Short Introduction of a
New Generalized Damage Model

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1 Introduction

Sound numerical models for material behavior and material failure are essential for reliable predictions in computational mechanics and simulations, e.g., in the areas of crashworthiness, metal forming applications, structural strength analysis, among others. For the material behavior itself, a vast number of models exist to constitute elastic stiffness, plastic flow, rate and thermal dependence, either for isotropic or anisotropic materials. When it comes to degradation and failure, either simple brittle rupture criteria or more advanced damage models exist to simulate the degradation process. In this contribution, we will concentrate on the latter subject and give a first insight into a new general approach to model multi-parameter anisotropic damage.

In LS-DYNA, several constitutive models exhibit properties that are based on Continuum Damage Mechanics (CDM). Associated isotropic or anisotropic stress degradation represents softening and failure behavior of metals (e.g., `*MAT_081` or `*MAT_104`), composites (e.g., `*MAT_221`), polymers (e.g., `*MAT_187`), and other material types. As an alternative, sophisticated (stress state dependent) damage models such as GISSMO [1, 2] or DIEM [3] can be used as add-ons to a wide range of standard material models through the `*MAT_ADD_EROSION` keyword.

In the release of LS-DYNA version R9, a new keyword `*MAT_ADD_GENERALIZED_DAMAGE` (MAGD) was added as a further step towards an even more versatile tool in this area. The primary idea was to provide non-isotropic (tensor type) damage with multiple independent damage variables. The user can define the entries of the damage tensor by functional input to achieve maximum flexibility. The evolution of damage variables is driven by strain based values that can be determined in a number of ways. They can either be arbitrary history variables of the accompanying material model or quantities derived from the plastic strain tensor. In this respect, transformations of that tensor to the principal strain system or to the local system of material directions can be selected. Besides the possibility of using individual plastic strain tensor components as damage driving quantities, functional combinations of them are also allowed. For the damage evolution laws itself, the GISSMO approach can be used where corresponding input variables (such as stress state dependent failure strain, regularization, etc.) can be defined separately for each damage parameter.

This paper is organized as follows: in Section 2, a short review of continuum damage mechanics is given focusing on the transition from isotropic to anisotropic damage. The new generalized damage model will then be presented in detail in Section 3. Numerical examples in Section 4 demonstrate the various possibilities of how the new approach could be used. Finally, conclusions and an outlook are given in Section 5.

2 Isotropic and anisotropic damage

The area of *continuum damage mechanics* (CDM) is a subfield of solid mechanics that covers the weakening and failure of materials as a consequence of degradation processes on a micro-mechanical level (see Fig.1). The creation and growth of microvoids and microcracks are of discontinuous nature, but in CDM they are considered as a continuous homogenized measure ("internal damage") at a larger scale. A wide range of literature exists in this research area, just to mention the textbooks by Kachanov [4], Krajcinovic [5], and Lemaitre [6] as an introduction to the topic. Here, we will only focus on a few aspects of that field to explain the transition from isotropic to anisotropic damage.
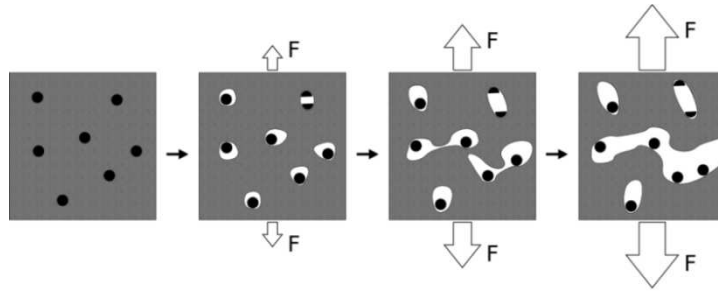
Fig.1:   Schematic illustration of nucleation, growth and coalescence of microvoids (Wikipedia)

One of the basic ideas of CDM is the effective stress concept that leads to the scalar relation between damaged (or nominal) stress σ and the undamaged (or effective) stress $\tilde{\sigma}$ in the uniaxial case:

$$\sigma = (1 - D)\,\tilde{\sigma} \tag{1}$$

In the equation above, D represents the internal damage measure that ranges from $D = 0$ for a virgin state of the material to $D = 1$ for a fully fractured condition. If we directly apply this approach to the multiaxial (3-D) case, then we obtain the following expression for the stress tensor $\boldsymbol{\sigma}$:

$$\boldsymbol{\sigma} = (1 - D)\,\tilde{\boldsymbol{\sigma}} \tag{2}$$

Due to the scalar form of the damage variable D, all components of the stress tensor are degraded in a uniform manner. This means that this definition can be interpreted as "isotropic damage", i.e., without any preferred direction. Most material models with damage in LS-DYNA and also the add-on modules GISSMO and DIEM use this approach.

However, damage is often non-isotropic due to microcracking more or less perpendicular to the largest positive principal stress. Another cause is associated to the very anisotropic nature of the material which leads to stronger or weaker directions when it comes to softening and failure. In order to constitute this kind of "anisotropic damage", several authors [7, 8, 9] proposed to introduce a fourth-order damage-effect tensor $\mathbf{M}$:

$$\boldsymbol{\sigma} = \mathbf{M}^{-1}{:}\,\tilde{\boldsymbol{\sigma}} \tag{3}$$

Many different concepts exist for the definition of that tensor, but in general it should have a structure (i.e., arrangement of zero and non-zero entries) similar to common constitutive tensors relating stress and strain tensors. As discussed in the following sections, the general framework of MAGD offers high flexibility in defining that damage tensor or better "damage matrix" since Voigt notation will be used.

In most publications the term "anisotropic damage" refers to the loading direction of the material. The idea behind that concept is that damage apparently grows faster in the direction of maximum principal stress than other directions (for some materials). That could be important in situations where two or more highly directional loads are applied sequentially. Each load will cause microcracks to grow in one preferential direction, affecting the material response to subsequent loads in other directions. This so-called Load Induced Anisotropy in Damage (LIAD) can be interpreted as non-spherical void growth on a microscopic scale (see Fig.2(b)).

On the other hand, anisotropic behavior in damage evolution and failure can be inherent to the virgin material itself. For instance, suppose that a metallic alloy has undergone a rolling or extrusion process or a composite possesses certain fiber directions. In such cases, these materials are designated "anisotropic" not just in their stress-strain behavior but perhaps also in their failure modes. This phenomenon is referred to as Material Induced Anisotropy in Damage (MIAD) according to Niazi et al. [10, 11]. For the constitutive description of such materials, orthotropic elasticity models as well as many different anisotropic plasticity models exist (Hill, Barlat, etc.). However, when it comes to the description of the anisotropic damage mechanics, not much literature exists at the moment, even if there is clear evidence that material failure can heavily depend on the material directions, see Fig.2(a).

The new generalized damage model that we will introduce in the next section is able to deal with LIAD as well as MIAD by providing the possibility to choose between different coordinate systems for the internal damage variables.
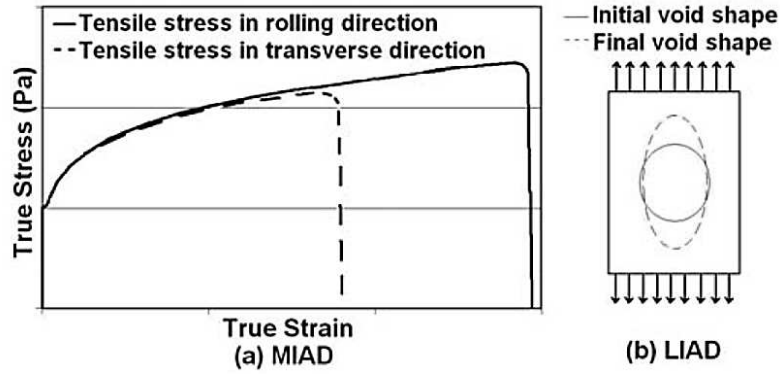
Fig.2:   Two kinds of anisotropic damage: material induced (a) and load induced (b)

3 A new generalized damage model: MAGD

Based on the ideas described above, a new general framework was implemented to add anisotropic damage to already existing material models. Therefore, standard LS-DYNA materials (`*MAT_...`) can now be supplemented by the new keyword `*MAT_ADD_GENERALIZED_DAMAGE`. It allows arbitrary definition of the damage tensor, wide choice of several history variables, different possibilities to define a damage strain coordinate system and separate treatment of damage evolution for each history variable. In the following, these different options are explained in detail accompanied by corresponding input descriptions.

3.1   Definition of the damage tensor

The fourth-order damage-effect tensor $\mathbf{M^{-1}}$ of equation (3) becomes a 6x6 matrix in Voigt notation and will be renamed $\mathbf{D}$ here. With the assumption of orthotropy (two orthogonal planes of material property symmetry), it contains up to 12 non-zero components D_{ij} to describe the relation between nominal (damaged) stresses σ_{ij} and effective (undamaged) stresses $\tilde{\sigma}_{ij}$:

$$\begin{bmatrix} \sigma_{11} \\ \sigma_{22} \\ \sigma_{33} \\ \sigma_{12} \\ \sigma_{23} \\ \sigma_{31} \end{bmatrix} = \begin{bmatrix} D_{11} & D_{12} & D_{13} & 0 & 0 & 0 \\ D_{21} & D_{22} & D_{23} & 0 & 0 & 0 \\ D_{31} & D_{32} & D_{33} & 0 & 0 & 0 \\ 0 & 0 & 0 & D_{44} & 0 & 0 \\ 0 & 0 & 0 & 0 & D_{55} & 0 \\ 0 & 0 & 0 & 0 & 0 & D_{66} \end{bmatrix} \begin{bmatrix} \tilde{\sigma}_{11} \\ \tilde{\sigma}_{22} \\ \tilde{\sigma}_{33} \\ \tilde{\sigma}_{12} \\ \tilde{\sigma}_{23} \\ \tilde{\sigma}_{31} \end{bmatrix} \tag{4}$$

In the plane stress case, e.g., for standard shell elements, the out-of-plane stress component σ_{33} is zero and therefore the damage matrix can be rearranged like this:

$$\begin{bmatrix} \sigma_{11} \\ \sigma_{22} \\ 0 \\ \sigma_{12} \\ \sigma_{23} \\ \sigma_{31} \end{bmatrix} = \begin{bmatrix} D_{11} & D_{12} & 0 & D_{14} & 0 & 0 \\ D_{21} & D_{22} & 0 & D_{24} & 0 & 0 \\ 0 & 0 & D_{33} & 0 & 0 & 0 \\ D_{41} & D_{42} & 0 & D_{44} & 0 & 0 \\ 0 & 0 & 0 & 0 & D_{55} & 0 \\ 0 & 0 & 0 & 0 & 0 & D_{66} \end{bmatrix} \begin{bmatrix} \tilde{\sigma}_{11} \\ \tilde{\sigma}_{22} \\ 0 \\ \tilde{\sigma}_{12} \\ \tilde{\sigma}_{23} \\ \tilde{\sigma}_{31} \end{bmatrix} \tag{5}$$

If requested, the non-zero entries D_{14}, D_{24}, D_{41} and D_{42} allow for a more general anisotropy than in the 3-D case (equation 4). Now, each of the damage tensor components D_{ij} is a function of up to three damage variables D_1, D_2, and D_3:

$$D_{ij} = f(D_1, D_2, D_3) \tag{6}$$

In the input format of `*MAT_ADD_GENERALIZED_DAMAGE` [12] this is realized by using the `*DEFINE_FUNCTION` capability: on cards 3 and 4, function identifiers can be defined for each of the 12 coefficients. The corresponding functions contain arithmetic expressions using the three damage variables d1, d2, and d3. For example,

```
*MAT_ADD_GENERALIZED_DAMAGE
...
$       D11        D22        D33        D44        D55        D66
          1          2          3          4          5          6
$       D12        D21        D23        D32        D13        D31
          7          8          9         10         11         12
...
*DEFINE_FUNCTION
          1
func1(d1,d2,d3)=1.0-d1
*DEFINE_FUNCTION
          2
func2(d1,d2,d3)=1.0-d2
*DEFINE_FUNCTION
          3
func3(d1,d2,d3)=1.0
...
```

The damage matrix has to be inverted in each calculation step which is less time consuming if only a diagonal matrix (i.e., when all non-diagonal terms are zero) is used. This is not necessary, but if this is the case, then card 4 should be left blank so that LS-DYNA automatically benefits from this circumstance. It is also good practice to define non-zero values for all diagonal terms on card 3, i.e., for stress components that are not affected by damage a function with a value of "1.0" should be specified (such as function 3 in the example above).

3.2 Choice of history variables (IFLG1)

The evolution of damage is driven by internal variables or so-called "history" variables. Currently, it is possible to specify a maximum number of 3 simultaneous history variables (NHIS) for the damage evolution. In MAGD, there are different possibilities to define these history variables and this is related to the definition of the parameter IFLG1. These variables can either be arbitrary histories from the material model at hand (IFLG1=0), specific components of the plastic strain tensor (IFLG1=1) or some special predefined functions also based on the the plastic strain tensor components (IFLG1=2). The different options are summarized in Table 1. The blue and green fields will be elucidated in the next section.

	IFLG1=0	IFLG1=1	IFLG1=2
$HIS_n=0$	plastic strain	plastic strain tensor components (see 3.3)	special predefined functions [13, 14]
$HIS_n>0$	history variable n	n.a.	n.a.
$HIS_n<0$	n.a.	user defined functions via `*DEFINE_FUNCTION` (see 3.3)	n.a.

Table 1: Different options to define history variables as damage driving quantities.

From a physical point of view and also in accordance with the principle of strain equivalence, damage is usually driven by the energy density release rate and/or the plastic strain rate. In the case of elastoplasticity coupled with anisotropic damage, certain components of the plastic strain rate tensor are commonly used. Therefore, this tensor is needed for the evolution of the damage variables. However, due to algorithmic reasons, LS-DYNA neither explicitly calculates nor stores the plastic strain rate tensor. Therefore, an assumption is used in MAGD based on the effective plastic strain rate $\dot{\varepsilon}^p_{eff}$ (which is available for all plasticity based models) and the total strain rate tensor $\dot{\varepsilon}$ (also always available) to obtain the plastic strain rate tensor $\dot{\boldsymbol{\varepsilon}}^p$:

$$\dot{\boldsymbol{\varepsilon}}^p = \frac{\dot{\varepsilon}^p_{eff}}{\dot{\varepsilon}_{eff}}\left[\dot{\boldsymbol{\varepsilon}} - \frac{\dot{\varepsilon}_{vol}}{3}\boldsymbol{\delta}\right] \tag{7}$$

This assumption provides the exact solution for J2 (i.e., von Mises) plasticity models (e.g., `*MAT_024` or `*MAT_124`) and is a fairly good approximation for other metal plasticity models.

The special case IFLG1=2 (along with IFLG2=1 and IFLG3=1) activates some special predefined functions that allow definition of damage and failure in 0°, 45°, and 90° with respect to the material orientation. This approach was used to model orthotropic failure in aluminum extrusions and has already been presented in detail in other publications [13, 14].

3.3 Choice of damage strain coordinate system (IFLG2)

In MAGD, it is also possible to select the coordinate system in which the damage strains (components of the plastic strain tensor) are defined. This is for instance necessary to deal with load induced anisotropic damage (LIAD) or material induced anisotropic damage (MIAD) as mentioned before and later shown in the examples section. The corresponding parameter IFLG2 is used for the selection of the damage strain coordinate system.

The standard description for tensorial quantities in LS-DYNA is either in the local element system for shell elements or in the global Cartesian system for solid elements. No transformations are necessary with the default selection (IFLG2=0).

On the other hand, if the damage strains should be defined in the material system (IFLG2=1), the plastic strain tensor has to be rotated to that material coordinate system. Therefore, the underlying material model must be anisotropic. That condition holds for most material models which possess the material axes option (AOPT in LS-DYNA) for shell elements. Currently supported anisotropic materials for solid elements are no. 22, 33, 41-50, 103, 122, 157, and 233.

If non-isotropic damage evolution should depend on the loading direction, then setting IFLG=2 or 3 would be the correct choice. In that case, the damage strain tensor is rotated into the principal strain system, which is a local quantity that can change in every step. The user can decide if that "rotating" system should always be active (IFLG2=2) or if it should be fixed when instability takes place (IFLG2=3). These two options can be interpreted as "rotating crack" and "fixed crack" approaches [15].

With the explanations of IFLG1 and IFLG2 in mind, we can now present the content of each history variable in Table 2 (linked to the blue and green fields from Table 1):

	IFLG1=1 and HIS$_n$=0	IFLG1=1 and HIS$_n$<0
IFLG2=0	HIS$_1 = \dot{\varepsilon}_{xx}^p$, HIS$_2 = \dot{\varepsilon}_{yy}^p$, HIS$_3 = \dot{\varepsilon}_{xy}^p(\dot{\varepsilon}_{zz}^p)$	HIS$_n = f_n\left(\dot{\varepsilon}_{xx}^p, \dot{\varepsilon}_{yy}^p, \dot{\varepsilon}_{zz}^p, \dot{\varepsilon}_{xy}^p, \dot{\varepsilon}_{yz}^p, \dot{\varepsilon}_{zx}^p\right)$
IFLG2=1	HIS$_1 = \dot{\varepsilon}_{aa}^p$, HIS$_2 = \dot{\varepsilon}_{bb}^p$, HIS$_3 = \dot{\varepsilon}_{ab}^p(\dot{\varepsilon}_{cc}^p)$	HIS$_n = f_n\left(\dot{\varepsilon}_{aa}^p, \dot{\varepsilon}_{bb}^p, \dot{\varepsilon}_{cc}^p, \dot{\varepsilon}_{ab}^p, \dot{\varepsilon}_{bc}^p, \dot{\varepsilon}_{ca}^p\right)$
IFLG2=2/3	HIS$_1 = \dot{\varepsilon}_1^p$, HIS$_2 = \dot{\varepsilon}_2^p$, HIS$_3 = \dot{\varepsilon}_3^p$	HIS$_n = f_n\left(\dot{\varepsilon}_1^p, \dot{\varepsilon}_2^p, \dot{\varepsilon}_3^p\right)$

Table 2: Meaning of history variables for different options IFLG2

The sub-indices x, y, and z in Table 2 refer to the local element system for shell elements and the global coordinate system for solid elements, respectively. The sub-indices a, b and c are used to describe the material orientations and 1, 2, and 3 are the principal directions. For shell elements, the third history variable is the shear component, but for solid elements it is the third direction (in brackets). So either specific components of the plastic strain rate tensor are used (HIS$_n$=0) or user defined functions can be specified with all tensor components as arguments (HIS$_n$<0). In the latter case, the ID of a `*DEFINE_FUNCTION` has to be referenced. The following example defines a history variable as an effective transverse shear strain in material coordinate system a-b-c for shells:

```
...
$      HIS1      HIS2      HIS3     IFLG1     IFLG2     IFLG3
     -1234                                       1         1
...
*DEFINE_FUNCTION
      1234
fhis1(eaa,ebb,ecc,eab,ebc,eca)=sqrt(ebc**2+eca**2)
...
```

3.4 Damage evolution

After the choice of the damage tensor setup and the definition of history variables, the evolution laws for the damage variables have to be specified. The idea of MAGD is that each of the NHIS damage variables can be defined independently using the GISSMO parameters and equations. This means that, for each damage variable D_n, the following evolution law applies

$$\dot{D}_n = \text{DMGEXP}_n \cdot D_n^{\left(1 - \frac{1}{\text{DMGEXP}_n}\right)} \cdot \frac{\dot{\text{HIS}}_n}{\varepsilon_{f,n}} \tag{8}$$

where $\dot{\text{HIS}}_n$ is the time derivative of the history variable, $\varepsilon_{f,n}$ is the "failure strain", and DMGEXP_n is an input parameter. In GISSMO, a nonlinear stress coupling term is used incorporating a critical damage value DCRIT_n and a fading exponent FADEXP_n. The same approach is adopted here for each damage variable separately, i.e., the damage variable is internally replaced by this expression:

$$D_n \quad \rightarrow \quad \left(\frac{D_n - \text{DCRIT}_n}{1 - \text{DCRIT}_n}\right)^{\text{FADEXP}_n} \tag{9}$$

All other GISSMO input parameters known from the `*MAT_ADD_EROSION` keyword have to be defined for each history variable. Therefore, $2 \cdot \text{NHIS}$ additional cards are necessary to complete the MAGD input.

4 Examples

The following numerical examples will demonstrate the main functionalities of the new generalized damage model. The goal is to show possible usage cases, explain basic procedures and clarify necessary input declarations. Expansion towards specific materials or comparisons with experimental data is not done here yet and will be the subject of future publications.

4.1 Isotropic damage: GISSMO vs. MAGD

The first example is the simplest case where MAGD is just used to replicate GISSMO. Suppose a material modeled with `*MAT_024` has the following input for GISSMO:

```
*MAT_ADD_EROSION
$      MID      EXCL    MXPRES     MNEPS    EFFEPS    VOLEPS    NUMFIP       NCS
       100                                                                    1
$   MNPRES     SIGP1     SIGVM     MXEPS     EPSSH     SIGTH   IMPULSE    FAILTM

$     IDAM    DMGTYP     LCSDG     ECRIT    DMGEXP     DCRIT    FADEXP    LCREGD
         1         1       101      -102       2.0                 1.0       103
$   SIZFLG     REFSZ     NAHSV     LCSRS      SHRF     BIAXF
                                     104       1.0       0.0
```

where stress state (triaxiality) dependent failure and instability curves are given as well as regularization and rate dependence are defined [12]. To transfer this input to the new keyword, we first have to consider the structure of the damage tensor. In the case of isotropic damage with only one damage variable, it is defined in a straightforward manner, that is:

$$\begin{bmatrix} \sigma_{11} \\ \sigma_{22} \\ \sigma_{33} \\ \sigma_{12} \\ \sigma_{23} \\ \sigma_{31} \end{bmatrix} = (1 - D_1) \begin{bmatrix} 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} \tilde{\sigma}_{11} \\ \tilde{\sigma}_{22} \\ \tilde{\sigma}_{33} \\ \tilde{\sigma}_{12} \\ \tilde{\sigma}_{23} \\ \tilde{\sigma}_{31} \end{bmatrix} \tag{10}$$

With that in mind and knowing that the internal history variable is plastic strain, we can set NHIS=1, HIS1=0, and the same function ID for all diagonal terms of the damage matrix. The function itself simply contains the expression $1 - D_1$ from equation (10). Options IFLG1 and IFLG2 can remain 0 since no plastic strain tensor components are needed and the coordinate system is irrelevant. Finally, all the other GISSMO-related parameters (LCSDG, etc.) are just transferred to the right positions:

```
*MAT_ADD_GENERALIZED_DAMAGE
$       MID      IDAM    DMGTYP     REFSZ     NUMFIP                               NHIS
        100         1         1                         1                            1
$      HIS1      HIS2      HIS3     IFLG1     IFLG2
          0                             0         0
$       D11       D22       D33       D44       D55       D66
        201       201       201       201       201       201
$       D12       D21       D23       D32       D13       D31

$     LCSDG     ECRIT    DMGEXP     DCRIT    FADEXP    LCREGD
        101      -102       2.0                 1.0       103
$     LCSRS      SHRF     BIAXF
        104       1.0       0.0
*DEFINE_FUNCTION
        201
funcd(d1,d2,d3)=1.0-d1
```

A comparison of both approaches was done with the aid of a tension test. That example was in fact part of the verification process of the new implementation. As expected, identical results are achieved as can be seen in Figure 3.
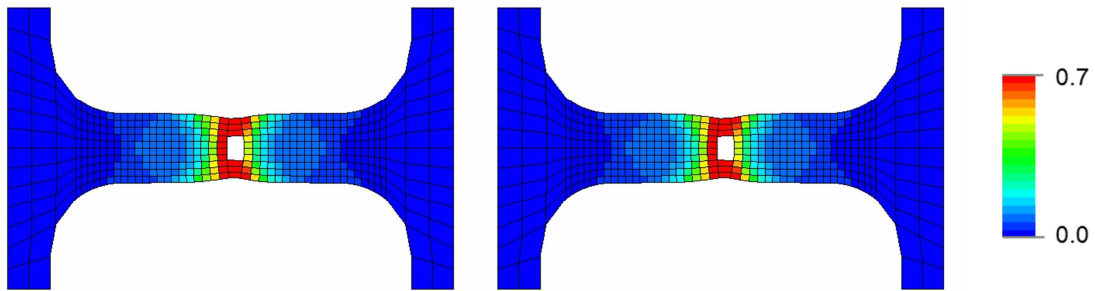

Fig.3:   Deformation and plastic strain distribution with GISSMO (left) and MAGD (right).

If CPU timings are considered, the addition of GISSMO shows a speed penalty factor of 1.6 when compared with "pure" `*MAT_024` which is typically observed in other computations as well. Currently, MAGD leads to a factor of over 6, which partly comes from the larger number of operations. Another reason could be the usage of the function calls. However, this has to be further investigated for improved numerical efficiency.

4.2   2-parameter isotropic damage: volumetric-deviatoric split

Usually, isotropic damage is formulated with only one internal damage variable as in equation (10). However, one could also think of a separate damage treatment for two different fundamental deformation modes. This idea is linked to the so-called volumetric-deviatoric split. Pure volumetric deformation means that a body just changes its volume without any shape modification. On the other hand, a purely deviatoric (or "isochoric") deformation comes with no volume change at all. If this split is performed for the effective stress tensor and both terms are scaled with two different damage measures, the following expression is obtained:

$$\sigma_{ij} = (1 - D_1)\left(\tilde{\sigma}_{ij} - \frac{1}{3}\tilde{\sigma}_{kk}\delta_{ij}\right) + (1 - D_2)\left(\frac{1}{3}\tilde{\sigma}_{kk}\delta_{ij}\right) \tag{11}$$

The first damage variable D_1 is responsible for the deviatoric part and D_2 describes volumetric degradation. If this equation is transformed into matrix notation and the assumption of plane stress is made, we have:

$$\begin{bmatrix} \sigma_{11} \\ \sigma_{22} \\ 0 \\ \sigma_{12} \\ \sigma_{23} \\ \sigma_{31} \end{bmatrix} = \begin{bmatrix} 1 - \frac{2}{3}D_1 - \frac{1}{3}D_2 & \frac{1}{3}D_1 - \frac{1}{3}D_2 & 0 & 0 & 0 & 0 \\ \frac{1}{3}D_1 - \frac{1}{3}D_2 & 1 - \frac{2}{3}D_1 - \frac{1}{3}D_2 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 - D_1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} \tilde{\sigma}_{11} \\ \tilde{\sigma}_{22} \\ 0 \\ \tilde{\sigma}_{12} \\ \tilde{\sigma}_{23} \\ \tilde{\sigma}_{31} \end{bmatrix} \tag{12}$$

The 2 history variables associated with the 2 damage variables are necessary in order to consider the volumetric-deviatoric split properly. For that purpose, the pressure dependent plasticity model with non-associated flow in `*MAT_SAMP` (`*MAT_187`) is well suited. In this material model, deviatoric and volumetric plastic strain components are used and stored in the history variables array on "slots" 0 and 6, respectively. Therefore, in the input for MAGD one should define NHIS=2, HIS1=0, HIS2=6, and the damage tensor functions as shown above. Finally, different failure strain curves (LCSDG) and different critical strain values (ECRIT) can be defined for the two plastic deformation modes. For instance, if a significantly smaller failure strain is defined for the second history variable, then this will be the decisive measure for damage and rupture, see Figures 4 and 5.
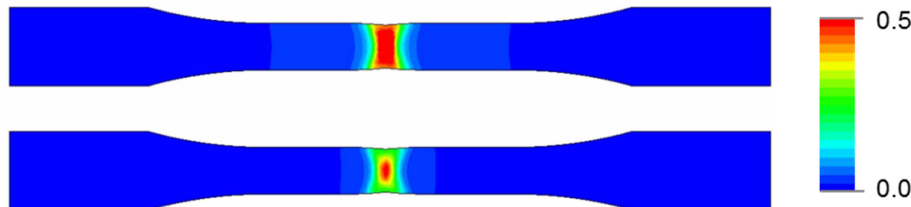

Fig.4:   Tensile specimen with `*MAT_187`*: deviatoric (above) and volumetric (below) plastic strain.*
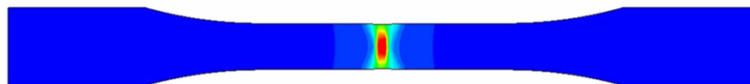

Fig.5:   Supplemental use of MAGD: distribution of damage value D_2 shortly before rupture.

4.3   User-defined history variables

Another option in MAGD is the free definition of damage driving quantities (history variables) based on plastic strain tensor components. As already shown in Table 2, it is necessary to set IFLG1=1 and then define (negative) `*DEFINE_FUNCTION` identifiers for HIS$_n$. A possible application could be the introduction of two different measures for shell elements, for example, in-plane and out-of-plane contributions:

$$\dot{\varepsilon}_{ip}^{p} = \sqrt{\tfrac{2}{3}\left[\left(\dot{\varepsilon}_{xx}^{p}\right)^2 + \left(\dot{\varepsilon}_{yy}^{p}\right)^2 + 2\left(\dot{\varepsilon}_{xy}^{p}\right)^2\right]} \tag{13}$$

$$\dot{\varepsilon}_{oop}^{p} = \sqrt{\tfrac{2}{3}\left[\left(\dot{\varepsilon}_{zz}^{p}\right)^2 + 2\left(\dot{\varepsilon}_{yz}^{p}\right)^2 + 2\left(\dot{\varepsilon}_{zx}^{p}\right)^2\right]} \tag{14}$$

In the keyword format, part of the input should be defined as follows:

```
*MAT_ADD_GENERALIZED_DAMAGE
$      MID      IDAM      DTYP      REFSZ     NUMFIP                                  NHIS
       100         1         1                    1                                     2
$     HIS1      HIS2      HIS3      IFLG1      IFLG2      IFLG3
      -801      -802                    1
...
*DEFINE_FUNCTION
       801
fhis1(exx,eyy,ezz,exy,eyz,ezx)=sqrt(2./3.*(exx**2+eyy**2+2.*exy**2))
*DEFINE_FUNCTION
       802
fhis2(exx,eyy,ezz,exy,eyz,ezx)=sqrt(2./3.*(ezz**2+2.*eyz**2+2.*ezx**2))
```

A suitable example for the application of this approach is the high velocity implact of a blunt projectile as illustrated in Fig. 6. In this event, a so-called plugging mode can often be observed. It is the result of evolving narrow shear bands that are usually difficult to capture in numerical simulations. With only one history variable for the damage evolution (equivalent plastic strain), plate rupture would happen in the center below the impactor since in-plane strain is the dominant part of the overall effective plastic strain. However, with the split into in-plane and out-of-plane deformations available in MAGD, it is now possible to define separate failure strains where, for instance, a significantly smaller value for the out-of-plane mode is set. This enables the realistic reproduction of the plugging mode.
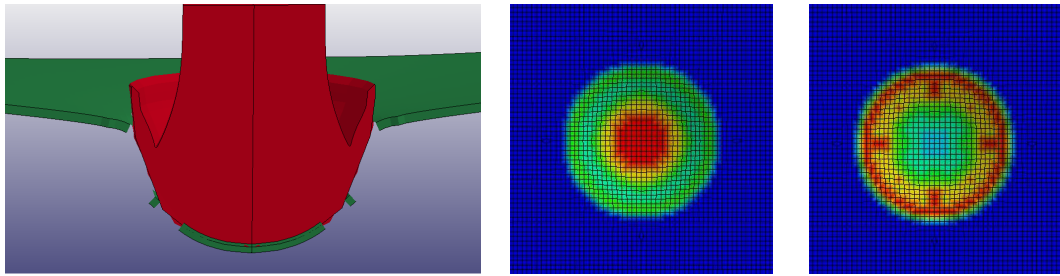
Fig.6: High velocity impact of a blunt projectile: deformation, in-plane strain, out-of-plane strain.

4.4 Load induced anisotropic damage

In this example, a biaxial specimen is subject to two subsequent loads: first in the horizontal and then in the vertical direction (see Figure 7). The goal is to demonstrate the effects of load induced anisotropic damage (LIAD). For the base material, the common `*MAT_024` is used since anisotropy is now only needed in the definition of the damage matrix where this contains the same expressions as used in `*MAT_104` with FLAG = -1 (one of the few material models in LS-DYNA with anisotropic damage so far):

$$
\begin{bmatrix} \sigma_{11} \\ \sigma_{22} \\ 0 \\ \sigma_{12} \\ \sigma_{23} \\ \sigma_{31} \end{bmatrix} = \begin{bmatrix} 1-D_1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1-D_2 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1-\frac{1}{2}(D_1+D_2) & 0 & 0 \\ 0 & 0 & 0 & 0 & 1-\frac{1}{2}D_2 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1-\frac{1}{2}D_1 \end{bmatrix} \begin{bmatrix} \tilde{\sigma}_{11} \\ \tilde{\sigma}_{22} \\ 0 \\ \tilde{\sigma}_{12} \\ \tilde{\sigma}_{23} \\ \tilde{\sigma}_{31} \end{bmatrix}
\tag{15}
$$

In addition, IFLG1 is set to 1 and IFLG2=3 to replicate `*MAT_104` where principal directions are kept constant as soon as the damage threshold (instability limit) is reached. The outcome of a simulation with these settings is that the first damage value D_1 grows in the first phase (horizontal loading), but not any further in the second phase (vertical loading), see Fig. 7 in the middle. On the other hand, the second damage variable D_2 remains zero in the first and only starts to grow in the second phase, see Fig.7 on the right. In fact, this anisotropic damage evolution does not lead to failure in this particular case. However, if GISSMO is used with a single damage variable that grows in both phases (i.e., independently from the loading direction), that quantity sums up to a higher value than the damage predicted with the anisotropic modeling with MAGD. This leads to an earlier failure as can be seen in Figure 7 on the left.
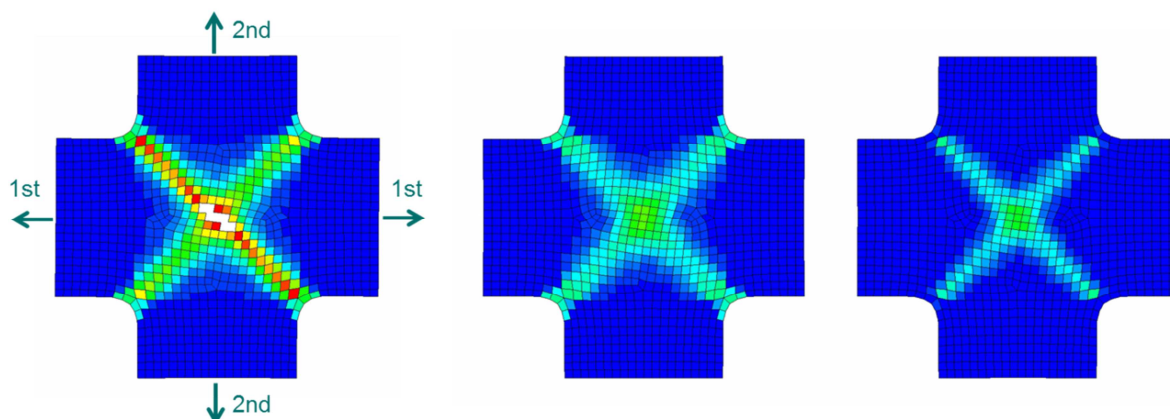

Fig.7: Biaxial specimen under sequential loading: GISSMO damage (left), MAGD damage D_1 (middle), MAGD damage D_2 (right). Damage ranges from 0 (blue) to 0.9 (red).

4.5   Material induced anisotropic damage

In this last example, a fictitious test case is used to demonstrate the effect of material induced anisotropic damage (MIAD). Therefore, a fixed round plate is dynamically loaded by a button-shaped impactor as shown in Fig.8 on the left.
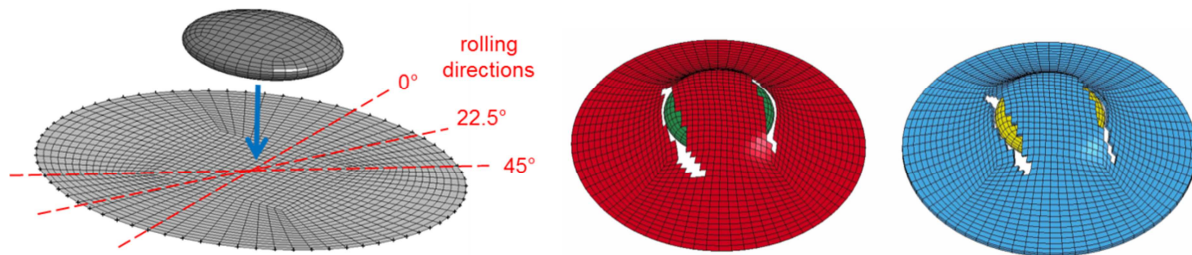

Fig.8:   Button-shaped rigid body impacts fixed round plate in 3 different configurations, deformation and failure with shell elements (middle) and solid elements (right).

The idea is to have a situation where the loading condition is isotropic, but the raw material itself has stronger and weaker directions when it comes to damage and failure. The plate material could be some metal with a preferred structural orientation, e.g., through a preceding rolling or extrusion process. For that purpose, the anisotropic Hill plasticity model from `*MAT_103` is used and three different rolling directions will be examined. To incorporate MIAD, IFLG1=1 and IFLG2=1 are applied whereas the same damage tensor with two damage variables is used as in the previous section, see equation (15). Additionally, it was chosen that the failure strain is two times larger for the 1st history variable (plastic strain in rolling direction) than for the 2nd history variable (perpendicular to it). As a consequence, it can be seen (Fig.9) that failure always happens in the weaker direction irrespective of the mesh discretization.
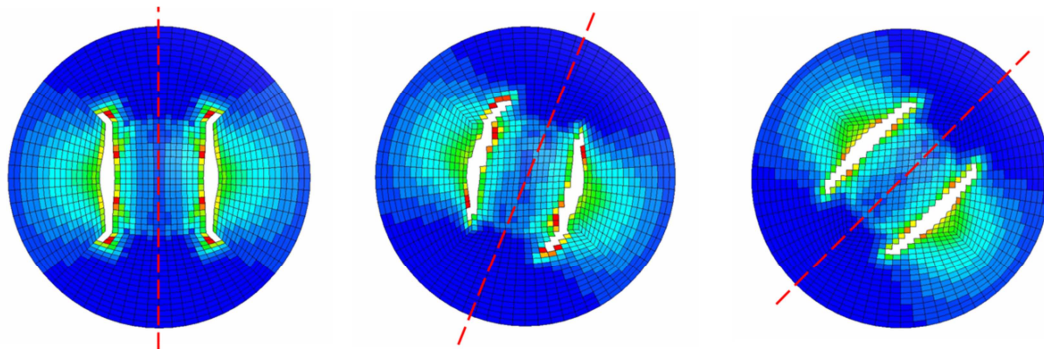

Fig.9:   Fixed round plate under impact loading (MAGD with IFLG2=1, i.e. MIAD): pronounced damage and failure occurs perpendicular to the rolling direction (dashed red lines)

The new generalized damage model allows a straightforward switch from MIAD to LIAD. For instance, setting IFLG2=2 is everything that has to be done in this example. With this minor modification, the fracture mode changes completely (Fig.10). Damage and failure now correspond to the loading condition (which is isotropic). A slight anisotropy can still be observed on the left due to the Hill plasticity model in `*MAT_103`. If the von Mises plasticity is considered with `*MAT_024`, the fracture mode is fully isotropic.
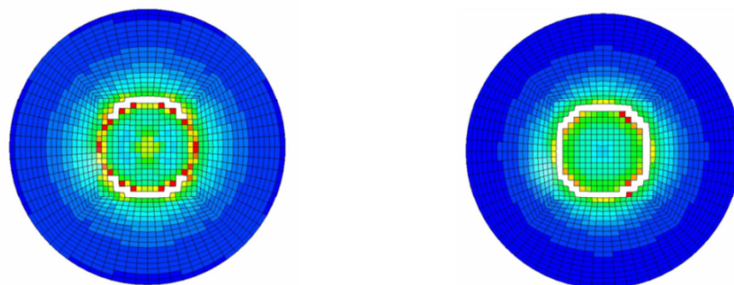

Fig.10: Fixed round plate under impact loading (MAGD with IFLG2=2, i.e. LIAD): damage and failure with `*MAT_103` (left) and `*MAT_024` (right).

5 Summary

A first glimpse of a new generalized damage model was given which can be added to many existing material models in a modular fashion. It was shown that it serves as a very flexible tool to describe multi-parameter anisotropic damage and failure. In this paper, we gave a first introduction into the topic, explained input parameters and various options of the new keyword and, finally, used different numerical examples to shed some light on its usage. The focus was not on specific material types, but rather on the demonstration of fundamental features. Suitable candidates for the use of MAGD seem to be metals with preferred orientations, thermoplastics and composites. Nevertheless, there may exist other application areas that will take advantage of this general approach.

The new keyword `*MAT_ADD_GENERALIZED_DAMAGE` is implemented in LS-DYNA release R9 for shell elements and will be available in the upcoming R10 for both shell and solid elements. Further extensions are underway for future releases such as an increased number of history variables, more options to obtain strain tensor components, possibility of using pre-defined damage tensors, among others. Finally, the focus is not only laid on the flexibility of the new approach, but also on the improvement of numerical efficiency in the ongoing further development of the keyword.

6 Literature

[1] Neukamm F., Feucht M., Haufe A., Roll K.: "On closing the constitutive gap between forming and crash simulation", 10th International LS-DYNA Users Conference, Detroit, 2008.

[2] Andrade F.X.C, Feucht, M., Haufe A., Neukamm F.: "An incremental stress state dependent damage model for ductile failure prediction", International Journal of Fracture, 200:127, 2016.

[3] Borrvall T., et al.: "A General Damage Initiation and Evolution Model (DIEM) in LS-DYNA", 9th European LS-DYNA Conference, Manchester, 2013.

[4] Kachanov, L.M.: *Introduction to Continuum Damage Mechanics*, Martinus Nijhoff Dortrecht, 1986.

[5] Krajcinovic, D., Lemaitre, J.: *Continuum Damage Mechanics Theory and Application*, Springer, 1987.

[6] Lemaitre, J., Desmorat, R.: *Engineering Damage Mechanics: Ductile, Creep, Fatigue and Brittle Failures*, Springer, 2005.

[7] Murakami, S., Ohno, N.: "A Continuum Theory of Creep and Creep Damage", Proc. 3rd IUTAM Symposium on Creep in Structures, Springer, Berlin, 1981.

[8] Chow, C.L., Wang, J.: "An Anisotropic Theory of Elasticity for Continuum Damage Mechanics", International Journal of Fracture, Vol. 33, 1987.

[9] Kattan, P.I., Voyiadjis, G.Z.: "A Coupled Theory of Damage Mechanics and Finite Strain Elasto-plasticity", International Journal of Engineering Science, Vol. 28, 1990.

[10] Niazi, M.S., et al.: "Implementation of an anisotropic damage material model for non-proportional loading", COMPLAS X, International Conference on Computational Plasticity, 2-4 September 2009, Barcelona.

[11] Niazi, M.S.: *Plasticity induced anisotropic damage modeling for forming processes*, PhD thesis, University of Twente, Enschede, The Netherlands, 2012.

[12] Hallquist, J.O.: *LS-DYNA Keyword User's Manual, Volume II – Material Models, LS-DYNA R9.0*, Livermore, 2016.

[13] Du Bois P., et al.: "A new versatile tool for simulation of failure in LS-DYNA and the application to aluminium extrusions", 14th International LS-DYNA Conference, Detroit, 2016.

[14] Andrade, F et al.: "Modeling of anisotropic damage with *MAT_ADD_GENERALIZED_DAMAGE", Nordic LS-DYNA Users Conference, Gothenburg, Sweden, 2016. .

[15] Willam K., Pramono E., Sture S.: "Fundamental Issues of Smeared Crack Models". In: Shah S.P., Swartz S.E. (eds) Fracture of Concrete and Rock. Springer, New York, NY, 1989.