Summary

The objective of this note is to give advices to a user wishing to carry out calculations with non-linear behaviors of elastoplastic type or élasto-visco-plastic to choose a law adapted to modelings considered. The materials concerned are mainly metals. For the other types of materials, the first paragraph returns to the suitable references.

Specificities and capacities of the laws élasto-visco-plastics are described. Then a description of the characteristics of the various types of work hardening is made, which makes it possible to put forth some recommendations.

Some general advices on the identification of the parameters of the laws are given.

One approaches also the effects of viscosity and the temperature. One gives finally elements of checking of the validity of the choices carried out concerning the behavior and his parameters.
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1 Introduction

1.1 Choice of the type of law of behavior

The choice of the law of behavior is of course function of the material which one models, but also phenomena to be treated: for example, the same steel will be elastoplastic at low temperature, and viscoplastic at high temperature.

This document gives tracks to advisedly use the behaviors élasto- (visco) - plastic (mainly for metals).

For other types of behaviors, the reading of the following documents is advised:

- For the laws with damage (case of the concrete for example), to see [U2.05.06] Realization of calculations of damage into quasi-static
- Pour metallurgy, to see [U2.03.04] Note of use for calculations thermometallomecanic on steels
- Pour porous environments in THM, to see [U2.04.05] Note of use of model THM and [R7.01.11] Model of behavior THHM
- For the use of elements CZM, to see [U2.05.07] Note of use of the models of cohesive zones
- For the specific laws of the discrete elements, to see [R5.03.17] Relations of behavior of the discrete elements
- For the laws specific to the elements 1D, to see [R5.03.09] nonlinear Relations of behavior 1D
- For the hyperelastic laws ( of Mooney-Rivlin type) to see [R5.03.19] hyperelastic Law of behavior. Almost incompressible material.
- For the laws of behavior specific to the fuel pins and metals under irradiation, to see [R5.03.08] elastoplastic Behaviour under irradiation of metals: application to the interns of tank
- For the laws of crystalline plasticity, to see [R5.03.11] mono and polycrystalline Behaviors elastoviscoplastic

1.2 Which elastoplastic laws to choose: which are their capacities?

In this document elements of choice of the laws of behavior are provided, according to their capacities, and the phenomena to be modelled.

Advices for the identification of the parameters will be given, while insisting on the field of validity of the models: the parameters are identified for deformations, speeds, quite specific temperatures, which must correspond to the studies considered.

In addition, if modelings considered require it, it can be necessary to lead the identifications in the field of the great deformations. One will be able to use for that of the formalism adapted:

- SIMO_MIEHE for the behaviors of Von Mises with isotropic work hardening, the laws with effect of the metallurgical phases, the law of Rousselier,
- GDEF_LOG for most behaviors,
- GROT_GDEP for the hyperelastic laws of type MOONEY-RIVLIN.

2 Specificities and capacities of the laws élasto-visco-plastics

We detail here the laws of behavior élasto- (visco) - plastic available in Code_Aster, (for modelings 2D and 3D), and their specificities.

2.1 Elastoplastic laws available

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Except linear elasticity (ELAS), elastoplastic models available are (cf. [U4.51.11] nonlinear Behaviors):

| Elastoplasticity of Von Mises with isotropic work hardening: VMIS_ISO_TP, VMIS_ISO_PUIS, VMIS_ISO_LINE | cf. [R5.03.02] Integration of the relations of elastoplastic behavior of Von Mises |
| Elastoplasticity of Von Mises with linear kinematic work hardening (only or combined with isotropic work hardening): VMIS_CINE_LINE | cf. [R5.03.02] Integration of the relations of elastoplastic behavior of Von Mises |
| Elastoplasticity with nonlinear kinematic work hardening (laws of J.L. Chaboche) VMIS_CIN1_CHAB, VMIS_CIN2_CHAB, VMIS_CIN2_MEMO | cf. [R5.03.04] Relations of behavior élasto-visco-plastic of Chaboche |
| Elastoplasticity with variable interns semi discrete for the cyclic loadings Visc TAHERI | cf. [R5.03.05] viscoplastic Relation of behavior TAHERI |
| Elastoplasticity of Von Mise S with isotropic work hardening of Jonhson-Cook (large speeds) VMIS_JOHN_COOK | cf. [R5.03.02] Integration of the relations of elastoplastic behavior of Von Mises |
| Nonlinear elasticity (laws of Hencky) ELAS_VMIS_LINE, ELAS_VMIS_TRAC, ELAS_VMIS_PUIS | cf. [R5.03.20] Relation of nonlinear elastic behavior in great displacements |

2.2 The laws élasto-visco-plastics available

The behaviors élasto-visco-plastics available are:

| Élasto-visco-plasticity with isotropic work hardening LEMAITRE | cf. [R5.03.08] Integration of the viscoelastic relations of behavior |
| Visc ENDO LEMA, VENDOCHAB | cf. [R5.03.15] viscoplastic Behavior with damage of CHABOCHE |
| HAYHURST | cf. [R5.03.13] viscoplastic Behavior with damage of HAYHURST |
| Élasto-visco-plasticity with nonlinear kinematic work hardening (laws of J.L. Chaboche) Visc_CIN1_CHAB, Visc_CIN2_CHAB, VISC_CIN2_MEMO | cf. [R5.03.04] Relations of behavior élasto-visco-plastic of Chaboche |
| ViscOCHAB | cf. [R5.03.12] viscoplastic Behavior with effect of memory and restoration of Chaboche |
| Visc TAHERI | cf. [R5.03.05] viscoplastic Relation of behavior TAHERI |
| Law of viscosity in hyperbolic sine and isotropic work hardening VISC_ISO_LINE, VISC_ISO_TRAC | cf. [R5.03.21] Modeling élasto (visco) plastic with isotropic work hardening in great deformations |

2.3 The choice of the type of work hardening

2.3.1 Isotropic work hardening

The elastoplastic laws with isotropic work hardening make it possible to model an increase in the size of elastic range with the identical plastic deformation in all the directions. So certain materials can
correspond to this kind of laws, for most metals, which present a strong kinematic work hardening, these laws are adapted to modelings in which the total loadings are monotonous, or possibly with discharges of low amplitude, to remain in the elastic mode.

It is a requirement so that the answer of the model is in conformity with reality (a complete model, to work hardenings kinematics and isotropic nonlinear, would give in this case the same result). But it is not a sufficient condition: it can exist structures in which a total monotonous loading produces local discharges.

The validity of the approach with a work hardening isotope can be checked a posteriori: it is enough that in any point, no discharge caused an entry in plasticity. This checking is detailed in § 5.2

To define the parameters of a law in isotropic work hardening, it is necessary to identify the behavior on a traction diagram, by checking that the identification is well carried out in the beach of deformations likely to be met during the structural analysis considered.

The various types of work hardening suggested (curve, law power) in general make it possible to reproduce the tensile test well (see [R5.03.02] and documents of formation: 15-constitutive laws).

a) Evolution field of elasticity 3D  
b) Evolution of Domaine of elasticity in 1D

Figure 2.3.1-a . Criterion of Von Mises, isotropic work hardening

In certain cases (breaking process), it is necessary to approach the elastoplastic behavior by a nonlinear elastic behavior are equivalent: they are the laws of Hencky (ELAS_VMIS_LINE, ELAS_VMIS_TRAC, ELAS_VMIS_PUIS). There still, these laws are valid only with one monotonous loading, and this time without any discharge, because they do not make it possible to model the plastic deformation.

A way very simplified to use an isotropic work hardening is to consider that it is linear (VMIS_ISOT_LINE). This can be valid in a range of deformations, and nonvalid in another. Let us take for example traction diagrams of a stainless steel:
One notes on the figure 2.3.1-b that it is possible to model the traction diagram by a linear work hardening, in great deformations, if one is not interested with precision in the small deformations (lower than 1%). In the contrary case (figure 2.3.1-c), it seems quite delicate to build a linear work hardening which is valid as of the entry in plasticity.

Moreover, C E standard of work hardening (like all the models with linear work hardening) risks to over-estimate constraints in the event of strong deformations, (or to underestimate the deformations with constraint imposed) because nothing limits the curve of work hardening. A parade with this difficulty is described in the paragraph 5.1.
By using the behavior `VMIS_ISOT_TRAC`, the risks are less great: the traction diagram is defined by a function `DEFI_FONCTION`, and `L` has maximum value of the X-coordinate (deformation) allows to define the field of validity and thus to avoid in the structural analysis exceeding this value (attention to leave the value by default `PROL_DROITE='EXCLU'` in `DEFI_FONCTION`).

2.3.2 Linear kinematic work hardening

The elastoplastic laws with linear kinematic work hardening are adapted to modelings in which the total loadings contain some discharges, and for which the approximation of the curve of work hardening by a line is acceptable. They make it possible to translate way very simplified the Bauschinger effect, present for most metals. Let us examine the law `VMIS_CINE_LINE`:

\[
\begin{align*}
  f(\sigma, X) &< 0 \\
  X &
\end{align*}
\]

a) Evolution field of elasticity 3D (cut)

![Evolution field of elasticity 3D (cut)](image)

b) Evolution field of elasticity in 1D

![Evolution field of elasticity in 1D](image)

**Figure 2.3.2-a. Criterion of Von Mises, work hardening kinematics**

**Advantage:**
- The interest of this model lies in its simplicity; It in particular makes it possible to test the effect of kinematic work hardening quickly, because the identification and the resolution are very fast.

**Limitations:**

1. This model does not present none isotropic work hardening.

2. The approximation of the real curve of traction and compression is often poor (cf preceding paragraph)
3. This model (like all the models with linear work hardening) risks to **over-estimate** the constraints in the event of strong deformations, (or to underestimate the deformations with imposed constraint) because nothing limits the curve of work hardening.

4. Lastly, if the loading comprises cycles, this model tends very quickly towards a stabilized cycle (in the uniaxial case, it is reached in only one cycle), which does not correspond to reality.

To raise the first limitation, it is possible to combine linear kinematic work hardening with an isotropic work hardening: they are the models VMIS_ECMI_LINE (but which presents the 3 other disadvantages), VMIS_ECMI_TRAC (which also makes it possible to answer the second limitation).

It is necessary to be very careful during the identification of VMIS_ECMI_TRAC (cf. [R5.03.16] elastoplasticBehaviour_with_isotropic_and_kinematic_work_hardening_mixed_linear) : indeed, the kinematic share of work hardening, in the range of studied deformation, must remain lower than the isotropic share of work hardening, if not, one can obtain a negative isotropic work hardening.

2.3.3 **Nonlinear kinematic work hardening: laws of J.L.Chaboche**

These laws at the same time make it possible to translate the Bauschinger effect (kinematic work hardening), its nonlinear evolution, and isotropic work hardening, as well as other phenomena (effect of memory of the maximum plastic deformation, restoration).

In their simplest form (VMIS_CIN1_CHAB) they lead to the particular shape of the curve of work hardening, with a given asymptote. The idea which underlies these models is well to reproduce the cycles of traction compression, in the face and form. To improve the description of the real curves, one can introduce several variable independent kinematics, each one playing a specific role to represent a level of deformation. In Code_Aster, one limited oneself to two variable kinematics (VMIS_CIN2_CHAB).

Their identification is more complex than for the preceding models: the number of parameters increases, and it is necessary has minimum a cyclic test (traction and compression on several cycles) to identify them correctly. Moreover of the tests on several levels of deformations are often necessary (and difficult to represent completely).

There still it is essential to target well the range of deformation expected in the studies, so that the parameters are adjusted on level of deformation. If one uses parameters coming from a former identification, it is necessary has minimum to check (via SIMU_POINT_MAT for example) on a modeling of the test of traction and compression) the answer of the model for these parameters.

To illustrate the advantage of using a nonlinear kinematic work hardening beyond some cycles of loading, let us consider an example of cycles of traction and compression to imposed deformation:
This curve is in fact a digital curve (simulated with VMIS_CIN2_CHAB) but it correctly reproduces the experimental curves on the stainless steel considered. It will be used as reference for the illustrations below.

The approximation of this curve by a linear kinematic work hardening (with an isotropic component, adjusted on the first traction diagram) shows that the answer is very distant:

One can improve the representation of the very first cycles while choosing VMIS_ECMI_TRAC, and by readjusting the values of the coefficient of Prager. It is noted that if the first 2 cycles are well represented, the model VMIS_ECMI_TRAC tends towards a state stabilized with an amplitude of constraint much higher than the real curve.
By continuing the cycles, this model would tend besides towards an adapted cycle, of amplitude 1600 MPa!

If modeling aims at envisaging a phenomenon of progressive deformation, the use of such models is delicate: indeed, they lead to a constant ratchet with nonworthless average constraint, of value very higher than the experimental ratchet (unless choosing the parameters so that one of work hardenings kinematics is linear, to which one quickly finds (too much) an adapted stabilized cycle).

It is preferable for these situations to use the model of TAHERI.

If the studied situation implements a pre-work hardening, it can be useful to identify the model VMIS_CIN2_MEMO on cyclic tests with pre-work hardening. (see for example [V6.08.105] SSND105 - Law of behavior visco-élasto-plastic with effect of memory.)
Other aspects can be taken into account, in particular on-work hardening due to cyclic loadings nonproportional. This is modelled in \texttt{VMIS\_CIN2\_CHAB} (without effect of memory) or \texttt{VMIS\_CIN2\_MEMO} (with effect of memory) via the parameters \texttt{DELTA1}, \texttt{DELTA2}.

### 2.3.4 Conclusions on the choice of the elastoplastic type of work hardening

The preceding paragraphs show that this choice is essential:
- for a monotonous loading, it is advisable to approach the traction diagram well in the range of deformation concerned, and to check that the structural analysis remains in this interval
- to model one or two cycles of load-discharge, a model with linear kinematic work hardening can be used, on condition that checking the answer in one or more points well.
- To simulate several cycles of loading, a model of the Chaboche type (or Taheri) is necessary.

### 2.4 Influence speed

For purely elastoplastic materials, the time used in simulations is a simple parameter of the loading (even if he has a physical meaning in the thermomechanical cases) and does not have direct influence on the laws of behavior.

But it necessary to take it into account in the behavior in the following cases:
- high speed of loading: elastoplastic law of Johnson-Cook

#### 2.4.1 Law of Johnson-Cook

This law makes it possible to take into account the vites directlySE of deformation, and the temperature, in the evolution of isotropic work hardening (cf. \texttt{R5.03.02} Integration of the relations of elastoplastic behavior of Von Mises page 11). It allows to deal with the problemS of impact, and to implement the thermomechanical coupling (see for example \texttt{V7.20.105} HSNA105 - Expansion of an infinite hollow roll with taking into account of thermal dissipations due to the mechanical deformations ).

#### 2.4.2 Élasto-visco-plasticity with isotropic work hardening

The élasto-visco-plastic model of Lemaître makes it possible to take into account secondary creep (at constant speed – it can be brought back for certain particular values of the parameters to a relation of behavior of Norton) and primary education creep. ( cf. \texttt{R5.03.08} Integration of the viscoelastic relations of behavior ).

The surface of load remains isotropic (not kinematic work hardening). Creep tests, of relieving, or the tensile tests at various speeds of deformation are necessary to the identification of the parameters.

There still, it should be checked that the values thus obtained are valid in the studies considered, i.e. that the speeds of deformation met in the studies are well in the range of those which were used for the identification.

If one wants to go further, i.e. to model tertiary creep (taken it into account of the great deformations is often necessary), one will be able to use the following models, which integrate a damage of creep:

- \texttt{VISC\_ENDO\_LEMA}, \texttt{VENDOCHAB}
  cf. \texttt{R5.03.15} viscoplastic Behavior with damage of CHABOCHE
- \texttt{HAYHURST}
  cf. \texttt{R5.03.13} viscoplastic Behavior with damage of HAYHURST

#### 2.4.3 Élasto-visco-plasticity with nonlinear kinematic work hardening

The following behaviors make it possible to take into account kinematic work hardening:

- \texttt{VISC\_CIN1\_CHAB}, \texttt{VISC\_CIN2\_CHAB}, \texttt{VISC\_CIN2\_MEMO}
These laws are extensions of the elastoplastic laws of J.L.Chaboche to the viscoplastic case. The different components of laws of Chaboche previously described are present, and viscosity should moreover be integrated (of Lemaitre type, i.e. allowing to reproduce creeps primary education and secondary). This means that their identification will have to take into account the speed of deformation (for example on the cyclic tests).

Other phenomena can be represented (hardening related to nonthe proportionality of the loading, restoration of work hardening), by the following model:

- **VISCOCHAB**
  
  cf. [R5.03.12] viscoplastic Behavior with effect of memory and restoration of Chaboche

The complete identification of this model requires a large number of different tests: tests cyclic at various speeds, and different levels from deformation, with pre-work hardening, tests of traction-torsion, tests of relieving.

### 2.4.4 Law of viscosity in hyperbolic sine and isotropic work hardening

Another form of law of viscosity is proposed in the following models:

- **VISC ISOT LINE, VISC ISOT TRAC**
  
  cf. [R5.03.21] Modeling élasto (visco) plastic with isotropic work hardening in great deformations

They are with isotropic work hardening, and require the employment of SIMO_MIEHE.

### 3 To identify the parameters: which tests are necessary?

The identification of the parameters of the models quickly becomes difficult manually, except for the simplest models (**VMIS_CINE_LINE, VMIS_ISOT_LINE, VMIS_ISOT_TRAC**).

One thus resorts to a procedure of optimization, available in the order **MACR_RECAL** [U4.73.02] Macro-order **MACR_RECAL**.

There are several advantages to use this order:

- simulation making it possible to find the curves digital (which will be compared with the experimental curves) is a classical command file of Code_Aster, which can be launched in an autonomous way, and which represents an unspecified calculation (not inevitably on a material point);
- the readjusted coefficients are directly usable in the studies, since they are parameters of the file of simulation;
- many algorithms are available, as well as ways of calculating making it possible to use architectures multiprocessors so necessary.

Details on the algorithms used can be consulted in the document [R4.03.06] Algorithm of retiming.

But the tools do not do all! Indeed, for seeking to identify the parameters of a model, it is necessary to raise several questions:

- the number of tests which one lays out is it sufficient with respect to the number of parameters to be readjusted;
- the tests highlight the physical phenomena simulated by the law of behavior (already evoked previously): load-discharge, cycles, effects of memory, restoration, nonradiality, high speed, viscosity,...);
- can one separate these effects, in order to identify the parameters successively, which will reduce the task of optimization and will make it possible to better apprehend the results.

To return more in detail of the identification, of the documents specific to the various behaviors are to be written; With regard to the cyclic behaviors élasto-visco-plastic, a more detailed note is in the course of writing, resulting from work EDF/R & D [4] and [5].
In addition, a rather general methodology is proposed in [1] page 617 and [3].

4 Simulations anisothermes

During simulations anisothermes, it is necessary most of the time to take into account the variation of the parameters with the temperature. It is thus necessary to take care of the good identification of these parameters.

In this paragraph, one illustrates some induced classical errors by the interpolation or the extrapolation of S values according to the temperature.

The tests are carried out with the laws VMIS_ISOT_TRAC and VMIS_CIN1_CHAB. However, the conclusions selected are not exclusive with a particular law.

4.1 Dangers of extrapolation:

To conduct a thermomechanical study with a law of behavior whose coefficients depend on the temperature, the user can want to extrapolate his curves to carry out his study at a given temperature. This is strongly disadvised. An example:

In the case of an isotropic work hardening, it is current to use experimental traction diagrams for some temperatures, variable for example enter 20° and 350°. The traction diagrams are indicated in the command file for various temperatures with the order 'DEFI_NAPPE'. Let us suppose that one defined the prolongations by PROL_DROITE='LINEAIRE' and PROL_GAUCHE='LINEAIRE'.

It is supposed that the user wishes to carry out a calculation at a temperature which exceeds the maximum temperature to which the identifications of the traction diagrams were made, that is to say 1000°C for example (it is a voluntarily exaggerated example, but which makes it possible to illustrate the matter). The coefficients materials of the law of this fact would be obtained with 1000 °C by extrapolation.

This can lead to aberrant results (Figure 4.1-a): the traction diagram obtained at the temperature extrapolated of 1000 °C present a concavity and a slope of work hardening contradictory compared to the other curves and compared to reality.

To avoid this kind of error, all should be avoided extrapolation compared to the temperature.
Figure 4.1-a. Traction diagrams according to the temperature – result with 1000 °C

4.2 Error in the interpolation of the temperature

This example highlights a possibility of error in the interpolation of the temperature generally due to a nonmonotonous evolution of the coefficients materials with the temperature. It is enough that only one of the coefficients does not evolve in a monotonous way so that the interpolation between two traction diagrams leads to a curve which does not lie between the two extremes.

To display this kind of error, with a standard law of behavior 'VMIS_CIN1_CHAB', one set up the following test:

Let us suppose known three in experiments identified traction diagrams at 3 different temperatures: 20 °, 100 ° and 200 ° C. One seeks to identify the parameters of the law 'VMIS_CIN1_CHAB' at these three temperatures. For understanding well, briefly let us point out L form of work hardening has law 'VMIS_CIN1_CHAB':

- Criterion: \( |\sigma - C \alpha|_{eq} - R(p) \leq 0 \)
- work hardening kinematics: \( \dot{\alpha} = \varepsilon_p - \gamma \alpha \)
- work hardening isotropic: \( R(p) = R_\infty + (R_0 - R_\infty) e^{-bp} \)

Let us suppose that the results of 3 identifications at three different temperatures are:

- with \( T = 20^\circ \) ; the parameters identified materials are: \( C_1 \), \( \gamma_1 \), \( R_0 \), nonworthless, and \( R_\infty \approx R_0 \), \( b \approx 0 \), ( that is to say a quasi pure kinematic behavior );
- with \( T = 100^\circ \) ; the coefficients identified materials are: \( C_2 \approx 0 \), \( R_0 \), \( R_\infty \), \( b_2 \). nonworthless, ( that is to say one quasi pure isotropic behavior )
- with \( T = 200^\circ \) ; the coefficients materials are: \( C_3 \), \( \gamma_3 \), \( R_0 \), nonworthless, \( R_\infty \approx R_0 \), \( b_3 \approx 0 \), ( that is to say again a pure kinematic behavior ).
Each one of these identifications is sufficiently precise, and makes it possible to find, for each temperature, of the digital curves very close to the experimental curves.

The simulation of the traction diagram with the temperature of $50^\circ C$ is represented on the figure 4.2-a.

It is noted that the curve obtained by interpolation with $50^\circ C$ is erroneous:

![Traction diagrams according to the temperature – result with 50°](image)

This comes owing to the fact that the identification were made independently, without checking the coherence of the results. The variations of each coefficient with the temperature are enormous: for example

<table>
<thead>
<tr>
<th>Temperature °C</th>
<th>C</th>
<th>b</th>
</tr>
</thead>
<tbody>
<tr>
<td>20</td>
<td>$C_1$</td>
<td>$\approx 0$</td>
</tr>
<tr>
<td></td>
<td>$\approx 0$</td>
<td>$b_2$</td>
</tr>
<tr>
<td></td>
<td>$C_3$</td>
<td>$\approx 0$</td>
</tr>
</tbody>
</table>

This example is of course extreme, but it allows émettre a recommendation:

- that is to say vérifier monotonous evolution of the parameters material according to the temperature, and to start again the identification for the values suspect,
- that is to say, if possible, to carry out the identification in once for all temperatures.
# 5 The field of validity

Several checks are possible to check that the law of behavior chosen, and the values of the parameters used, are valid for simulation.

In addition to the advices given previously, for choosing well the law of behavior according to what one wants to model, certain additional checks can be carried out using specific tools.

## 5.1 Validity of the parameters in the range of deformation and speed.

The parameters of the selected model being identified in a certain range of deformation, it is important to check that in the studies using these parameters, these deformations remain well in the interval of the identification.

Traction diagrams defined by `DEFI_FONCTION` integrate a “parapet”: the maximum value of the X-coordinate (\(\text{EPSI}\)) cannot be exceeded in the study. But if ever that occurs, instead of defining a prolongation constant (or worse: linear) it is advisable to take again the identification to define additional points in the traction diagram.

Linear work hardenings (\(\text{ECRO_LINE}\)), or defined by an analytical function (\(\text{ECRO_PUIS}, \text{VMIS_CINx*_CHAB}\), etc.) are much more dangerous. Nothing will prevent in the studies from largely exceeding the level of deformation of the identification. This is why a protection should be installation in a forthcoming version.

In any case, it is relatively easy, in postprocessing of a study, to calculate (\(\text{CALC_CHAMP}\)) the standard of the field of deformations (\(\text{EPEQ_ELGA}\)) and of from of extracted the maximum (\(\text{POST_ELEM/MINMAX}\), or graphic postprocessing in \(\text{SALOME_MECA}\)).

If the study results in using a formalism of great deformations, it is necessary that the identification uses it too.

With regard to the speed of deformation, there still a checking is necessary. Its automatic calculation should be proposed in a forthcoming version.

## 5.2 Discharge: validity of isotropic work hardening (and of the laws of Hencky)

How to check that the discharges are sufficiently small so that calculation with an isotropic work hardening is valid? There exists in \(\text{CALC_FIELD}\) an indicator of discharge \(\text{DERA_ELGA}\) (cf. [U4.81.04]).

- Components \(\text{DCHA_V}, \text{DCHA_T}\) indicate if there exist discharges on the constraints (either on Von Mises, or the total tensor), thus invalidating calculation with a nonlinear elastic law.

- The component \(\text{IND_DCHA}\) provides an indicator which indicates if there is a risk to return in plasticity in discharge, thus invalidating calculation with isotropic work hardening.

For more precise details on their calculation, to see [R4.20.01] Indicating of discharge and loss of proportionality of the loading in elastoplasticity.

## 5.3 Radiality: effects of nonproportionality

In the case of cyclic loadings strongly nonproportional, the effect of on-work hardening can be been unaware of by the selected behavior. While using, in \(\text{CALC_FIELD}\) the indicator of discharge and
radiality of the loading: DERA_ELGA (cf. [U4.81.04] Operator CALC.CHAMP), the component ERR.RADI measurement the mistake made by the rotation of the normal on the surface of load. If this value is important, it is then necessary to use a model making it possible to take into account this effect (for example VISCOCHAB).

6 References