Nonlinear behavior models 1D

Summarized:
This document describes quantities calculated by the operator STAT_NON_LINE necessary to the implementation of the quasi static nonlinear algorithm describes in [R5.03.01] in the case as of elastoplastic or viscoplastic behaviors monodimensional. These behaviors are applicable to the elements of BAR, the beam elements and beams multifibre (direction axial only) and to the elements of concrete reinforcement (modelization GRILL).

The behaviors described in this document are:

- the behavior of Von Mises with linear isotropic hardening: VMIS_ISOT_LINE, and unspecified VMIS_ISOT_TRAC,
- the behavior of Von Mises with linear kinematic hardening: VMIS_CINE_LINE,
- the behavior of Von Mises with linear, asymmetric hardening in tension and compression: with restoration of the center of the elastic domain: VMIS_ASYM_LINE. This last was developed to model the action of the soil on the Cables with Gas Insulation,
- the behavior of PINTO-MENEGOTTO which makes it possible to represent the uniaxial elastoplastic behavior of reinforcements of the reinforced concrete. This model translates for it not linearity of the hardening of the bars under cyclic loading and takes into account the Bauschinger effect. It makes it possible of more than simulate the buckling of reinforcements in compression. This relation is available in *the Code_Aster* for the elements of bar and the elements of grid,
- viscoplastic behaviors with effect of the irradiation: LMARC_IRRA, VISC_IRRA_LOG, GRAN_IRRA_LOG and LEMAITRE_IRRA.
- the behavior of MAZARS in its version $1D$. The version $1D$ model of MAZARS makes it possible to give an account of the restoration of stiffness in the event of reclosing of cracks.

The resolution is made in all the cases by an implicit integration method from time of preceding computation, one calculates the stress field resulting from an increment of strain, and the tangent behavior which makes it possible to build the tangent matrixes.
One describes finally a method, similar to the method due to R.de Borst [R5.03.03] allowing to use all the behaviors available in 3D in 1D elements. Contents

1Utilization

1 of the behavior models 1D Behavior models

1.1 1D in the Code_Aster

the relations treated in this document are: VMIS_ISOT_LINE

Von Mises	with linear isotropic hardening symmetric VMIS_ISOT_TRAC
Von Mises	with isotropic hardening unspecified VMIS_CINE_LINE
Von Mises	with symmetric linear kinematic hardening. ECRO
_CINE_1D Von Mises	with symmetric linear kinematic hardening. GRILLE_ISOT_LINE
Von Mises	with linear isotropic hardening symmetric GRILLE_CINE_LINE
Von Mises	with linear kinematic hardening symmetric PINTO_MENEGOTTO
Behavior	of reinforced concrete GRILLE_PINTO_MEN reinforcements
Behavior	of reinforced concrete reinforcements VMIS_ASYM_LINE
Von Mises	with asymmetrical linear hardening and restoration LEMAITRE
, LEMAITRE_IRRA Behavior	viscoplastic of the fuel assemblies: Model LEMAITRE LMARC_IRRA
Behavior	viscoplastic of the fuel assemblies under irradiation: Model LMA – RC VISC_IRRA_LOG
, GRAN_IRRA_LOG Behavior	viscoplastic of the fuel assemblies: Models resulting from the tests REFLECTION AND HALIBUT MAZARS
Behavior	from MAZARS IN its version. 1D These

behavior models (incremental) are given in operator STAT_NON_LINE [U 4.51.03] under the key word factor COMP_INCR , by the key word RELATION [U 4.51.03]. They are valid only in small strains. N described for each behavior model the computation of the stress field from an increment of strain given (cf algorithm of Newton [R5.03.01]), the computation of the nodal forces **and** R tangent matrix. K_i^n General

1.2 notations All

the quantities evaluated at previous time are subscripted par. -

the quantities evaluated at time $t+\Delta t$ are not subscripted.

The increments are indicated par. Δ One has as follows: tensor

$$\mathbf{Q}=\mathbf{Q}(t+\Delta t)=\mathbf{Q}^{-}(t)+\Delta\,\mathbf{Q}=\mathbf{Q}^{-}+\Delta\,\mathbf{Q}$$

$\boldsymbol{\sigma}$	of the stresses (in 1D, one is interested only in the single uniaxial non-zero component). deviative
$\tilde{\boldsymbol{\sigma}}$	operator: . $\tilde{\boldsymbol{\sigma}}_{ij}=\boldsymbol{\sigma}_{ij}-\frac{1}{3}\boldsymbol{\sigma}_{kk}\boldsymbol{\delta}_{ij}$ equivalent
$(\ )eq$	value of Von Mises, equalizes in 1D with the absolute value increment
$\Delta\,\boldsymbol{\varepsilon}$	of strain. elasticity tensor
$\mathbf{A}$	, equal in 1D to the Young modulus E moduli
λ,μ,E,K	of the isotropic elasticity. secant
α	thermal coefficient of thermal expansion. temperature
T	. positive
$(\ )_+$	part. cumulated
P	plastic strain plastic strain
ε^p	Change

1.3 of variables Whatever the

type D `finite element which refers to a constitutive law 1D, it is necessary to carry out a change of variables to pass from the elementary quantities (forces, displacements) to the stresses and strains. Computation

1.3.1 of the strains (small strains) For

each one of the finite elements of Code_Aster *, in* STAT_NON_LINE , the total algorithm (Newton) provides to the elementary routine, which integrates the behavior, an increase in the field of displacement. For
the elements of bar, one calculates the strain (only one axial component) by: ,

$$\varepsilon=\frac{u(l)-u(0)}{l}$$ and

the increase in strain by: ,

$$\Delta\varepsilon=\frac{\Delta u(l)-\Delta u(0)}{l}$$ For

the elements of grid (modelizations GRILL and GRILLE_MEMBRANE), one calculates the membrane strain as for shell elements DKT. Simply, only one direction corresponds physically to the directions of reinforcements. One thus finds oneself in the presence of a behavior 1D. In addition
, in small strains, for all the models described in this document, one writes for any time the partition of the strains in the form of an elastic contribution, thermal thermal expansion, and plastic strain: for

$$\boldsymbol{\varepsilon}(t)=\boldsymbol{\varepsilon}^{\mathbf{e}}(t)+\boldsymbol{\varepsilon}^{\mathbf{th}}(t)+\boldsymbol{\varepsilon}^{\mathbf{p}}(t)$$ Computation

$$\boldsymbol{\varepsilon}^{\mathbf{e}}(t)=\mathbf{A}^{-1}(T(t))\boldsymbol{\sigma}(t)=\frac{1}{E(T)}\boldsymbol{\sigma}(t)$$

$$\boldsymbol{\varepsilon}^{\mathbf{th}}(t)=\boldsymbol{\alpha}(T(t))(T(t)-T_{ref})\mathbf{Id}$$

1.3.2 of the forces generalized (forced integrated) After

integration of the behavior 1D, it is necessary to integrate the component of stresses obtained, for providing to the total algorithm (Newton) a vector containing the generalized forces. For
the elements of bar, one calculates the force (uniform in the element, by supposing that the section is constant) by: and $N=S\,\sigma$,

the vector forces nodal equivalent (as for the beam elements, [R3.08.01]) by: For

$$F=\begin{bmatrix}-N\\N\end{bmatrix}$$

the elements of GRILL , one calculates the forces as for shell elements DKT (membrane forces) by integration of the stresses in the thickness (only one layer and only one point of integration). Behavior

2 of Von-Put at linear isotropic hardening: VMIS_ISOT_LINE or VMIS_ISOT_TRAC Equations

2.1 of model VMIS_ISOT_LINE They

are the restriction of the behavior 3D [R5.03.02] on the uniaxial case: with

$$\begin{cases} \dot{\varepsilon}^p = \frac{3}{2}\dot{p}\frac{\tilde{\sigma}}{\sigma_{eq}} = \dot{p}\frac{\sigma}{|\sigma|} \\ \frac{\sigma}{E} = \varepsilon - \varepsilon^p - \varepsilon^{th} \\ \sigma_{eq} - R(p) = |\sigma| - R(p) \leq 0 \\ \begin{cases} \dot{p} = 0 \; si \; \sigma_{eq} - R(p) < 0 \\ \dot{p} \geq 0 \; si \; \sigma_{eq} - R(p) = 0 \end{cases} \end{cases}$$

: •

plastic $\dot{\varepsilon}^p$ strainrate, •

cumulated p plastic strain, •

thermal strain $\varepsilon^{th} = \alpha(T - T_{ref})$, •

function $R(p) = \frac{E E_T}{E - E_T} p + \sigma_y$ of linear hardening isotropic, or $R(p)$ refines per pieces, deduced from curve of tension. In

the case VMIS_ISOT_LINE , the data of the characteristics of materials are those provided under the key word factor ECRO_LINE or ECRO_LINE_FO of operator DEFI _MATERIAU [U 4.43.01]. /

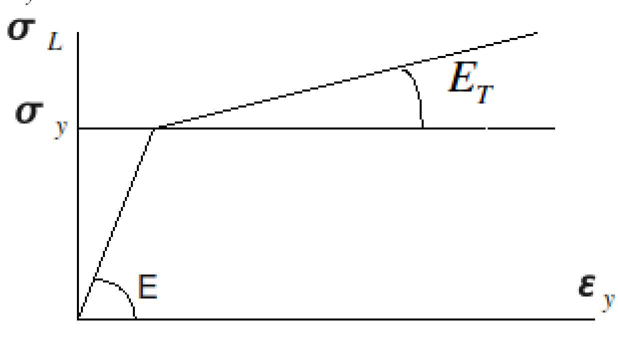
ECRO_LINE = (D_SIGM_EPSI =, E_T SY =) σ_y /

ECRO_LINE_FO = (D_SIGM_EPSI =, E_T SY =) σ_y In

the case VMIS_ISOT_TRAC , the data of the characteristics of the materials are provided under the key word factor TENSION of operator DEFI _MATERIAU [U 4.43.01]. TENSION

= _F (SIGM = courbe_traction) curve

_traction represents curve of tension, point by point. The first point makes it possible to define the elastic limit and σ_y the modulus Young [R E 5.03.02]. ECRO_LINE_FO



corresponds if and E_T depends σ_y on the temperature and is then calculated for the temperature of the current Gauss point. The Young modulus and E the Poisson's ratio are ν those provided under the key keys factors ELAS or ELAS_FO . In this case curve of tension is the following one: When

$$\begin{cases} \sigma_L = E\,\varepsilon_L & si\,\varepsilon_L < \dfrac{\sigma_y}{E} \\ \sigma_L = \sigma_y + E_T\left(\varepsilon_L - \dfrac{\sigma_y}{E}\right) & si\,\varepsilon_L \geq \dfrac{\sigma_y}{E} \end{cases}$$

the criterion is reached one a:,

$\sigma_L - R(p) = 0$ therefore from where $\sigma_L - R\left(\varepsilon_L - \dfrac{\sigma_L}{E}\right) = 0$: In the case of

$$R(p) = \frac{E_T E}{E - E_T}\,p + \sigma_y = H\,p + \sigma_y$$

a curve of tension, the approach is identical to [R5.03.01]. Integration

2.2 of relation VMIS_ISOT_LINE By

direct implicit discretization of the behavior models, in a way similar to integration 3D [R5.03.02] one obtains: Two

$$\begin{cases} \left|\sigma^- + \Delta\sigma\right| - R(p^- + \Delta p) \leq 0 \\ E\left(\Delta\varepsilon - \Delta\varepsilon^{th}\right) - \left(\sigma^- + \Delta\sigma\right) + \dfrac{E}{E^-}\sigma^- = E\,\Delta p\,\dfrac{\sigma^- + \Delta\sigma}{\left|\sigma^- + \Delta\sigma\right|} \\ \Delta p \;\geq\; 0 \quad si \quad \left|\sigma^- + \Delta\sigma\right| = R\left(p^- + \Delta p\right) \\ \Delta p \;=\; 0 \quad si \quad \left|\sigma^- + \Delta\sigma\right| < R\left(p^- + \Delta p\right) \end{cases}$$

cases arise: •
in $\left|\sigma^- + \Delta\sigma\right| < R\left(p^- + \Delta p\right)$

this case is $\Delta p = 0$ thus $\sigma = \mathrm{E}\left(\Delta\varepsilon - \Delta\varepsilon^{\mathrm{th}}\right) + \dfrac{\mathrm{E}}{\mathrm{E}^-}\sigma^-$

• $\left|\sigma^- \dfrac{\mathrm{E}}{\mathrm{E}^-} + \mathrm{E}\left(\Delta\varepsilon - \Delta\varepsilon^{th}\right)\right| < R(p^-)$

in $\left|\sigma^- + \Delta\sigma\right| = R(p^- + \Delta p)$
this case thus $\Delta p \geq 0$
. $\left|\dfrac{\sigma^- E}{E^-} + E\left(\Delta\varepsilon - \Delta\varepsilon^{th}\right)\right| \geq R(p^-)$ One
from of deduced the algorithm from resolution: let us pose
so $\sigma^e = \dfrac{\mathrm{E}\,\sigma^-}{\mathrm{E}^-} + E\left(\Delta\varepsilon - \Delta\varepsilon^{th}\right)$
then $\left|\sigma^e\right| \leq R(p^-)$ and $\Delta p = 0$ so $\Delta\sigma = \mathrm{E}\left(\Delta\varepsilon - \Delta\varepsilon^{th}\right)$
then $\left|\sigma^e\right| > R(p^-)$ it is necessary to solve: thus

$$\sigma^e=\sigma^-+\Delta\sigma+E\,\Delta p\,\frac{\sigma^-+\Delta\sigma}{\left|\sigma^-+\Delta\sigma\right|}$$

$$\sigma^e=\left(1+\frac{E\,\Delta p}{\left|\sigma^-+\Delta\sigma\right|}\right)\left(\sigma^-+\Delta\sigma\right)$$

by taking the absolute value: maybe

$$\left|\sigma^e\right|=\left(1+\frac{E\,\Delta p}{\left|\sigma^-+\Delta\sigma\right|}\right)\left(\sigma^-+\Delta\sigma\right)$$

, by means of. $\left|\sigma^-+\Delta\sigma\right|= R\left(p^-+\Delta p\right)$ $\left|\sigma^e\right|=R\left(p^-+\Delta p\right)+E\,\Delta p$ One

from of thus deduced: in the case of

- a linear hardening: and $\Delta p=\dfrac{\left|\sigma^e\right|-\left(\sigma_y+Hp^-\right)}{E+H}$
- in the case of an unspecified hardening, the curve $R(p)$ being refined per pieces, one solves the equation directly in: Δp in the same way qu $E\,\Delta p+R\left(p^-+\Delta p\right)=\left|\sigma^e\right|$ "in 3D [R5.03.02]. Let us notice

on the way that: formulate $\dfrac{\sigma^e}{\left|\sigma^e\right|}=\dfrac{\sigma}{R(p)}$

Moreover $\sigma=\left(\sigma^-+\Delta\sigma\right)=\dfrac{\sigma^e}{\left|\sigma^e\right|}R(p)=\dfrac{\sigma^e}{1+\dfrac{E\,\Delta p}{R(p)}}$

, L" option FULL `_MECA allows` to calculate the tangent matrix with $\mathbf{K_i^n}$ each iteration. The tangent operator who is used for building it is calculated directly on the preceding discretized system. One obtains directly: if

not $\left|\sigma^e\right|>R\left(p^-\right)$ $\qquad \dfrac{\delta\sigma}{\delta\varepsilon}=E_T$

Note $\qquad \dfrac{\delta\sigma}{\delta\varepsilon}=E$

:

The option RIGI `_MECA_TANG which` makes it possible to calculate the tangent matrix used $\mathbf{K_i^0}$ in the phase of prediction of the algorithm of Newton, takes account of the indicator of plasticity at previous time: if

$\chi=1$ $\dfrac{\delta\sigma}{\delta\varepsilon}=E_T$ *Local variables* $\chi=0$ $\dfrac{\delta\sigma}{\delta\varepsilon}=E$

2.3

behavior model VMIS_ISOT_LINE `produces` two local variables: and p Behavior χ

3 of Von Mises, linear kinematic hardening 1D: VMIS_CINE_LINE Equation

3.1 of model VMIS_CINE_LINE For

reasons of performances the relation is written in 1D. They are the restriction of the behavior 3D ([R5.03.02] and [R5.03.16]) on the uniaxial case. The behavior 3D is written: with

$\boldsymbol{\sigma}=\mathbf{K}\left(\boldsymbol{\varepsilon}-\boldsymbol{\varepsilon}^{\mathbf{p}}-\boldsymbol{\varepsilon}^{\mathbf{th}}\right)$ operator $\mathbf{K}$ of elasticity with

$\mathbf{X}=C\,\boldsymbol{\varepsilon}^{\mathbf{p}}$

$F(\boldsymbol{\sigma},\mathbf{R},\mathbf{X})=(\tilde{\boldsymbol{\sigma}}-\mathbf{X})_{\mathbf{eq}}-\sigma_y$ In $\mathbf{A}_{\mathbf{eq}}=\sqrt{\frac{3}{2}\tilde{\mathbf{A}}\cdot\tilde{\mathbf{A}}}$

$$\dot{\boldsymbol{\varepsilon}}^{\mathbf{p}}=\dot{p}\frac{\partial F}{\partial\boldsymbol{\sigma}}=\frac{3}{2}\dot{\mathbf{p}}\frac{\tilde{\boldsymbol{\sigma}}-\mathbf{X}}{(\tilde{\boldsymbol{\sigma}}-\mathbf{X})_{\mathbf{eq}}}\quad\begin{cases}\text{si } F<0 & \dot{p}=0\\ \text{si } F=0 & \dot{p}\geq 0\end{cases}$$

the uniaxial case, the tensors are written: with

$$\tilde{\boldsymbol{\sigma}}=\sigma\,\mathbf{D}\qquad\mathbf{X}=X\,\mathbf{D}\qquad\boldsymbol{\varepsilon}^{\mathbf{p}}=\frac{3}{2}\varepsilon^{p}\,\mathbf{D}\ \text{ As long as }\ \mathbf{D}=\begin{bmatrix}2/3 & & \\ & -1/3 & \\ & & -1/3\end{bmatrix}$$

the loading is monotonous, the following relations immediately are obtained: C

$$p=\varepsilon^{p}\qquad X=\frac{3}{2}C\,\varepsilon^{p}\qquad\sigma=\frac{3}{2}C\,\varepsilon^{p}+\sigma_y\qquad\sigma=F(\varepsilon)=\sigma_y+\frac{E\cdot E_T}{E-E_T}\,p$$

is determined by: . $C=\frac{2}{3}\frac{E\,E_T}{E-E_T}$ One poses: $H=\frac{E\,E_T}{E-E_T}=\frac{3}{2}C$

The behavior model 1D is written then:

$$\left|\begin{array}{l}\left|\sigma^{-}+\Delta\sigma-X^{-}-\Delta X\right|\\ E\,\Delta\varepsilon^{p}=E\left(\Delta\varepsilon-\Delta\varepsilon^{th}\right)-\left(\sigma^{-}+\Delta\sigma\right)+\frac{E}{E^{-}}\sigma^{-}\\ X=\frac{3}{2}C\,\varepsilon^{p}=H\,\varepsilon^{p}\\ \left|\sigma-X\right|-\sigma_y\leq 0\\ \begin{cases}\dot{p}=0\,si\left|\sigma-X\right|-\sigma_y<0\\ \dot{p}\geq 0\,si\left|\sigma-X\right|-\sigma_y=0\end{cases}\end{array}\right.$$

The data of the characteristics of materials are those provided under the key word factor ECRO_LINE or ECRO_LINE_FO of operator DEFI _MATERIAU [U 4.43.01]: /

ECRO_LINE = (D_SIGM_EPSI =, E_T SY =) σ_y /

ECRO_LINE_FO = (D_SIGM_EPSI =, E_T SY =) σ_y Integration

3.2 of relation VMIS_CINE_LINE By

direct implicit discretization of the behavior models, in a way similar to integration 3D ([R5.03.02] and [R5.03.16]) one obtains: with

$$\begin{cases} |\sigma^- + \Delta\sigma - X^- - \Delta X| - \sigma_y \le 0 \\ E\,\Delta\varepsilon^p = E(\Delta\varepsilon - \Delta\varepsilon^{th}) - (\sigma^- + \Delta\sigma) + \dfrac{E}{E^-}\sigma^- \\ \Delta\varepsilon^p = \Delta p \dfrac{\sigma^- + \Delta\sigma - X^- - \Delta X}{|\sigma^- + \Delta\sigma - X^- - \Delta X|} \\ \dfrac{X}{H} - \dfrac{X^-}{H^-} = \Delta\varepsilon^p \\ \Delta p \ge 0 \quad si \quad |\sigma^- + \Delta\sigma - X^- - \Delta X| = \sigma_y \\ \Delta p = 0 \quad si \quad |\sigma^- + \Delta\sigma - X^- - \Delta X| < \sigma_y \end{cases}$$

Two $\Delta\varepsilon^{th} = \alpha\,(T - T_{ref}) - \alpha^-(T^- - T_{ref})$

cases present themselves: •

in $|\sigma^- + \Delta\sigma - X^- - \Delta X| < \sigma_y$ this case is $\Delta p = 0$ thus $\sigma = E(\Delta\varepsilon - \Delta\varepsilon^{th}) + \dfrac{E}{E^-}\sigma^- - \dfrac{H}{H^-}X^-$,

$\left|\sigma^- \dfrac{E}{E^-} - X^- \dfrac{H}{H^-} + E(\Delta\varepsilon - \Delta\varepsilon^{th})\right| < R(p^-)$ •

if not . $\Delta p \ge 0$

To simplify the writings one will pose: . $\sigma^e = \dfrac{E}{E^-}\sigma^- - \dfrac{H}{H^-}X^- + E(\Delta\varepsilon - \Delta\varepsilon^{th})$ One

from of deduced the algorithm from resolution: so

1) then $|\sigma^e| \le \sigma_y$ if not $\Delta p = 0,\quad X = X^- \dfrac{H}{H^-},\quad \sigma = E(\Delta\varepsilon - \Delta\varepsilon^{th}) + \dfrac{E}{E^-}\sigma^-$
2) it is necessary to solve: Let us notice

$$\begin{cases} E\,\Delta\varepsilon^p = E(\Delta\varepsilon - \Delta\varepsilon^{th}) - \Delta\sigma = \sigma^e - (\sigma^- + \Delta\sigma) + X^- \dfrac{H}{H^-} \\ \Delta\varepsilon^p = \Delta p \dfrac{\sigma^- + \Delta\sigma - X^- - \Delta X}{|\sigma^- + \Delta\sigma - X^- - \Delta X|} = \Delta p \dfrac{\sigma - X}{|\sigma - X|} \\ X - \dfrac{H}{H^-}X^- = H\,\Delta\varepsilon^p \\ |\sigma^- + \Delta\sigma - X^- - \Delta X| - \sigma_y = 0 \end{cases}$$

that: . $\dfrac{H}{H^-}X^- = X - H\,\Delta\varepsilon^p$ One

deduces then from the first equation: One $\sigma^e = \sigma - X + (E + H)\Delta\varepsilon^p$

thus obtains, while eliminating from $\sigma - X$ the second equation: While

$$\Delta\varepsilon^p = \sigma^e \frac{\Delta p}{(E+H)\Delta p + \sigma_y}$$

replacing in $\Delta\varepsilon^p$ the relation enters and σ^e , $\sigma - X$ one obtains: By

$$\sigma - X = \sigma^e \left(\frac{\sigma_y}{(E+H)\Delta p + \sigma_y} \right)$$

taking the absolute value of the two members of the preceding equation, one finds: Δp Once

$$(E+H)\Delta p + \sigma_y = |\sigma^e|$$

determined Δp , one can calculate: and

$$\Delta\varepsilon^p = \Delta p \frac{\sigma^e}{|\sigma^e|}$$

$$X = X^- + \Delta X = \frac{H X^-}{H^-} + H \Delta p \frac{\sigma^e}{|\sigma^e|}$$

by means of: , $\frac{\sigma - X}{\sigma_y} = \frac{\sigma^e}{|\sigma^e|}$ one obtains directly: Moreover $\sigma = \sigma_y \frac{\sigma^e}{|\sigma^e|} + X$

, option FULL _MECA makes it possible to calculate the tangent matrix with $\mathbf{K_i^n}$ each iteration. The tangent operator who is used for building it is calculated directly on the preceding discretized system. One obtains directly: if

not $|\sigma^e| > R(p^-)$ $\frac{\delta \partial}{\delta \varepsilon} = E_T$

$\frac{\delta \sigma}{\delta \varepsilon} = E$

the option RIGI _MECA_TANG which makes it possible to calculate the tangent matrix used $\mathbf{K_i^0}$ in the phase of prediction of the algorithm of Newton is obtained using the indicator of plasticity of χ^- previous time: •

so then $\chi^- = 1$ • $\frac{\delta \sigma}{\delta \varepsilon} = E_T$

so then $\chi^- = 0$ Local variables $\frac{\delta \sigma}{\delta \varepsilon} = E$

3.3

behavior model VMIS_CINE_LINE produces two local variables: .et X Behavior χ

4 of Von Mises, linear kinematic hardening 1D: vmis _CINE_GC EQUATION

4.1 of model VMIS _CINE_GC For

reasons of performances the relation is also written in 1D for a use with of the finite elements of standard multifibre beam. The equations result from the restriction of the behavior 3D ([R5.03.02] and [R5.03.16]) on the uniaxial case.
The equations of the model are the same ones as those of the § 3.1 10

The data of the materials are those provided under the key word factor ECRO_LINE of operator DEFI _MATERIAU [U
ECRO_LINE = _F (♦

D_ SIGM_EPSI=	formulates E_T	] ♦
SY =	formula σ_y	] ◊
SIGM_LIM=	sigmlim [Real	] ◊
EPSI _LIM=	epsilim [Real	])

the operands sigm _LIM AND espi _LIM MAKE IT POSSIBLE to define the limits which correspond to the limiting states of service and ultimate, classically used during study in civil engineering. ◊

SIGM _LIM = SIGMLIM Definition
of the ultimate stress. ◊

EPSI _LIM = epslim Definition
of the limiting strain. These

limits are compulsory when behavior VMIS _CINE_GC (cf [U4.51.11] is used nonlinear Behaviors, [U4.42.07] DEFI _MATER_GC) . In the other cases they are not taken into account. Integration

4.2 of relation VMIS _CINE_GC

the integration method identical to that is presented to the § 3.2 11

4.3 The modelization

supported is 1D , the numbers of local variables is of 6. •
formulate $V1$ This variable represents the stress divided by the ultimate stress sigmlim . •
formulate $V2$ This variable represents the total deflection divided by the strain limits epslim . •
formulate $V3$ Kinematic hardening: XCINXX . IN 1D only a scalar is necessary. •
formulate $V4$ Plastic indicator: INDIPLAS . INDICATE if the material exceeded the elastic criterion. •
formulate $V5$ nonrecoverable dissipation: DISSIP . DURING seismic computations it can be useful for the user to know nonrecoverable dissipated energy. The variable dissip REPRESENTS the nonrecoverable office plurality of energy. The nonrecoverable increment of energy is written in the form: formulate

$$\Delta Eg=\frac{1}{2}\left(E^{+}\Delta\varepsilon-\left(\sigma^{+}-\sigma^{-}\right)\right)\Delta\varepsilon$$

formulate $V6$ thermodynamic dissipation: DISSTHER . The thermodynamic increment of dissipation is written in the form: formulate $\Delta Eg=\sigma_y\,p$

5 of Von Mises with asymmetrical linear hardening: VMIS_ASYM_LINE Equations

5.1 of model VMIS_ASYM_LINE Behavior

5.1.1 asymmetrical in tension and compression It

is a behavior decoupled in tension and compression, built from VMIS_ASYM_LINE , but with elastic limits and different hardening moduli in tension and compression. We adopt an index for T the tension and C compression. Elastic behavior in tension and compression identical and is characterized by the same Young modulus. There are two fields of isotropic hardening defined by and R_T . R_C The two fields are independent one of the other. elastic limit

YT	in tension. In absolute value. elastic limit
YC	in compression. In absolute value. Local variable
p_T	in tension. Algebraic value. Local variable
p_C	in compression. Algebraic value. Slope
E_{TT}	of hardening in tension. Slope
E_{TC}	D "hardening in compression.

The equations of the model of behavior are: :

$$\begin{cases} \dot{\varepsilon}^p = \dot{\varepsilon} - \mathrm{E}^{-1}\sigma - \dot{\varepsilon}^{th} \\ \dot{\varepsilon}^p = \dot{\varepsilon}^p_C + \dot{\varepsilon}^p_T \\ \dot{\varepsilon}^p_C = \dot{\varepsilon}_C \dfrac{\sigma}{|\sigma|} \\ \dot{\varepsilon}^p_C = \dot{\varepsilon}_T \dfrac{\sigma}{|\sigma|} \\ \sigma - R_T\left(p_T\right) \le 0 \\ -\sigma - R_C\left(p_C\right) \le 0 \end{cases} \quad \text{avec} \begin{cases} \dot{p}_C = 0 \quad si \quad -\sigma - R_C\left(p_C\right) < 0 \\ \dot{p}_C \ge 0 \quad si \quad -\sigma = R_C\left(p_C\right) \\ \dot{p}_T = 0 \quad si \quad \sigma - R_T\left(p_T\right) < 0 \\ \dot{p}_T \ge 0 \quad si \quad \sigma = T_T\left(p_T\right) \end{cases}$$

$\dot{\varepsilon}^p_C$ plastic strainrate in compression:

$\dot{\varepsilon}^p_T$ plastic strainrate in tension:

$\dot{\varepsilon}^{th}$ strain D" thermal origin: It $\varepsilon^{th} = \alpha\left(T - T_{ref}\right)$

is noticed that one cannot have simultaneously plasticization in tension and compression: either, $\dot{p}_C = 0$ or, $\dot{p}_C = 0$ or both are null.

The data of the characteristics of materials are those provided under the key word factor ECRO_ASYM_LINE of operator DEFI _MATERIAU [U 4.43.01]. ECRO_ASYM_LINE

= _F (DT_SIGM_EPSI
=, E_{TT} SY_T = , σ_{yT} DC_SIGM_EPSI
=, SY_C E_{TC} = ,) σ_{yC}

the Young modulus E is provided under the key keys factors ELAS or ELAS_FO . One calculates the functions of hardening by: Integration

$$R_T(p)=\frac{E_{TT}E}{E-E_{TT}}p_T+\sigma_{yT}=H_T\cdot p_T+\sigma_{yT}$$
$$R_C(p)=\frac{E_{TC}E}{E-E_{TC}}p_C+\sigma_{yC}=H_C\cdot p_C+\sigma_{yC}$$

5.2 of behavior VMIS_ASYM_LINE By

direct implicit discretization of the asymmetrical behavior model, in a way similar to the preceding one, one obtains:

$$\begin{cases}
\Delta\varepsilon^p=\Delta\varepsilon_T^p+\Delta\varepsilon_C^p \\
\Delta\varepsilon^p=\Delta\varepsilon-\Delta\varepsilon^{th}-\dfrac{\Delta\sigma}{E} \\
\Delta\varepsilon_T^p=\Delta p_T\dfrac{\sigma^-+\Delta\sigma}{|\sigma^-+\Delta\sigma|} \\
\Delta p_T\geq 0 \quad si \quad (\sigma^-+\Delta\sigma)-R_T(\bar{p}_T+\Delta\bar{p}_T) \leq 0 \\
\Delta p_T=0 \quad si \quad (\sigma^-+\Delta\sigma)-R_T(\bar{p}_T+\Delta\bar{p}_T) < 0 \\
\\
\Delta\varepsilon_C^p=\Delta p_C\dfrac{\sigma^-+\Delta\sigma}{|\sigma^-+\Delta\sigma|} \\
-(\sigma^-+\Delta\sigma)-R_C(\bar{p}_C+\Delta\bar{p}_C)\leq 0 \\
\Delta p_C\geq 0 \quad si \quad -(\sigma^-+\Delta\sigma)-R_C(\bar{p}_C+\Delta\bar{p}_C) = 0 \\
\Delta p_C=0 \quad si \quad -(\sigma^-+\Delta\sigma)-R_C(\bar{p}_C+\Delta\bar{p}_C) < 0
\end{cases}$$

Integration is similar to that of VMIS_ISOT_LINE `for` each direction of tension and compression. It should well be seen that the centers of the fields of elasticity are data (calculated explicitly with the preceding step) for the incremental problem to solve. Four

cases arise: •
one $\Delta\varepsilon-\Delta\varepsilon^{th}>0$ so poses $\sigma_T^e=\sigma^-+E(\Delta\varepsilon-\Delta\varepsilon^{th})$

- ◦ in $\sigma_T^e<R_T(\bar{p}_T)$ this case thus $\Delta p_T = 0$ and $\sigma=\sigma_T^e$ ◦ $\dfrac{\delta\sigma}{\delta\varepsilon} = E$

- if not : , $\Delta p_T=\dfrac{|\sigma_T^e|-(\sigma_{yT}+H_T p_T^-)}{E+H_T}$ • $\Delta p_C=0$ $\quad \sigma=\dfrac{\sigma_T^e}{1+\dfrac{E\Delta p_T}{R_T(p_T)}}=\dfrac{\sigma_T^e}{|\sigma_T^e|}R_T(p_T)$ $\quad \dfrac{\delta\sigma}{\delta\varepsilon}=E_{TT}$

one $\Delta\varepsilon-\Delta\varepsilon^{th}<0$ so poses $\sigma_C^e=\sigma^-+E(\Delta\varepsilon-\Delta\varepsilon^{th})$

- ◦ in $-\sigma_C^e<R_C(\bar{p}_C)$ this case thus $\Delta p_C = 0$ and $\sigma=\sigma_C^e$ ◦ $\dfrac{\delta\sigma}{\delta\varepsilon} = E$

if not : , $\Delta p_C = \frac{\left|\sigma_C^e\right| - \left(\sigma_{yC} + H_C p_C^{-}\right)}{E + H_C}$ Note $\Delta p_T = 0$ $\sigma = \frac{\sigma_C^e}{1 + \frac{E \Delta p_C}{R_C\left(p_C\right)}} = \frac{\sigma_C^e}{\left|\sigma_C^e\right|} R_C\left(p_C\right)$

$\frac{\delta \sigma}{\delta \varepsilon} = E_{TC}$

:

The initial tangent matrix (option RIGI `_MECA_TANG)` is taken equal to the elastic matrix. Local variables

5.3

behavior model VMIS_ASYM_LINE `produces` 2 local variables: . p_C p_T It is not usable for the elements of grid. The model

6 model PINTO_MENEGOTTO

presented in this chapter describes the behavior 1D reinforcing steels of the reinforced concrete [feeding-bottle 1].1The constitutive law of these steels is made up of two distinct parts: the monotonic loading made up of three successive zones (linear elasticity, plastic bearing and hardening) and the cyclic loading whose analytical formulation was proposed by A. Giuffré and P. Pinto was developed in 1973 [feeding-bottle 22 and then by Mr. Menegotto [feeding-bottle 3].3During

the cycles, the way of loading between two points of inversion (semi-cycle) is described by a curve of analytical statement of the type. $\sigma = f(\varepsilon)$ The interest of this formulation is that the same equation controls the discharge and load diagrams (see for example the figures [Figure 6.1.1-a6.1.1-a [Figure 6.1.2-a6.1.2-a The parameters attached to the function f are reactualized after each inversion of loading. The reactualization of these parameters depends on the way carried out in the plastic zone during the half - preceding cycle. In addition

, this model can treat the inelastic buckling of the bars (G. Monti and C. Nuti [feeding-bottle 4])4 The introduction of new parameters into the equation of the curves then makes it possible to simulate the softening of the response stress-strain in compression. Formulation

6.1 of the model Monotonic loading

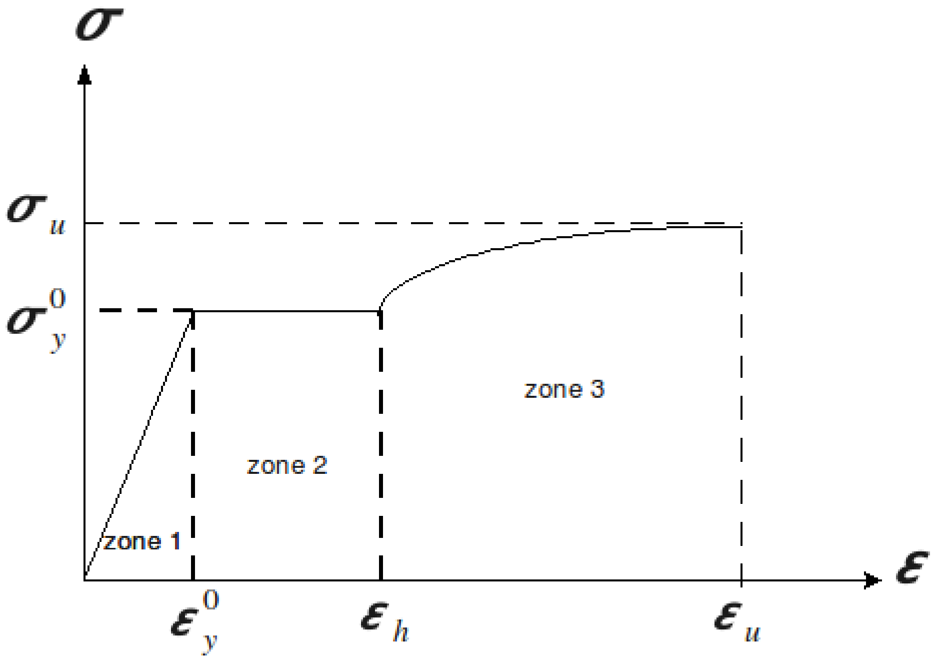
6.1.1 This

chapter describes the first loading which the bar undergoes, i.e. the part preceding activation by the curve of Giuffré [Figure 6.1.1-a6.1.1-a
The monotonous curve of tension of steel is typically followed by the three following successive zones:
•

The linear elasticity, defined by the elastic limit and Young modulus E . σ_y (zone $\sigma = E\varepsilon$ 1, [Figure 6.1.1-a6.1.1-a•
The plastic bearing, ranging between the elastic strain limits and ε_y^0 the strain of hardening, ε_h limits higher plate in strain. During the bearing the stress remains constant. (zone $\sigma = \sigma_y^0$ 2, [Figure 6.1.1-a6.1.1-a•
L'écrouissage, following curve of tension up to the ultimate point of stress and strain. $(\varepsilon_u, \sigma_u)$
This part is represented by a polynomial of the fourth degree: (zone $\sigma = \sigma_u - (\sigma_u - \sigma_y^0)\left(\frac{\varepsilon_u - \varepsilon}{\varepsilon_u - \varepsilon_h}\right)^4$

2, [Figure 6.1.1-a6.1.1-a The hardening slope

(used thereafter, for the cyclic behavior) is defined here by: . $E_h = \frac{\sigma_u - \sigma_y^0}{\varepsilon_u - \varepsilon_y^0}$ It is the average slope of zones 2 and 3 of the following figure. Figure



6.1 6.1.1-a Curve of behavior. Cyclic

6.1.2 loading One

is placed now if the bar undergoes a consecutive discharge with the first loading. Two cases arise then: •

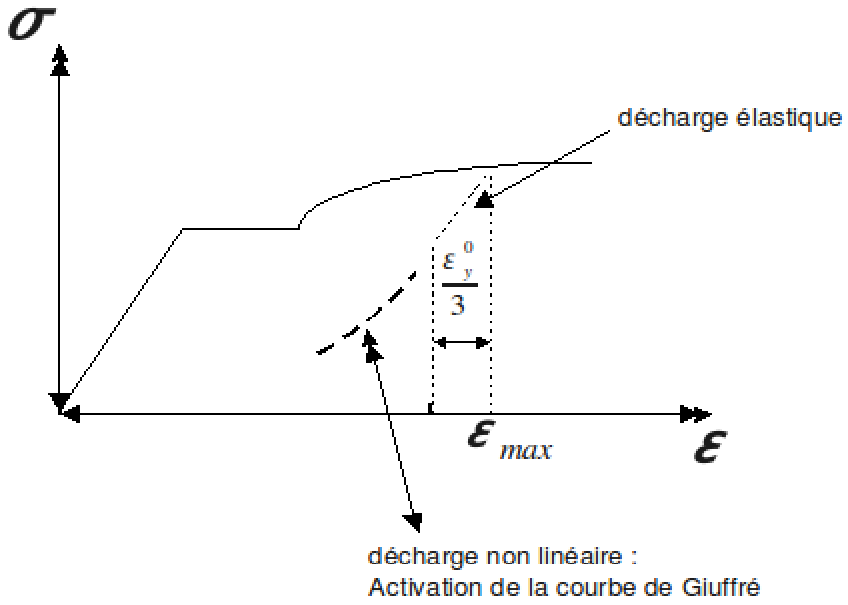
the starting position is in the elastic zone. The discharge remains in this elastic case, •

the starting position is in the plastic zone (). $\varepsilon \geq \varepsilon_y^0$ The response is first of all elastic , then, for a certain value of the strain, the discharge becomes nonlinear [Figure 6.1.2-a6.1.2-athis is true for a discharge from zone 2 or of zone 3).

The relation which the strain must satisfy so that the curve of Giuffré is activated is the following one: ,

$\left| \varepsilon_{max} - \varepsilon \right| > \dfrac{\left|\varepsilon_y^0\right|}{3.0}$ with ε_{max} the maximum strain reached in load. As soon as

one crossed this limit with the first discharge, it is the cyclic behavior (curve of Giuffré [Figure 6.1.2-a6.1.2-a which is activated. Figure



6.1 6.1.2-a Curve of behavior with discharge. Presentation

6.1.2.1 of the nth semi-cycle

the shape of the curve of the nth semi-cycle depends on the plastic excursion carried out during the half - preceding cycle. The following quantities are defined [6.1.2.1 Figure6.1.2.1-a: •

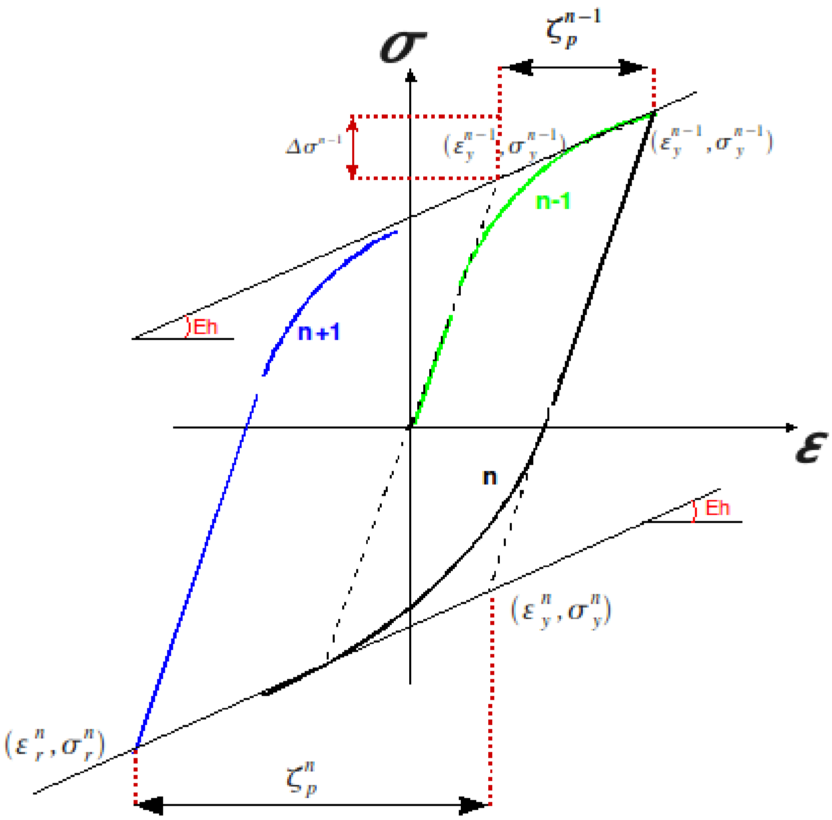
: σ_y^n Elastic limit of the nth semi-cycle. (Computation clarified with [§ 5.1.2.2]) •

: σ_r^{n-1} Stress at the last point of inversion (maximum stress reached with the n-1ième semi-cycle). •

: ε_r^{n-1} Strain at the last point of inversion (maximum strain attack with the n-1ième semi-cycle). •

: ε_y^n Strain corresponding to: σ_y^n • $\varepsilon_y^n=\varepsilon_r^{n-1}+\frac{\sigma_y^n-\sigma_r^{n-1}}{E}$

: $f(t)$ Plastic excursion of the nth cycle Appears



6.1.2.1 6.1.2.1-a Behavior cyclic. Model

6.1.2.2 of hardening The model

is based on a model of kinematic hardening. The branches of the semi-cycles lie between two asymptotes of slope (asymptotic E_h slope of hardening). One

thus determines in the following way σ_y^n : where $\sigma_y^n=\sigma_y^{n-1}.sign\left(-\zeta_p^{n-1}\right)+\Delta\sigma^{n-1}$ the function if $sign(x)=-1$ and $x<0$ if 1 and $x>0$ where is $\Delta\sigma^{n-1}$ the plastic increment of stress of the preceding semi-cycle [6.1.2.1 Figure6.1.2.1-a is defined by: . $\Delta\sigma^{n-1}=E_h\zeta_p^{n-1}$ For

each semi-cycle one thus determines according to σ_y^n and σ_y^{n-1} , ζ_p^{n-1} one from of deduced, then ε_y^n the following semi-cycle is calculated (by the constitutive law below). The maximum strain (in absolute value) attack before changing meaning will make it possible to calculate the plastic excursion. $\zeta_p^n=\varepsilon_r^n-\varepsilon_y^n$ Analytical

6.1.2.3 description of the curves $\sigma=f(\varepsilon)$

the statement chosen in the model following the curves of loading is the following one: With

$$\sigma^*=b\varepsilon^*+\left(\frac{1-b}{\left(1+\left(\varepsilon^*\right)^R\right)^{1/R}}\right)\varepsilon^*$$

ratio $b=\dfrac{E_h}{E}$ of the slope of hardening on the slope of elasticity.

$$\varepsilon^{*}=\frac{\varepsilon-\varepsilon_r^{n-1}}{\varepsilon_y^n-\varepsilon_r^{n-1}}$$

$$\sigma^{*}=\frac{\sigma-\sigma_r^{n-1}}{\sigma_y^n-\sigma_r^{n-1}}$$

$$\xi_p^{n-1}=\frac{\zeta_p^{n-1}}{\varepsilon_y^n-\varepsilon_r^{n-1}}$$

The quantity makes it possible R to describe the pace of the curvature of the branches. It is function of the plastic way carried out during the preceding semi-cycle: where

$$R(\xi)=R_0-g(\xi) \quad g(\xi)=\frac{A_1.\xi}{A_2+\xi}$$

the parameters and R_0, A_1 are A_2 constants without unit depending on the mechanical properties of steel. Their values are obtained in experiments and Menegotto [feeding-bottle 3]3: Cases

$$R_0=20.0 \qquad A_1=18.5 \qquad A_2=.015$$

6.1.3 of inelastic buckling Monti

and Nuti [feeding-bottle 4]4 that for a relationship between the length and L the diameter of D the bar lower than 5, the curve of compression is identical to that of tension. On the other hand, when $L/D>5$ a buckling of the bar is observed. In this case the curve of compression in the plastic zone has a lenitive behavior. The model available in Code_Aster *allows* to also describe this phenomenon.

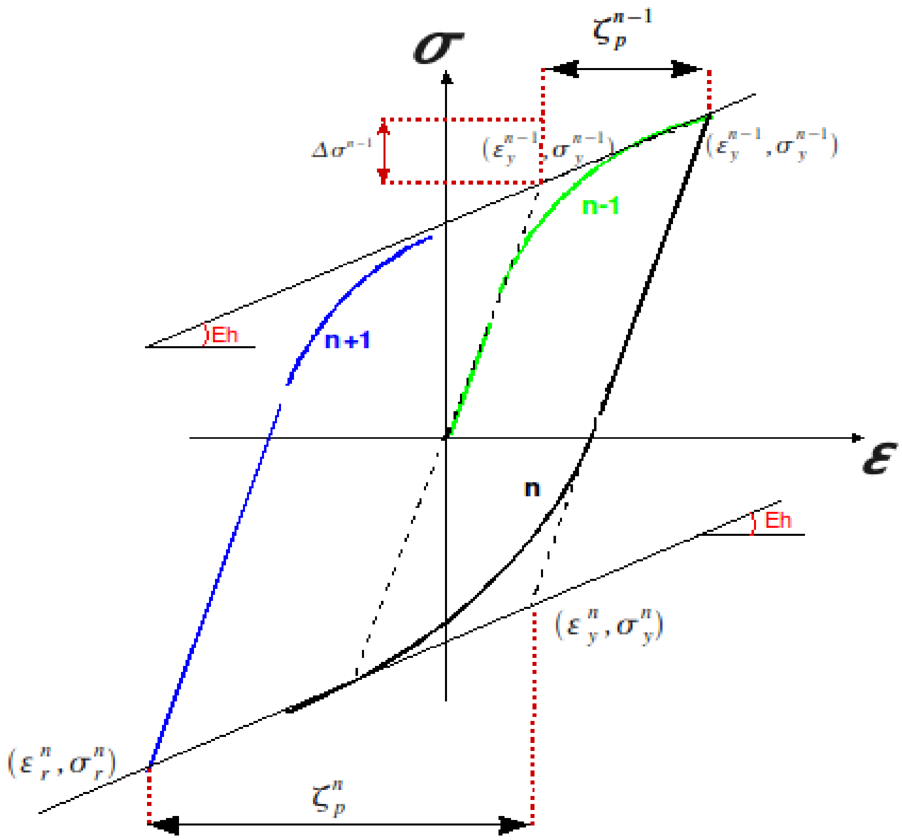
The following variables are defined [Figure 6.1.3-a6.1.3-a: •

: E_0 Initial elastic Young modulus (corresponding with E without buckling). •

: b_c Ratio of the slope of hardening on the elastic slope in compression. •

: b_t Ratio of the slope of hardening on the elastic slope in tension (refill after compression with buckling). •

: E_r Modulus Young reduced in tension (slope of the curve of refill after compression with buckling). Figure



6.1 6.1.3-a Cyclic curve of behavior. Compression

6.1.3.1 One

introduces a negative slope, $b_c \times E$ where b_c is defined by: With

$$b_c = a(5.0 - L/D)\, e\left(b\zeta' \frac{E}{\sigma_y^0 - \sigma^\infty}\right)$$

and $\sigma_\infty = 4.0 \dfrac{\sigma_y^0}{L/D}$ $\zeta' = \max\left(\left|\zeta_p^n\right|\right)$ the greatest plastic way carried out during the loading. It

is necessary then, as in the model without buckling, to determine. σ_y^n The method is identical, but one adds a complementary stress in order to σ_s^* correctly position the curve compared to the asymptote [Figure 6.1.3-a6.1.3-awhere

$$\sigma_s^* = \gamma_s b E \frac{b - b_c}{1 - b_c}$$

γ_s is given by: And $\gamma_s = \dfrac{11.0 - L/D}{10\left(e^{cL/D} - 1.0\right)}$

one thus has: This $\sigma_y^n = \left(\sigma_y^n\right)_{\text{sans flambage}} + \sigma_s^*$

During modifies also the value of $\varepsilon_y^n = \varepsilon_r^{n-1} + \dfrac{\sigma_y^n * \sigma_r^{n-1}}{E}$

6.1.3.2 Tension

the semi-cycle in tension according to one adopts a reduced Young modulus defines by: with

$$E_r = E_0\left(a_5 + \left(1.0 - a_5\right) e^{\left(-a_6 \zeta_p^2\right)}\right)$$ Note: $a_5 = 1.0 + (5.0 - L/D)/7.5$

:

The parameters and a, c *are* a_6 *constants (without unit) depend on the mechanical properties of steel and are in experiments given. The values adopted by Monti and Nuti [feeding-bottle 4]4: Establishment* $a=0.006$ $c=0.500$ $a_6=620.0$

6.2 in Code_Aster *This*

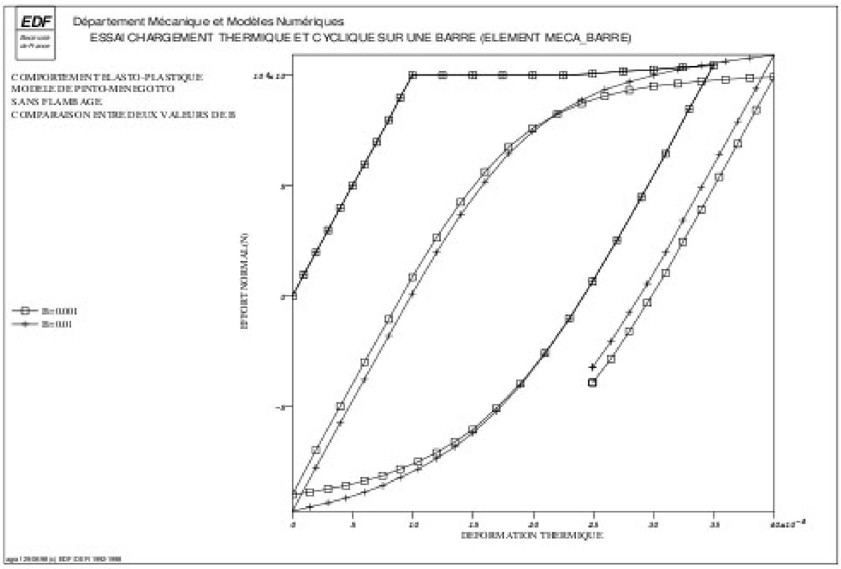
model is accessible in Code_Aster *from* key word COMP_INCR (RELATION = "PINTO_MENEGOTTO") or (RELATION = "GRILLE_PINTO_MEN") of the command STAT_NON_LINE [U 4.51.03]. All the parameters of the model are given via command DEFI _MATERIAU (key word factor PINTO_MENEGOTTO) [U4.43.01]. One indexes the parameters here intervening in the model: Parameters

of the model Intervenes	in adopted	value by default in Aster *First*
σ_y^0	loading _	First
ε_u	loading _	First
σ_u	loading _	First
ε_h	loading _	Cycles
$b=\frac{E_h}{E}$	If	no value entered one takes the computed value with the first loading Cycles
R_0	20	Cycles
a_1	18.5	Cycles
a_2	0.15	Cycles
L/D	with buckling (if) $L/D>5$ 4	(to be by default except buckling) Buckling
a_6	620	Buckling
c	0.5	Buckling
a	the 0.006	

parameters and R_0, a_1, a_2, a_6, c depend a on the mechanical properties of steel and are in experiments given. The adopted values by default in Code_Aster *are* those proposed in the literature [feeding-bottle 1].1One

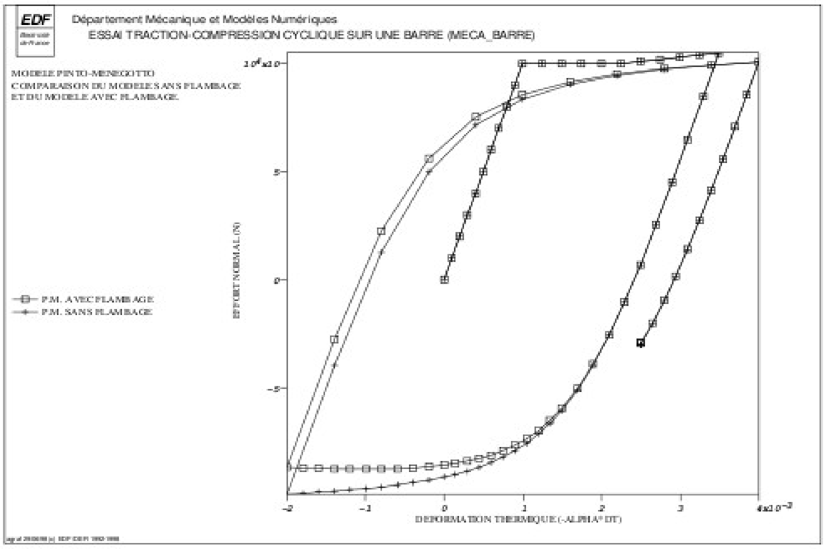
gives in [Figure 6.2-a6.2-a a comparison of the model following the value of for $b=\frac{E_h}{E}$ two values:

and $b=0.01$ Figure $b=0.001$



6.2 6.2-a Comparison of 2 sets of parameters. One

gives in [Figure 6.2-b6.2-b a comparison of the model without buckling and the model and buckling. Figure



6.2 6.2-b Comparison with and without buckling. Local variables

6.3 They

8, and are defined by: Behavior

$V1 = \varepsilon_r^{n-1}$

$V2 = \varepsilon ,_r^n$

$V3 = \sigma_r^n$

$V4 = \varepsilon^- + \Delta\varepsilon - \alpha(T - T^-)$ $V5 = \Delta\varepsilon + \alpha(T - T^-)$

$V6 =$ cycl = 0 si le comportement cyclique n'est pas activé
= 1 dans le cas contraire

$V7 = \chi$ = 0 si le pas de temps correspond à une évolution linéaire
= 1 dans le cas contraire (indicateur de plasticité

$V8 =$ indicateur de flambage

7 of LEMAITRE (LEMAITRE_IRRA) The model

presented in this chapter describes the nonlinear viscoelastic behavior 1D of J.Lemaître developed for the modelization of the fuel assemblies, and applicable to the beam elements, in the axial direction [feeding-bottle 6].6Formulation

7.1 of the model

the equations are the following ones:

$$\begin{cases} \dot{\varepsilon}^{vp}=\dot{p}\dfrac{\sigma}{|\sigma|} \\ \dot{p}=\left[\dfrac{|\sigma|}{p^{\frac{1}{m}}}\right]^{n}\cdot\left(e^{-\frac{Q}{RT}}\right)\cdot\left(\dfrac{\dot{\Phi}}{K\,\Phi_0}+L\right)^{\beta} \quad , \quad \mathrm{n}>0 \quad , \quad \dfrac{1}{\mathrm{K}} \quad , \quad \dfrac{1}{\mathrm{m}}\geq 0 \quad , \quad \dfrac{\mathrm{Q}}{\mathrm{R}}\geq 0 \\ \dfrac{\dot{\sigma}}{E}=\dot{\varepsilon}-\dot{\varepsilon}^{vp}-\dot{\varepsilon}^{g}-\dot{\varepsilon}^{th} \end{cases}$$

The coefficients are provided under key word LEMAITRE_IRRA of DEFI _MATERIAU and is Φ_t the fluence. Note:

$$\varepsilon^{g}(t)=f\left(T,\Phi_t(x,y,z)\right)$$

The neutron flux $\dot{\Phi}(x,y,z)$ is expressed obligatorily in. $10^{20}\,n/cm^2/s$ This implies that the units of the other quantities are built-in: •
are E,K,σ in, MPa •
times are in seconds, •
coordinates in • mm
in $T,\dfrac{Q}{R}$ Kelvin Two

types of integrations are available according to the value of key word PARM_THETA : •
purely implicit integration, if PARM_THETA =1.0 (default value)•
implicit semi integration, if PARM_THETA =0.5 Only
these two values are authorized. Implicit

7.2 integration By

direct implicit discretization of the behavior models, one obtains: One

$$\begin{cases} \Delta\varepsilon^{vp}=\Delta p\dfrac{\sigma^{-}+\Delta\sigma}{|\sigma^{-}+\Delta\sigma|} \\ \Delta p=\left[\dfrac{|\sigma{-}+\Delta\sigma|}{\left(p^{-}+\Delta p\right)^{\frac{1}{m}}}\right]^{n}\cdot\left(e^{-\frac{Q}{RT}}\right)\cdot\left(\dfrac{\Phi-\Phi^{-}}{K\,\Phi_0\Delta t}+L\right)^{\beta}\cdot\Delta t \\ \dfrac{\sigma}{E}-\dfrac{\sigma^{-}}{E^{-}}=\Delta\varepsilon-\Delta\varepsilon^{vp}-\Delta\varepsilon^{g}-\Delta\varepsilon^{th} \\ \text{avec} \\ \Delta\varepsilon^{th}=\alpha(T)\left(T-T_{ref}\right)-\alpha(T^{-})\left(T^{-}-T_{ref}\right) \\ \Delta\varepsilon^{g}=f\left(T^{+},\Phi_t^{+}\right)-f\left(T^{-},\Phi_t^{-}\right) \end{cases}$$

can still bring back oneself there to only one nonlinear scalar equation in, Δp while posing: then

$$\sigma^e = \frac{E}{E^-}\sigma^- + E\left(\Delta\varepsilon - \Delta\varepsilon^g - \Delta\varepsilon^{th}\right)$$

the system is reduced to: and

$$\begin{cases} \Delta p = \left[\frac{1}{K}\frac{|\sigma|}{\left(p^- + \Delta p\right)^{\frac{1}{m}}}\right]^n \cdot \left(e^{-\frac{Q}{RT}}\right)\left(\frac{\Delta\Phi}{K\Phi_0\Delta t} + L\right)^\beta \cdot \Delta t \\ \sigma^e = \sigma + E\Delta\varepsilon^{\mathrm{vp}} = \sigma + E\Delta p\frac{\sigma}{|\sigma|} = \sigma\left(1 + \frac{E\Delta p}{|\sigma|}\right) \end{cases}$$

by taking the absolute value of the two members of the last equation, one obtains: what $\left|\sigma^e\right| = |\sigma| + E\Delta p$

results in solving the equation: Once

$$\Delta p = \left[\frac{1}{K}\frac{\left|\sigma^e\right| - E\Delta p}{\left(p^- + \Delta p\right)^{\frac{1}{m}}}\right]^n \cdot \left(e^{-\frac{Q}{RT}}\right)\left(\frac{\Delta\Phi}{K\Phi_0\Delta t} + L\right)^\beta \cdot \Delta t$$

this solved equation (by a research method of zero of function scalar), one obtains the stresses by:

Semi-implicit $$\sigma = \frac{\sigma^e}{1 + \frac{E\Delta p}{\left|\sigma^e\right| - E\Delta p}} = \sigma^e\left(1 - \frac{E\Delta p}{\left|\sigma^e\right|}\right)$$

7.3 integration In

fact, in elastoplasticity, one uses the implicit integration of the models of behavior, because convergence towards the solution of the problem continuous in time, excellent, and is led moreover to unconditionally stable diagrams. For

viscoelastic or viscoplastic behaviors, utilizing explicitly physical time, the implicit discretization always leads to unconditionally stable diagrams, but convergence towards the solution is not also any more fast. It is preferable to use an semi-implicit integration then. It is the choice which we made here, following in that the integration of the model of Lemaître in Aster and Cyrano3 [feeding-bottle 5].5The method put in work here is not theta - general method: it functions only for. $theta = 0.5$ It makes it possible however to get correct results. For more generality, it would be necessary to use more sophisticated method, for example the method of RUNGE KUTTA of order 2 or 4. Here

, one writes simply: One

$$\begin{cases}\Delta \varepsilon^{vp}=\Delta p\dfrac{\sigma^{-}+\dfrac{\Delta\sigma}{2}}{\left|\sigma^{-}+\dfrac{\Delta\sigma}{2}\right|}\\ \Delta p=\left[\dfrac{1}{K}\dfrac{\left|\sigma^{-}+\dfrac{\Delta\sigma}{2}\right|}{\left(p^{-}+\dfrac{\Delta p}{2}\right)^{\frac{1}{m}}}\right]^{n}\cdot\left(e^{-\frac{Q}{R\left(T+\frac{\Delta T}{2}\right)}}\right)\cdot\left(\dfrac{\Delta\Phi}{K\Phi_0\Delta t}+L\right)^{\beta}\cdot\Delta t\\ \dfrac{1}{2}\left(\dfrac{\sigma}{E}-\dfrac{\sigma^{-}}{E^{-}}\right)=\dfrac{\Delta\varepsilon}{2}-\dfrac{\Delta\varepsilon^{vp}}{2}-\dfrac{\Delta\varepsilon^{g}}{2}-\dfrac{\Delta\varepsilon^{th}}{2}\\ \Delta\varepsilon_{th}=\alpha(T)\left(T-T_{ref}\right)-\alpha(T^{-})\left(T^{-}-T_{ref}\right)\\ \Delta\varepsilon^{g}=f\left(T^{+},\Phi_t^{+}\right)-f\left(T^{-},\Phi_t^{-}\right)\end{cases}$$

seeks to calculate. $\sigma^{-}+\dfrac{\Delta\sigma}{2}$ One can write: thus

$$\frac{\sigma}{2}=\frac{\sigma^{-}}{2}+\frac{\Delta\sigma}{2}=\frac{E}{E^{-}}\frac{\sigma^{-}}{2}+\frac{E\,\Delta\varepsilon}{2}-\frac{E\,\Delta\varepsilon^{vp}}{2}-E\frac{\Delta\varepsilon^{g}}{2}-E\frac{\Delta\varepsilon^{th}}{2}$$

Like

$$\sigma^{-}+\frac{\Delta\sigma}{2}=\frac{\sigma^{-}}{2}+\frac{E}{E^{-}}\frac{\sigma^{-}}{2}+E\left(\frac{\Delta\varepsilon}{2}-\frac{\Delta\varepsilon^{g}}{2}-\frac{\Delta\varepsilon^{th}}{2}\right)-\frac{E\,\Delta\varepsilon^{v}}{2}$$

previously, one solves while posing: then

$$\sigma^{e}=\frac{E}{E^{-}}\frac{\sigma^{-}}{2}+\frac{\sigma^{-}}{2}+e\left(\frac{\Delta\varepsilon}{2}-\frac{\Delta\varepsilon^{g}}{2}-\frac{\Delta\varepsilon^{th}}{2}\right)$$

the system is reduced to: from where

$$\frac{\Delta p}{2}=\left[\frac{1}{K}\frac{\left|\sigma^{-}+\dfrac{\Delta\sigma}{2}\right|}{\left(p^{-}+\dfrac{\Delta p}{2}\right)^{\frac{1}{m}}}\right]^{n}.\left(e^{\frac{-Q}{R\left(T+\frac{\Delta T}{2}\right)}}\right)\left(\frac{\Delta\Phi}{K\Phi_0\Delta t}+L\right)^{\beta}\cdot\frac{\Delta t}{2}$$

$$\sigma^{e}=\sigma^{-}+\frac{\Delta\sigma}{2}+E\frac{\Delta p}{2}\frac{\sigma^{-}+\dfrac{\Delta\sigma}{2}}{\left|\sigma^{-}+\dfrac{\Delta\sigma}{2}\right|}=\left(\sigma^{-}+\frac{\Delta\sigma}{2}\right)\left(1+\frac{E\dfrac{\Delta p}{2}}{\left|\sigma^{-}+\dfrac{\Delta\sigma}{2}\right|}\right)$$

: $\left|\sigma^{e}\right|=\left|\sigma^{-}+\dfrac{\Delta\sigma}{2}\right|+E\dfrac{\Delta p}{2}$

The equation to be solved is exactly same form as the implicit equation: Once

$$\frac{\Delta p}{2}=\left[\frac{1}{K}\frac{\left|\sigma^{e}\right|-E\frac{\Delta p}{2}}{\left(p^{-}+\frac{\Delta p}{2}\right)^{\frac{1}{m}}}\right]^{n}\cdot\left(e^{\frac{-Q}{R\left(T+\frac{\Delta T}{2}\right)}}\right)\left(\frac{\Delta\Phi}{K\,\Phi_0\,\Delta t}+L\right)^{\beta}\cdot\frac{\Delta t}{2}$$

this solved equation, one obtains the local variables while multiplying by 2 the value obtained and the forced by: One

$$\sigma^{-}+\frac{\Delta\sigma}{2}=\sigma^{e}\left(1-\frac{E\,\Delta p}{\left|\sigma^{e}\right|}\right)$$

$$\sigma^{-}+\Delta\sigma=2\left(\sigma^{-}+\frac{\Delta\sigma}{2}\right)-\sigma^{-}$$

can thus use the same routines of resolution as in the implicit case, while calculating simply in σ^{e} $\frac{\Delta\varepsilon}{2}$ $\frac{\Delta\varepsilon^{g}}{2}$. $\frac{\Delta\varepsilon^{th}}{2}$ On

an elementary test of creep (test SSNL109A), one obtains by the semi-implicit method result correct (to 0.02% of the analytical solution) if 2 time step are used (instead of 100 time step necessary to have a correct solution with implicit integration). Local variables

7.4 Three

local variables are calculated in this model: p, the neutron fluence calculated with time step running and the strain of growth formulates ε^{g}

7.5 of the parameters of the model It

is done from creep tests (uniaxial test with constant stress imposed under constant neutron flux). By integration of the equations of the model, one obtains then: Behavior model

$$\varepsilon^{vp}(t)=\left[\frac{n+m}{m}\left(\frac{\dot{\Phi}}{K\,\Phi_0}+L\right)^{\beta}e^{\frac{-Q}{RT}}\sigma^{n}\right]^{\frac{m}{n+m}}$$

8 of LMA-RC (LMARC_IRRA) The model

presented in this chapter describes the viscoplastic behavior 1D LMA-RC (Laboratory of Mechanics Applied R.Chaléat of Besancon) developed for the modelization of the fuel assemblies, and applicable to the beam elements, in the axial direction [feeding-bottle 6].6Formulation

8.1 of the model The model

élasto-viscoplastic developed with the LMA-RC to describe the orthotropic behavior of the tubes of sheaths of the fuel pin [R5.03.10] is written in 1D isotropic: with

$$\begin{cases} \frac{\dot{\sigma}}{E}=\dot{\varepsilon}-\dot{\varepsilon}^{vp}-\dot{\varepsilon}^{g}-\dot{\varepsilon}^{th} \\ \dot{\varepsilon}^{vp}=\dot{p}.\xi \\ \xi=\frac{(\sigma-X)}{|\sigma-X|} \\ \dot{p}=\dot{\varepsilon}_0\left\{\sin\text{h}\left(\frac{|\sigma-X|}{K}\right)\right\}^n \\ \dot{X}=q\left(Y(p)\dot{\varepsilon}^{vp}-\left(X-X^{(1)}\right)\dot{p}\right)-\left\{r_m\sin\text{h}\left(\left(\frac{|X|}{X_0}\right)^m\right)\right\}\frac{X}{|X|} \\ \dot{X}^{(1)}=q_1\left(Y(p)\dot{\varepsilon}^{vp}-\left(X^{(1)}-X^{(2)}\right)\dot{p}\right) \\ \dot{X}^{(2)}=q_2\left(Y(p)\dot{\varepsilon}^{vp}-X^{(2)}\dot{p}\right) \end{cases}$$

: $Y(v)=Y_{\infty}+\left(Y_0-Y_{\infty}\right)e^{bp}$

The coefficients, as in, are 3D provided by key word LMARC_IRRA (one does not use here the coefficients related to the anisotropy) (correspond q, q_1, q_2 respectively to the parameters of p, p_1, p_2 key word LMARC_IRRA).

The model of growth is identical to that used for the model of Lemaitre: formulate

$$\varepsilon^g(t)=f\left(T,\Phi_t(x,y,z)\right)$$

neutron flux is Φ the product of a function of (clevis x pin, in front of being confused with one of the axes of the total reference) and of a function of and y . z Note:

•

The fluence is worth. $\Phi_t(x, y, z)$ •

Only one diagram of integration is available: a purely implicit diagram. •

The neutron flux $\Phi(x,y,z)$ is expressed obligatorily in. $10^{20}n/cm^2/s$ This implies that the units of the other quantities are built-in: ◦

is E, K, σ in, MPa ◦

times are in seconds, ◦

the coordinates in. mm Implicit

8.2 integration

to integrate these behavior models, while being brought back if possible to only one equation to solve, it is necessary to make an assumption on. $\xi=\frac{(\sigma-X)}{|\sigma-X|}$ Indeed, it can take only two values: or $+1$.

-1 This known sign is thus supposed (initialized by). $\xi=\frac{(\sigma^{-}-X^{-})}{|\sigma^{-}-X^{-}|}$ If one cannot solve the equation obtained with this assumption, one takes the opposite sign. The rest of the equations can be integrated in a purely implicit way. The system is written: There

$$\begin{cases} \sigma=\sigma^{-}+\Delta\sigma=E\left(\frac{\sigma^{-}}{E^{-}}+\Delta\varepsilon-\Delta\varepsilon^{g}-\Delta\varepsilon^{th}-\Delta p\,\xi\right)=\sigma_e-E\,\xi\,\Delta p \\ \Delta p=\dot{\varepsilon}_0\Delta t\left\{\sin\mathrm{h}\left(\frac{|\sigma-X|}{K}\right)\right\}^{n}=f_v(\sigma,X)\Delta t \\ \Delta\dot{X}=q\,\Delta p\left(Y(p)\,\dot{\varepsilon}-\left(X-X^{(1)}\right)\right)-\left\{r_m\sin\mathrm{h}\left(\left(\frac{|X|}{X_0}\right)^{m}\right)\right\}\frac{X}{|X|}=f(p,X,X^{(1)}) \\ \dot{X}^{(1)}=q_1\Delta p\left(\xi Y(p)-\left(X^{(1)}-X^{(2)}\right)\right)=f_1(p,X^{(1)},X^{(2)}) \\ \dot{X}^{(2)}=q_2\Delta p\left(\xi Y(p)-X^{(2)}\right)=f_2(p,X^{(2)}) \end{cases}$$

is thus a system of 5 equations to 5 unknowns: $\Delta\sigma,\Delta p,\Delta X,\Delta X^{(1)},\Delta X^{(2)}$
The second equation is also written: By means of

$$\frac{|\sigma-X|}{K}=\log\left(\left(\frac{\Delta p}{\dot{\varepsilon}_0\Delta t}\right)^{\frac{1}{n}}+\sqrt{1+\left(\frac{\Delta p}{\dot{\varepsilon}_0\Delta t}\right)^{\frac{2}{n}}}\right)$$

the first equation, one can express according to ΔX : $\Delta \mathrm{p}$ In addition

$$\sigma-X=\sigma_e-E\,\xi\,\Delta\mathrm{p}-X=\xi|\sigma-X|$$

$$\rightarrow\Delta X=F_1(\Delta\mathrm{p})=\sigma_e-E\,\xi\,\Delta\mathrm{p}-X^{-}-K\,\xi\log\left(\left(\frac{\Delta\mathrm{p}}{\dot{\varepsilon}_0\Delta t}\right)^{\frac{1}{n}}+\sqrt{1+\left(\frac{\Delta\mathrm{p}}{\dot{\varepsilon}_0\Delta t}\right)^{\frac{2}{n}}}\right)$$

, by integration successive of the functions and f_2 one f_1 can also bring back themselves to an equation utilizing only and ΔX : $\Delta\mathrm{p}$ like

$$\Delta X^{(2)}=\frac{q_2\Delta\mathrm{p}\left(\xi Y(p)-X^{(2)-}\right)}{1+q_2\Delta\mathrm{p}}$$

$$\Delta X^{(1)}=\frac{q_1\Delta\mathrm{p}\left(\xi Y(p)-\left(X^{(1)-}-X^{(2)-}-\Delta X^{(2)}\right)\right)}{1+q_1\Delta\mathrm{p}}$$

, $\Delta X=f\left(p,X,X^{(1)}\right)$ and according to $\Delta X^{(1)}=g(\Delta p)$ the preceding statements one can write: . $\Delta X=F_2\left(\Delta p\right)=F_1\left(\Delta p\right)$ The equation to solve find is $\Delta\mathrm{p}$ thus: Once

$$F(\Delta\mathrm{p})=F_2(\Delta\mathrm{p})-F_1(\Delta\mathrm{p})=0$$

calculated, $\Delta\mathrm{p}$ one obtains the stresses by: Local variables $\sigma=\sigma_e-E\,\xi\,\Delta\mathrm{p}$

8.3 They

are 6:

$$V1 = p$$
$$V2 = X$$
$$V3 = X^{(1)}$$
$$V4 = X^{(2)}$$

$V5 =$ neutron fluence calculated with time step running. formulate

$V21 =$ the strain of growth formulates ε^g

8.4 of the parameters of the model

the identification of the parameters is carried out in the reference [feeding-bottle 7].7It relates to the ZIRCALOY 4 with 350°C. Behaviors

9 VISC_IRRA_LOG and GRAN_IRRA_LOG The model

presented in this chapter describes 1D viscoplastic behaviors VISC_IRRA_LOG and GRAN_IRRA_LOG (creep and growth under irradiation of the alloys M5 and Zircaloy-4) for the modelization of the fuel assemblies, and applicable to the elements of bars and multifibre beams. Formulation

9.1 of the model

the equations are the following ones: These

$$\begin{cases} \dot{\varepsilon}^{vp} = \dot{\varepsilon}\dfrac{\sigma}{|\sigma|} \\ \dot{\varepsilon} = |\sigma|.\left(e^{\frac{-Q}{T}}\right).\,\dot{\Phi}\left(\dfrac{A\,\omega}{1+\omega\Phi}+B\right) \\ \dfrac{\dot{\sigma}}{E} = \dot{\varepsilon} - \dot{\varepsilon}^{vp} - \dot{\varepsilon}^{g} - \dot{\varepsilon}^{th} \end{cases}$$

relations are deduced from the REFLECTION and creep tests HALIBUT [8] for various neutron flux values .

The coefficients are provided under key word VISC_IRRA_LOG or GRAN_IRRA_LOG of DEFI _MATERIAU and is Φ the neutron fluence (integral flux compared to time). represent ε^{g} the strain of growth under flux. She is taken into account only in behavior GRAN_IRRA_LOG and is expressed in the form: make

$\varepsilon^{g}(t) = f(T, \Phi_t(x, y, z))$

1) *The neutron fluence $\Phi_t(x, y, z)$ is expressed obligatorily in. $10^{20} n/cm^2$ By convention in DEFI _MATERIAU [U 4.43.01], if the value provided under key word FLUX_PHI is equal to 1, it is the field of fluence which is used for the behavior. In the contrary case, the value provided in DEFI _MATERIAU is used like constant neutron flux. It*
2) *is a field at nodes defined as command variable in command AFFE_MATERIAU . Caution:*
3) *The exposure field is incremental and corresponds to the history of irradiation (stored in local variable – cf below) to which one adds the increment of the field of fluence coming from the command variable. Local variables*

9.2 Three

local variables: •

: $V1$ cumulated viscoplastic strain: ; ε_p •

: $V2$ memorizing of the history of irradiation (fluence). •

formulate $V3$ strain of growth: formulate ε^{g}

9.3 integration By

direct implicit discretization of the behavior models, one obtains: One

$$
\begin{cases}
\Delta \varepsilon^{vp} = \Delta p \dfrac{\sigma\left(t^- + \Delta t\right)}{\left|\sigma\left(t^- + \Delta t\right)\right|} \\
\Delta p = \left|\sigma\left(t^- + \Delta t\right)\right| \left(e^{\frac{-Q}{T}}\right) . \left(\dfrac{A\,\omega}{1+\omega\,\Phi(t^- + \Delta t)} + B\right) \Delta \Phi \\
\dfrac{\sigma}{E} - \dfrac{\sigma^-}{E^-} = \Delta \varepsilon - \Delta \varepsilon^{vp} - \Delta \varepsilon^{g} - \Delta \varepsilon^{th} \\
\text{avec} \\
\Delta \varepsilon^{th} = \alpha(T)\left(T - T_{ref}\right) - \alpha(T^-)\left(T - T_{ref}\right) \\
\Delta \varepsilon^{g} = f\left(T^+, \Phi_t^+\right) - f\left(T^-, \Phi_t^-\right)
\end{cases}
$$

can solve these equations explicitly while posing: then $\sigma^e = \dfrac{E}{E^-}\sigma^- + E\left(\Delta \varepsilon - \Delta \varepsilon^g - \Delta \varepsilon^{th}\right)$

the system is reduced to: thus $\sigma = \sigma^e - E\,\sigma \left(e^{\frac{-Q}{T}}\right) . \left(\dfrac{A\,\omega}{1+\omega\,\Phi} + B\right) \Delta \Phi$

the solution is obtained immediately: and $\sigma = \dfrac{\sigma^e}{1 + E\left(e^{\frac{-Q}{T}}\right) . \left(\dfrac{A\,\omega}{1+\omega\,\Phi} + B\right) \Delta \Phi}$

the tangent operator is written: 1D $\dfrac{\partial \sigma}{\partial \varepsilon} = \dfrac{E}{1 + E\left(e^{\frac{-Q}{T}}\right) . \left(\dfrac{A\,\omega}{1+\omega\,\Phi} + B\right) \Delta \Phi}$

10 model MAZARS in Equations

10.1 of the model

the purpose of this modelization is to give an account of the reclosing of cracks. This model is used only with the multifibre beams. The equations presented in the document [R7.01.08] " Models damage of Mazars "are taken again and rewritten formula $1D$.

$$\begin{cases}\sigma_{xx}=(1-D_t)E\langle\varepsilon^e_{xx}\rangle_+\\ \sigma_{xx}=(1-D_c)E\langle\varepsilon^e_{xx}\rangle_-\end{cases}$$ -

: •

formulate E Young modulus, •

formulate D_t the variable of damage in tension. •

formulate D_c the variable of damage in compression. •

formulate ε^e_{xx} the elastic strain formulates $\varepsilon^e_{xx}=\varepsilon-\varepsilon^{th}$

formulate $\varepsilon^{th}=\alpha(T-T_{ref})$ thermal thermal expansion

the only modification is to have a damage of tension and compression. The coupling formula $\alpha_t^\beta D_t+(1-\alpha_t)^\beta D_C$ does not exist any more. The damage remains always controlled by the extensions.

The damages of tension and compression are defined by the following equations if formula $\varepsilon_{eq}\geq\varepsilon_{d0}$ formulate

$$D_c=1-\frac{\varepsilon_{d0}(1-A_c)}{\varepsilon_{eq}}-\frac{A_c}{\exp\left[B_c(\varepsilon_{eq}-\varepsilon_{d0})\right]} \qquad D_c\in[0,1[$$ **10.1**

$$D_t=1-\frac{\varepsilon_{d0}(1-A_t)}{\varepsilon_{eq}}-\frac{A_t}{\exp\left[B_t(\varepsilon_{eq}-\varepsilon_{d0})\right]} \qquad D_t\in[0,1[$$ **10.1**

formula $A_c, A_t, B_c, B_t, \varepsilon_{d0}$ materials parameters to identify.

The damage is controlled by the equivalent strain formulates ε_{eq} The extensions are paramount in the phenomenon of cracking of the concrete, the introduced equivalent strain is defined starting from the positive values of the strains, that is to say: make

$$\begin{cases}si\;\varepsilon^e_{xx}\geq 0\;alors\;\varepsilon_{eq}=|\varepsilon^e_{xx}|\\ si\;\varepsilon^e_{xx}\leq 0\;alors\;\varepsilon_{eq}=\sqrt{2}\,\nu|\varepsilon^e_{xx}|\end{cases}$$ **10.1 10.1-4**

: If

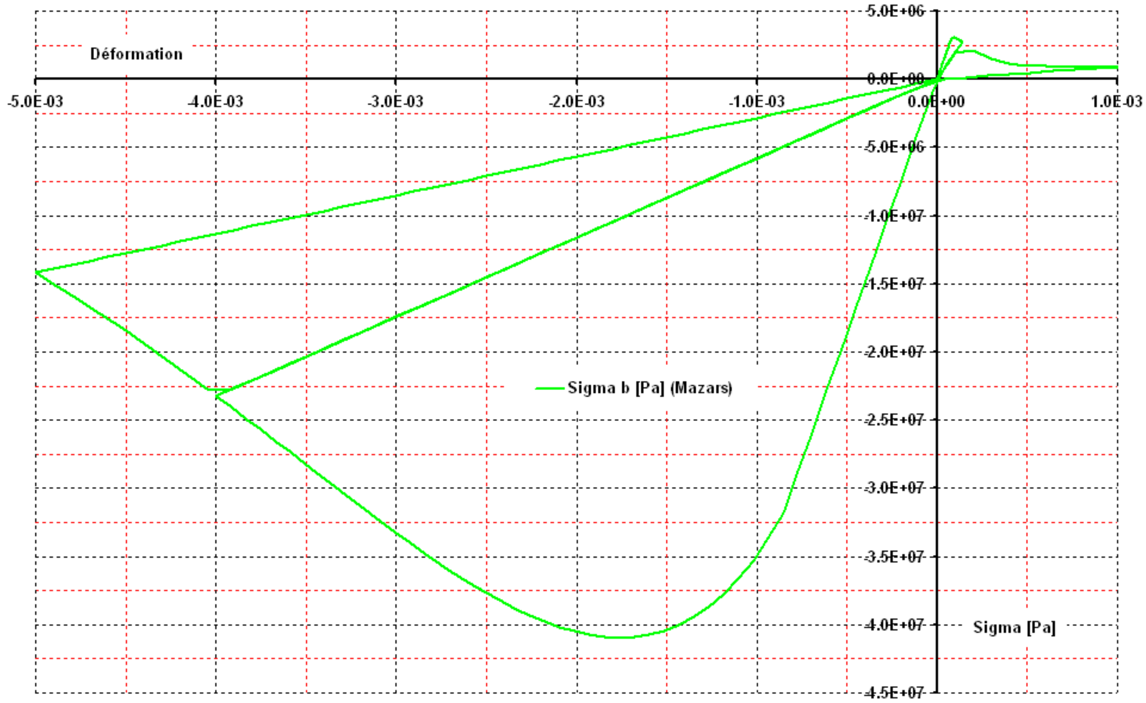
formula $\varepsilon^e_{xx}\leq 0$ of them $1D$ the principal strains in other directions are formula $\varepsilon^e_{yy}=\varepsilon^e_{zz}=-\nu\varepsilon^e_{xx}$ the formula one $\varepsilon_{eq}=\sqrt{\langle\varepsilon_1\rangle^2_+ + \langle\varepsilon_2\rangle^2_+ + \langle\varepsilon_3\rangle^2_+}$ obtains the preceding statement well.

The tangent matrix with for statement: formulate $\dfrac{d\,\sigma_{xx}}{d\,\varepsilon^e_{xx}}=(1-\tilde{D})E-\dfrac{d\,\tilde{D}}{d\,\varepsilon^e_{xx}}E\,\varepsilon^e_{xx}$: formulate

$$si\;\varepsilon^e_{xx}\geq 0\;et\;\varepsilon_{eq}\geq\varepsilon_{d0} \quad \frac{d\,\tilde{D}}{d\,\varepsilon^e_{xx}}= \quad \frac{d\,D_t}{d\,\varepsilon^e_{xx}}= \quad \left(\frac{\varepsilon_{d0}(1-A_t)}{\varepsilon^2_{eq}}+\frac{A_t B_t}{\exp\left[B_t(\varepsilon_{eq}-\varepsilon_{d0})\right]}\right)$$

$$si\;\varepsilon^e_{xx}<0\;et\;\varepsilon_{eq}\geq\varepsilon_{d0} \quad \frac{d\,\tilde{D}}{d\,\varepsilon^e_{xx}}= \quad \frac{d\,D_c}{d\,\varepsilon^e_{xx}}= \quad -\sqrt{2}\,\nu\left(\frac{\varepsilon_{d0}(1-A_c)}{\varepsilon^2_{eq}}+\frac{A_c B_c}{\exp\left[B_c(\varepsilon_{eq}-\varepsilon_{d0})\right]}\right)$$

the cases test [V6.02.120], [V6.02.119], [V5.02.130] IMPLEMENT the constitutive law of mazars IN its version formulates 1D



10.1 10.1-a Behavior of Mazars in its version formulates 1D Local variables

10.2

the constitutive law is written by uncoupling the damages from tension and of compression, the 2 damages S have local variables: ENDO _T, ENDO _C. THIS

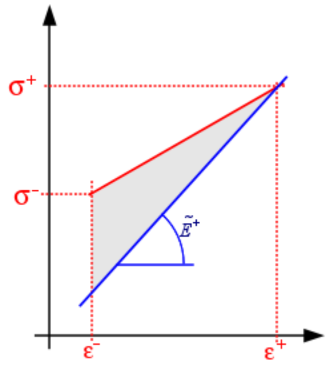
model is dedicated to computations of civil engineer. To facilitate interpretations of the results 2 variables are created to describe the state " limits" concrete material, in accordance with what this fact in the regulations of reinforced concrete computation to the limiting states. •

The variable sigmlim GIVES information compared to the stress state. This variable represents the stress divided by the ultimate stress of the concrete given by user SIGM _LIM. •

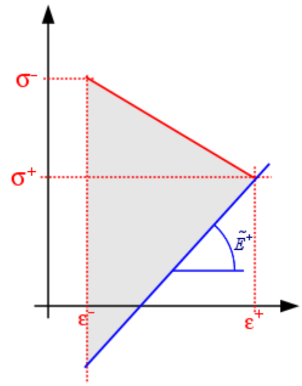
The variable epsilim GIVES information compared to the strain state. This variable represents the equivalent strain formulates ε_{eq} by the strain limits given by the user using key key EPSI _LIM.

The values of ultimate stress SIGM _LIM and limiting strain EPSI _LIM are modifiable by the user at the time of the definition of the material: challenge _MATERIAU [U _MATER_GC [U 4.42.0 7] .

The writing of the model of mazars does not make it possible to calculate an intrinsic dissipation with the model. But, during seismic computations it can be useful for the user to know nonrecoverable dissipated energy. The variable dissip REPRESENTS the nonrecoverable office plurality of energy. The nonrecoverable increment of energy is written formula $\Delta Eg=\frac{1}{2}\left(E(1-D^{+})\Delta\varepsilon-\left(\sigma^{+}-\sigma^{-}\right)\right)\Delta\varepsilon$



NON-polishing substance Material



softening

the local variables for the model of mazars `IN` formula $1\mathrm{D}$ formulate

- $V1$: `NORMALIZED` stress formula
- $V2$: `NORMALIZED` strain. formulate
- $V3$ `_T:` damage in tension. formulate
- $V4$ `_C:` damage in compression. formulate
- $V5$: non recoverable energy. Method

11 to use in 1D all the behaviors 3D As

for the processing of the plane stresses [R5.03.03], it is possible to profit for the modelizations 1D from the behaviors available in 3D. One 1D extends for that the method due to R.de Borst to the case, by treating this condition (unidimensional stress field) not with the level of the constitutive law but with the level of the equilibrium. One obtains thus during iterations of the algorithm of STAT_NON_LINE `of the stress fields` which tend towards an one-way field. One checks, with convergence of the total iterations of Newton, that the stress fields are indeed one-way, except for an accuracy, if not one continues the iterations. The method consists in breaking up the strain fields and of stresses into a purely one-way part (direction X) and a part relative to the other directions, and to carry out a static condensation by writing that the components of the stresses relative to the other directions are null. One considers in the tensors (order 2) only the diagonal terms, written in the form of vectors with 3 components. Direction X corresponds to the direction of the element (bar, multifibre beam) or to the direction of reinforcements of grid. A an unspecified time of the resolution of the incremental behavior, the tangent operator connects D the increase in stresses to the increase in strain by: that L $d\sigma=\left[\frac{\partial\sigma}{\partial\varepsilon}\right]d\varepsilon=D\,d\varepsilon$ "one rewrites: . By

$$\begin{bmatrix} d\sigma_x \\ d\sigma_y \\ d\sigma_z \end{bmatrix}=\begin{bmatrix} D_{11} & D_{12} & D_{13} \\ D_{21} & D_{22} & D_{23} \\ D_{31} & D_{32} & D_{33} \end{bmatrix}\begin{bmatrix} d\varepsilon_x \\ d\varepsilon_y \\ d\varepsilon_z \end{bmatrix}$$ writing

these increases like the difference between the iterations and in n Newton $n+1$, one obtains: , A

$d\sigma=\sigma^{n+1}-\sigma^n=\Delta\sigma^{n+1}-\Delta\sigma^n$ convergence $d\varepsilon=\Delta\varepsilon^{n+1}-\Delta\varepsilon^n$

, this variation must tend towards zero. By introducing

the conditions and ($\sigma_y^{n+1}=0$ one-way σ_z^{n+1} behavior), one obtains, for L" iteration: $n+1$ The two

$$\begin{bmatrix} d\sigma_x \\ d\sigma_y \\ d\sigma_z \end{bmatrix}=\begin{pmatrix} \sigma_x^{n+1}-\sigma_x^n \\ \sigma_y^{n+1}-\sigma_y^n \\ \sigma_z^{n+1}-\sigma_z^n \end{pmatrix}=\begin{pmatrix} \sigma_x^{n+1}-\sigma_x^n \\ -\sigma_y^n \\ -\sigma_z^n \end{pmatrix}=\begin{bmatrix} D_{11} & D_{12} & D_{13} \\ D_{21} & D_{22} & D_{23} \\ D_{31} & D_{32} & D_{33} \end{bmatrix}\begin{bmatrix} d\varepsilon_x \\ d\varepsilon_y \\ d\varepsilon_z \end{bmatrix}$$

last equations make it possible to express and according to $d\varepsilon_y$ $d\varepsilon_z$: maybe $d\varepsilon_x$

$$\begin{cases} d\varepsilon_y=\dfrac{1}{D_{22}}\left(-\sigma_y^n-D_{21}d\varepsilon_x-D_{23}d\varepsilon_z\right) \\ d\varepsilon_z=\dfrac{1}{D_{33}}\left(-\sigma_z^n-D_{31}d\varepsilon_x-D_{32}d\varepsilon_y\right) \end{cases}$$

with

$$d\varepsilon_y=\frac{1}{\Delta}\left(-D_{33}\sigma_y^n+D_{23}\sigma_z^n+D_y\,d\varepsilon_x\right)$$
$$d\varepsilon_z=\frac{1}{\Delta}\left(-D_{32}\sigma_y^n+D_{22}\sigma_z^n+D_z\,d\varepsilon_x\right)$$

by deferring $\Delta=D_{33}D_{22}-D_{23}D_{32},\quad D_y=D_{23}D_{31}-D_{21}D_{33},\quad D_z=D_{32}D_{21}-D_{31}D_{22}$

these statements in the first equation, one obtains: The equilibrium

$$\sigma_x^{n+1}=\sigma_x^n+\left(D_{11}+\frac{D_{12}D_y+D_{13}D_z}{\Delta}\right)d\varepsilon_x+\frac{D_{12}D_{23}-D_{22}D_{13}}{\Delta}\sigma_z^n+\frac{D_{12}D_{32}-D_{12}D_{33}}{\Delta}\sigma_y^n$$

with the iteration is written $n+1$: It is thus noted

$$\int D^T \sigma^{n+1} dv = \int B^T \sigma_x^{n+1} dv = \int B^T \left(D_{11} + \frac{D_{12} D_y + D_{13} D_z}{\Delta} \right) d\varepsilon_x$$
$$+ \int B^T \left(\sigma_x^n + \frac{D_{12} D_{23} - D_{22} D_{13}}{\Delta} \sigma_z^n + \frac{D_{12} D_{32} - D_{12} D_{33}}{\Delta} \sigma_y^n \right) dv$$
$$= K^n du^{n+1} + \int B^T \left(\sigma_x^n + \frac{D_{12} D_{23} - D_{22} D_{13}}{\Delta} \sigma_z^n + \frac{D_{12} D_{32} - D_{12} D_{33}}{\Delta} \sigma_y^n \right) dv$$

that the taking into account of the unidimensional behavior intervenes on two levels: •in
the tangent matrix, by the corrective term: •in

$$\int B^T \frac{D_{12} D_y + D_{13} D_z}{\Delta} B \ dv$$

the writing of the second member, by the corrective term:

$$\frac{\int B^T}{\Delta} \left((D_{12} D_{23} - D_{22} D_{13}) \sigma_z^n + (D_{12} D_{32} - D_{12} D_{33}) \sigma_y^n \right) dv$$

To implement this method, it is enough to calculate these corrective terms and to add them to the stresses and tangent matrix obtained of the resolution 3D of the behavior. For that it is necessary to store information of an iteration of Newton to the other, by the means of 4 additional local variables. The stages of the resolution are: •with

the iteration, $n+1$ the data are: and the $\Delta u^{n+1}, \sigma^-, \alpha^-$ 4 local variables (calculated with the iteration): n •before

$$V1 = \Delta \varepsilon_y^n + \frac{1}{\Delta} \left(D_{23} \sigma_z^n - D_{33} \sigma_y^n - D_y \Delta \varepsilon_x^n \right), V2 = \frac{D_y}{\Delta}$$

$$V3 = \Delta \varepsilon_z^n + \frac{1}{\Delta} \left(D_{32} \sigma_z^n - D_{22} \sigma_z^n - D_z \Delta \varepsilon_x^n \right), V4 = \frac{D_z}{\Delta}$$

carrying out the integration of the behavior (carried out into axisymmetric) one calculates: •

$$\Delta \varepsilon_y^{n+1} = \Delta \varepsilon_y^n + \frac{1}{\Delta} \left(-D_{33} \sigma_y^n + D_{23} \sigma_z^n + D_y d\varepsilon_x \right)$$
$$\Delta \varepsilon_z^{n+1} = \Delta \varepsilon_z^n + \frac{1}{\Delta} \left(-D_{32} \sigma_y^n + D_{22} \sigma_z^n + D_z d\varepsilon_x \right)$$

the integration of the behavior provides the stresses and σ^{n+1} the tangent operator, • D one modifies the second member and the tangent matrix as indicated above, •one stores the new local variables and one checks if and, $\left|\sigma_z^{n+1}\right| < \eta$ with $\left|\sigma_y^{n+1}\right| < \eta$,

RESI_INTE_RELA $\eta = \xi \left|\sigma_x^{n+1}\right|$ $\xi =$ Note

: The 4

additional local variables are added after the local variables of the constitutive law. Bibliography

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10.2	FLÉJOU ECRO_LINE_1d	Addition
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