Good old *MAT_024:
A review of LS-DYNA’s most popular material model

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Outline

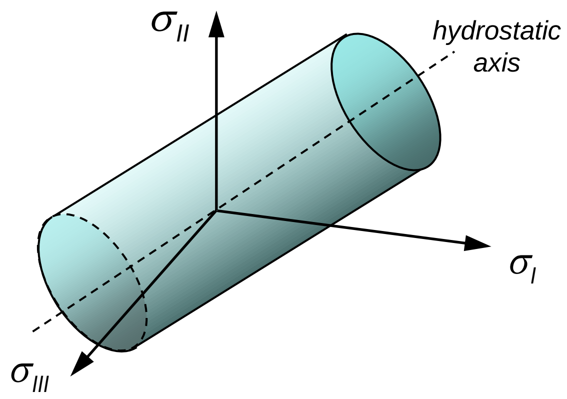
- Short review of the theory behind *MAT_024
- Presentation of the *MAT_024 keyword
- Working with load curves
- Formulations for strain rate dependence through the VP flag
- Internal handling of curves and tables
- Final remarks regarding the use of *MAT_024

J2-based plasticity

Yield function, plastic flow and numerical algorithm

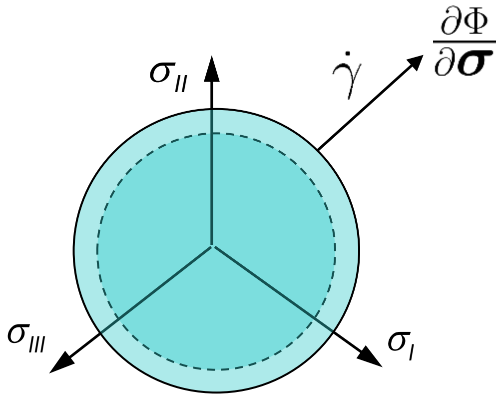
Yield function

$$\Phi(\boldsymbol{\sigma}) = \sigma_{eq} - \sigma_y(\varepsilon^p) = 0$$



Flow rule

$$\dot{\boldsymbol{\varepsilon}}^p = \dot{\gamma}\frac{\partial \Phi}{\partial \boldsymbol{\sigma}} = \frac{3}{2}\dot{\gamma}\frac{\mathbf{s}}{\sigma_{eq}}$$



Numerical algorithm (no rate dep.)

In case of no strain rate dependence, the plastic strain increment can be easily calculated through

$$\Delta\varepsilon^p = \frac{\sigma_{eq}^{trial} - \sigma_y(\varepsilon_n^p)}{3G + H}$$

In case of viscoplasticity, an iterative procedure is necessary in order to find the solution of the elasto-plastic problem

*MAT_024 / *MAT_PIECEWISE_LINEAR_PLASTICITY

Keyword definition in LS-DYNA

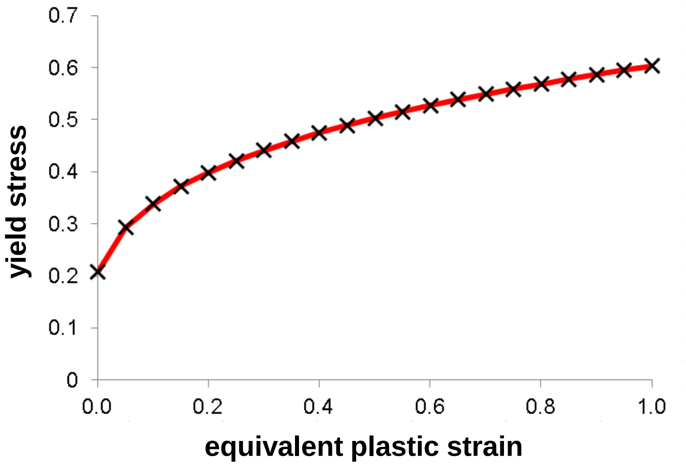
```
*MAT_PIECEWIESE_LINEAR_PLASTICITY
$      MID        RO         E        PR      SIGY      ETAN      FAIL      TDEL
         1   2.7E-06      70.0       0.3
$        C         P      LCSS      LCSR        VP
                           100                   1
$     EPS1      EPS2      EPS3      EPS4      EPS5      EPS6      EPS7      EPS8

$      ES1       ES2       ES3       ES4       ES5       ES6       ES7       ES8

```

- SIGY: Yield stress (in case of linear hardening)
- ETAN: Hardening modulus (in case of linear hardening)
- C, P: Strain rate parameters C and P for *Cowper-Symonds* strain rate model
- LCSS: Load curve or table ID (yield curve, supersedes SIGY and ETAN)
- LCSR: Load curve ID defining strain rate effects on yield stress
- VP: Formulation for rate effects

Hardening rule

Working with load curves (recommended)

```
*MAT_PIECEWISE_LINEAR_PLASTICITY
$       MID        RO         E        PR
          1  7.85E-06     210.0       0.3
$         C         P      LCSS      LCSR
                            100
```

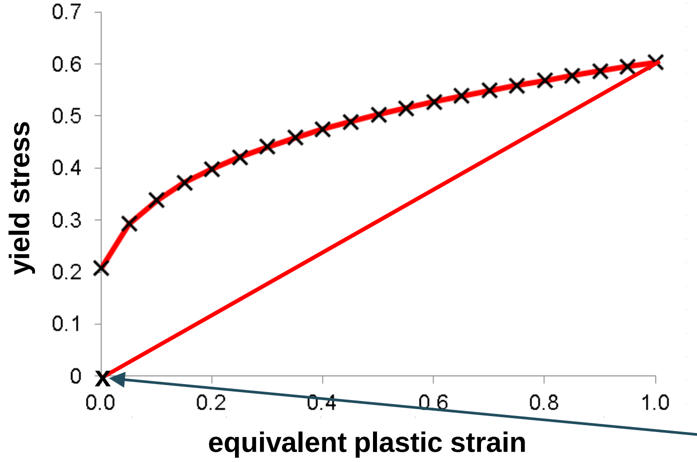



```
*DEFINE_CURVE
$      LCID      SIDR       SFA       SFO
        100                 1.0       1.0
$                  A1                  O1
                 0.00               0.208
                 0.05               0.292
                 0.10               0.338
                 0.15               0.371
                 0.20               0.398
                 0.25               0.421
                 0.30               0.441
                 0.35               0.458
                 0.40               0.474
                 0.45               0.489
                 0.50               0.502
                 0.55               0.515
                 0.60               0.527
                 0.65               0.538
                 0.70               0.549
                 0.75               0.559
                 0.80               0.568
                 0.85               0.577
                 0.90               0.586
                 0.95               0.595
                 1.00               0.603
```

Hardening rule

Working with load curves (recommended)

Common mistake: Blank line at the end of the curve
LS-DYNA behavior: Default value is 0.0




```
*DEFINE_CURVE
$       LCID      SIDR       SFA       SFO
         100                 1.0       1.0
$                   A1                  O1
                  0.00               0.208
                  0.05               0.292
                  0.10               0.338
                  0.15               0.371
                  0.20               0.398
                  0.25               0.421
                  0.30               0.441
                  0.35               0.458
                  0.40               0.474
                  0.45               0.489
                  0.50               0.502
                  0.55               0.515
                  0.60               0.527
                  0.65               0.538
                  0.70               0.549
                  0.75               0.559
                  0.80               0.568
                  0.85               0.577
                  0.90               0.586
                  0.95               0.595
                  1.00               0.603

```

Strain rate effects

```
*MAT_PIECEWIESE_LINEAR_PLASTICITY
$      MID        RO         E        PR      SIGY      ETAN      FAIL      TDEL
         1  2.7E-06      70.0       0.3
$        C         P      LCSS      LCSR        VP
       0.5       1.0        10                   1
$     EPS1      EPS2      EPS3      EPS4      EPS5      EPS6      EPS7      EPS8

$      ES1       ES2       ES3       ES4       ES5       ES6       ES7       ES8

```

– C, P: *Cowper-Symonds* equation – scaling of yield stress:

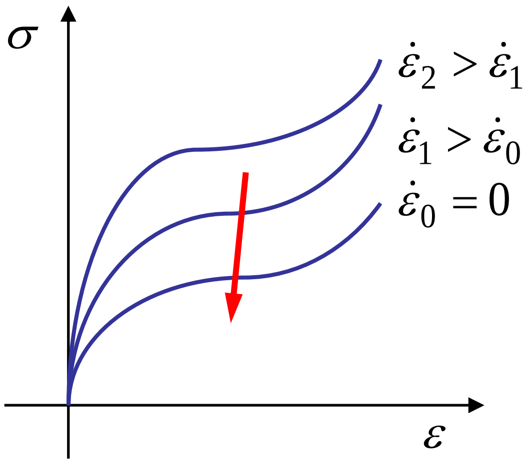
$$\sigma_y(\varepsilon^p_{eff}, \dot{\varepsilon}^p_{eff}) = \left[1 + \left(\frac{\dot{\varepsilon}^p_{eff}}{C}\right)^{1/p}\right] \sigma^S_y(\varepsilon^p_{eff})$$

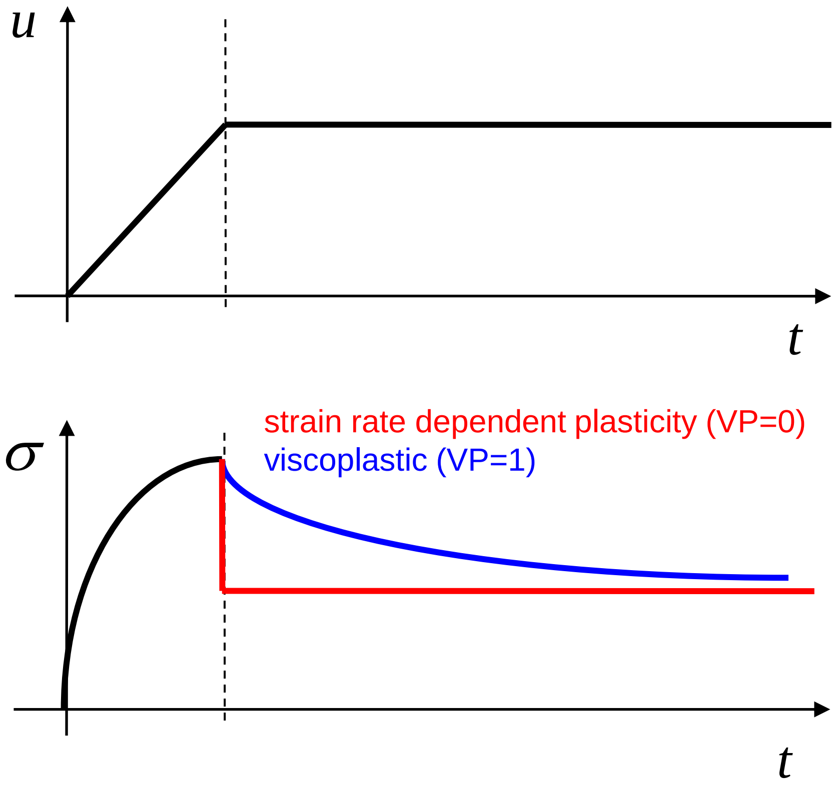
– LCSR: Strain rate dependence through scaling of the yield stress with load curve
– LCSS: Different σ_y-ε^p-curves for different strain rates
– VP: Formulation for strain rate effects
  – VP=0: Scale yield stress (default) → uses the **total** strain rate
  – VP=1: Viscoplastic formulation → uses the **plastic** strain rate
  – VP=3: Like VP=0, but filters the total strain rate → since R9.3 (shells), R12 (solids)

Strain rate effects

Influence of the VP flag

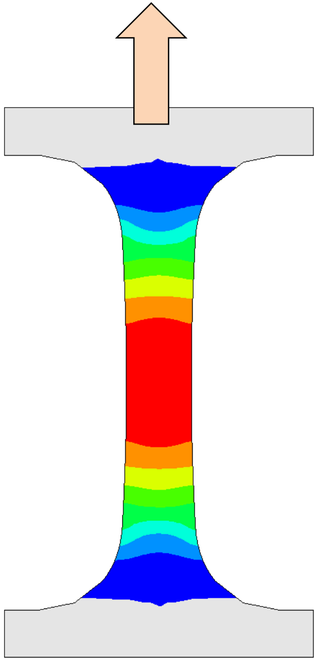
Relaxation test

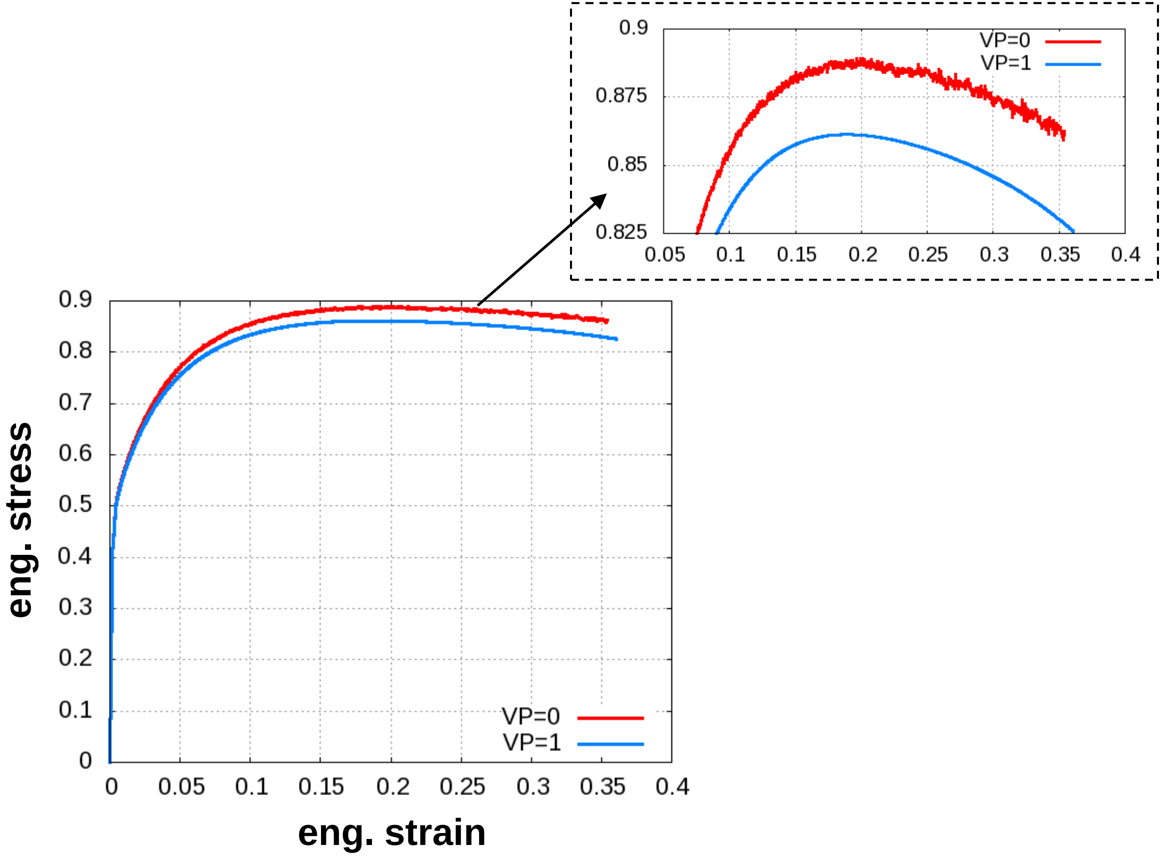




Strain rate effects

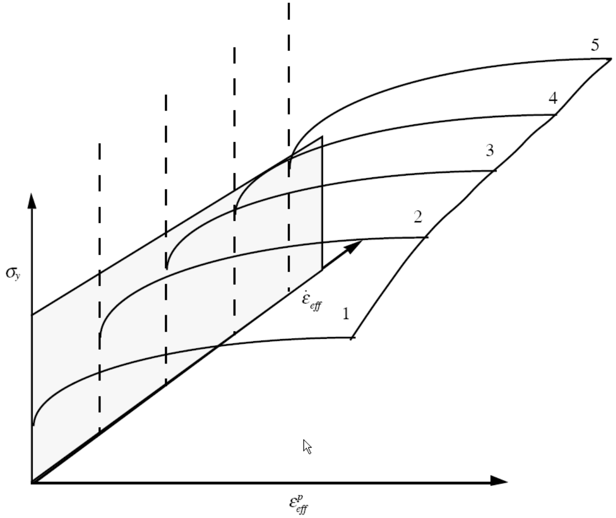
Influence of the VP flag





Working with *DEFINE_TABLE

```
*MAT_PIECEWISE_LINEAR_PLASTICITY
$       MID        RO         E        PR
          1  7.85E-06     210.0       0.3
$         C         P      LCSS      LCSR
                             10
```




```
*DEFINE_TABLE
$     TBID
        10
$         strain rate
               0.001
                0.15
*DEFINE_CURVE
$     LCID      SIDR       SFA       SFO
         1         0     1.000     1.000
$                 A1                  O1
               0.000                0.66
               0.024                0.91
               0.056                0.99
               0.096                1.05
               0.250                1.15
               1.000                1.30
*DEFINE_CURVE
$     LCID      SIDR       SFA       SFO
         2         0     1.000     1.000
$                 A1                  O1
               0.000                0.79
               0.024                1.09
               0.056                1.18
               0.096                1.26
               0.250                1.38
               1.000                1.56
```

Working with *DEFINE_TABLE

Linear or logarithmic interpolation (LS-DYNA R9)

LINEAR INTERPOLATION

```
*MAT_PIECEWISE_LINEAR_PLASTICITY
$       MID          RO          E         PR
          1    7.85E-06      210.0        0.3
. . . . .
*DEFINE_TABLE
         10
                  0.01
                  0.15
```

LOGARITHMIC INTERPOLATION

```
*MAT_PIECEWISE_LINEAR_PLASTICITY
$       MID          RO          E         PR
          1    7.85E-06      210.0        0.3
. . . . .
*DEFINE_TABLE
$      TBID
         10
$          strain rate
      -4.60517018599
      -1.89711998489
```

ln(0.01)=-4.60517018599

ln(0.15)=-1.89711998489

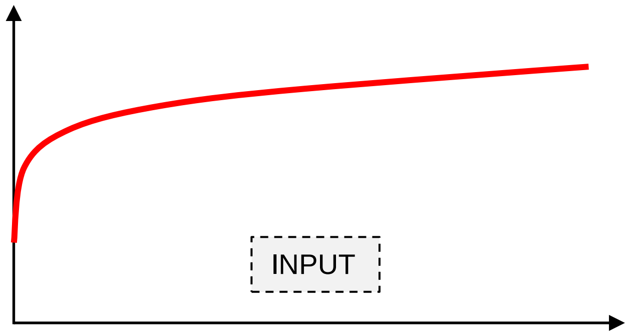
```
*MAT_PIECEWISE_LINEAR_PLASTICITY_LOG_INTERPOLATION
$       MID          RO          E         PR
          1    7.85E-06      210.0        0.3
. . . . .
*DEFINE_TABLE
$      TBID
         10
$          strain rate
                  0.01
                  0.15
```

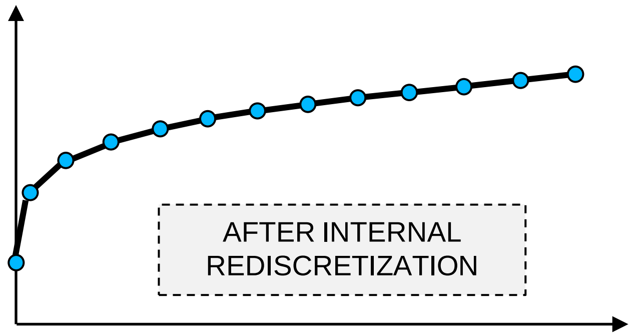
*DEFINE_CURVE and *DEFINE_TABLE

General handling of curves and tables in LS-DYNA for material models

Generally, curves in the input of material models are internally rediscretized in LS-DYNA by default. The number of equally spaced intervals used in the rediscretization can be defined through the flag LCINT of the keyword *CONTROL_SOLUTION.

```
*CONTROL_SOLUTION
$      SOLN       NLQ     ISNAN     LCINT
          0         0         1      1001
```





By default, LCINT is set to 100, but it is recommended to increase this value in order to avoid loosing resolution of the input curve.

*DEFINE_CURVE and *DEFINE_TABLE

General handling of curves and tables in LS-DYNA for material models

The rediscretization procedure is internally called “digitalization” in LS-DYNA. The user can output the digitized curves to the message and d3hsp files by setting IPCURV=1 in the keyword *CONTROL_OUTPUT. Warning: d3hsp might get quite long for models with several curves.

```
*CONTROL_OUTPUT
$     NPOPT    NEECHO    NREFUP    IACCOP     OPIFS    IPNINT    IKEDIT    IFLUSH

$     IPRTF    IERODE     TET10    MSGMAX    IPCURV      GMDT   IP1DBLT      EOCS
                                                  1
```

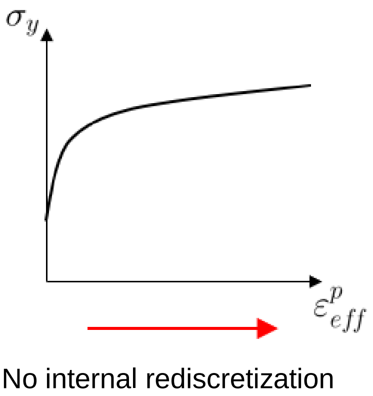
output in the d3hsp file contains all digitized curves if IPCURV=1

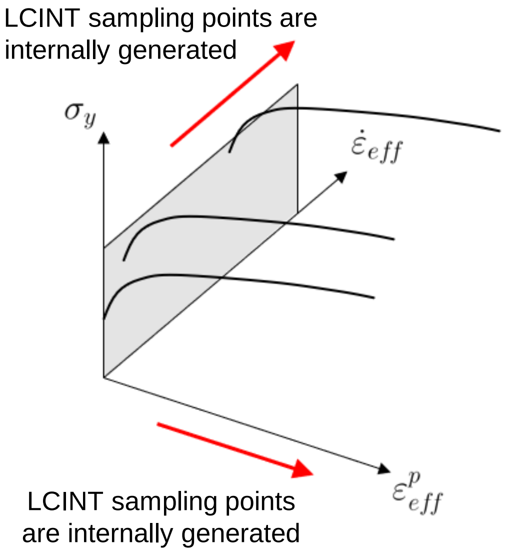
```
D i g i t i z e d   l o a d   c u r v e   d a t a

    Note: Curves rediscretized into LCINT intervals
          (default=100; See *CONTROL_SOLUTION) are
          tabulated below.  Note that the rediscretized
          form of the curve is used in the solution ONLY
          in the case where the curve defines material
          input, e.g., stress vs. strain.  The redis-
          cretized form is not used if the curve defines
          a time variation of a load or boundary condition.


    load function id number=          2
$    lcid     sidr
          2          0
$          abscissa            ordinate
   -6.666600108E-01    3.000000000E+00
   -6.653267145E-01    3.000000000E+00
   -6.639933586E-01    3.000000000E+00
   -6.626600623E-01    3.000000000E+00
   -6.613267064E-01    3.000000000E+00
   -6.599934101E-01    3.000000000E+00
```

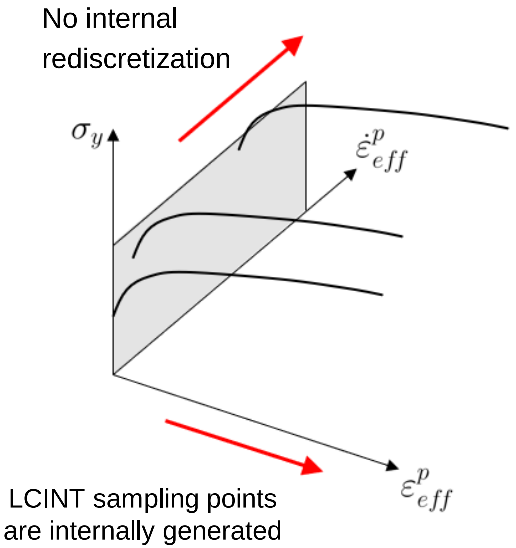
*DEFINE_CURVE and *DEFINE_TABLE

General handling of curves and tables in LS-DYNA for material models

only one curve:	table, VP=0 and VP=3	table and VP=1



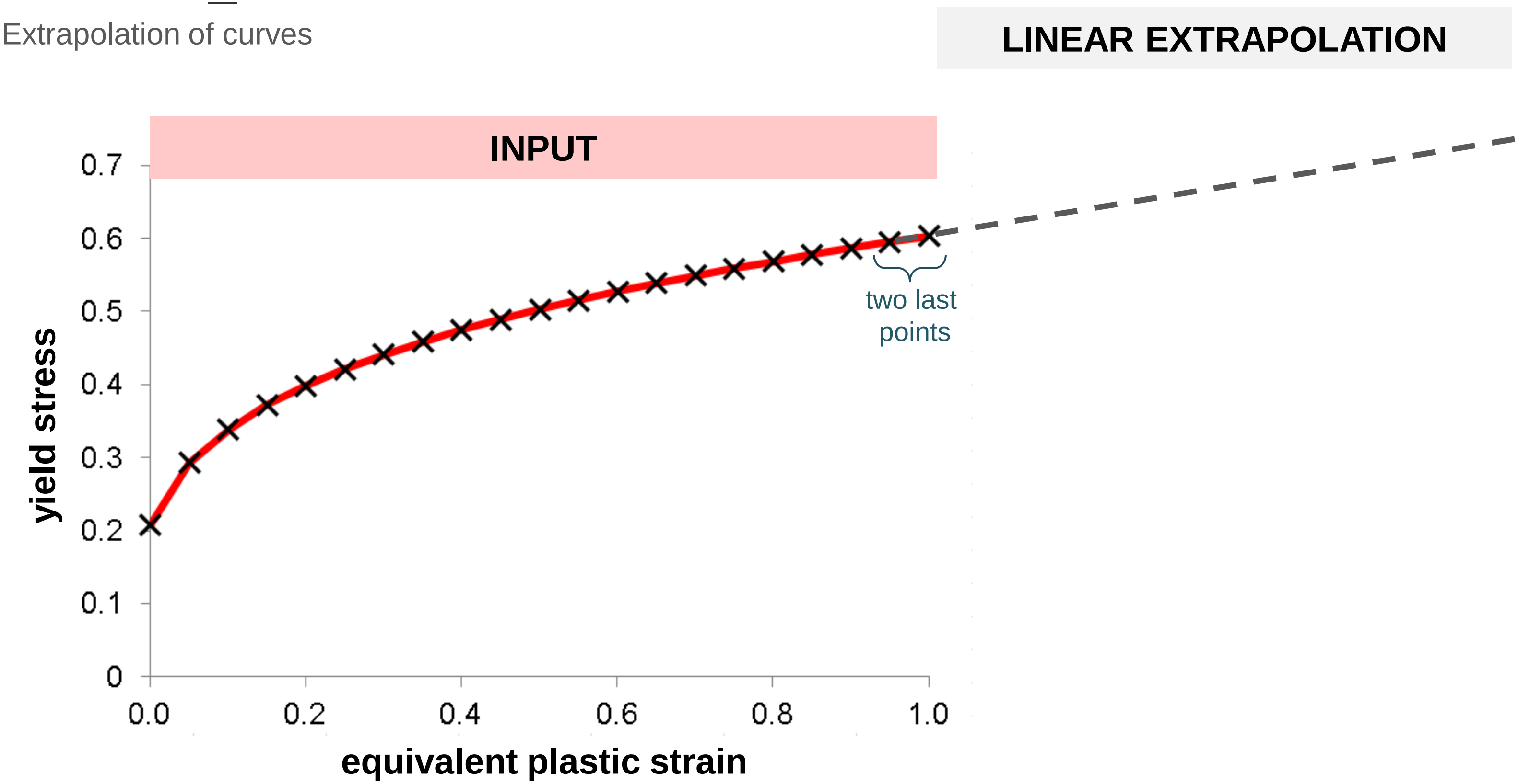




Recommendation: Use the same number of points for all strain rate dependent hardening curves.

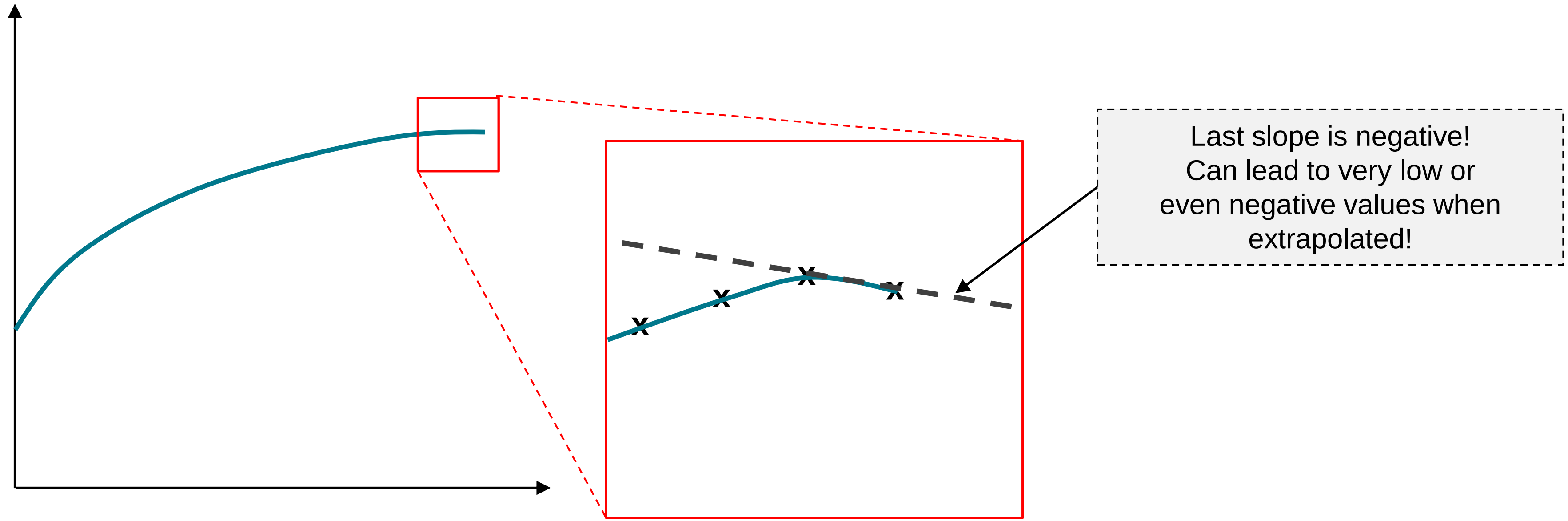
*DEFINE_CURVE

Extrapolation of curves



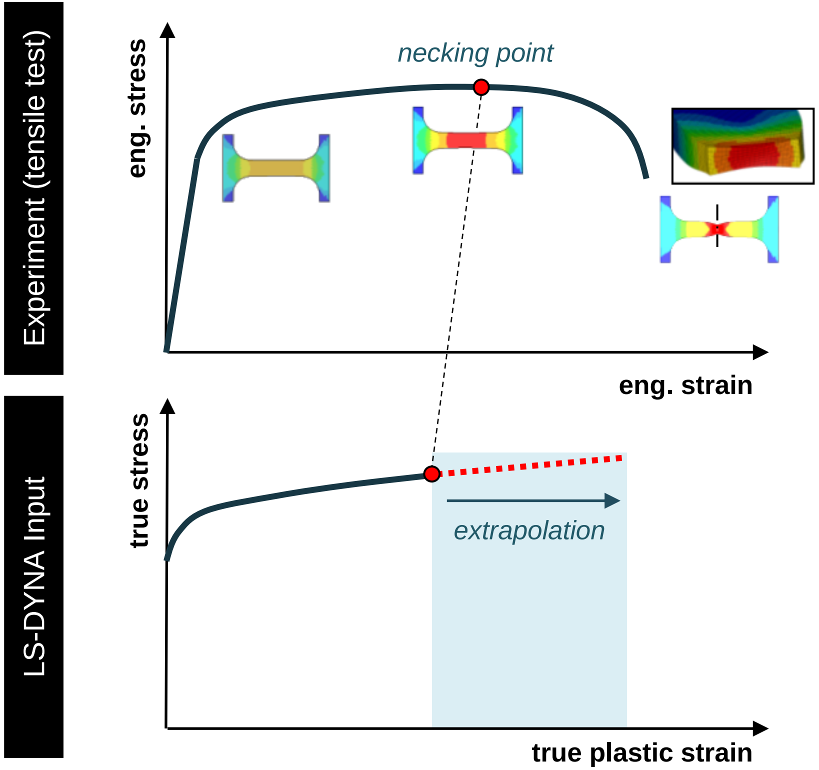
*DEFINE_CURVE

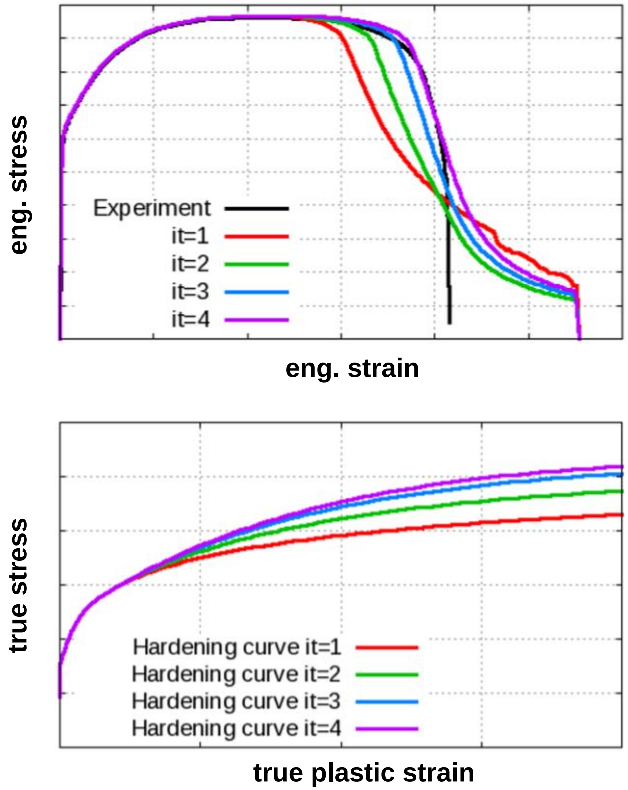
Extrapolation of curves



*DEFINE_CURVE

Typical procedure for the calibration of the yield curve





*MAT_024 / *MAT_PIECEWISE_LINEAR_PLASTICITY

Additional options and similar material models

Additional options in *MAT_024:

- _2D: Actual plane stress treatment (transverse shear stresses not part of the eq. stress, shells only)
- _MIDFAIL: Failure is checked only at the mid-plane of the element (shells only)
- _STOCHASTIC: Allows spatially varying yield and failure behavior

Some similar material models:

- *MAT_123: With additional enhanced failure criteria
- *MAT_224: With additional temperature dependence and an enhanced failure criterion
- *MAT_225: Isotropic and kinematic hardening possible
- *MAT_251: Table can be a function of a history variable (e.g., hardness, …)

*MAT_024 / *MAT_PIECEWISE_LINEAR_PLASTICITY

Final remarks

- “Work horse” in crash simulations (very fast!)
- Available for shells, solids, beams, …
- Load curve based input makes this material model very flexible
- No kinematic hardening is considered (*MAT_225 is similar to *MAT_024, but allows additionally the definition of kinematic hardening)
- Unless viscoplasticity (i.e., VP=1) is activated, the plasticity routine **does not iterate** (works very well in explicit, possibly problematic for large steps in implicit analysis)

HINT: Set IACC=1 in *CONTROL_ACCURACY in order to make *MAT_024 always iterate (only for implicit)

- The points between the rate-dependent curves in a table are interpolated either linearly or logarithmically
- The load curves are extrapolated in the direction of plastic strain by using the last slope of the curve
- No extrapolation is done in the direction of strain rate, i.e., the lowest (highest) curve defined is used if the current strain rate lies under (above) the input curves
- Negative and zero slopes are permitted but should generally be avoided

Thank you for your attention!