}^{eff}$$

$$\pm_{yy} = (1 - d_2)\pm_{yy}^{eff}$$

$$\pm_{xy} = \left(1 - \frac{d_1 + d_2}{2}\right)\pm_{xy}^{eff}$$

A reference : load induced anisotropic damage

- This model of anisotropic damage is implemented in MAT_104 in LS-DYNA, combined with an anistropic plasticity model (Hill)
- The limitations of this model are the following :
  - The principal directions of damage and the principal directions of plastic strain are identical only under proportional loading
  - The failure and rupture strains are the same in all directions, it is equivalent to having identical GISSMO cards in all directions and just use different history variables to drive them
  - The damage evolution is independent of the state of stress, so not only should the GISSMO cards be identical in all directions but the LCSDG and the ECRIT curves should be horizontal (constant) functions of triaxiality (as long as the first principal stress is positive)



Single element example

- 5 single shell elements in uniaxial tension, compression, plane strain, simple shear and EBT
- Isotropic material properties defined by MAT_104 and MAT_036 with m=2
- Anisotropic damage defined using MAT_104 and MAT_ADD_DAMAGE_GENERAL using IFLG2=2 , this activates damage accumulation in the principal strain system
- The damage models are fully equivalent under proportional loading where the principal strain system does not rotate
- Under non-proportional loading differences could occur as the principal strain system in MAT_ADD_DAMAGE_GENERAL can be either frozen or corotating with the principal system, in MAT_104 the damage frame is frozen as the principal strain system at the moment when damage starts in some direction

Single element example

```
*MAT_ADD_GENERALIZED_DAMAGE
$      pid      idam    dmgtyp     refsz    numfip                                  nhis
        36         1         1                   1                                     2
$     his1      his2      his3     iflg1     iflg2     iflg3
                                       1         2         0
$    dam11     dam22     dam33     dam44     dam55     dam66
        41        42        44        43        44        44
$    dam12     dam21     dam24     dam42     dam14     dam41

$    lcsdg     ecrit    dmgexp     dcrit    fadexp    lcregd
       300      0.00       1.0     0.333       1.0
$    lcsrs      shrf     biaxf

$    lcsdg     ecrit    dmgexp     dcrit    fadexp    lcregd
       300      0.00       1.0     0.333       1.0
$    lcsrs      shrf     biaxf

$--------1---------2---------3---------4---------5---------6---------7---------8
*DEFINE_CURVE
300
-1.0,300.
-0.33, 300.
-0.32, 0.30
1.0,0.30
```

$$his1 = \pounds_1^p$$

$$his2 = \pounds_2^p$$

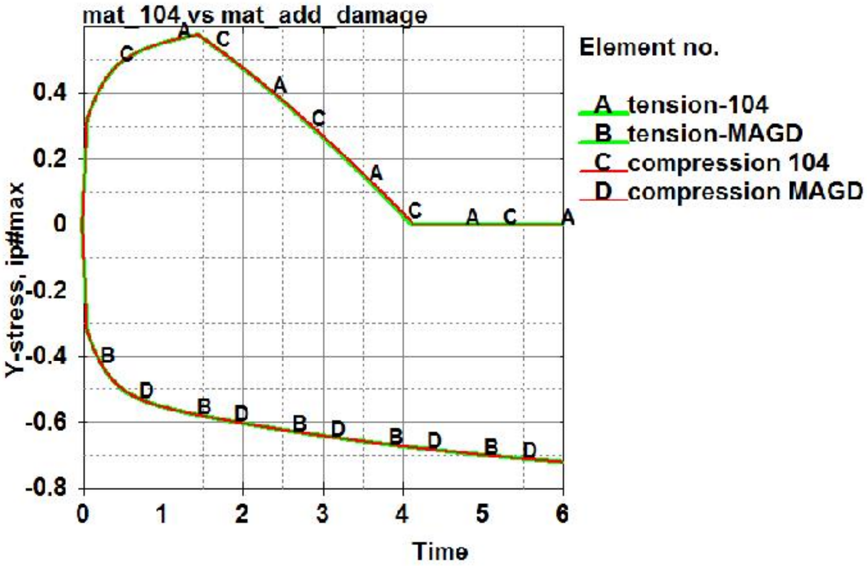
$$func41(d_1, d_2) = 1 - d_1$$

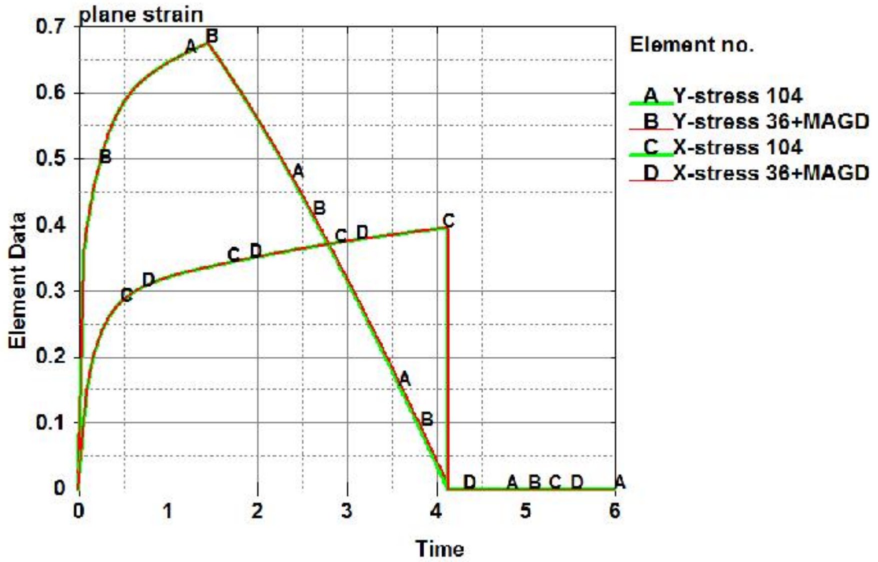
$$func42(d_1, d_2) = 1 - d_2$$

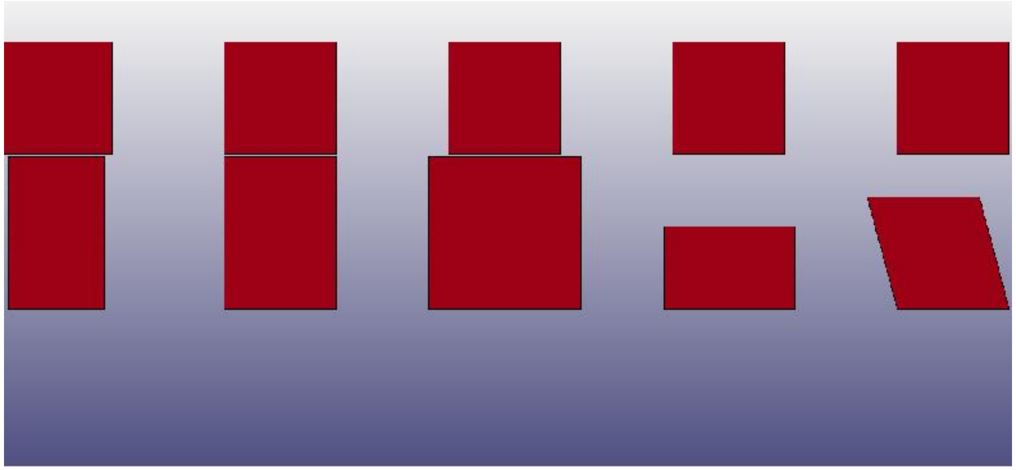
$$func43(d_1, d_2) = 1 - \frac{d_1 + d_2}{2}$$

```
$--------1---------2---------3---------4---------5---------6---------7---------8
$ PART2 - SECTION - MATERIAL
$--------1---------2---------3---------4---------5---------6---------7---------8
*MAT_DAMAGE_1
$      MID        RO         E        PR                LCSS
       104  2.70E-06      70.0       0.3                   2
$#      q1        c1        q2        c2      epsd      espr        dc      flag
                                               0.1       0.3                -1
$#      vk        vm  r00 or f  r45 or g  r90 or h         l         m         n
                           1.0       1.0       1.0
$#    aopt                          macf
     2.000.
$#      xp        yp        zp        a1        a2        a3
     0.000     0.000     0.000  0.000000     1.000     0.000
$#      v1        v2        v3        d1        d2        d3      beta
     0.000  0.000000     0.000     1.000     0.000     0.000     0.000
$--------1---------2---------3---------4---------5---------6---------7---------8
```

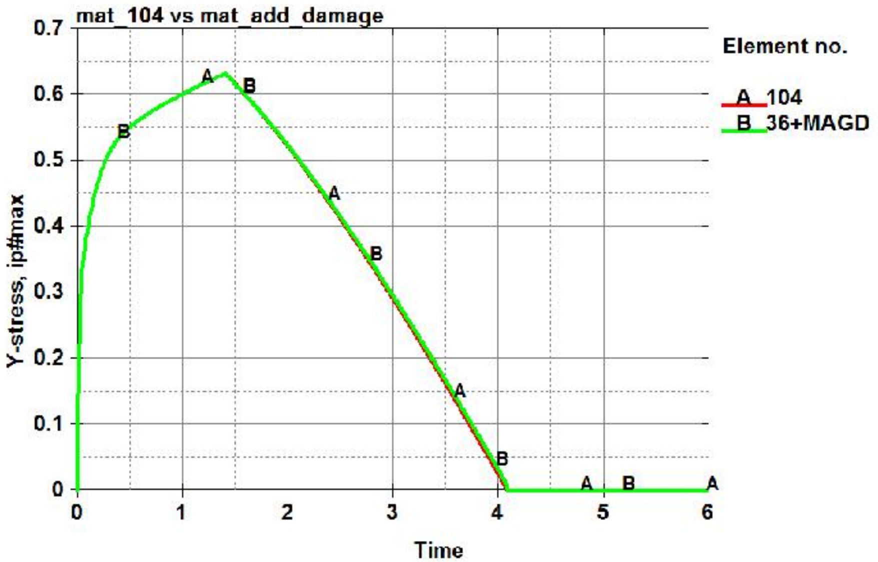
Equivalence of MAT_104 vs MAT_036 with MAGD

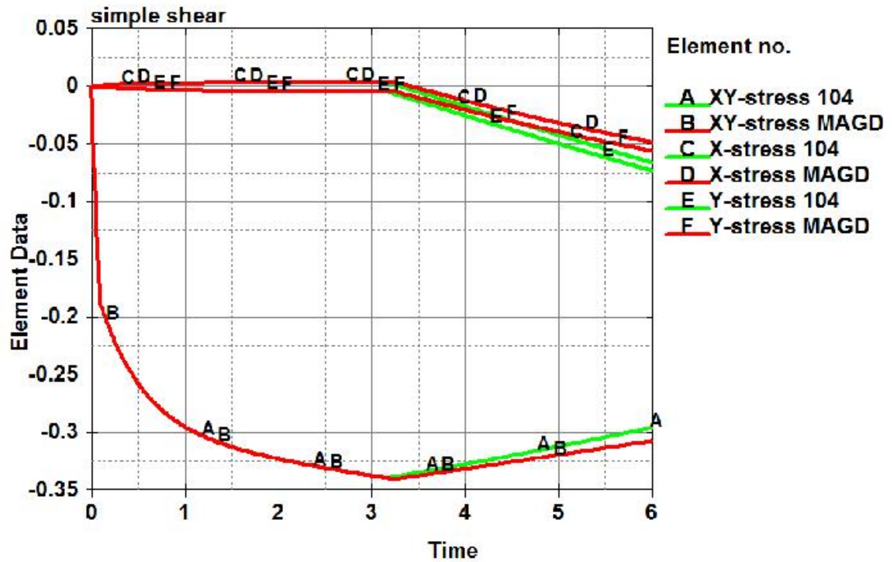


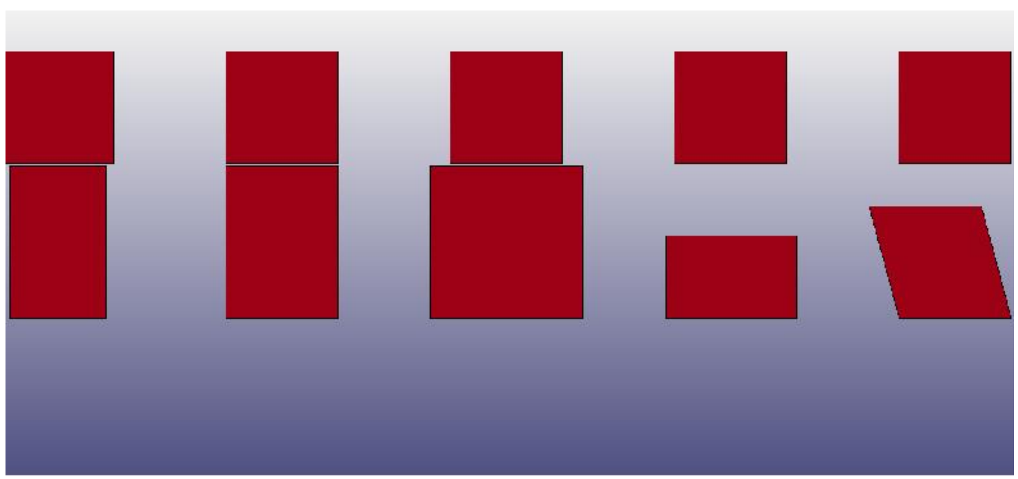




Equivalence of MAT_104 vs MAT_036 with MAGD







Damage evolution in principal system : conclusion

- Load induced anisotropic damage can now be added to any elasto-plastic material law in LS-DYNA

Functions of Plastic strain rate tensor as damage driver

- Optionally (IFLAG1=1) we can use functions of the components of the plastic strain rate tensor as the damage drivers by specifying negative numbers for the history variables : NHISi<0

$$IFLAG2=0 \qquad \left\langle f\left(\pounds_{xx}^{p},\pounds_{yy}^{p},\pounds_{xy}^{p}\right)\right\rangle \ \left\langle g\left(\pounds_{xx}^{p},\pounds_{yy}^{p},\pounds_{xy}^{p}\right)\right\rangle \ \left\langle h\left(\pounds_{xx}^{p},\pounds_{yy}^{p},\pounds_{xy}^{p}\right)\right\rangle$$

$$IFLAG2=1 \qquad \left\langle f\left(\pounds_{aa}^{p},\pounds_{bb}^{p},\pounds_{ab}^{p}\right)\right\rangle \ \left\langle g\left(\pounds_{aa}^{p},\pounds_{bb}^{p},\pounds_{ab}^{p}\right)\right\rangle \ \left\langle h\left(\pounds_{aa}^{p},\pounds_{bb}^{p},\pounds_{ab}^{p}\right)\right\rangle$$

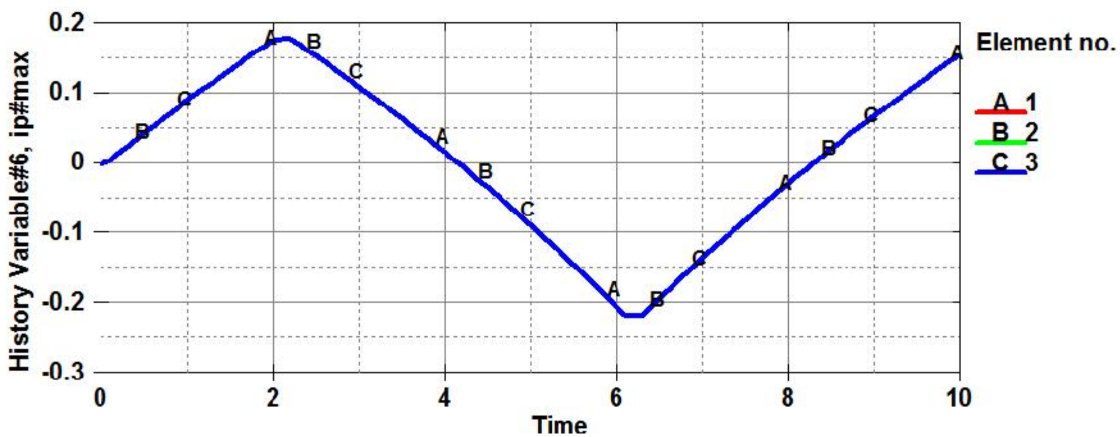
$$IFLAG2=2 \qquad \left\langle f\left(\pounds_{1}^{p},\pounds_{2}^{p},g\right)\right\rangle \ \left\langle g\left(\pounds_{1}^{p},\pounds_{2}^{p},g\right)\right\rangle \ \left\langle h\left(\pounds_{1}^{p},\pounds_{2}^{p},g\right)\right\rangle$$

Functions of Plastic strain rate tensor as damage driver

- Use MAT_SAMP to model cyclic uniaxial tension/compression of a foam-like material :

```
*MAT_SAMP-1
$#     mid        ro      bulk      gmod      emod       nue    rbcfac    numint
         11.00000E-6 33.4999997.22000003      20.00.40000001       0.0         0
$#  lcid-t    lcid-c    lcid-s    lcid-b      nuep    lcid-p              incdam
         2         0         0         0       0.0         0         0         0
$#  lcid_d    epfail    deprpt  lcid-tri   lcid_lc
         0  100000.0       0.0         0         0
$#   miter     mipds             incfail     iconv      asaf
         0         0         0         0         0         0
```

- TH of volumetric plastic strain :



Functions of Plastic strain rate tensor as damage driver

- Now apply 3 different damage models

```
$
*MAT_ADD_GENERALIZED_DAMAGE
$#     mid      idam      dtyp     mneps    effeps    voleps    numfip      nhis
         3       1.0       1.0                                                  1
$#    his1      his2      his3    iflg1     iflg2     iflg3
$        6         0         0         0         0         0
$      -11         0         0         1         0         0
       -12         0         0         1         0         0
$#     d11       d22       d33       d44       d55       d66
        41        41        42        41        42        42
$#
         0         0         0         0         0         0
$#   lcsdg     ecrit    dmgexp     dcrit    fadexp    lcregd
         3       0.0       1.0      0.01       1.0         0
$#   lcsrs    regshr    rgbiax
         0         0         0
*DEFINE_FUNCTION
      11
fhis1(exx,eyy,ezz,exy,eyz,ezx)=3.*eyy/2.
*DEFINE_FUNCTION
      12
fhis2(exx,eyy,ezz,exy,eyz,ezx)=max(3.*eyy/2.,-3.*eyy/2.)
$
```

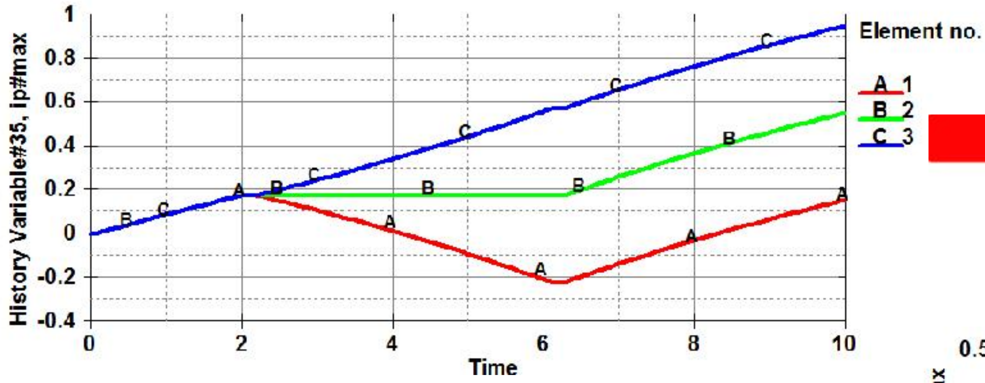
$$\dot{d} = n d^{1-\frac{1}{n}} \frac{\langle \pounds_v \rangle}{\pounds_{vf}}$$

$$\dot{d} = n d^{1-\frac{1}{n}} \frac{\left\langle \frac{3}{2} e_{yy} \right\rangle}{\pounds_{vf}}$$

$$\dot{d} = n d^{1-\frac{1}{n}} \frac{\left| \frac{3}{2} \dot{e}_{yy} \right|}{\pounds_{vf}}$$

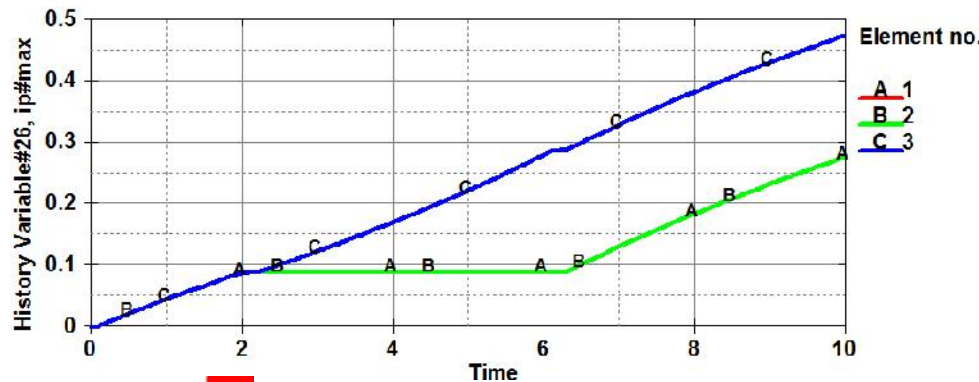
$$\textit{note that } \frac{3}{2}\dot{e}_{yy} = \pounds_{yy} = \pounds_v$$

Functions of Plastic strain rate tensor as damage driver

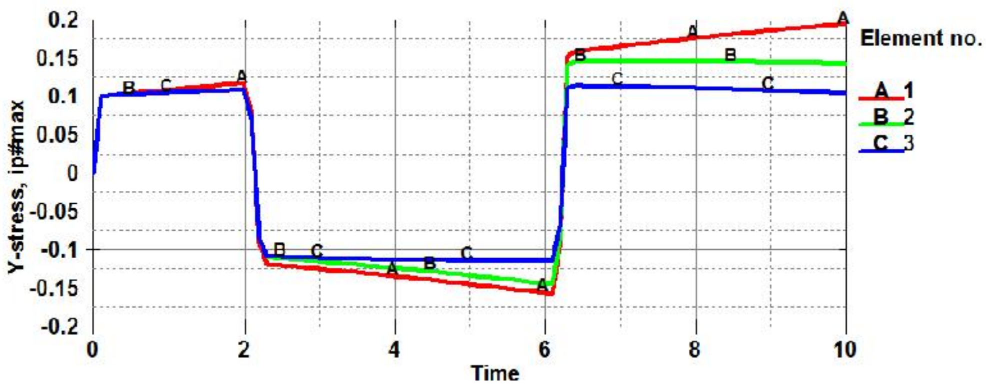


TH of damage driving history variable

TH of the damage



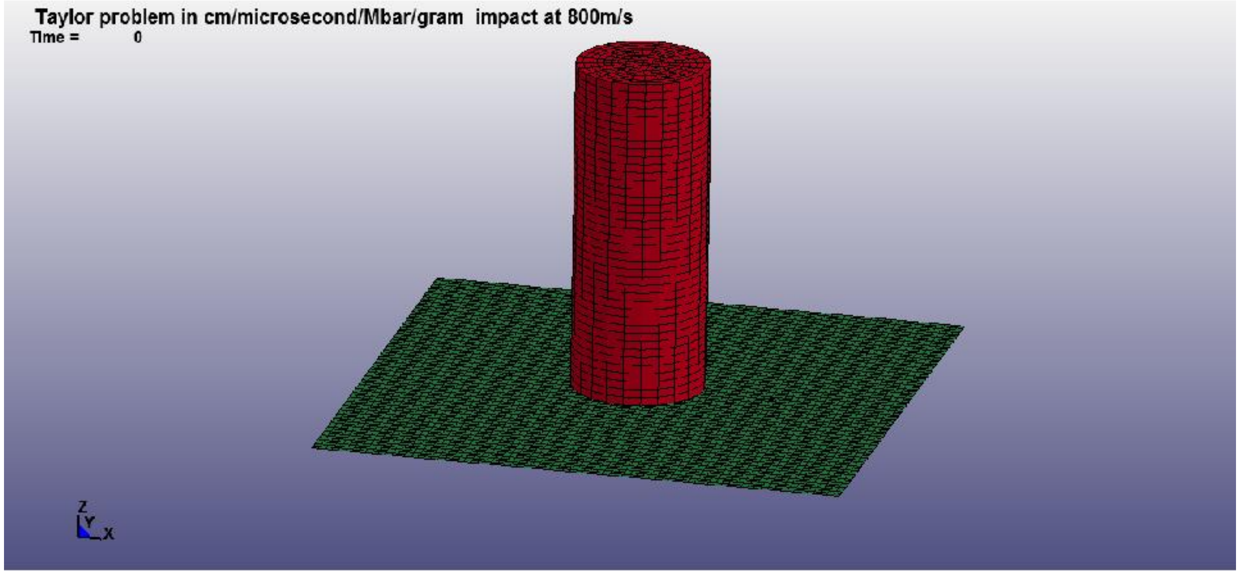
TH of the true stress (DTYP=0 for case A)



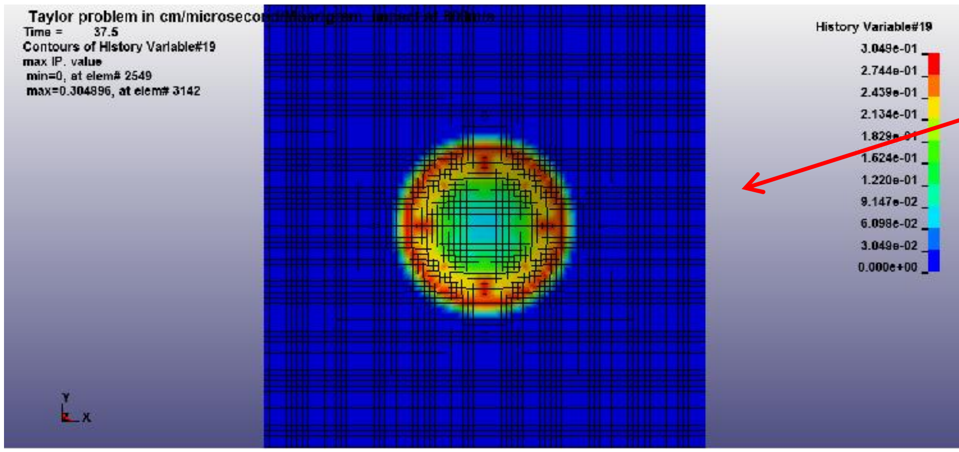
The example illustrates the use of absolute value as an alternative to the Macaulay bracket

High velocity impact of a blunt projectile : plugging

- Impact of a blunt projectile often results in a plugging mode
- Narrow shearbands are hard to simulate
- Problem is amplified by highly deformable projectile due to thermal softening

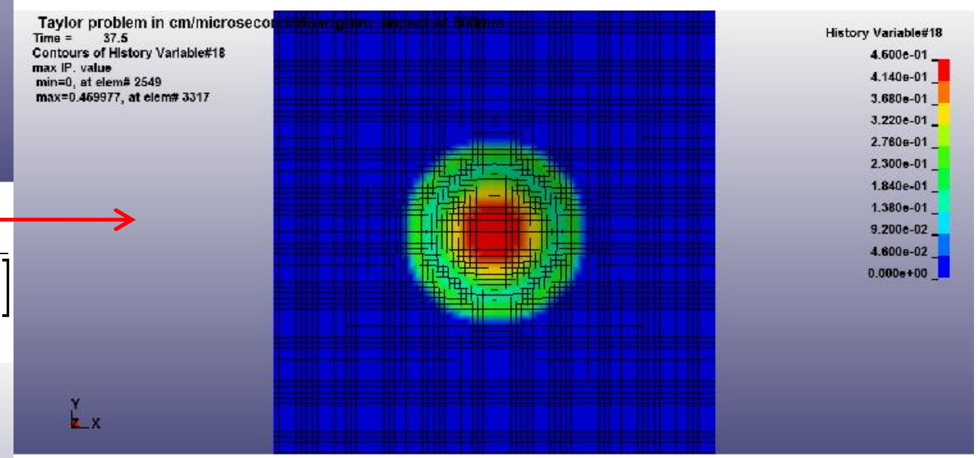


High velocity impact of a blunt projectile : plugging



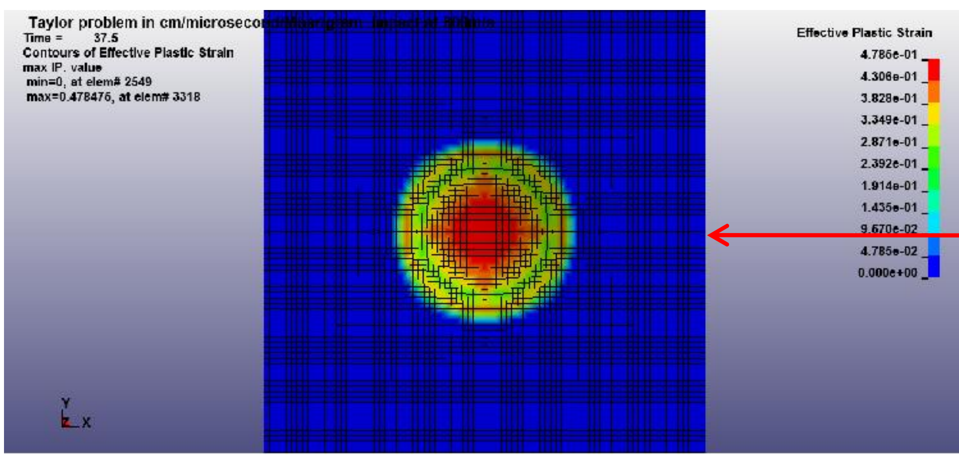
hisv #19

$$\pounds_p^{OOP} = \sqrt{\frac{2}{3}\left[2\left(\pounds_{zx}^{p}\right)^2 + 2\left(\pounds_{yz}^{p}\right)^2\right]}$$



hisv #18

$$\pounds_p^{inplane} = \sqrt{\frac{2}{3}\left[\left(\pounds_{xx}^{p}\right)^2 + \left(\pounds_{yy}^{p}\right)^2 + \left(\pounds_{zz}^{p}\right)^2 + 2\left(\pounds_{xy}^{p}\right)^2\right]}$$



equivalent plastic strain rate

$$\pounds_p = \sqrt{\frac{2}{3}\left[\left(\pounds_{xx}^{p}\right)^2 + \left(\pounds_{yy}^{p}\right)^2 + \left(\pounds_{zz}^{p}\right)^2 + 2\left(\pounds_{xy}^{p}\right)^2 + 2\left(\pounds_{yz}^{p}\right)^2 + 2\left(\pounds_{zx}^{p}\right)^2\right]}$$

High velocity impact of a blunt projectile : plugging

- MAGD allows to consider inplane and OOP damage simultaneously

```
*MAT_ADD_GENERALIZED_DAMAGE
$#     mid      idam      dtyp     mneps    effeps    voleps    numfip      nhis
         3       1.0       1.0                                                  2
$#    his1      his2      his3     iflg1     iflg2     iflg3
       -11       -12         0         1         0         0
$#     d11       d22       d33       d44       d55       d66
        41        41        42        41        43        43
$#
         0         0         0         0         0         0
$#   lcsdg     ecrit    dmgexp     dcrit    fadexp    lcregd
        31       0.0       1.0      0.80       10.         0
$#   lcsrs    regshr    rgbiax
         0         0         0
$#   lcsdg     ecrit    dmgexp     dcrit    fadexp    lcregd
        32       0.0       1.0      0.80       2.0         0
$#   lcsrs    regshr    rgbiax
         0         0         0
*DEFINE_FUNCTION
      11
fhis11(exx,eyy,ezz,exy,eyz,ezx)=sqrt((2./3.)*(exx**2+eyy**2+ezz**2+2.*exy**2))
*DEFINE_FUNCTION
      12
fhis12(exx,eyy,ezz,exy,eyz,ezx)=sqrt((4./3.)*(eyz**2+ezx**2))
```

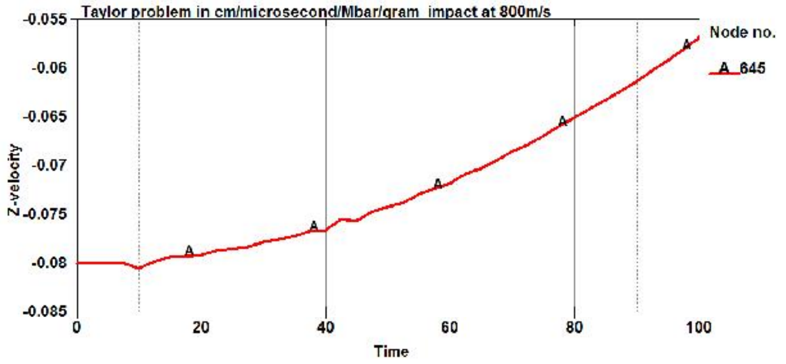
function #11

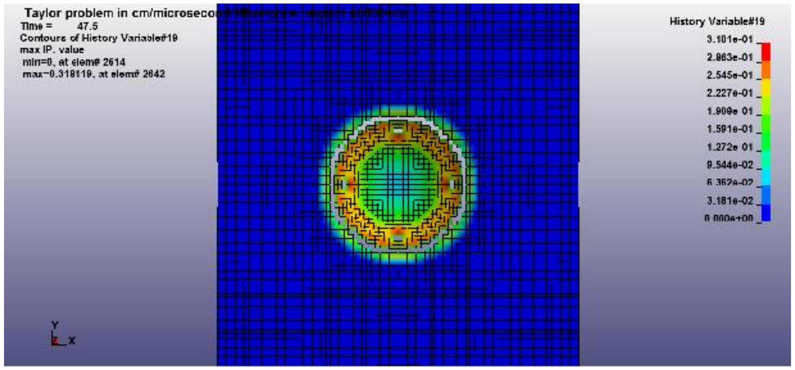
$$\varepsilon_p^{inplane} = \sqrt{\frac{2}{3}\left[\left(\varepsilon_{xx}^p\right)^2 + \left(\varepsilon_{yy}^p\right)^2 + \left(\varepsilon_{zz}^p\right)^2 + 2\left(\varepsilon_{xy}^p\right)^2\right]}$$

function #12

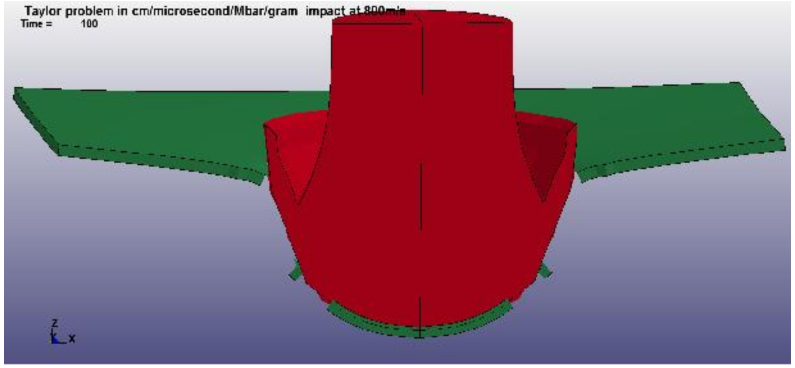
$$\varepsilon_p^{OOP} = \sqrt{\frac{2}{3}\left[2\left(\varepsilon_{zx}^p\right)^2 + 2\left(\varepsilon_{yz}^p\right)^2\right]}$$

High velocity impact of a blunt projectile : plugging



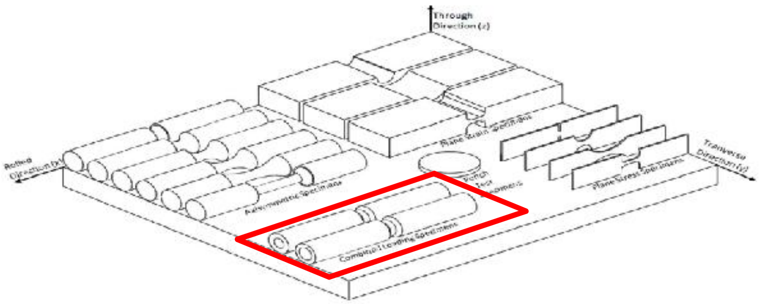


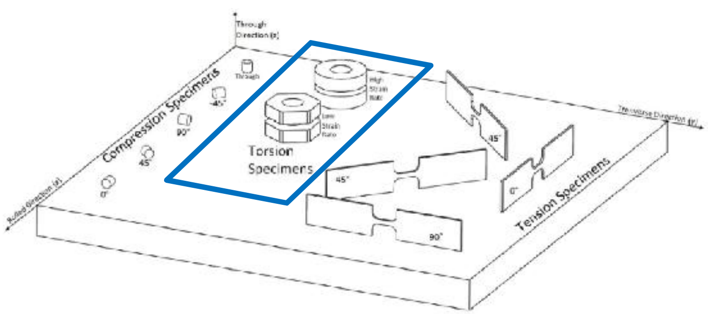
High velocity impact of a blunt projectile : plugging

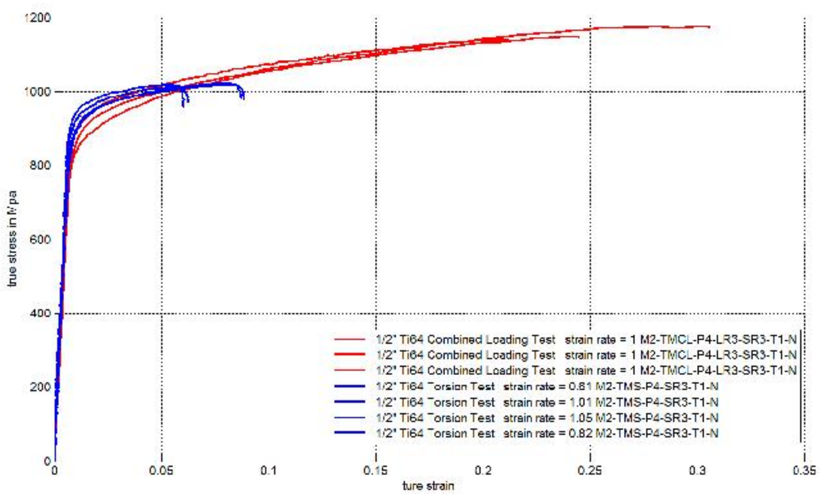


High velocity impact of a blunt projectile : plugging

- Doing the same with solid elements requires a material law that is at least transversely isotropic (allows to define thickness direction)
- This may be necessary also as medium thick plates will have different properties in the thickness direction







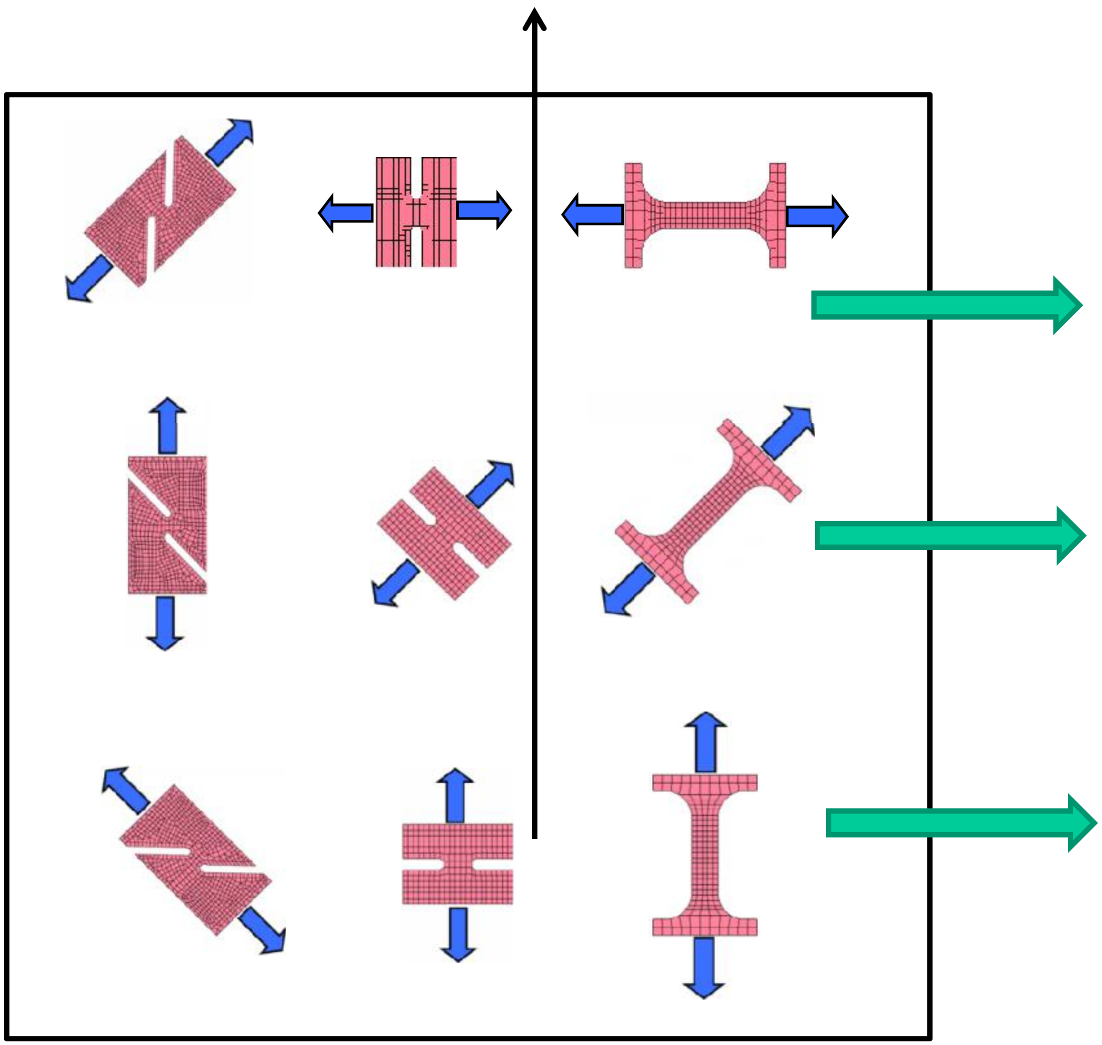
The plane stress orthotropic failure model :

- The versatility of MAT_ADD_GENERALIZED_DAMAGE allows the simulation of plane stress orthotropic failure in metals

- Orthotropic failure means that the material has 3 symmetry planes and in particular failure strains under 45 degree and under 135 degree to the material x-axis are the same

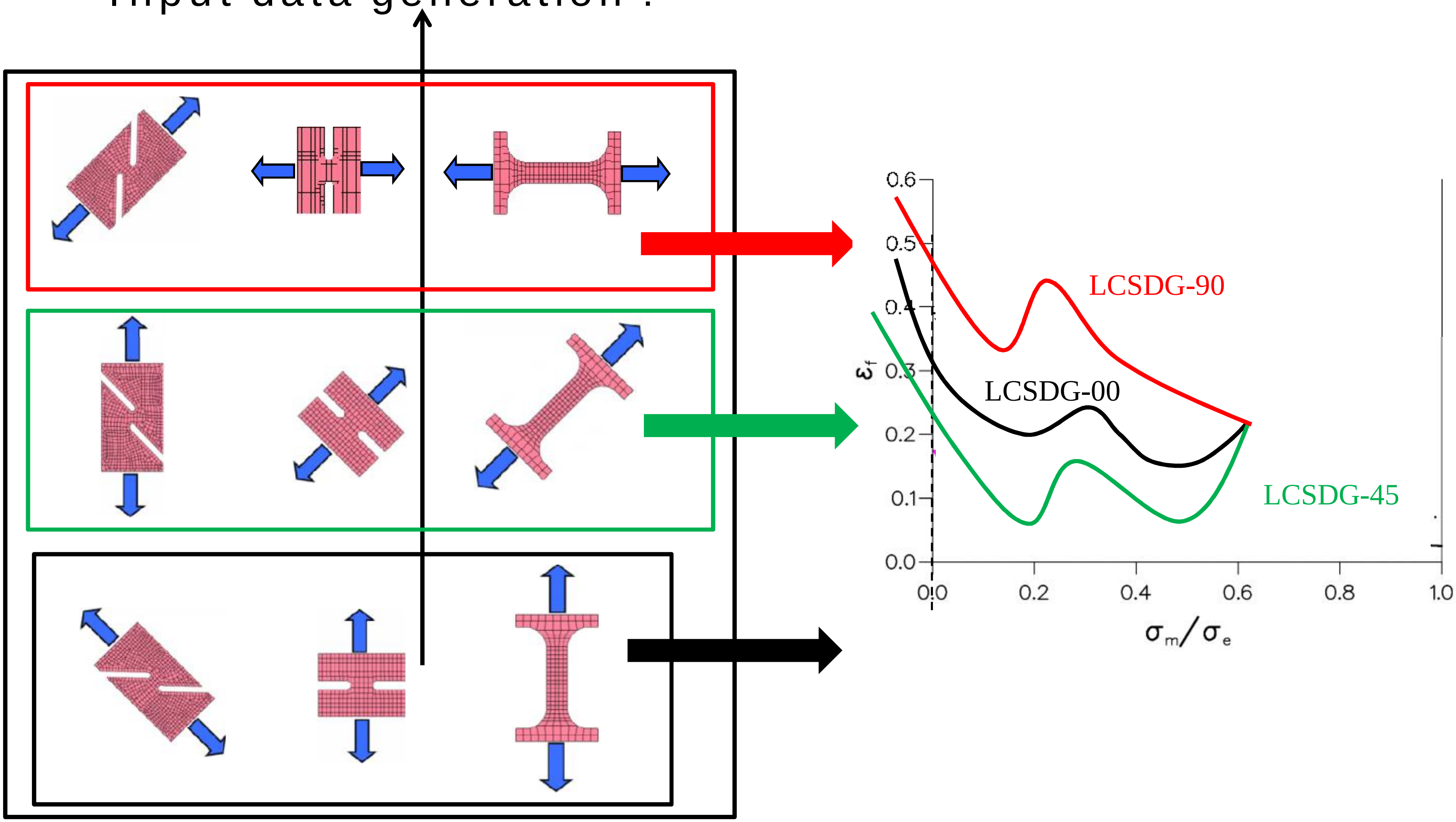
- We remain consistent with orthotropic plasticity models in plane stress where material properties are specified under 0, 45 and 90 degrees to the material x-axis. Consequently the model will require GISSMO type input based on experiments with the first principal stress direction under 0, 45 and 90 degrees to the material x-axis

Experimental database



- Tensile, notched and shear tests needed in 3 directions
- ‘direction’ of the shear tests is the first principal stress direction (tensile diagonal)
- Only 1 biaxial test needed

Input data generation :



Input data generation

- A consistent input deck also requires the instability curves (ECRIT) to have coincident biaxial points
- Swift curves generated for material hardening curves in 3 directions will usually not have coincident biaxial points

Summary :

- The model will be orthotropic with respect to failure, different failure strains can be defined in different directions for the same state of stress
- Since we define failure in 3 directions, 3 GISSMO cards will be required, thus NHIS=3
- The dependency of failure on state of stress and load path remains the same as in GISSMO
- How fast damage accumulates depends upon the loading direction

Damage drivers

- 3 functions of plastic strain rate components are used to drive the 3 damage components :

$$£_{45}^{ep} = 2\left|£_1^{p} 2\left|\cos g \sin g\right|\right|\sqrt{\frac{1}{3}\left(1+b^2+b\right)} \geq 0$$

$$£_{90}^{ep} = 2\left|£_1^{p}\left\langle \sin^2 g - \left|\cos g \sin g\right|\right\rangle\right|\sqrt{\frac{1}{3}\left(1+b^2+b\right)} \geq 0$$

$$£_{00}^{ep} = 2\left|£_1^{p}\left\langle \cos^2 g - \left|\cos g \sin g\right|\right\rangle\right|\sqrt{\frac{1}{3}\left(1+b^2+b\right)} \geq 0$$

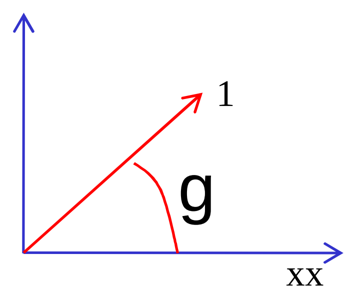
$$£_1^{p} = \frac{£_{xx}^{p} + £_{yy}^{p}}{2} + \frac{1}{2}\sqrt{\left(£_{xx}^{p} - £_{yy}^{p}\right)^2 + 4\left(£_{xy}^{p}\right)^2}$$

$$£_2^{p} = \frac{£_{xx}^{p} + £_{yy}^{p}}{2} - \frac{1}{2}\sqrt{\left(£_{xx}^{p} - £_{yy}^{p}\right)^2 + 4\left(£_{xy}^{p}\right)^2}$$

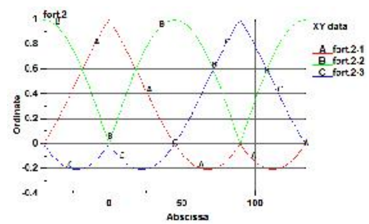
$$g = \frac{1}{2} a\tan\left(\frac{2£_{xy}^{p}}{£_{xx}^{p} - £_{yy}^{p}}\right) \qquad b = \frac{£_2^{p}}{£_1^{p}}$$

- If IFLAG1=2 these functions are default and thus his1=his2=his3=0

- Theta is the angle between the extrusion direction (material x-axis) and the first principal (loading) direction



Damage drivers



- The table shows the values of the damage driving functions :

	ε_{00}^{ep}	ε_{45}^{ep}	ε_{90}^{ep}
$\gamma = 0$	ε_p	0	0
$0 < \gamma < 45$	$\varepsilon_p\left(\cos^2\gamma - \lvert\cos\gamma\sin\gamma\rvert\right)$	$2\varepsilon_p\lvert\cos\gamma\sin\gamma\rvert$	0
$\gamma = 45$	0	ε_p	0
$045 < \gamma < 090$	0	$2\varepsilon_p\lvert\cos\gamma\sin\gamma\rvert$	$\varepsilon_p\left(\sin^2\gamma - \lvert\cos\gamma\sin\gamma\rvert\right)$
$\gamma = 90$	0	0	ε_p
$90 < \gamma < 135$	0	$2\varepsilon_p\lvert\cos\gamma\sin\gamma\rvert$	$\varepsilon_p\left(\sin^2\gamma - \lvert\cos\gamma\sin\gamma\rvert\right)$
$\gamma = 135$	0	ε_p	0
$135 < \gamma < 180$	$\varepsilon_p\left(\cos^2\gamma - \lvert\cos\gamma\sin\gamma\rvert\right)$	$2\varepsilon_p\lvert\cos\gamma\sin\gamma\rvert$	0
$\gamma = 180$	ε_p	0	0

The absolute value ensures the orthotropie of the formulation

Damage accumulation

- Damage can now be accumulated in the material system (IFLAG2=1) using the failure criteria that were determined from testing in each direction :

$$£_{45}^{ep} = 2\left|£_1^p 2\right|\cos g \sin g\left|\right|\sqrt{\frac{1}{3}\left(1+b^2+b\right)} \qquad \dot{d}_{00} = n d_{00}^{1-\frac{1}{n}} \frac{£_{00}^{ep}}{£_{00}^{f}} \qquad d_{00} = \int \dot{d}_{00} dt$$

$$£_{90}^{ep} = 2\left|£_1^p\left\langle \sin^2 g - \left|\cos g \sin g\right|\right\rangle\right|\sqrt{\frac{1}{3}\left(1+b^2+b\right)} \qquad \dot{d}_{90} = n d_{90}^{1-\frac{1}{n}} \frac{£_{90}^{ep}}{£_{90}^{f}} \qquad d_{90} = \int \dot{d}_{90} dt$$

$$£_{00}^{ep} = 2\left|£_1^p\left\langle \cos^2 g - \left|\cos g \sin g\right|\right\rangle\right|\sqrt{\frac{1}{3}\left(1+b^2+b\right)} \qquad \dot{d}_{45} = n d_{45}^{1-\frac{1}{n}} \frac{£_{45}^{ep}}{£_{45}^{f}} \qquad d_{45} = \int \dot{d}_{45} dt$$

- No problems with the sign of the damage as equivalent strain rates are all positive
- Strain rate components only contribute to the damage if they have a positive coefficient

isotropic damage and failure variable :

- If IFLG3=1 a single isotropic damage value is computed :

$$£_p = \sqrt{\frac{\left(£_{45}^{ep}\right)^2 + \left(£_{00}^{ep}\right)^2 + \left(£_{90}^{ep}\right)^2}{\left[6\cos^2 g \sin^2 g + \sin^4 g + \cos^4 g - 2\left|\cos g \sin g\right|\right]}}$$

$$\Delta d = \sqrt{\frac{\Delta d_{45}^2 + \Delta d_{00}^2 + \Delta d_{90}^2}{\left[6\cos^2 g \sin^2 g + \sin^4 g + \cos^4 g - 2\left|\cos g \sin g\right|\right]}} \qquad d = \int \Delta d \le 1$$

- Or :

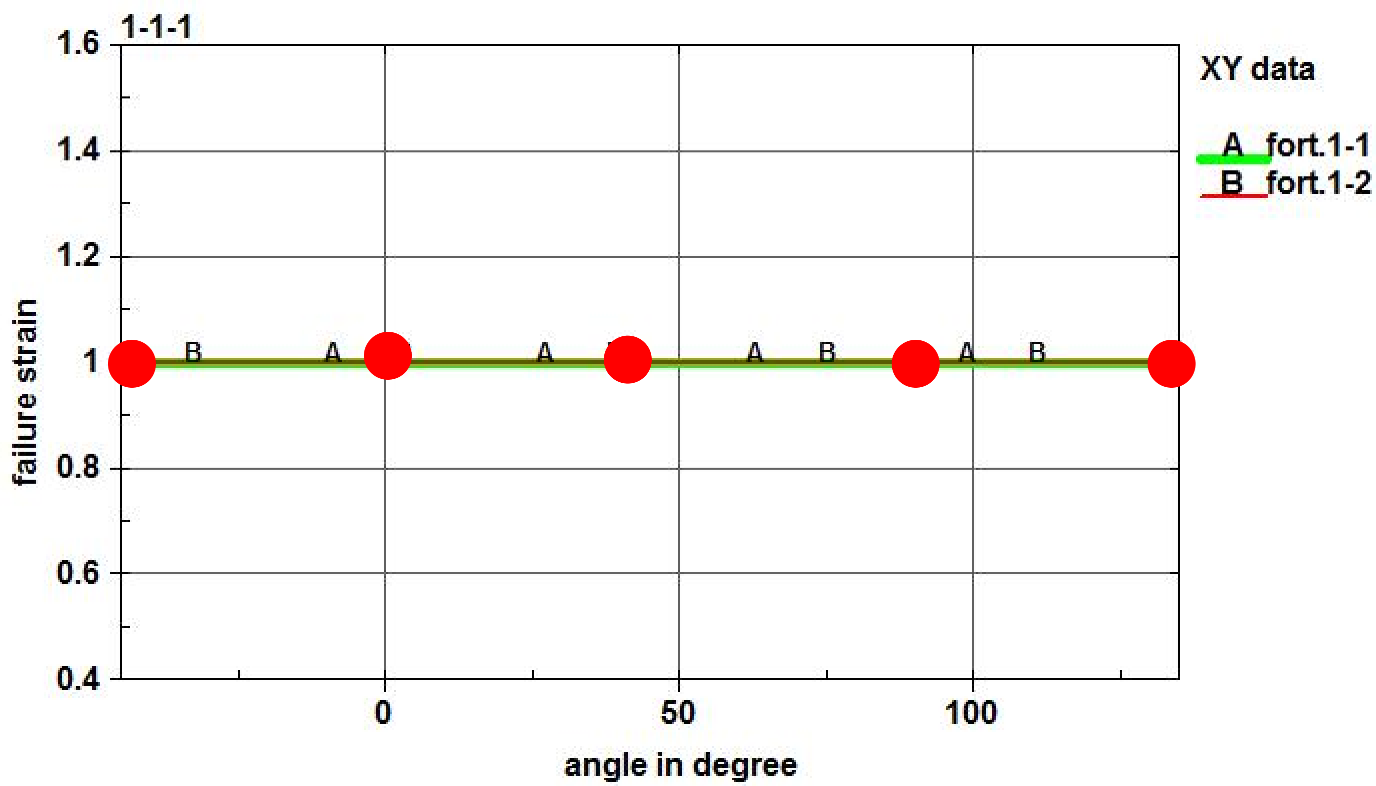
$$\cos^2 g - \left|\sin g \cos g\right| > 0 \Rightarrow \Delta d = \sqrt{\frac{\Delta d_{45}^2 + \Delta d_{00}^2}{£_{45}^2 + £_{00}^2} £_p^2} = \sqrt{\frac{\Delta d_{45}^2 + \Delta d_{00}^2}{5\cos^2 g \sin^2 g + \cos^4 g - 2\cos^3 g \sin g}}$$

$$\sin^2 g - \left|\sin g \cos g\right| < 0 \Rightarrow \Delta d = \sqrt{\frac{\Delta d_{45}^2 + \Delta d_{90}^2}{£_{45}^2 + £_{90}^2} £_p^2} = \sqrt{\frac{\Delta d_{45}^2 + \Delta d_{90}^2}{5\cos^2 g \sin^2 g + \sin^4 g - 2\cos g \sin^3 g}} \quad \backslash$$

- The model is now semi-analytical rather then fully tabulated

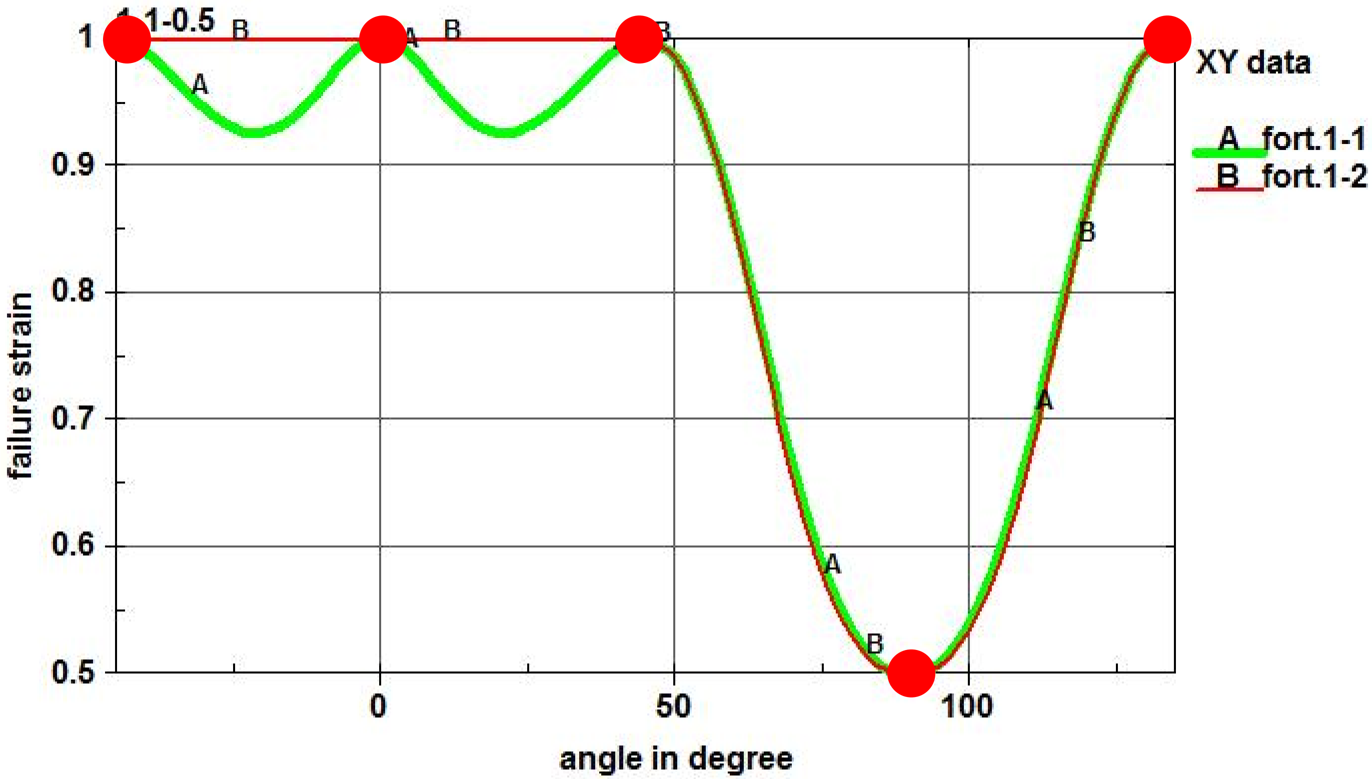
isotropic damage

- This approach results in a smooth and monotonic model (no new maxima or minima are generated between the failure surfaces defined for 00-45-90 degrees)



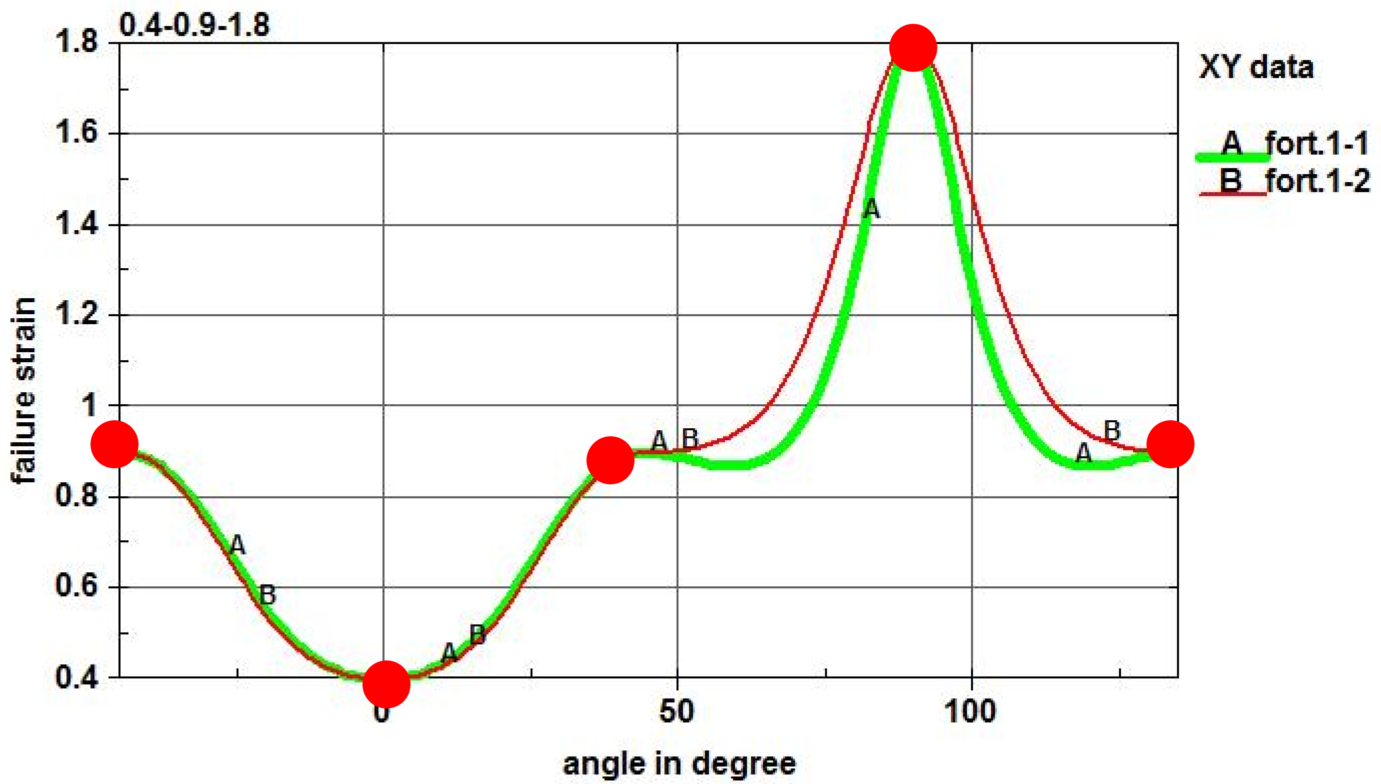
isotropic damage

- This approach results in a smooth and monotonic model (no new maxima or minima are generated between the failure surfaces defined for 00-45-90 degrees)



isotropic damage

- This approach results in a smooth and monotonic model (no new maxima or minima are generated between the failure surfaces defined for 00-45-90 degrees)



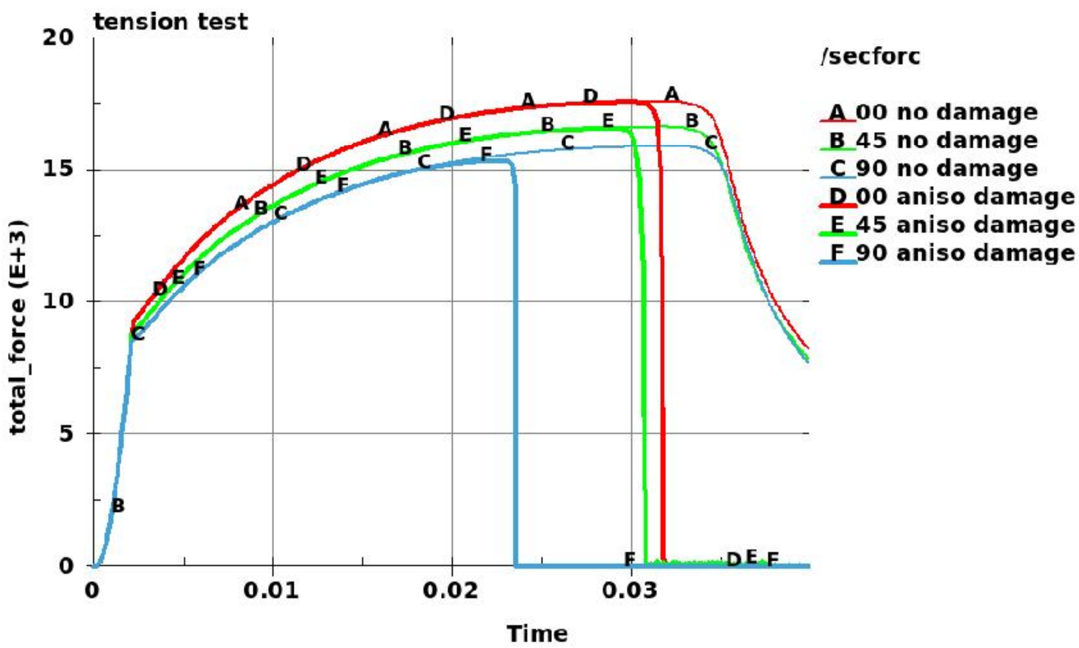
Input summary for orthotropic failure model :

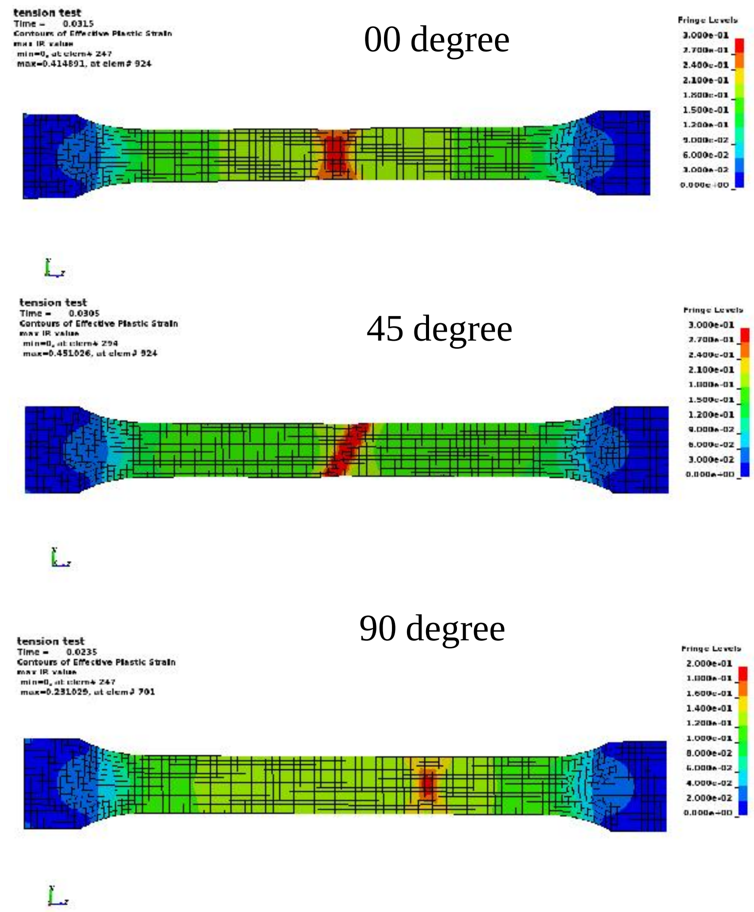
- Damage coupling is isotropic : a scalar function defines the relationship between true stress and effective stress, thus IFLG3=1
- Since all data are defined in the material system, damage must be accumulated in the material system, thus IFLG2=1
- the damage drivers for the 3 GISSMO models are internally computed from the plastic strain tensor components , thus IFLG1=2

```
*MAT_ADD_GENERALIZED_DAMAGE
$      pid      idam    dmgtyp     refsz    numfip                          nhis
         1         1         1                  80                             3
$     his1      his2      his3     iflg1     iflg2     iflg3
                                       2         1         1
$    dam11     dam22     dam33     dam44     dam55     dam66
        41        42        44        43        44        44
$    dam12     dam21     dam24     dam42     dam14     dam41

$    lcsdg     ecrit    dmgexp     dcrit    fadexp    lcregd
       997     -1097       2.0                 8.0
$    lcsrs      shrf     biaxf

$    lcsdg     ecrit    dmgexp     dcrit    fadexp    lcregd
       999     -1099       2.0                 8.0
$    lcsrs      shrf     biaxf

$    lcsdg     ecrit    dmgexp     dcrit    fadexp    lcregd
       998     -1098       2.0                 8.0
$    lcsrs      shrf     biaxf

$---+----1----+----2----+----3----+----4----+----5----+----6----+----7----+---
*DEFINE_FUNCTION
        41
func41(d1,d2,d3,a,x)=1.-d1
*DEFINE_FUNCTION
        42
func42(d1,d2,d3,a,x)=1.-d2
*DEFINE_FUNCTION
        43
func43(d1,d2,d3,a,x)=1.-d3
*DEFINE_FUNCTION
        44
func44(d1,d2,d3,a,x)=1.
```

Large scale validation

Uniaxial tensile test : MAT_036 + MAT_ADD_D_G





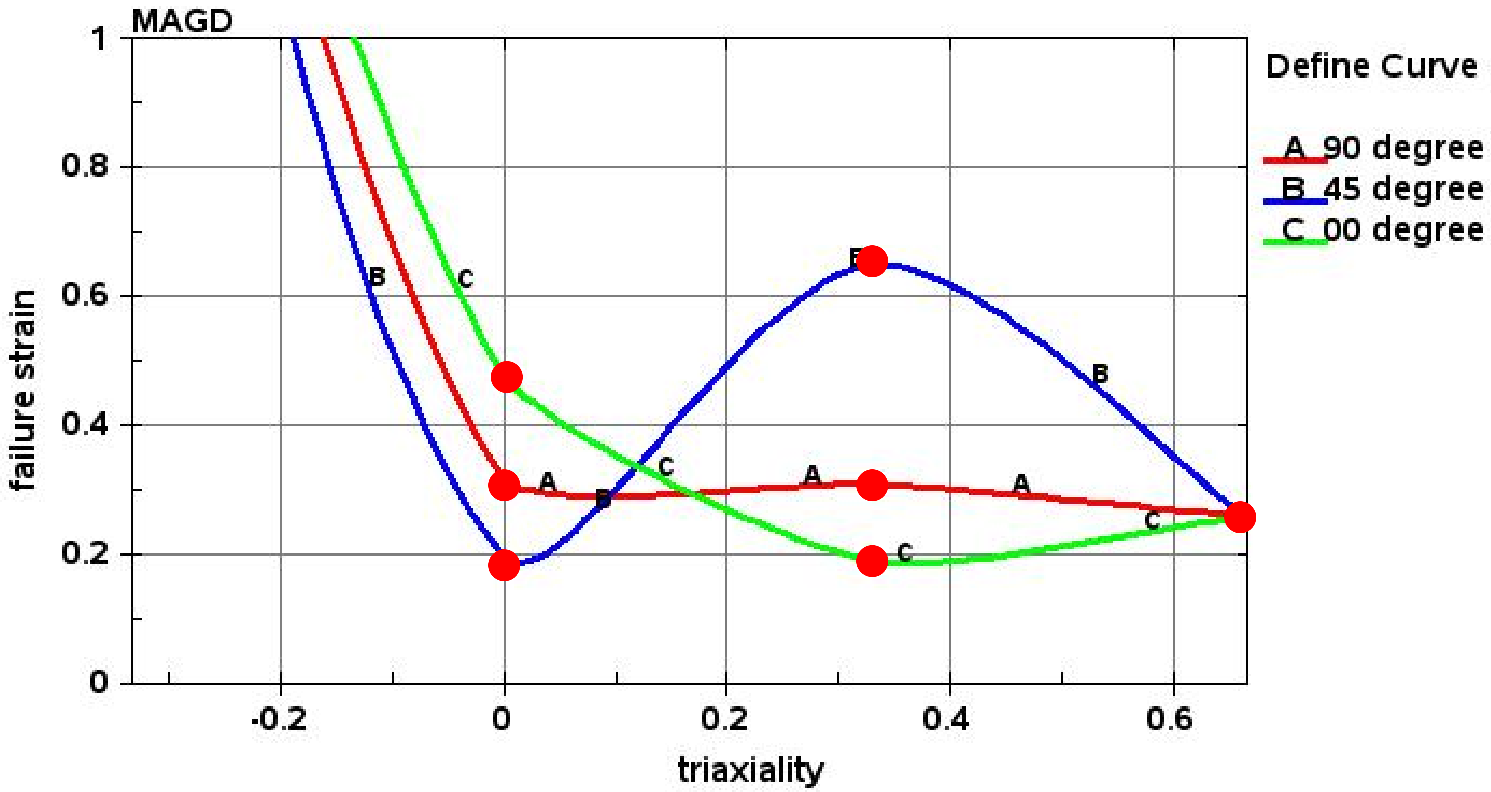
MAGD and Al7108

- For MAGD we ‘invent’ a fourth datapoint and set the failure strain in uniaxial compression to 2.0
- We can then generate 3 load curves LCSDG for 3 GISSMO cards matching all the available datapoints exactly
- The datapoints are connected by a SPLINE function (Splinifyer)
- These load curves show the failure strains under proportional loading

	tension	shear	biaxial
00 degree	0.19	0.48	0.26
45 degree	0.65	0.20	0.26
90 degree	0.31	0.32	0.26

MAGD and Al7108

- Curves LCSDG : 7 datapoints matched



Visualisation of anisotropic failure surface

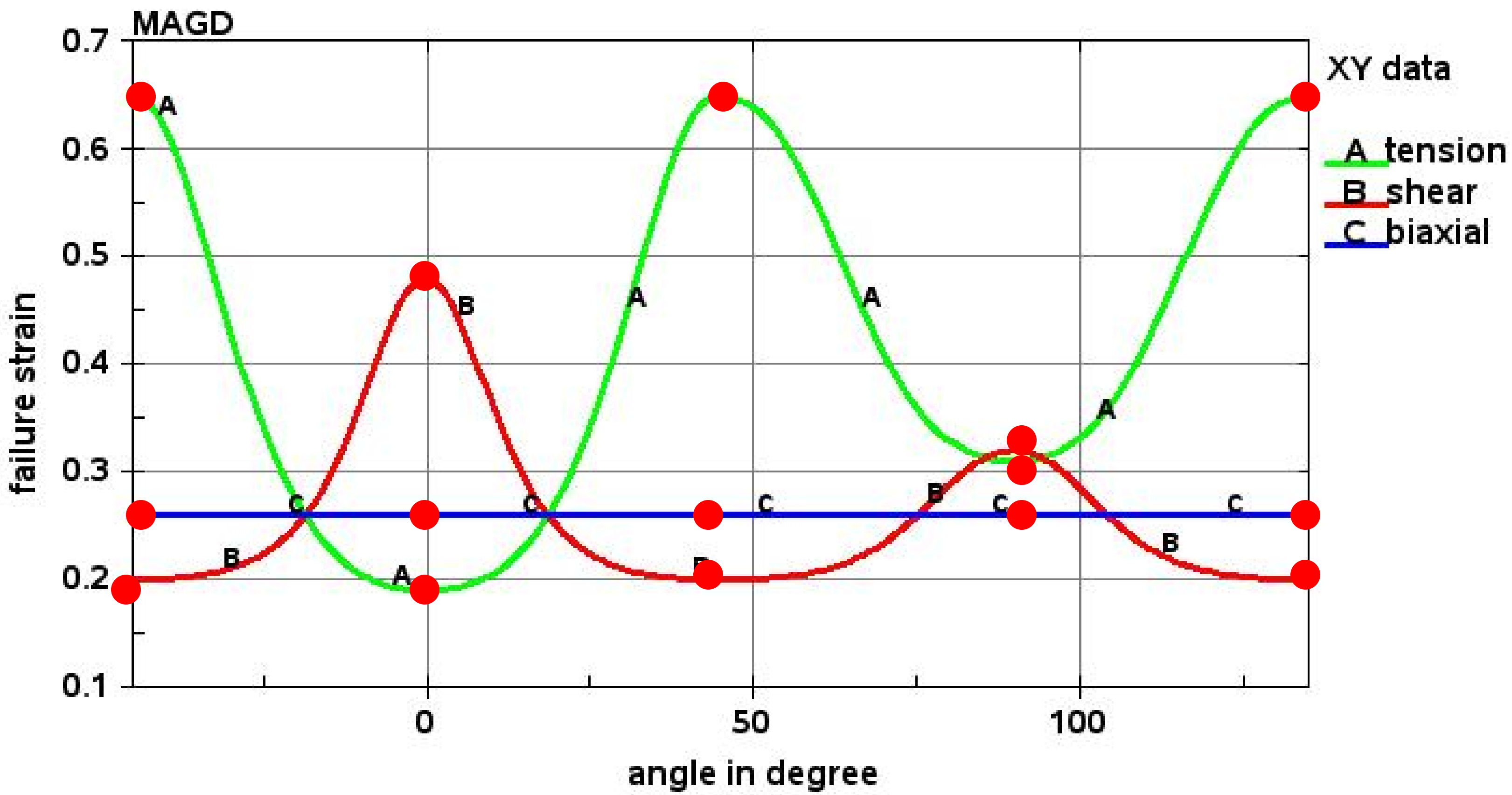
- We know the failure curves for 00 / 45 / 90 degrees
- Then for every value of triaxiality and every angle we get the failure strain as a function of the failure strains in 00 / 45 / 90 at the same triaxiality

$$00 \le g \le 45 \Rightarrow \pounds^{g}_{fail} = \sqrt{\frac{5\cos^2 g \sin^2 g + \cos^4 g - 2\cos^3 g \sin g}{\left(\frac{2\cos g \sin g}{\pounds^{45}_{fail}}\right)^2 + \left(\frac{\cos^2 g - \cos g \sin g}{\pounds^{00}_{fail}}\right)^2}}$$

$$45 \le g \le 90 \Rightarrow \pounds^{g}_{fail} = \sqrt{\frac{5\cos^2 g \sin^2 g + \sin^4 g - 2\cos g \sin^3 g}{\left(\frac{2\cos g \sin g}{\pounds^{45}_{fail}}\right)^2 + \left(\frac{\sin^2 g - \cos g \sin g}{\pounds^{90}_{fail}}\right)^2}}$$

MAGD and Al7108

- Note the monotonic Interpollation over the anisotropy angle
- Variation of failure strain with the angle between extrusion/principal



MAGD and Al7108

- This example shows the ability of the MAGD model to fit a high number of experimental datapoints
- However proportional loading (and failure on the LCSDG) was assumed, this is not reality
- Next we show an industrial example where detailed simulations were used to determine the MAGD input parameters taking non-proportional loading and localisation of plastic strain into account

Aluminium extrusions

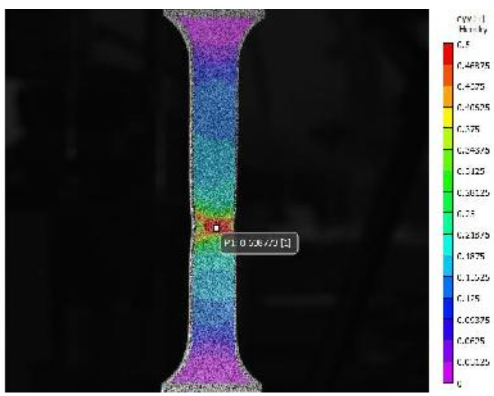
- Lightweight material
- Fracture is an issue
- Increasing use in automotive industry
- Yield seems mildly anisotropic or even isotropic
- Flow is strongly anisotropic , indicating non-associated flow

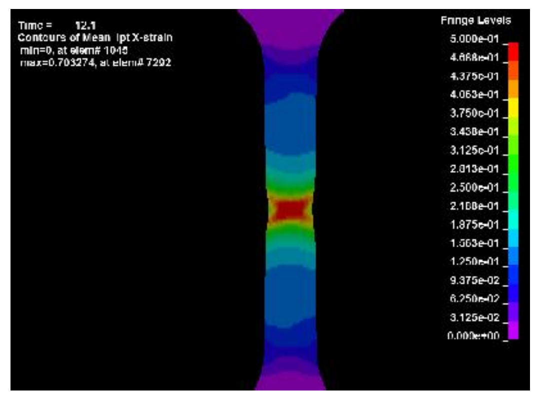
1	Time	Displacem	Load	Eng. Strain	Eng. Stress	True Strair	True Stress		Hencky Strain State - Failure Point				
2	(s)	(mm)	(N)		(MPa)		(MPa)		exx	eyy	exy	e1	e2
3	0	0	563.0887	0	27.49462	0	27.49462		1.05E-17	-2.9E-17	-3.3E-18	1.08E-17	-2.9E-17
4	0.5	-0.00178	628.6324	-3.5E-05	30.695	-3.5E-05	30.69392		4.99E-05	-0.00062	-0.00025	0.000133	-0.00071
5	1	-0.00165	616.5137	-3.3E-05	30.10327	-3.3E-05	30.10228		0.000316	-0.00053	-0.00016	0.000345	-0.00056
6	1.5	-0.00043	325.3973	-8.6E-06	15.88857	-8.6E-06	15.88844		-0.00016	-0.00066	-0.00045	0.000106	-0.00093
7	2	-0.00013	543.7942	-2.5E-06	26.5525	-2.5E-06	26.55244		-0.00012	-0.00037	-0.00025	3.49E-05	-0.00052
8	2.5	-0.00043	142.019	-8.5E-06	6.934536	-8.5E-06	6.934477		-0.00016	-0.00023	-0.00033	0.000136	-0.00052
9	3	-0.00072	585.7463	-1.4E-05	28.60095	-1.4E-05	28.60054		0.00011	-0.00061	-0.00027	0.000199	-0.00069
10	3.5	-0.00155	26.409	-3.1E-05	1.289505	-3.1E-05	1.289465		5.98E-05	-0.00052	-0.00028	0.000177	-0.00064
11	4	-0.00044	229.7394	-8.8E-06	11.21777	-8.8E-06	11.21767		0.000137	-0.00037	-0.00022	0.000216	-0.00045

- R-values can be very accurately measured using DIC
- Values are highly directionally dependent in extrusions

Aluminium extrusions

- For crash simulations the prime concern is and remains capturing the correct stress levels
- However the R-values (anisotropic flow) will influence the failure
- Need to capture the strain field prior to failure to predict failure

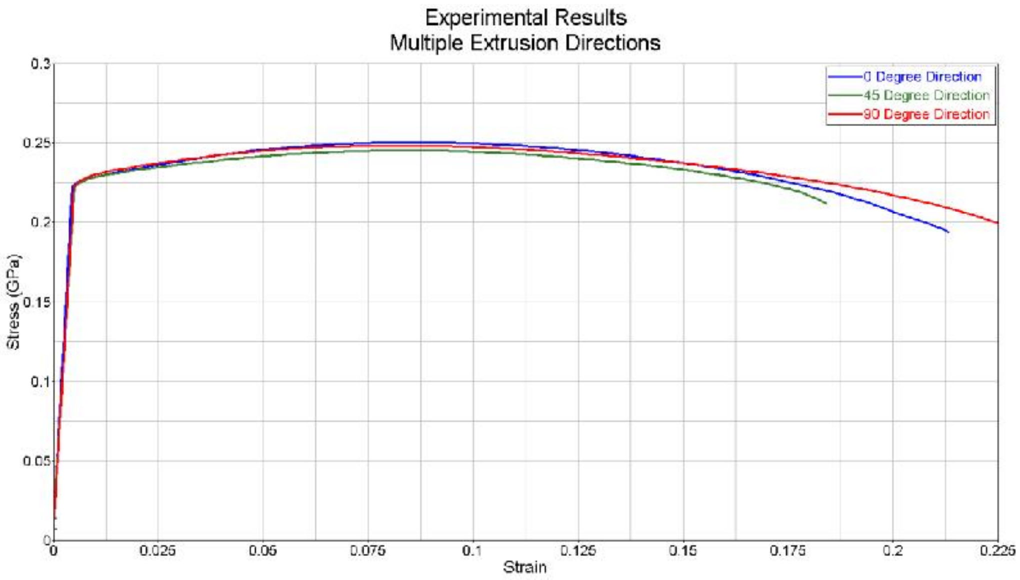




- This leads to a consideration of anisotropy in the crash simulation
- Possible as the extrusion direction is known
- Interest goes up to failure...far beyond necking, this has lead to the introduction of distortional hardening (multiple yield curves)

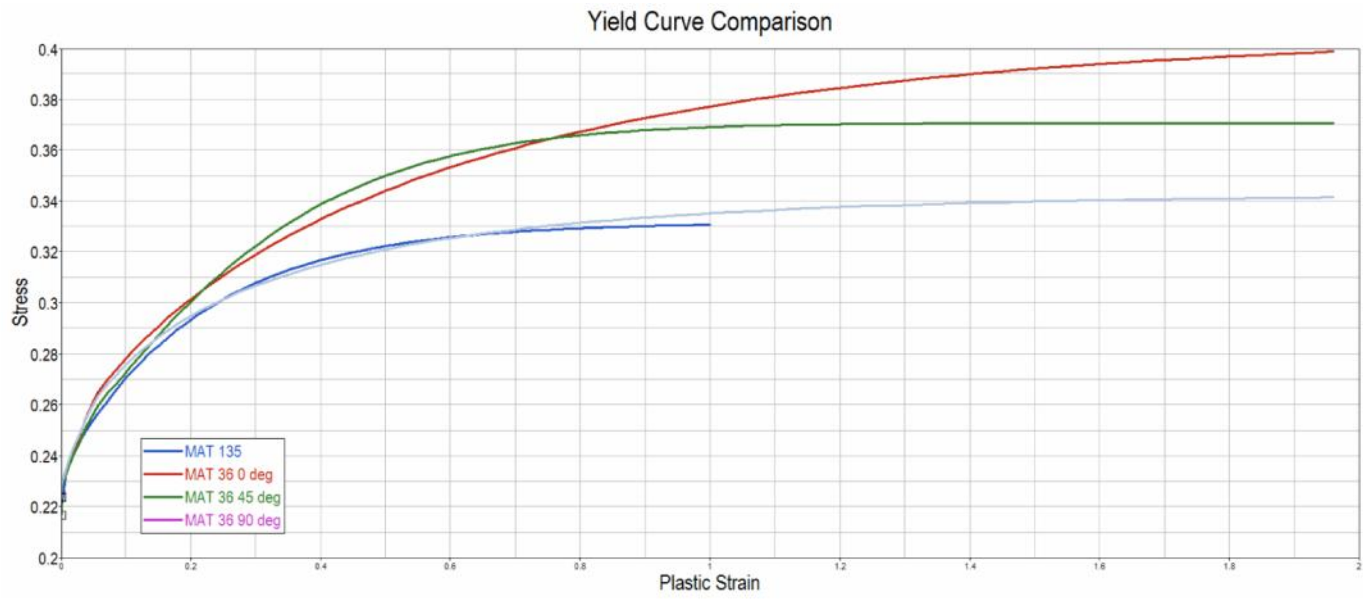
Aluminium extrusion AW6060-T66

- Material has isotropic yield

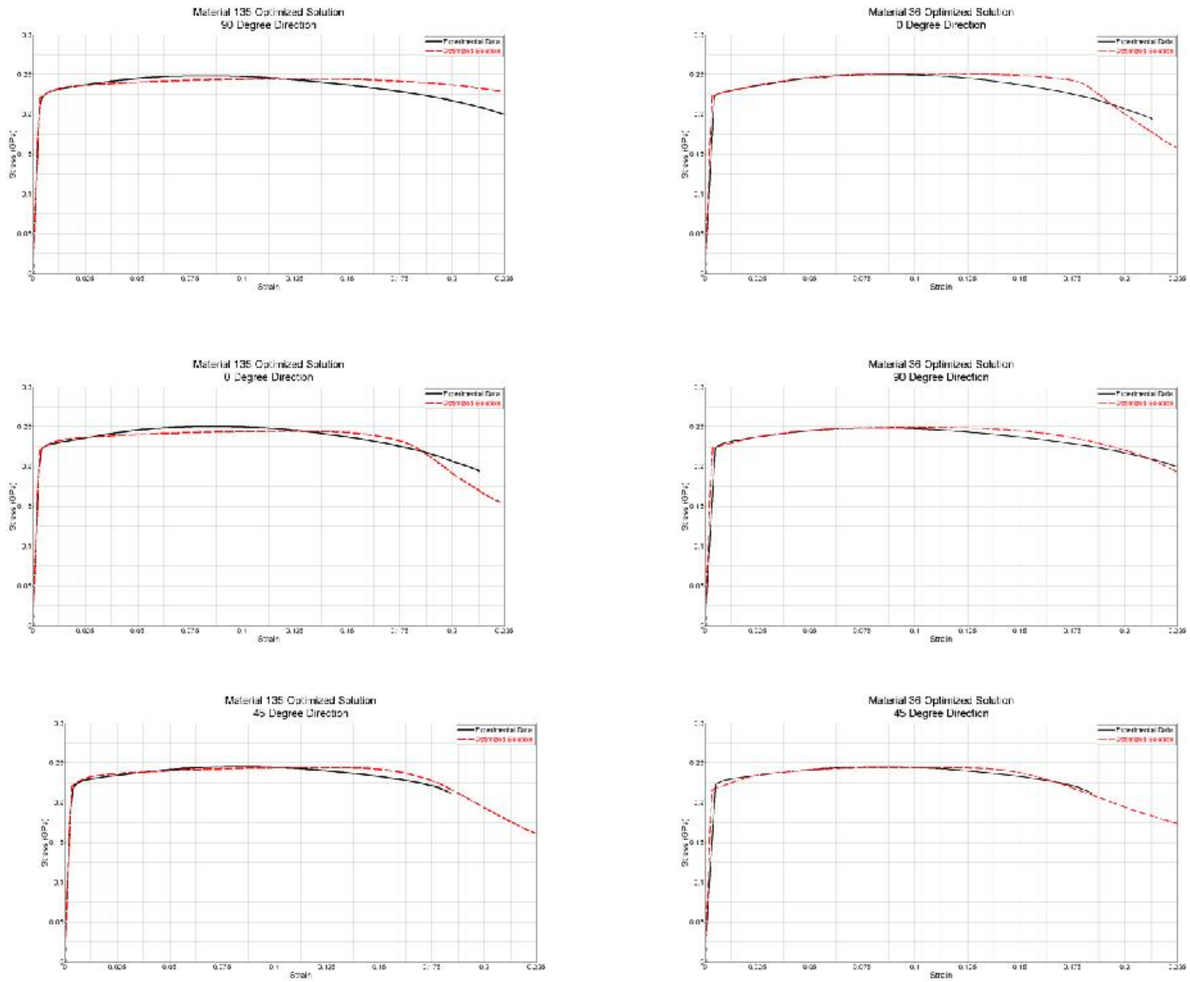


Alumimium extrusion AW6060-T66

- Reference shows R values as: R00 = 0.48, R45 = 0.29, R90 = 1.76
  - "Bumper Beam Longitudinal System Subjected to Offset Impact Loading" Kokkula (PhD Thesis)
  - AA-6060 T1 Aluminum
- R values for AW-6060 T66 are: R00 = 0.49, R45 = 0.27, R90 = 1.69

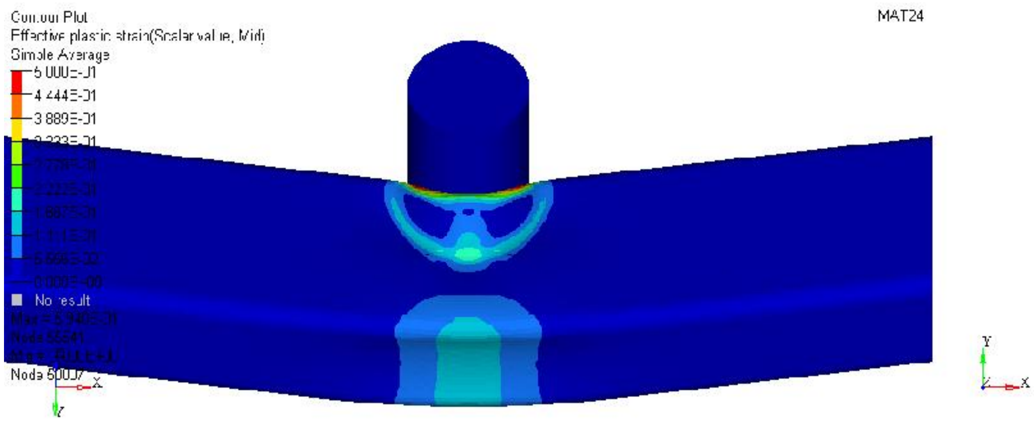


Aluminium extrusion AW6060-T66

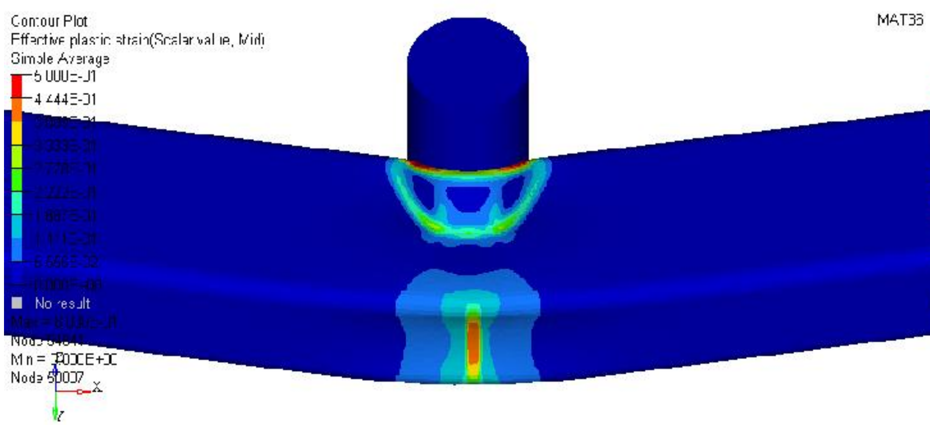


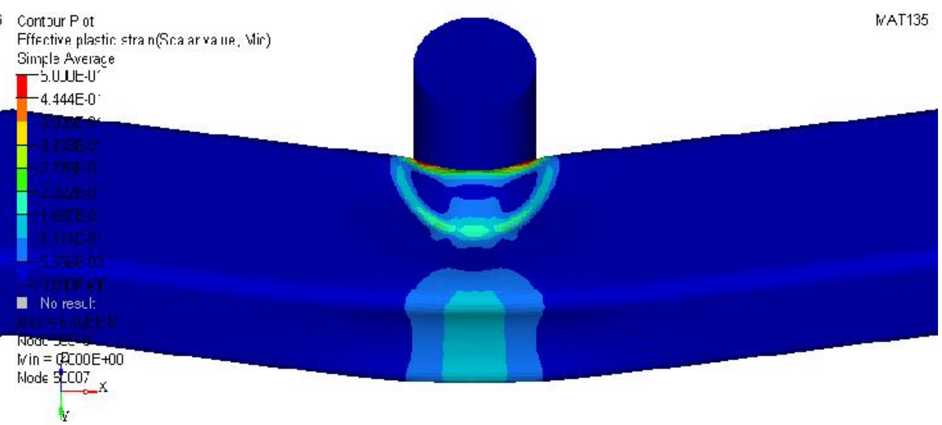
Comparison between elasto-plastic models with self-similar hardening (Aretz) and distortional hardening (Fleischer-Borrvall)

Aluminium extrusion AW6060-T66

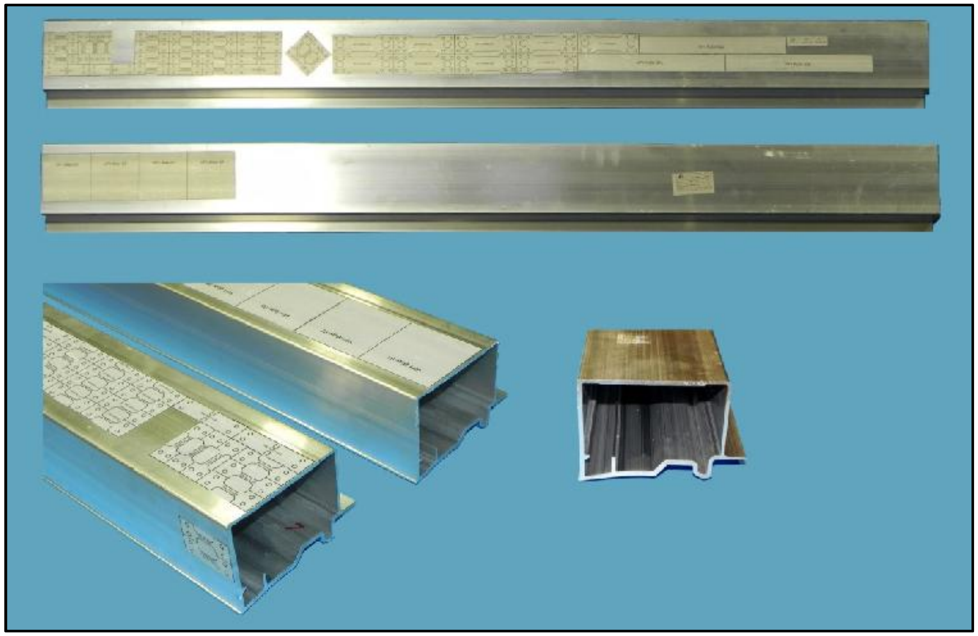


Reference :
Testing and Validation of a New Damage Model for Application in Automotive Crashworthiness Simulations
Sean Haight, 2012 (internal report)

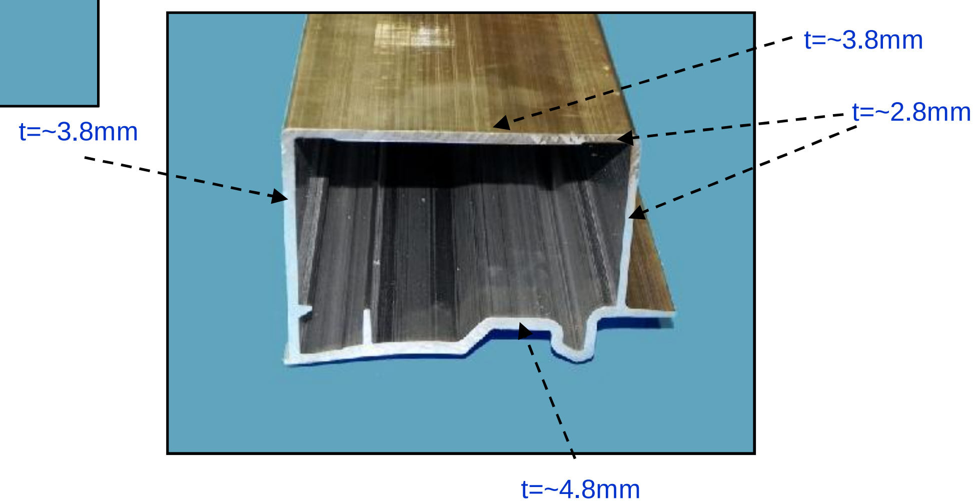




Experimental data AW6082-T6



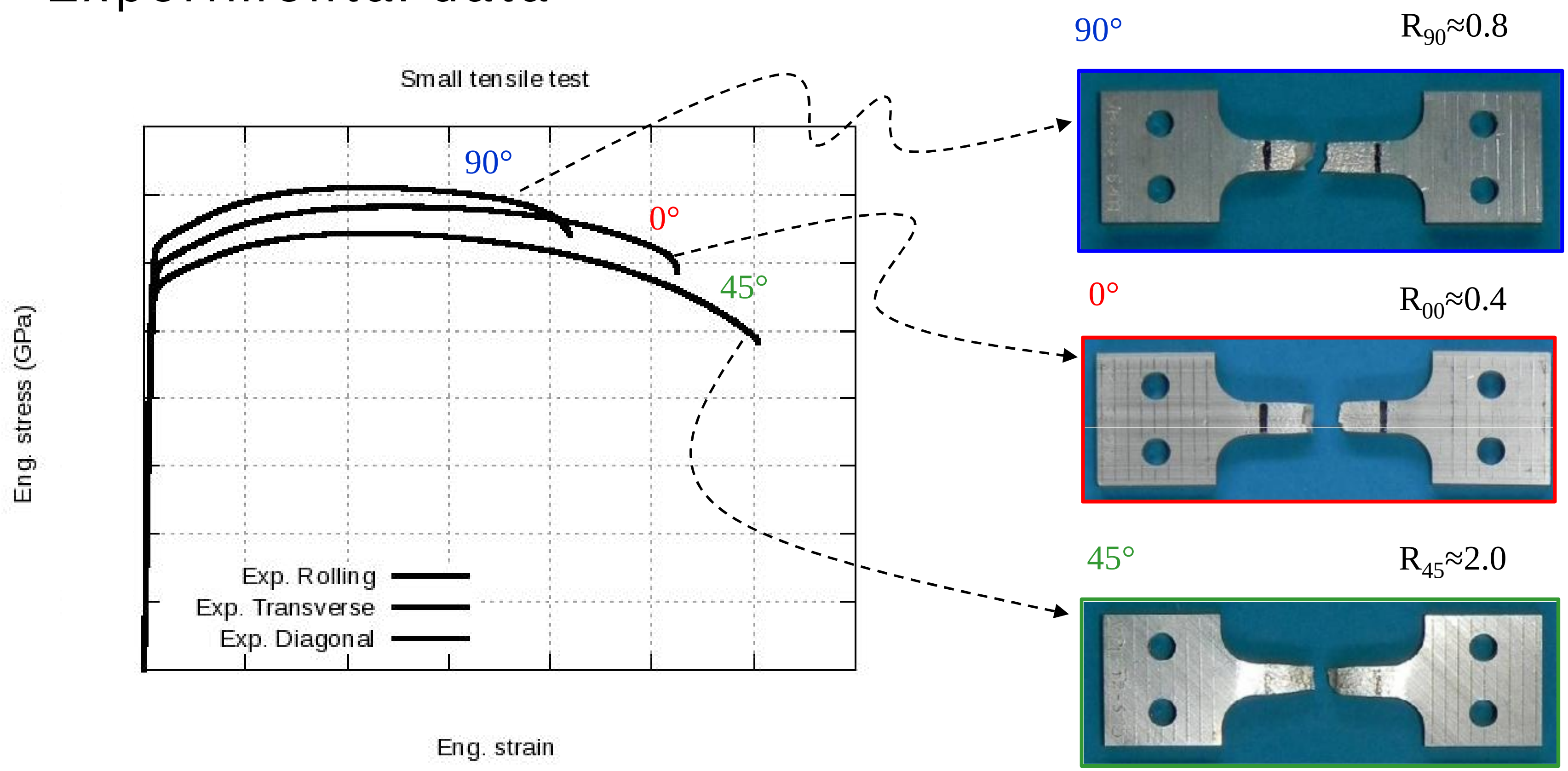
Specimens cut from a thick-walled aluminum extrusion



Fraunhofer IWM

Experiments conducted at the Fraunhofer Institute for Mechanics of Materials in Germany

Experimental data

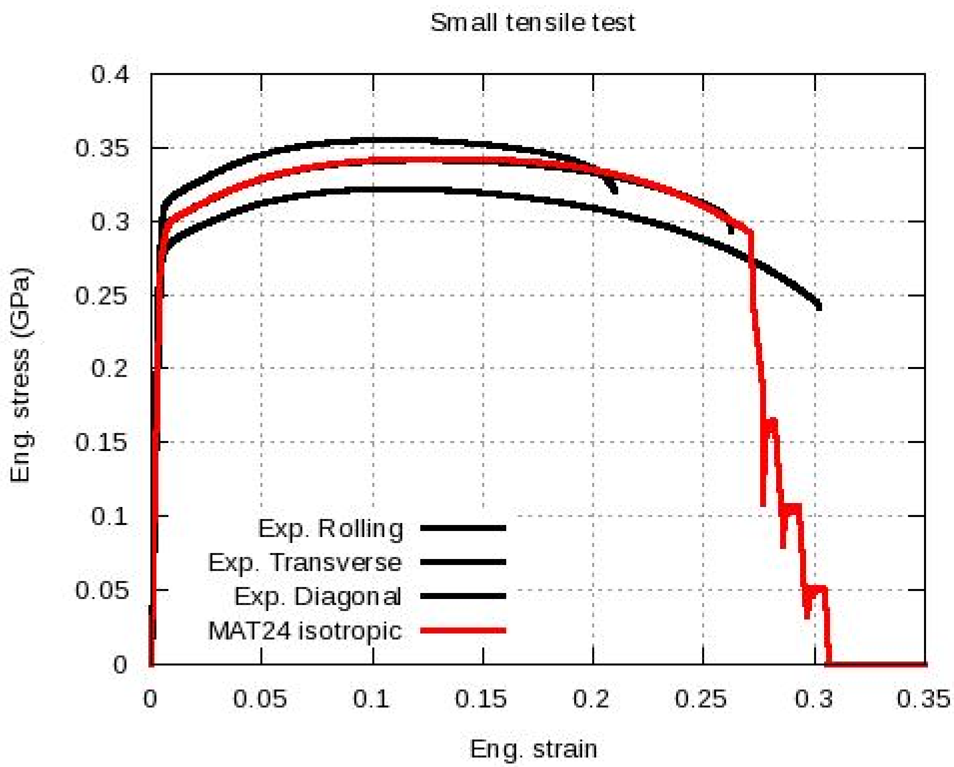


Experiments conducted at the Fraunhofer Institute for Mechanics of Materials in Germany

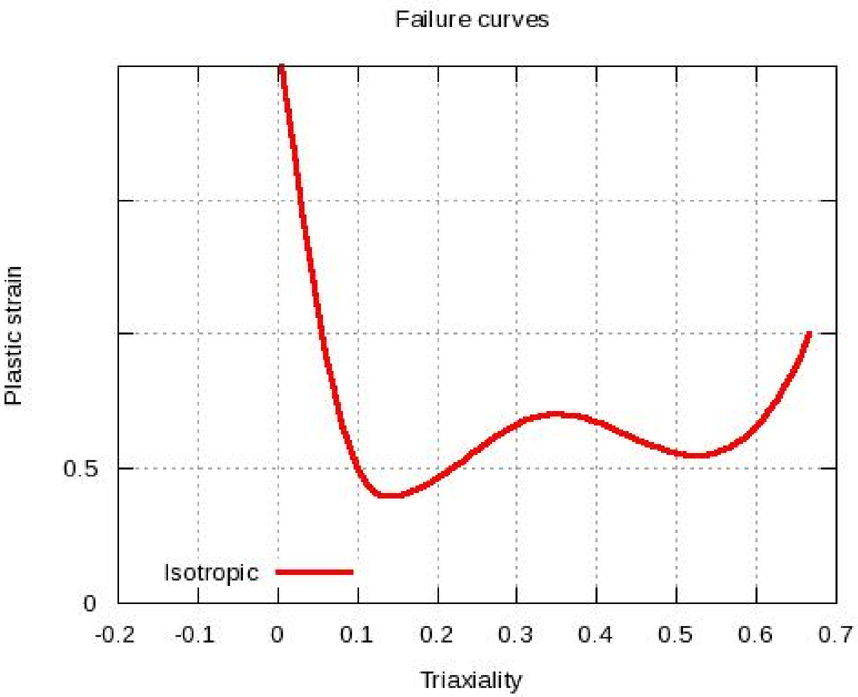
- Large variation of the R-values in the different directions
- Visibly less necking in rolling and transverse directions
- The material is more ductile in the diagonal direction
- Plastic straining and fracture are strongly orientation dependent

Material modeling in LS-DYNA

Isotropic plasticity (*MAT_024)
Isotropic damage (*MAT_ADD_EROSION)

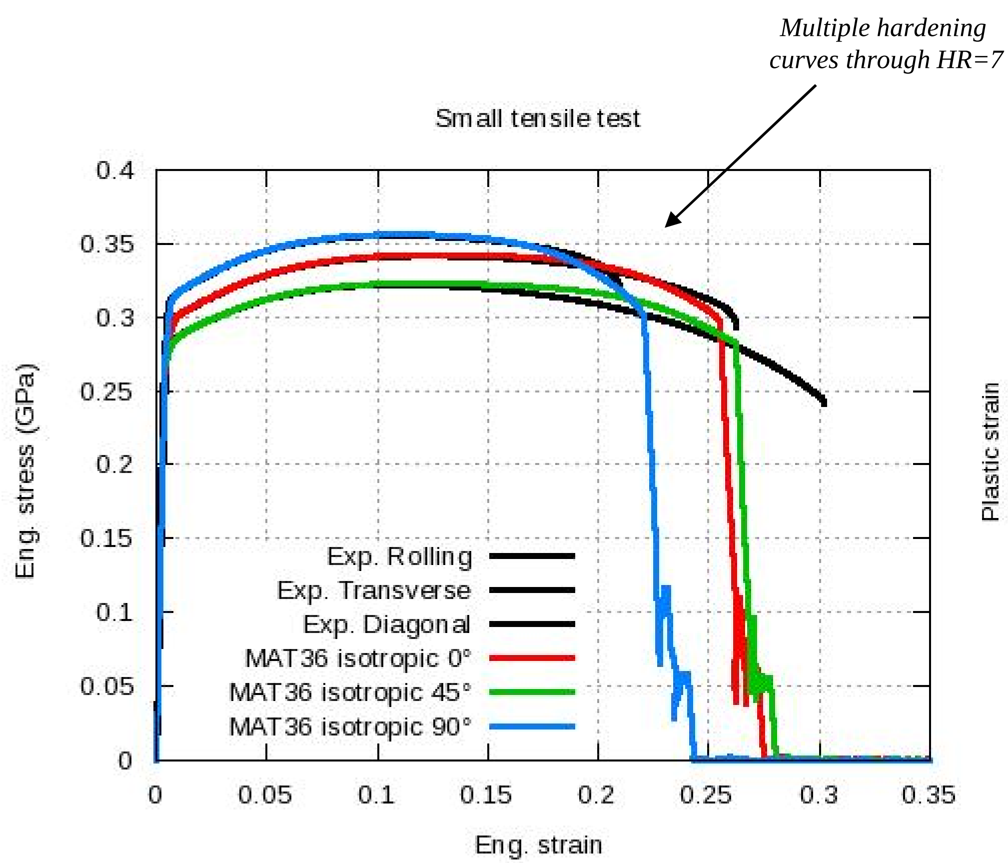


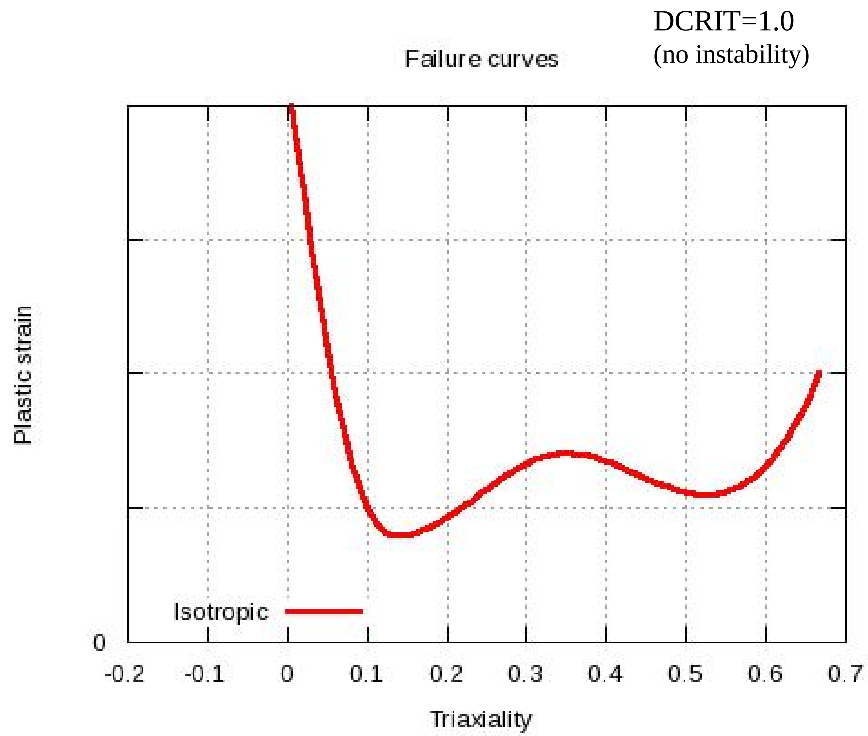
DCRIT=1.0
(no instability)



Material modeling in LS-DYNA

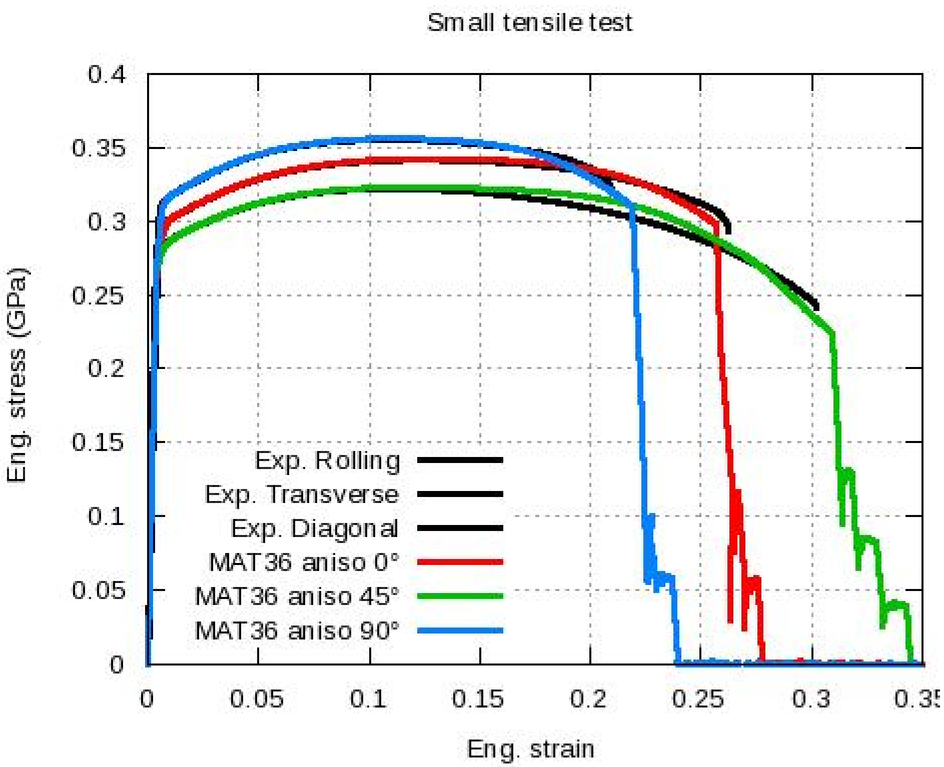
Anisotropic plasticity (*MAT_036)
Isotropic damage (*MAT_ADD_EROSION)



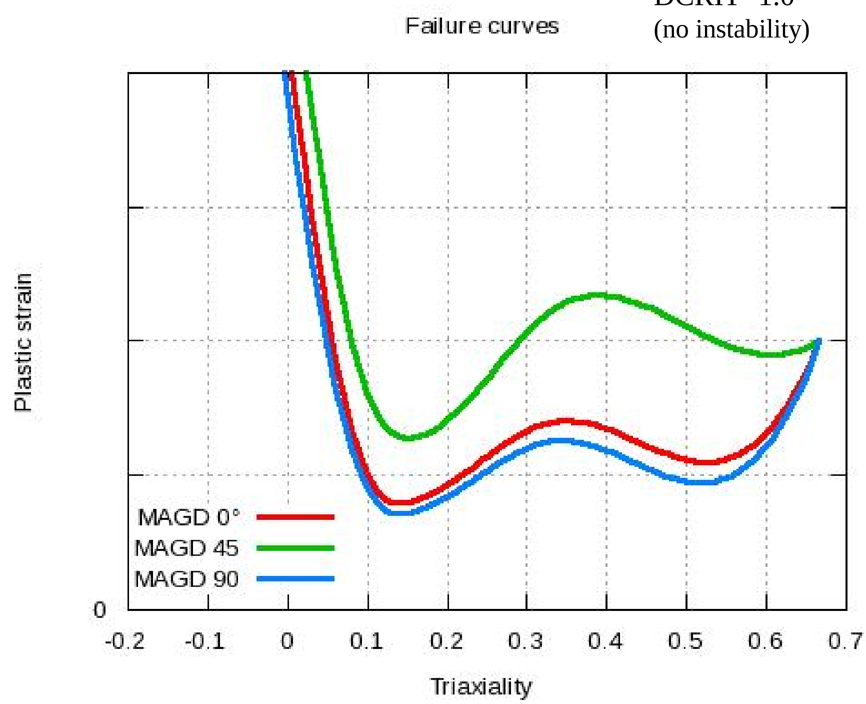


Material modeling in LS-DYNA

Anisotropic plasticity (*MAT_036)
Anisotropic damage (*MAT_ADD_GENERALIZED_DAMAGE

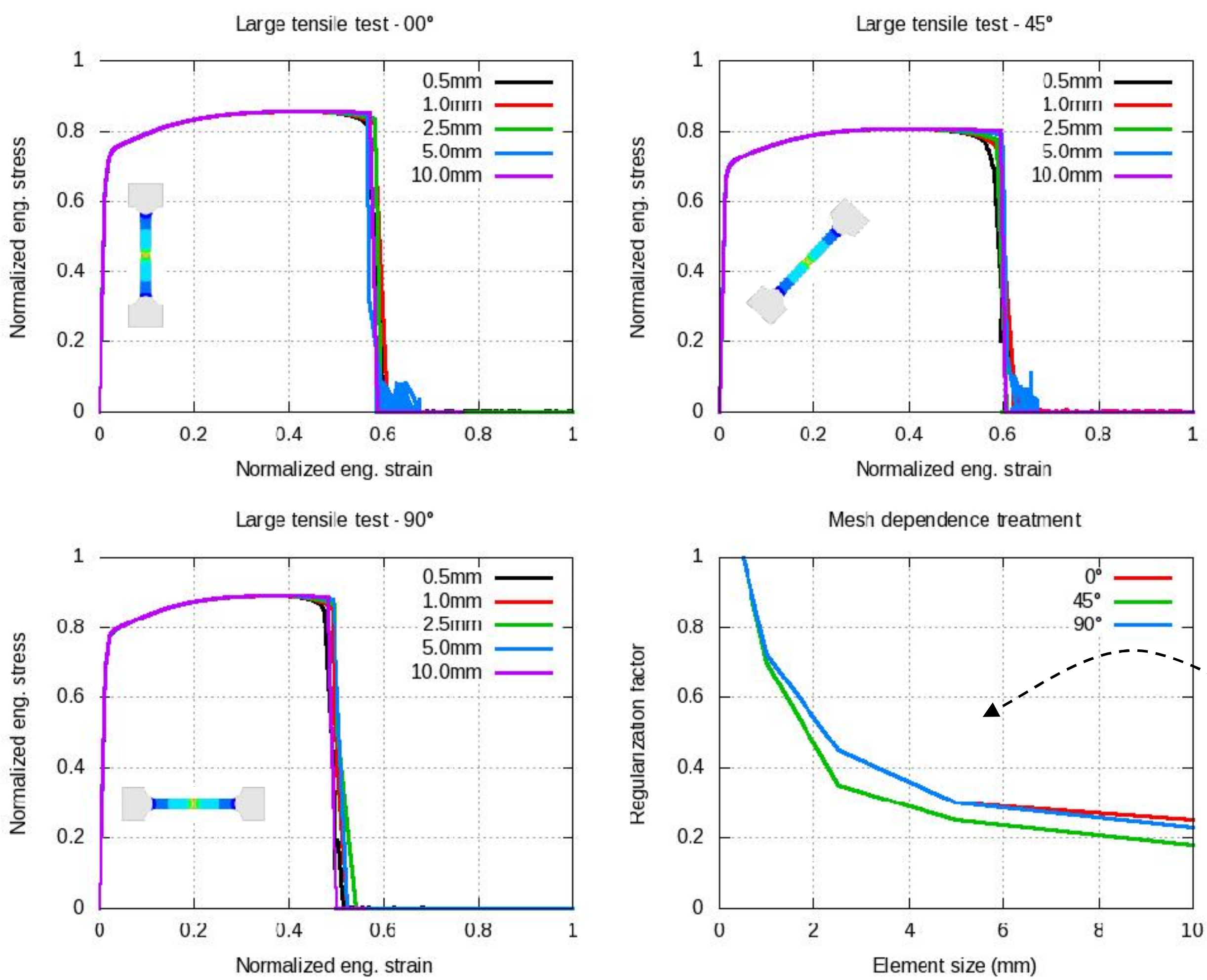


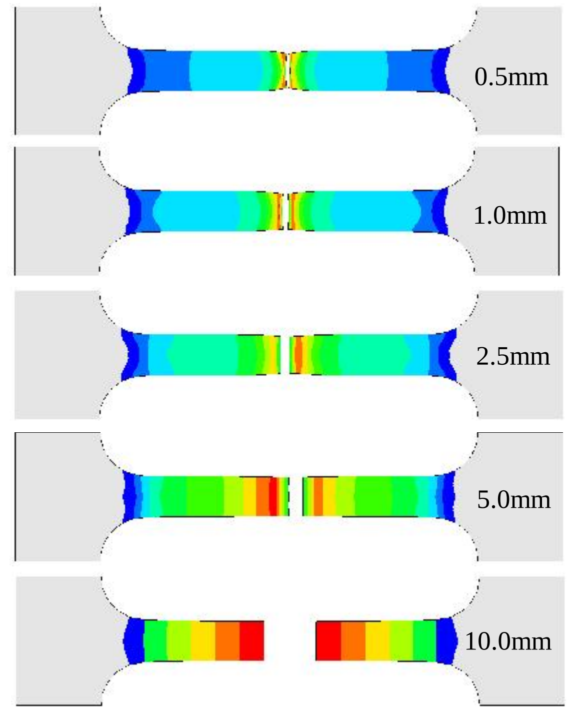
DCRIT=1.0
(no instability)



Material modeling in LS-DYNA

*MAT_036 + *MAT_ADD_GENERALIZED_DAMAGE
Treatment of the mesh dependence



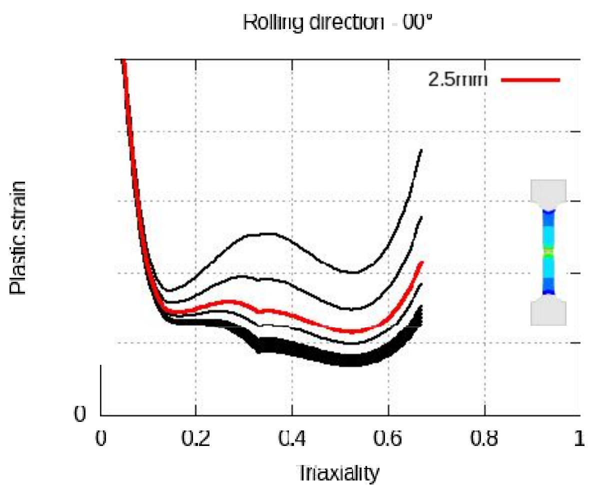


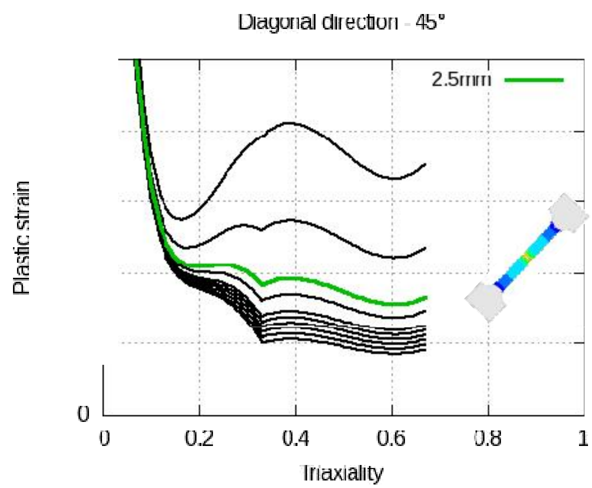
Regularization depends on the orientation

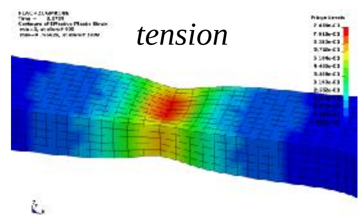
Material modeling in LS-DYNA

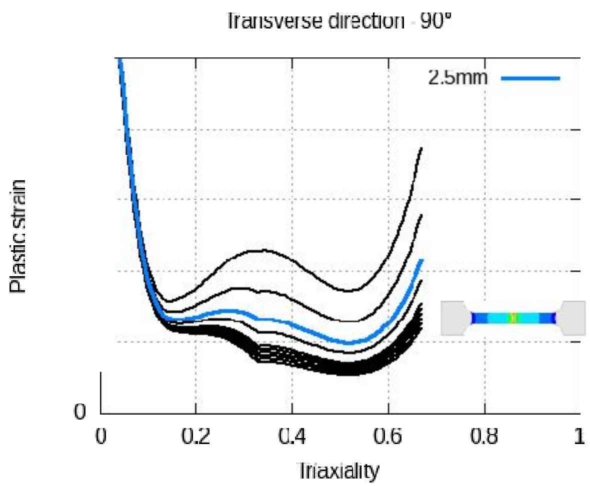
*MAT_036 + *MAT_ADD_GENERALIZED_DAMAGE

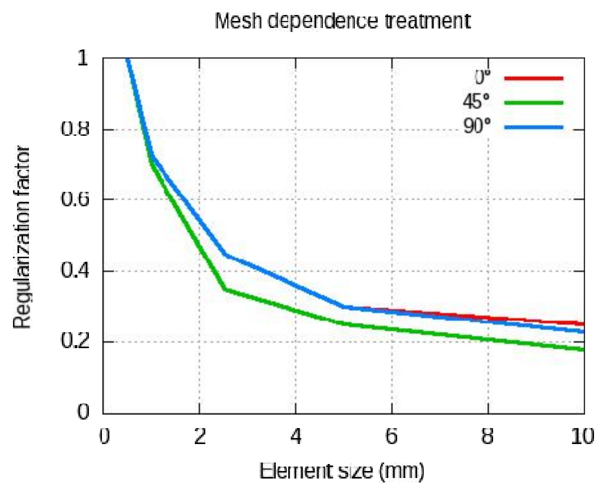
Treatment of the mesh dependence – influence of the triaxiality

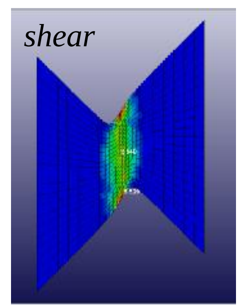












Regularization also depends on the stress state! The flags SHRF and BIAXF can be defined in different directions

Conclusions

- Due to pronounced anisotropic flow the prediction of failure in aluminium extrusions has been an elusive goal
- Progress was made thanks to extensive code development in both plasticity (MAT_036) and anisotropic failure (M_A_G_D)
- Remarkable work done by Thomas Borrvall from Dynamore Nordic and Tobias Erhart from Dynamore
- The development was customer driven by Mercedes-Benz and Honda-NA
- The orthotropic failure model in M_A_G_D is to our knowledge the only failure model that allows for directional dependency of the failure strain upon the state of stress
- Procedures need to be developed for the data generation of aluminium extrusions to speed up the process
- Magnesium extrusions could be even more challenging

Potential further development

- Increasing NHIS to 4 would allow simultaneous consideration of 3 inplane and 1 OOP failure criteria
- Modeling self-healing can be achieved by modifying the damage evolution equation as follows :

$$\dot{d} = n\left|d\right|^{1-\frac{1}{n}} \frac{\text{£}_{his}}{\text{£}_{pf}}$$

- This may however compromise the robustness of the model
- Complete the QA for solid elements
- Validate in component and full vehicle models

The (preliminary) end