Stress state dependent regularization

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Introduction

The issue of spurious mesh dependence, regularization

Mesh dependence

Different types

The expression "mesh dependence" is somewhat vague and can as such have different interpretations. Therefore, it is important to highlight the main differences between the typical interpretations of this term.

Geometrical mesh dependence

- A consequence of discretization using finite elements
- May affect solution under any loading (purely elastic, plastic, etc.)
- Generally converging when mesh is fine enough → **can be solved by refining or higher order elements**
- Shells and solids affected in a similar way

"Spurious" mesh dependence

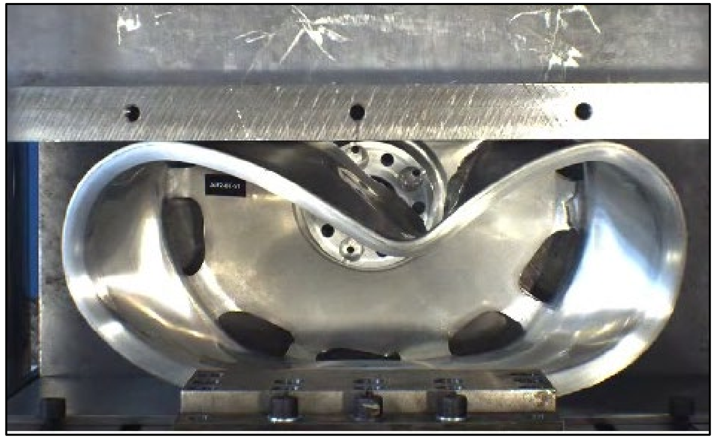
- A consequence of local continuum mechanics
- Only affects solution under certain conditions (e.g., after the necking point under a uniaxial stress state)
- Generally non-converging regardless how fine the mesh is → **cannot be solved by refining**
- Shells generally exhibit more spurious mesh dependence than solids

Regularization strategies are intended to tackle the **spurious kind of mesh dependence**

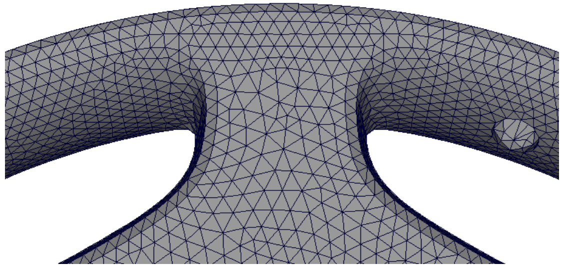
Ideally, only geometrically converged models should be regularized

Example: Geometrical mesh dependence

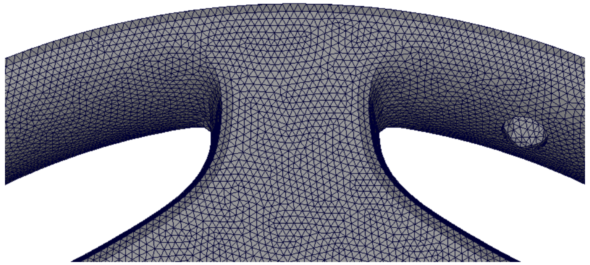
Wheel simulation



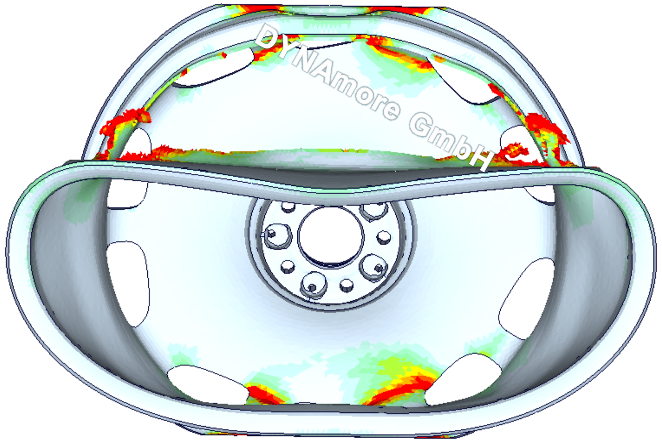
5.0mm



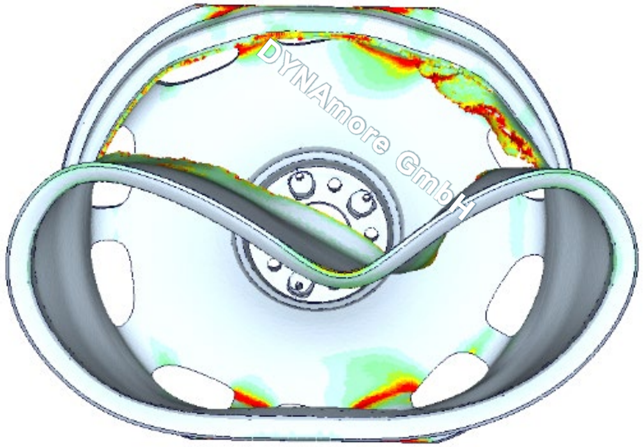
2.5mm

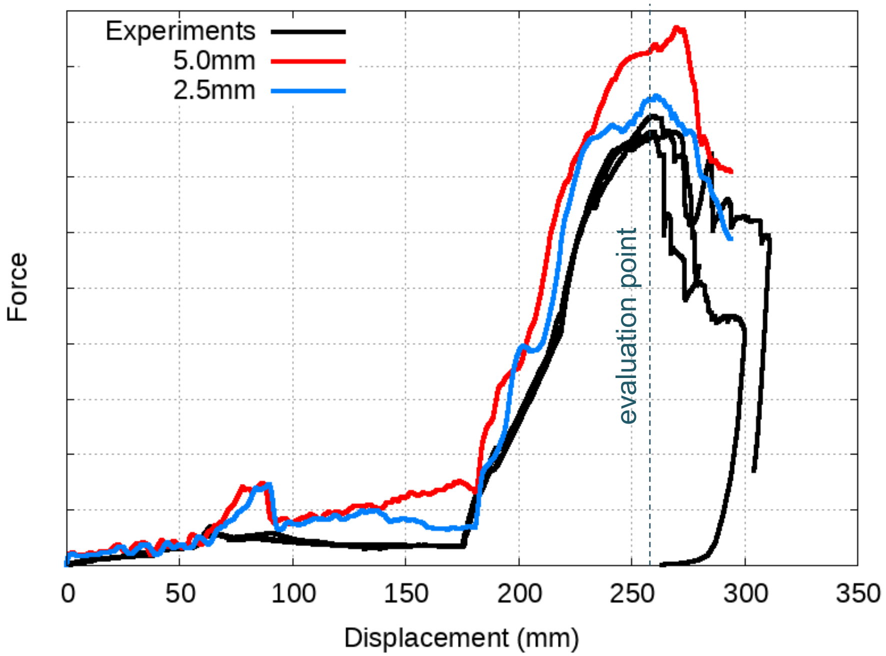


5.0mm



2.5mm

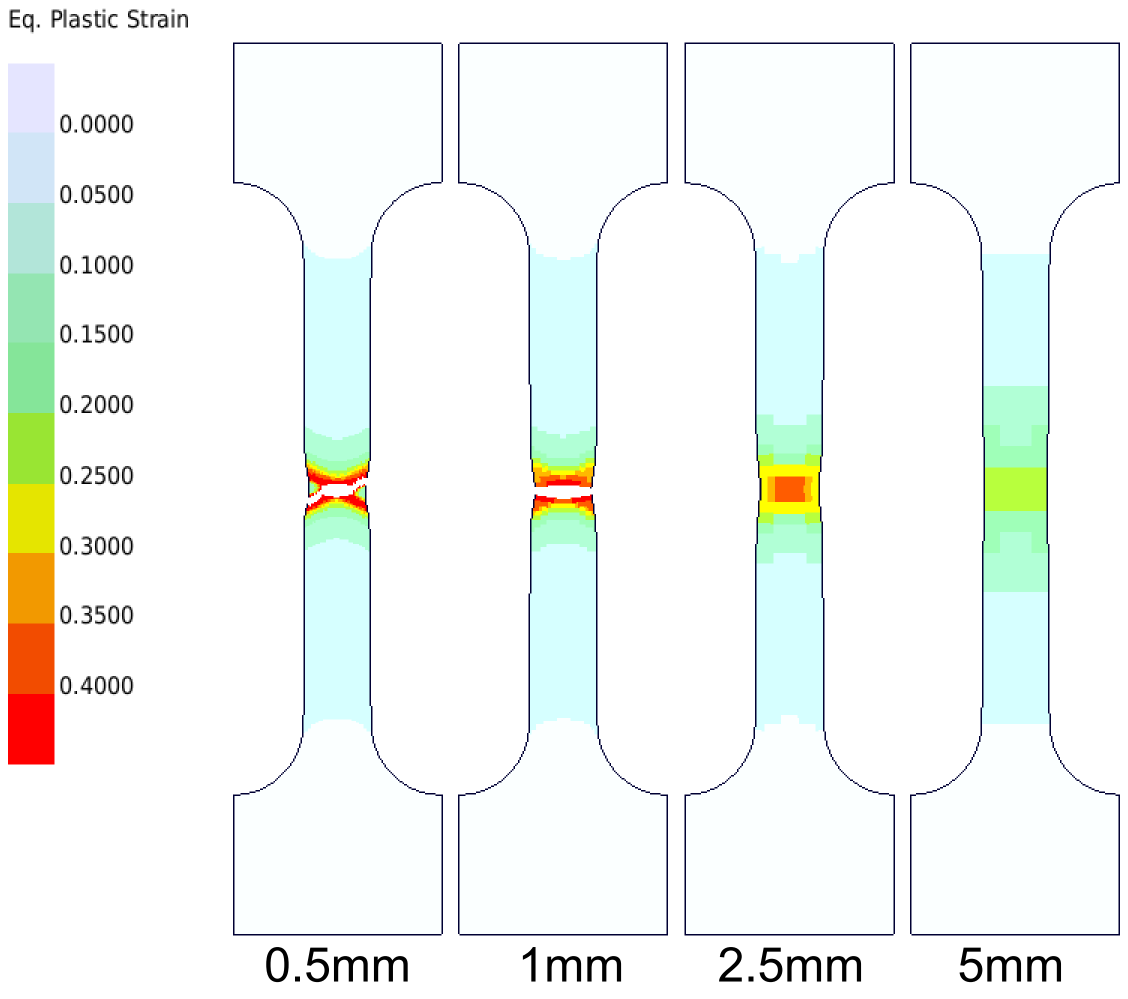


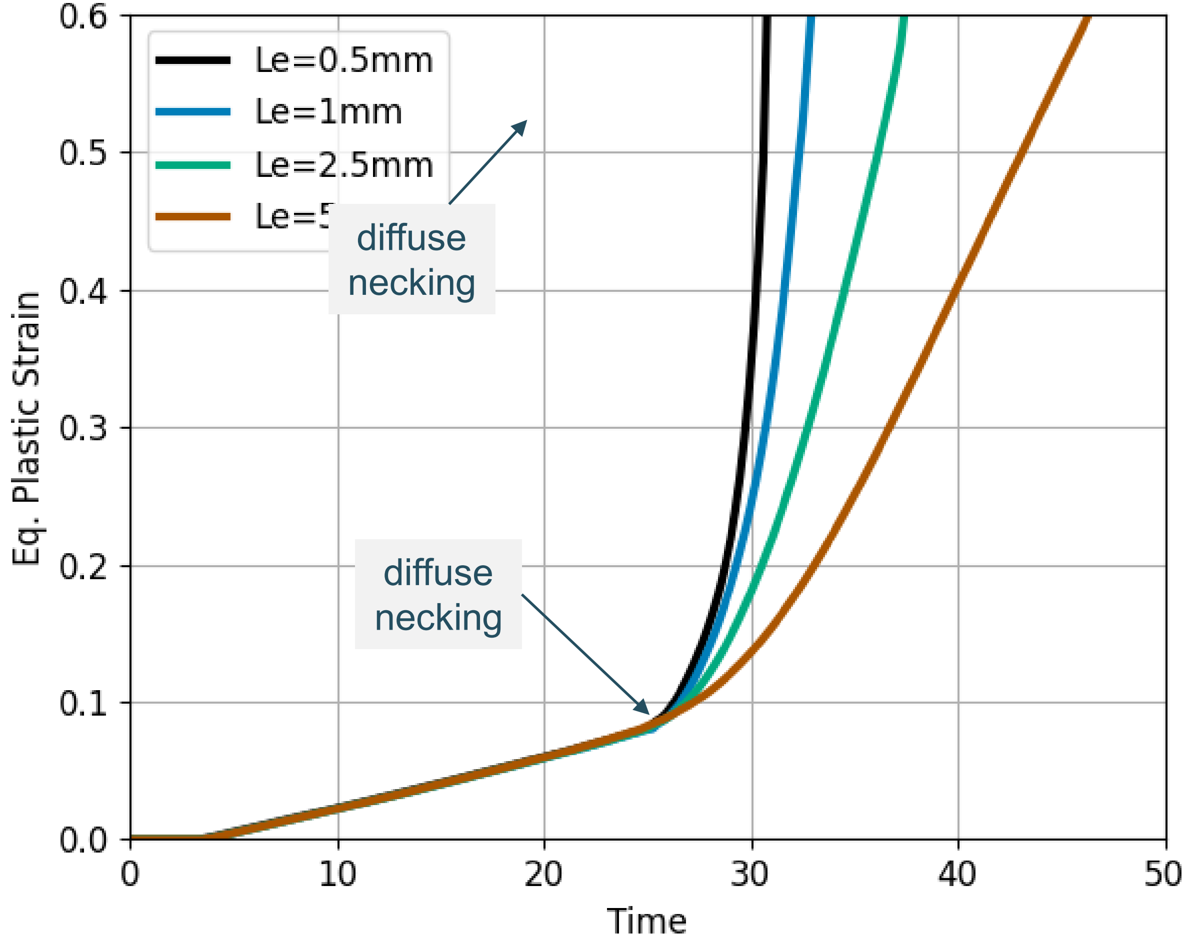


Andrade, Feucht, Haufe, Aspects of spatial discretization and constitutive modeling of aluminum wheels under compressive loadings. 2020

Onset of spurious mesh dependence

Reference: Quasi-static tensile test with different element sizes
Triaxiality 1/3 up to necking point



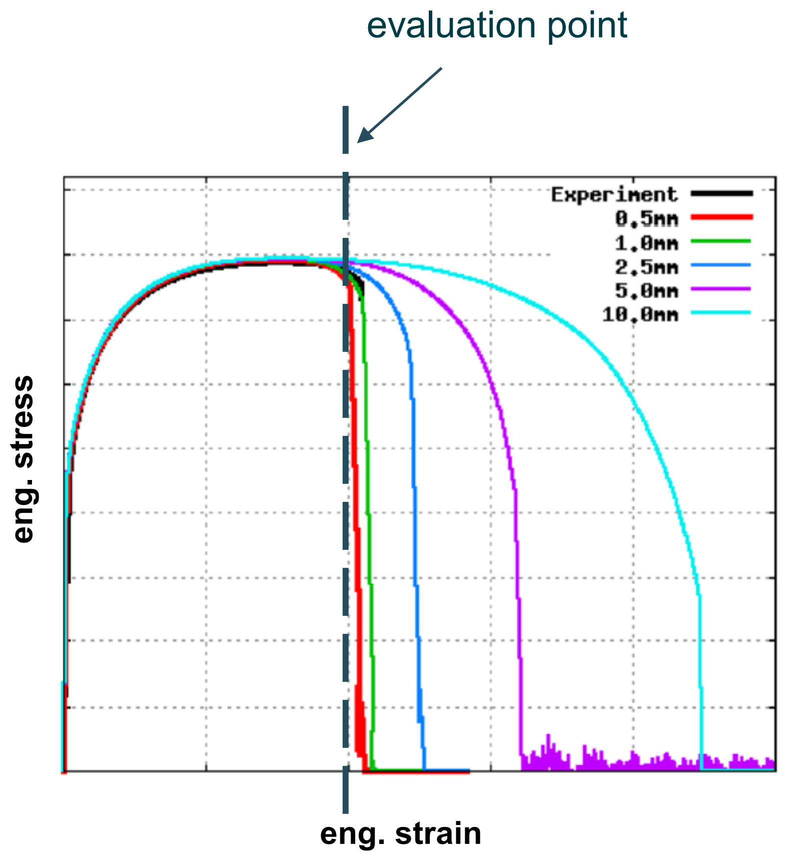


***MAT_024 + GISSMO (without regularization), monotonic hardening curve, no strain rate dependence**

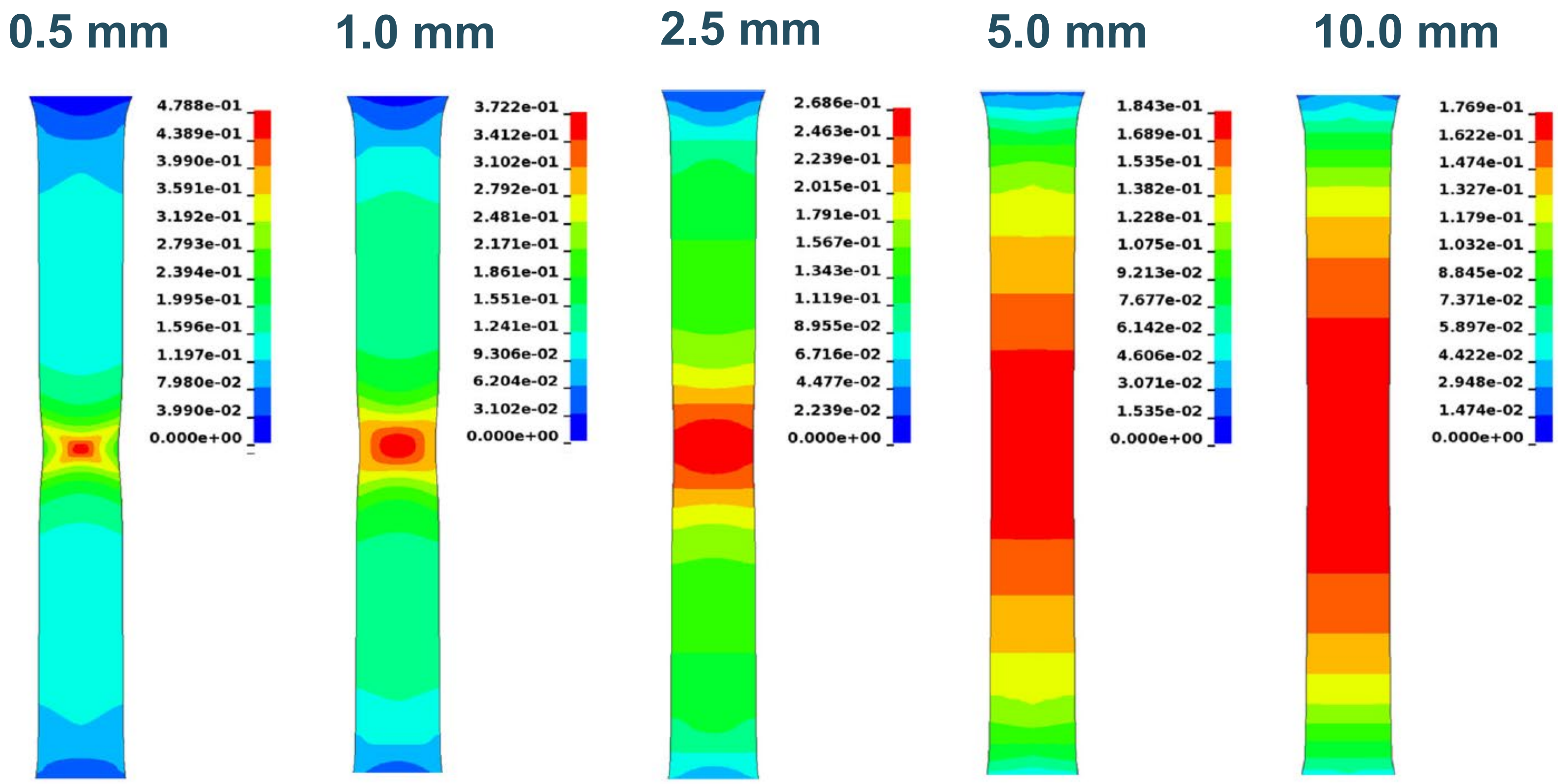
Example: Spurious mesh dependence

Simulation of a large tensile test, evaluation at the same deformation point

Different plastic strain distribution for each mesh size, failure takes place at different deformation points.



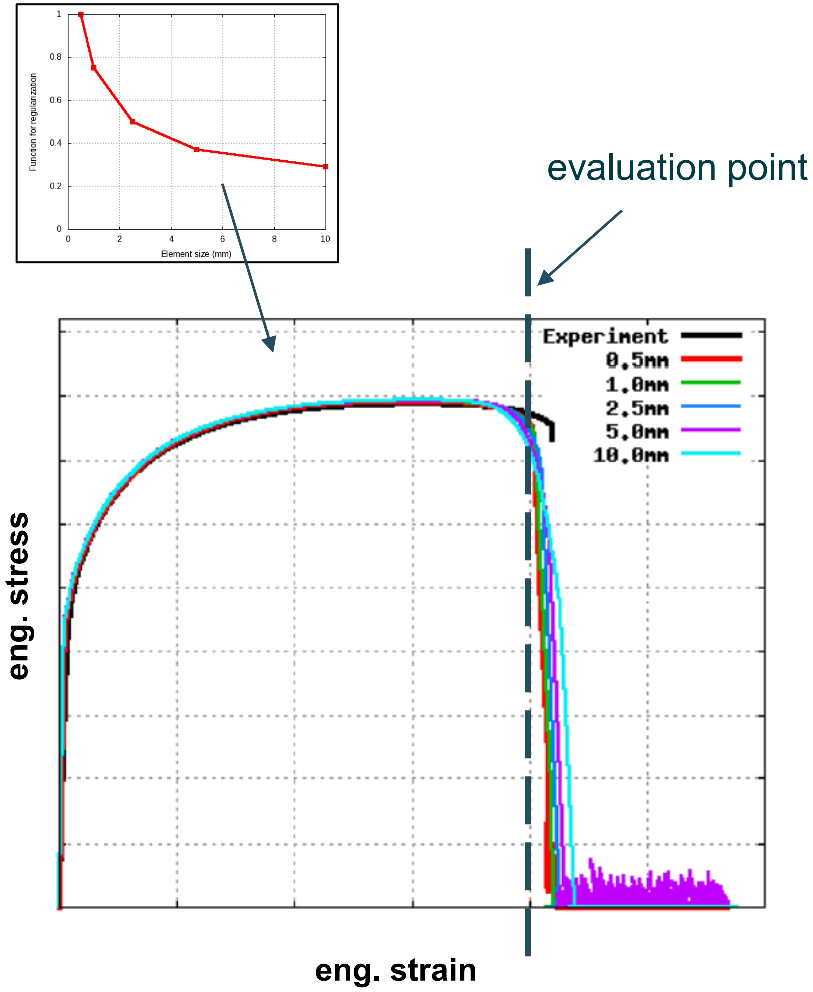
*MAT_024 + GISSMO (without regularization), monotonic hardening curve, no strain rate dependence



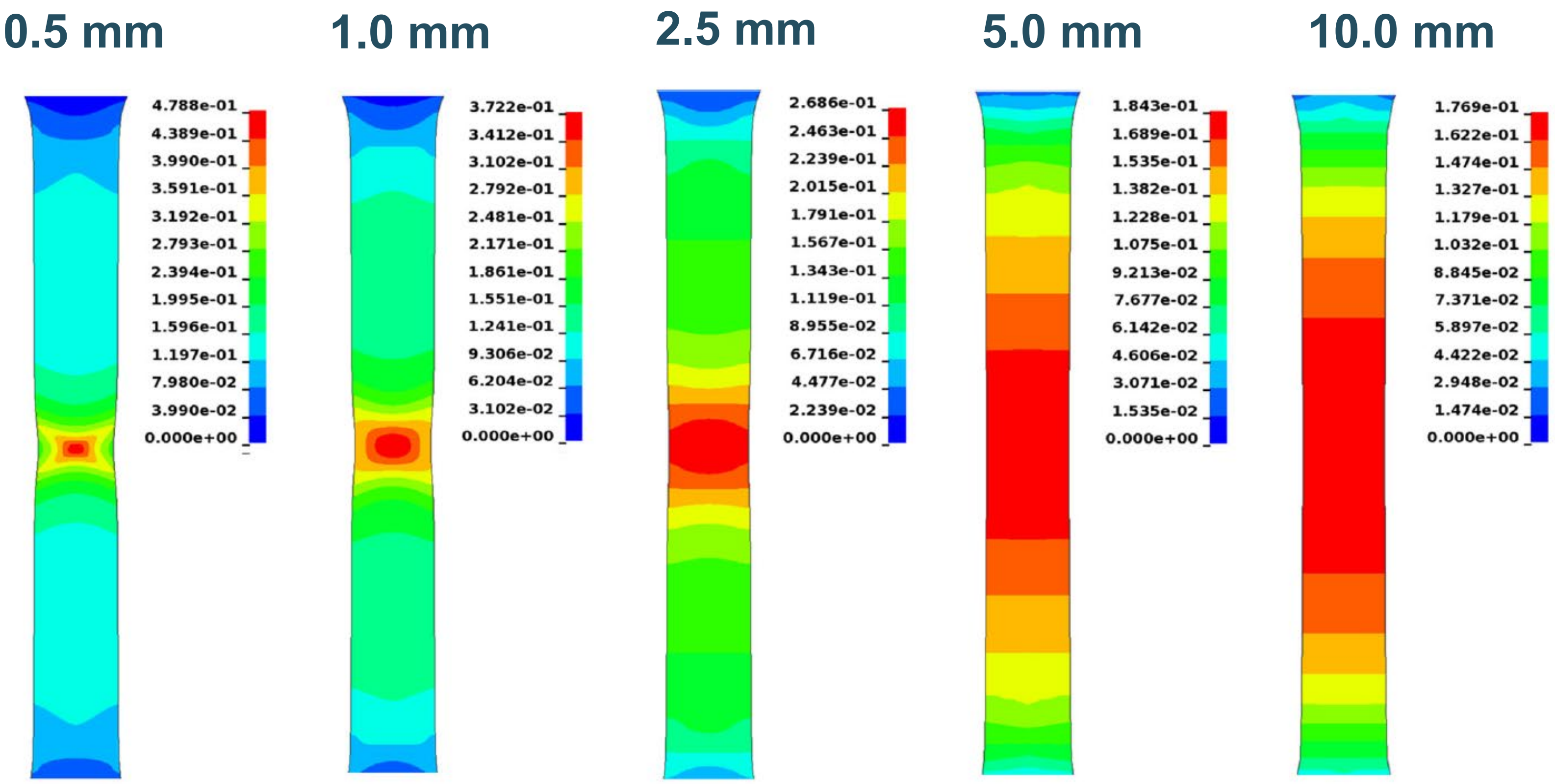
Example: Spurious mesh dependence

Simulation of a large tensile test after regularization (<u>no stress-damage coupling</u>)

No change of plastic strain distribution, however, the deformation point at which failure occurs is now identical



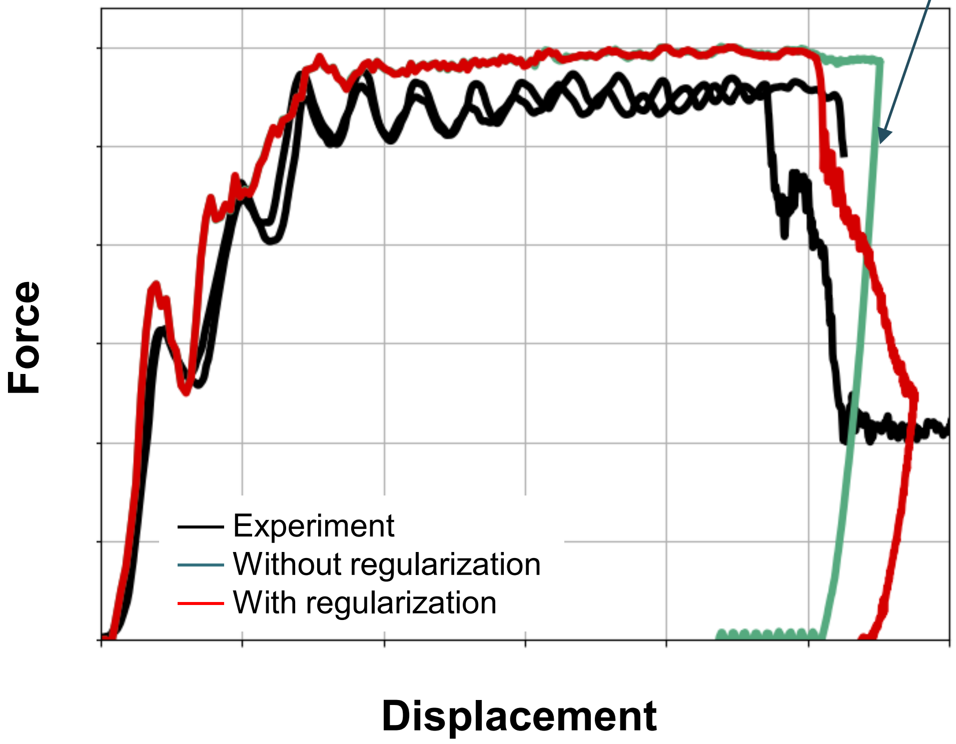
*MAT_024 + GISSMO (with regularization),
monotonic hardening curve, no strain rate dependence

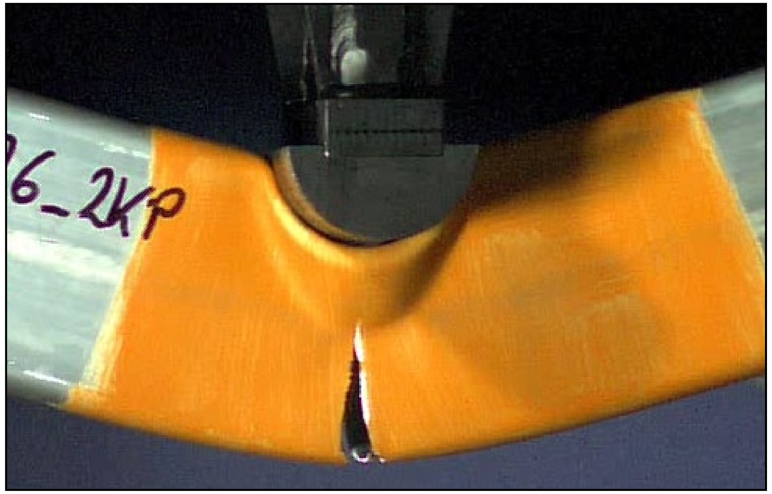


Effect on component test simulation

With and without regularization, shell elements, element size 3 mm
*MAT_024 + GISSMO, aluminum extrusion

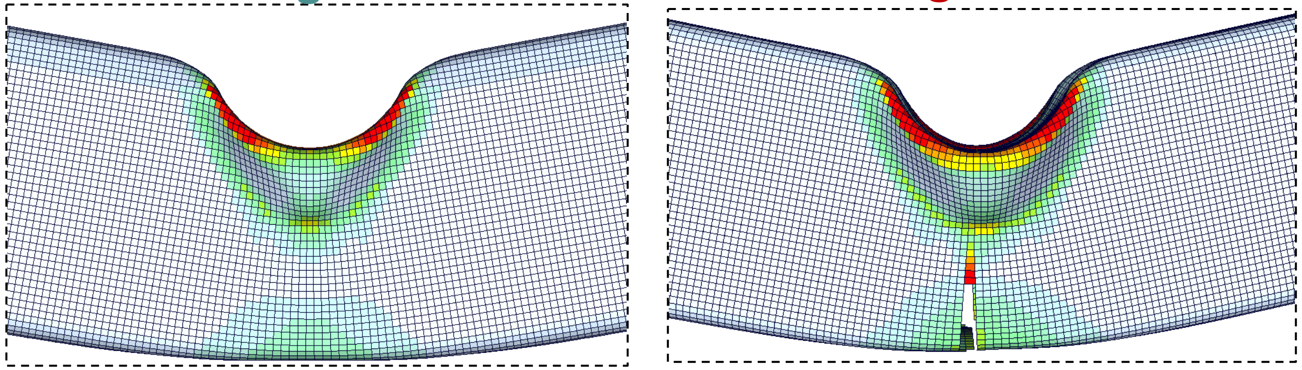
Elastic rebound is observed when running the simulation without regularization because **no element failure** has taken place





without regularization

with regularization



Remarks

Spurious mesh dependence and regularization

- Simple regularization strategies do not solve the underlying problem of spurious mesh dependence but compensate for its effects

- **Regularization will not help against geometrical mesh dependence!**

- Spurious mesh dependence is dependent on the stress state

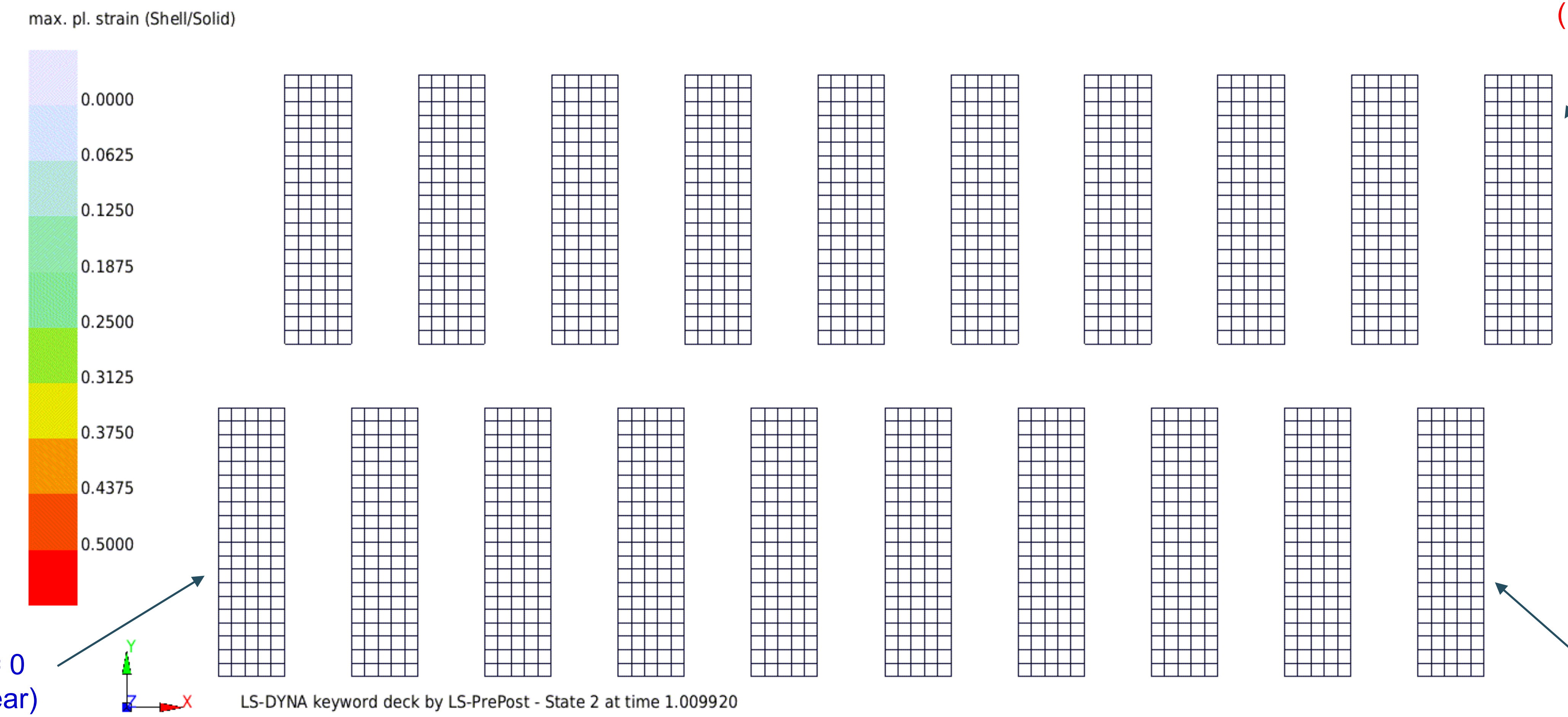
Spurious mesh dependence

Onset depends on the stress state

Plane stress (shell elements)

Simulation of element blocks (width=5mm, height=20mm, element size=1.0mm)

η ≈ 2/3
(nearly equibiaxial tension)



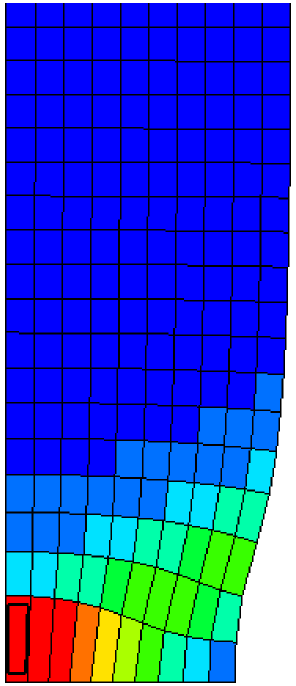
η = 0
(shear)

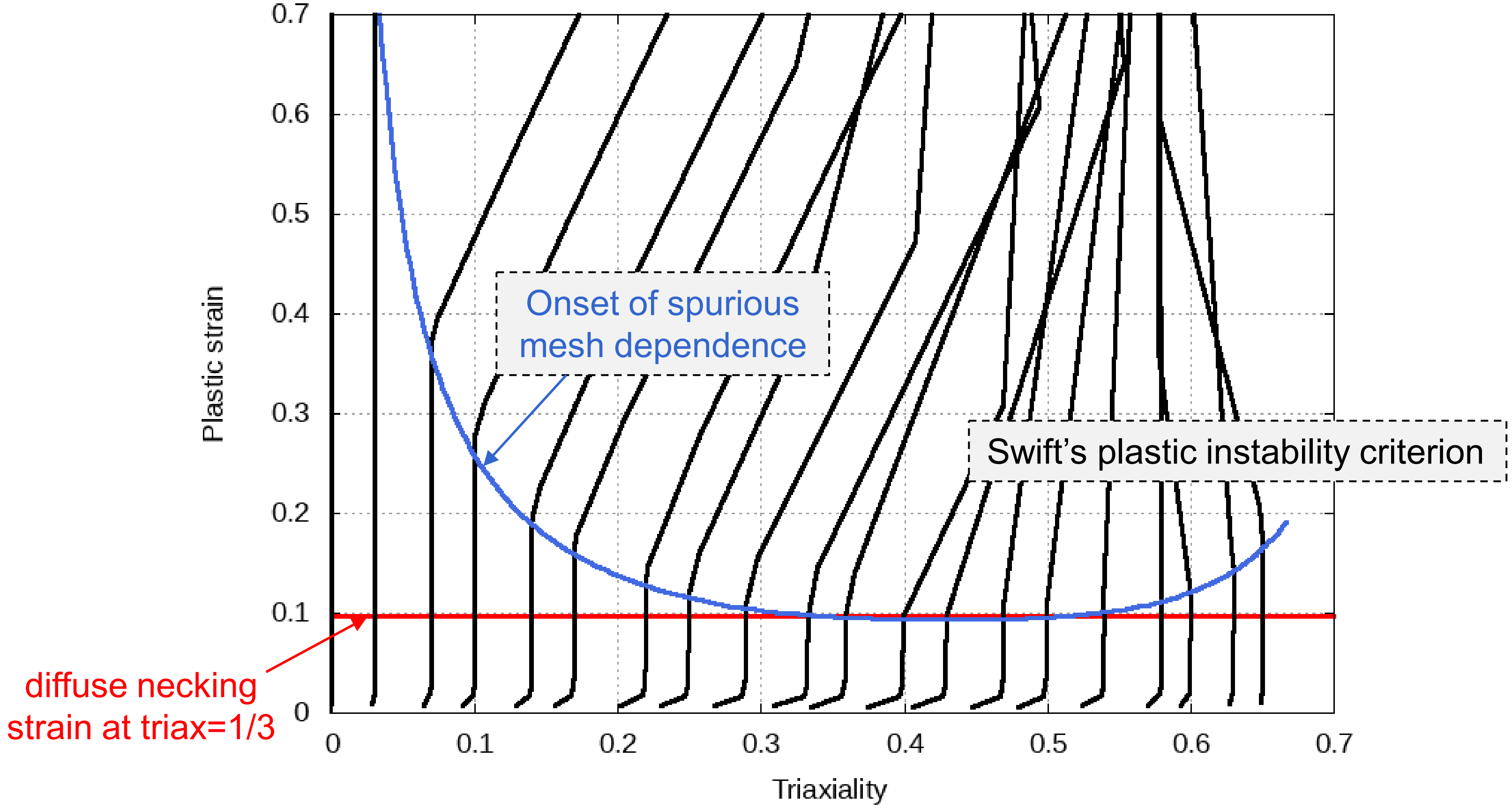
η = 1/3
(uniaxial tension)

Simulation with *MAT_024, monotonic hardening curve, aluminum properties, failure strain = 2.0 for all triaxialities

Plane stress (shell elements)

Strain-triaxiality paths (width=5mm, height=40mm, element size=0.5mm)
Aluminum extrusion

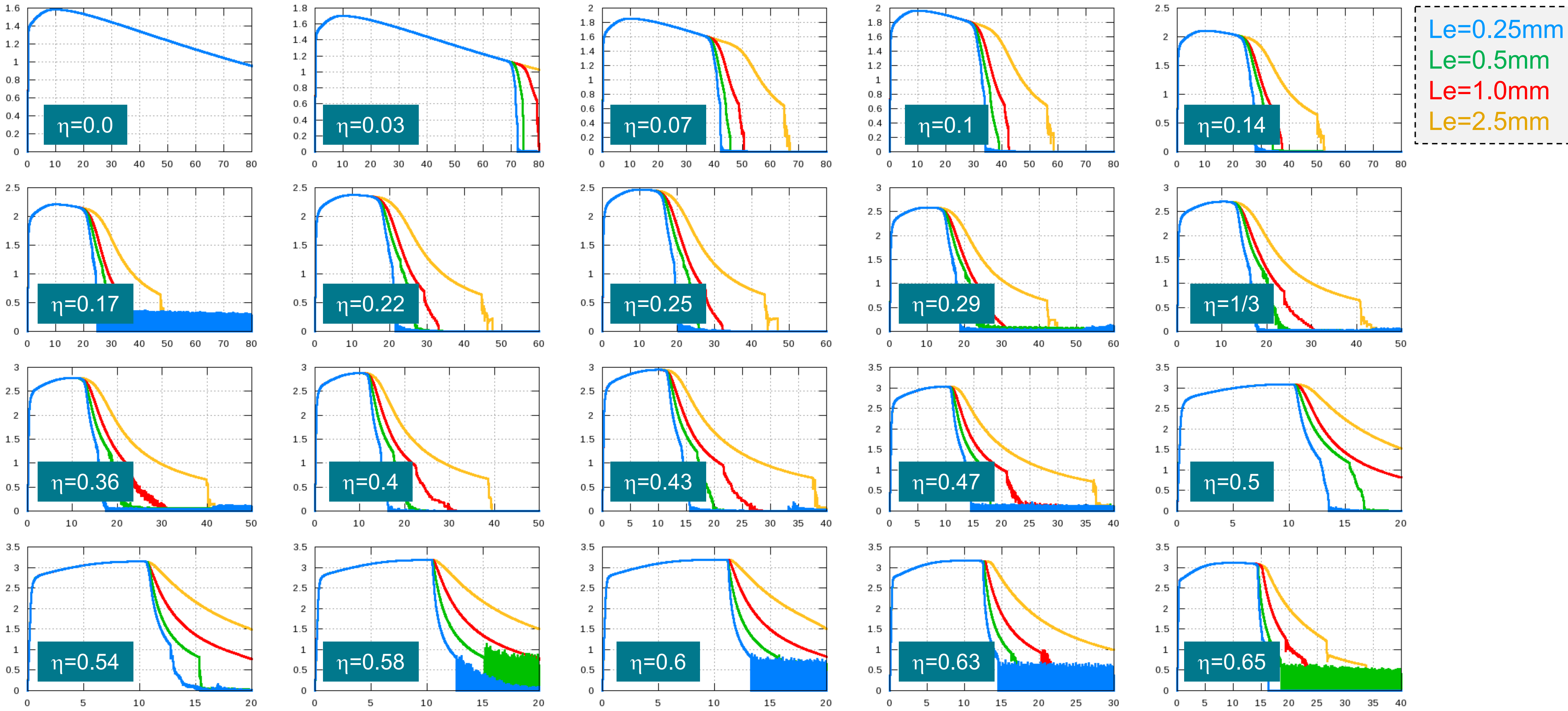




DuBois, Feucht, Andrade, Graf, Conde, Haufe. Instability and Mesh Dependence – Part I.
Andrade, Feucht, DuBois, Graf, Conde, Haufe. Instability and Mesh Dependence – Part II.
16th LS-DYNA Forum, Bamberg, 2022.

Plane stress (shell elements)

Vertical reaction force vs. time (width=5mm, height=40mm)



Simulation with *MAT_024, monotonic hardening curve, aluminum properties, failure strain = 2.0 for all triaxialities

Regularization in LS-DYNA

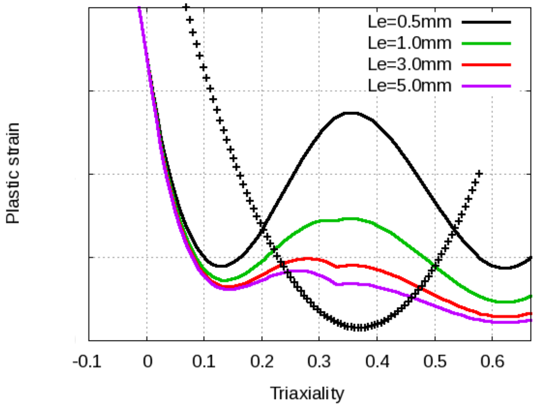
*MAT_ADD_DAMAGE_GISSMO

*MAT_ADD_DAMAGE_GISSMO

SHRF and BIAXF

```
*MAT_ADD_DAMAGE_GISSMO
$      MID                          DTYP       REFSZ      NUMFIP
        10                             1                   -80
$    LCSDG       ECRIT     DMGEXP      DCRIT      FADEXP      LCREGD
       100        -200          2                  2.5         502
$    LCSRS        SHRF       BIAXF     LCDLIM    MIDFAIL       HISVN
                   1.0         0.0
```

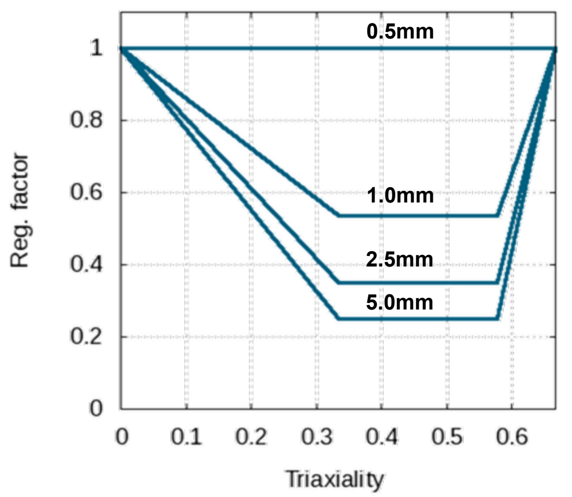
```
*DEFINE_CURVE
$  Regularisierung Girlande, triax = 0.3333333
$      lcid       sidr       scla       sclo       offa
        502          0        1.0        1.0
$                    x                     y
                0.5000                1.0000
                1.0000                0.5350
                2.5000                0.3500
                5.0000                0.2500
               10.0000                0.1800
```



TABLE

```
*MAT_ADD_DAMAGE_GISSMO
$      MID                          DTYP       REFSZ      NUMFIP
        10                             1                   -80
$    LCSDG       ECRIT     DMGEXP      DCRIT      FADEXP      LCREGD
       100        -200          2                  2.5        -500
$    LCSRS        SHRF       BIAXF     LCDLIM    MIDFAIL       HISVN
```

```
*DEFINE_TABLE
$     tbid
       500
$                triax
             0.0000000
             0.3333333
             0.5773500
             0.6666666
*DEFINE_CURVE
$  Regularisierung Girlande, triax = 0.0
$      lcid       sidr       scla       sclo       offa
        501          0        1.0        1.0
$                    x                     y
                0.5000                1.0000
                1.0000                1.0000
                2.5000                1.0000
                5.0000                1.0000
               10.0000                1.0000
*DEFINE_CURVE
$  Regularisierung Girlande, triax = 0.3333333
$      lcid       sidr       scla       sclo       offa
        502          0        1.0        1.0
$                    x                     y
                0.5000                1.0000
                1.0000                0.5350
                2.5000                0.3500
                5.0000                0.2500
               10.0000                0.1800
*DEFINE_CURVE
$  Regularisierung Girlande, triax = 0.57735
$      lcid       sidr       scla       sclo       offa
        503          0        1.0        1.0
$                    x                     y
                0.5000                1.0000
                1.0000                0.5350
                2.5000                0.3500
                5.0000                0.2500
               10.0000                0.1800
*DEFINE_CURVE
$  Regularisierung Girlande, triax = 0.6666666
$      lcid       sidr       scla       sclo       offa
        504          0        1.0        1.0
$                    x                     y
                0.5000                1.0000
                1.0000                1.0000
                2.5000                1.0000
                5.0000                1.0000
               10.0000                1.0000
```

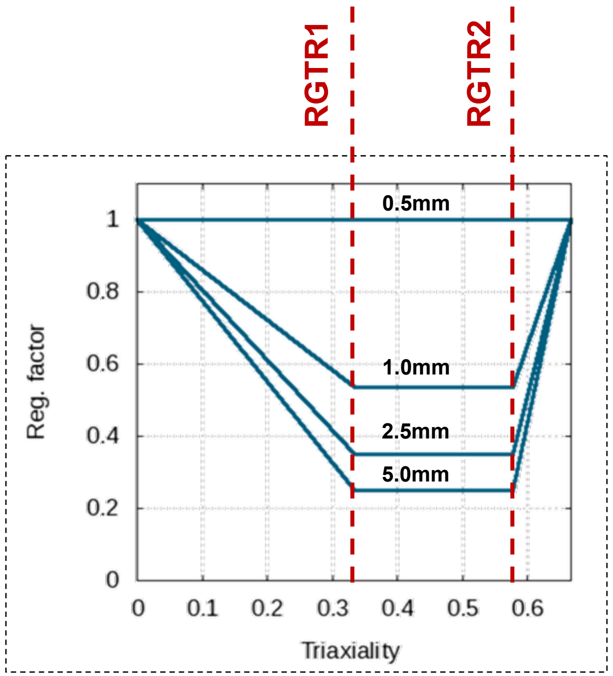


*MAT_ADD_DAMAGE_GISSMO

New feature! Available in current development versions

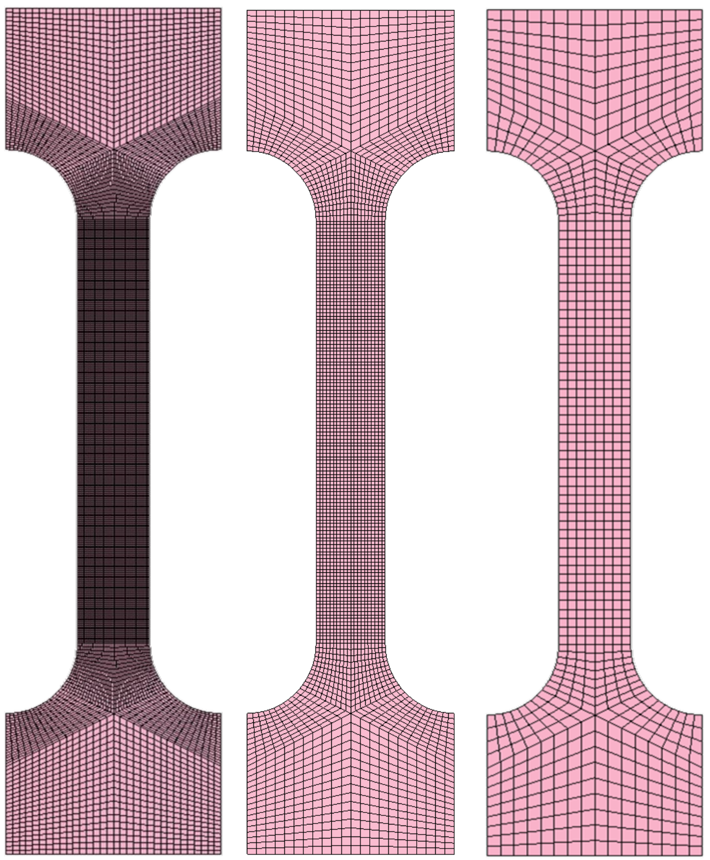
```
*MAT_ADD_DAMAGE_GISSMO
$      MID                DTYP     REFSZ    NUMFIP
        10                   1                 -80
$    LCSDG     ECRIT    DMGEXP     DCRIT    FADEXP    LCREGD
       100      -200         2                 2.5       502
$    LCSRS      SHRF     BIAXF    LCDLIM   MIDFAIL     HISVN

$    RGTR1     RGTR2
   0.33333   0.57735
```

```
*DEFINE_CURVE
$  Regularisierung Girlande, triax = 0.3333333
$     lcid      sidr      scla      sclo      offa
       502         0       1.0       1.0
$                  x                   y
              0.5000              1.0000
              1.0000              0.5350
              2.5000              0.3500
              5.0000              0.2500
             10.0000              0.1800
```

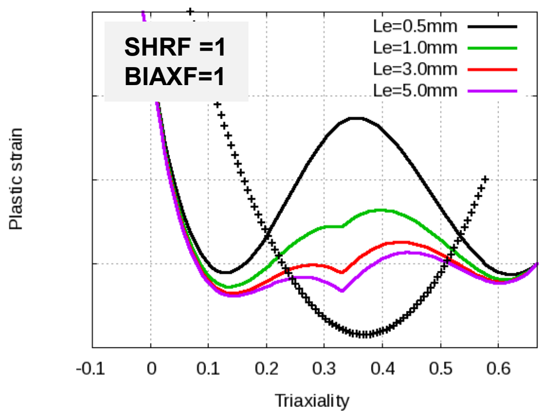


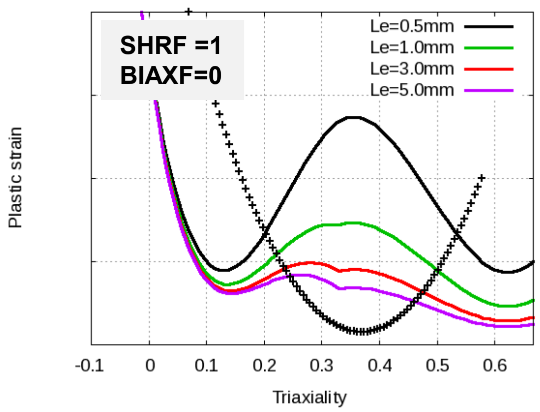
Example: Aluminum

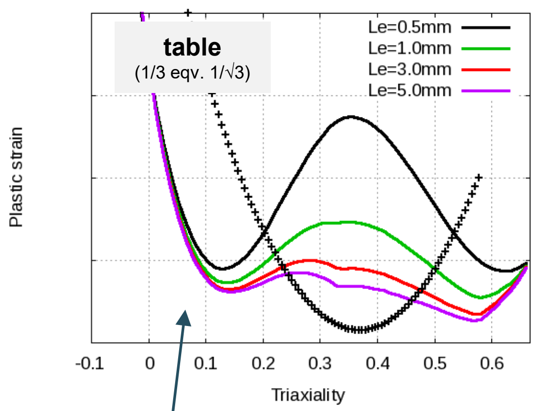
GISSMO material card, regularization factors from A80 tensile test

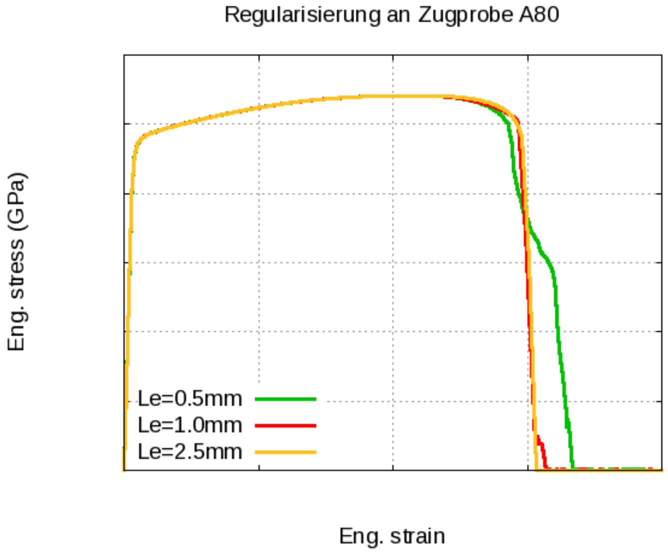


0.5mm (Reference) **1.0mm** **2.5mm**

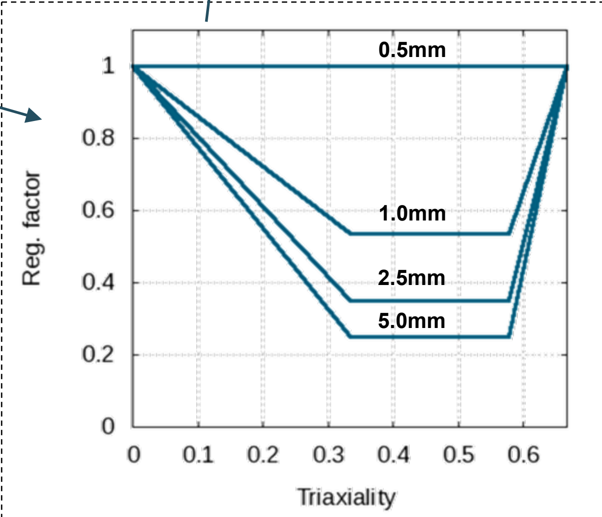






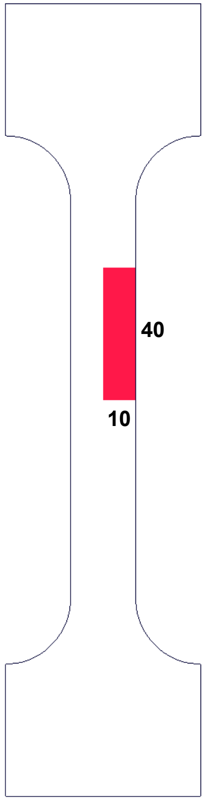


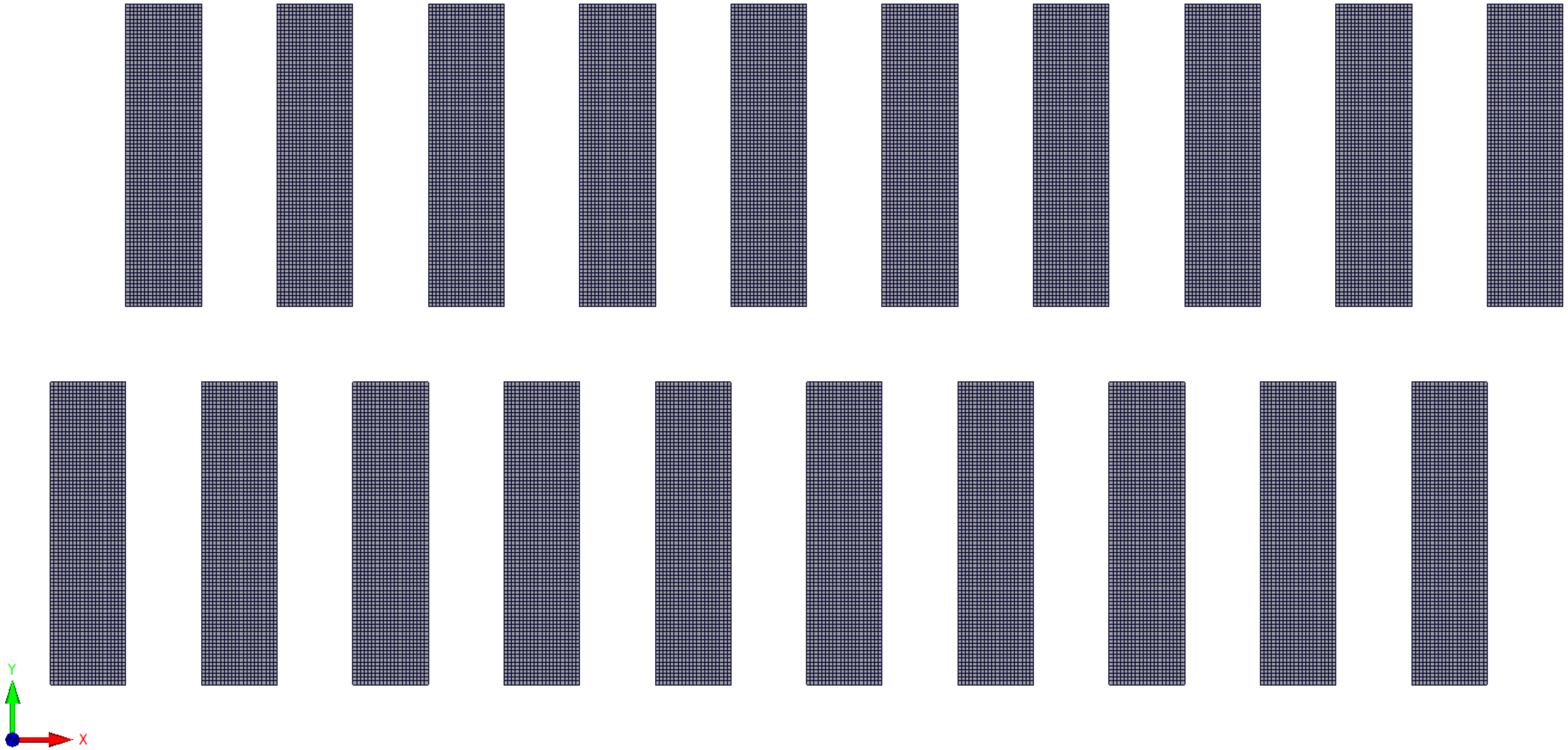

```
*DEFINE_TABLE
$     tbid
       500
$                triax
          0.0000000
          0.3333333
          0.5773500
          0.6666666
*DEFINE_CURVE
$  Regularisierung Girlande, triax = 0.0
$     lcid      sidr      scla      sclo      offa
       501         0       1.0       1.0
$                    x                   y
             0.5000              1.0000
             1.0000              1.0000
             2.5000              1.0000
             5.0000              1.0000
            10.0000              1.0000
*DEFINE_CURVE
$  Regularisierung Girlande, triax = 0.3333333
$     lcid      sidr      scla      sclo      offa
       502         0       1.0       1.0
$                    x                   y
             0.5000              1.0000
             1.0000              0.5350
             2.5000              0.3500
             5.0000              0.2500
            10.0000              0.1800
*DEFINE_CURVE
$  Regularisierung Girlande, triax = 0.57735
$     lcid      sidr      scla      sclo      offa
       503         0       1.0       1.0
$                    x                   y
             0.5000              1.0000
             1.0000              0.5350
             2.5000              0.3500
             5.0000              0.2500
            10.0000              0.1800
*DEFINE_CURVE
$  Regularisierung Girlande, triax = 0.6666666
$     lcid      sidr      scla      sclo      offa
       504         0       1.0       1.0
$                    x                   y
             0.5000              1.0000
             1.0000              1.0000
             2.5000              1.0000
             5.0000              1.0000
            10.0000              1.0000
```



From A80 tensile test to blocks

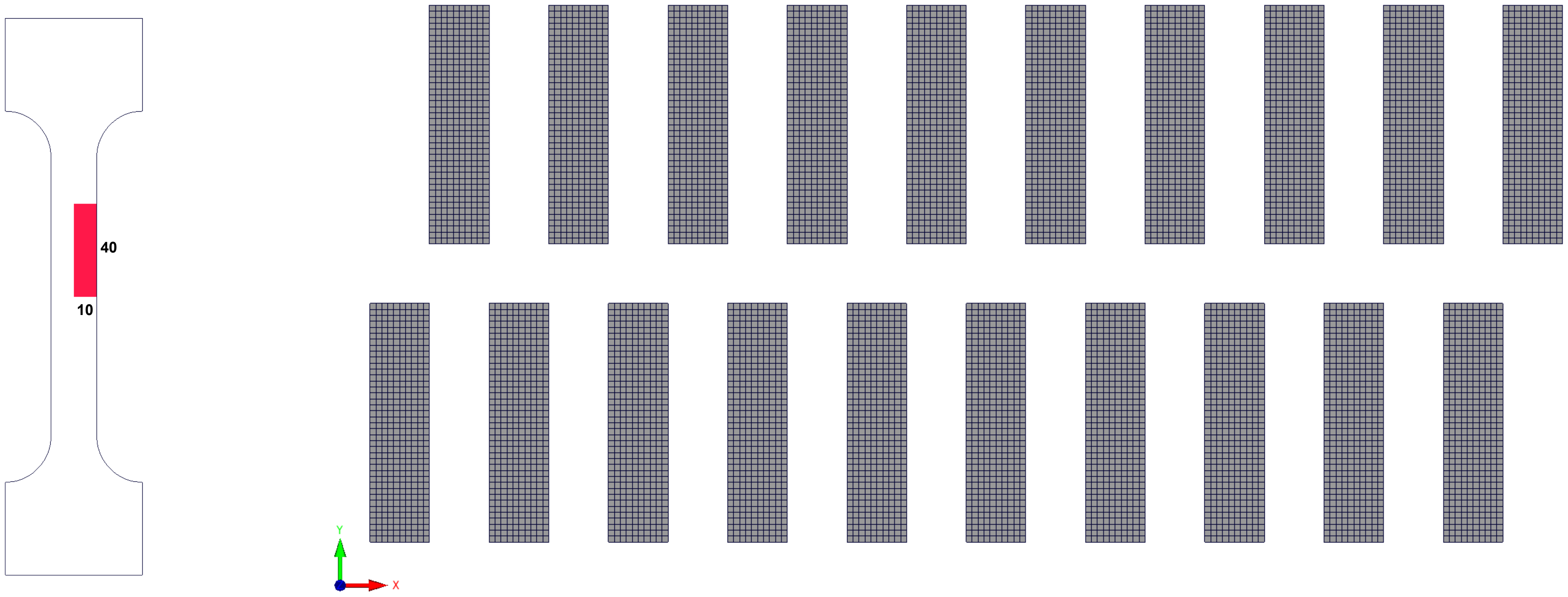
Le=0.5mm





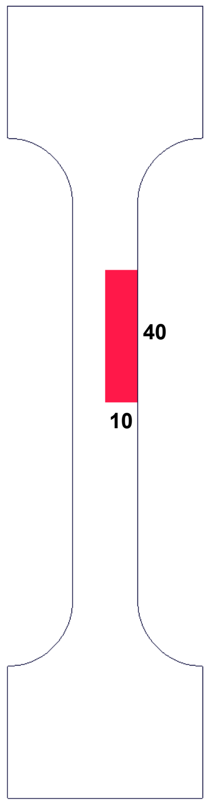
From A80 tensile test to blocks

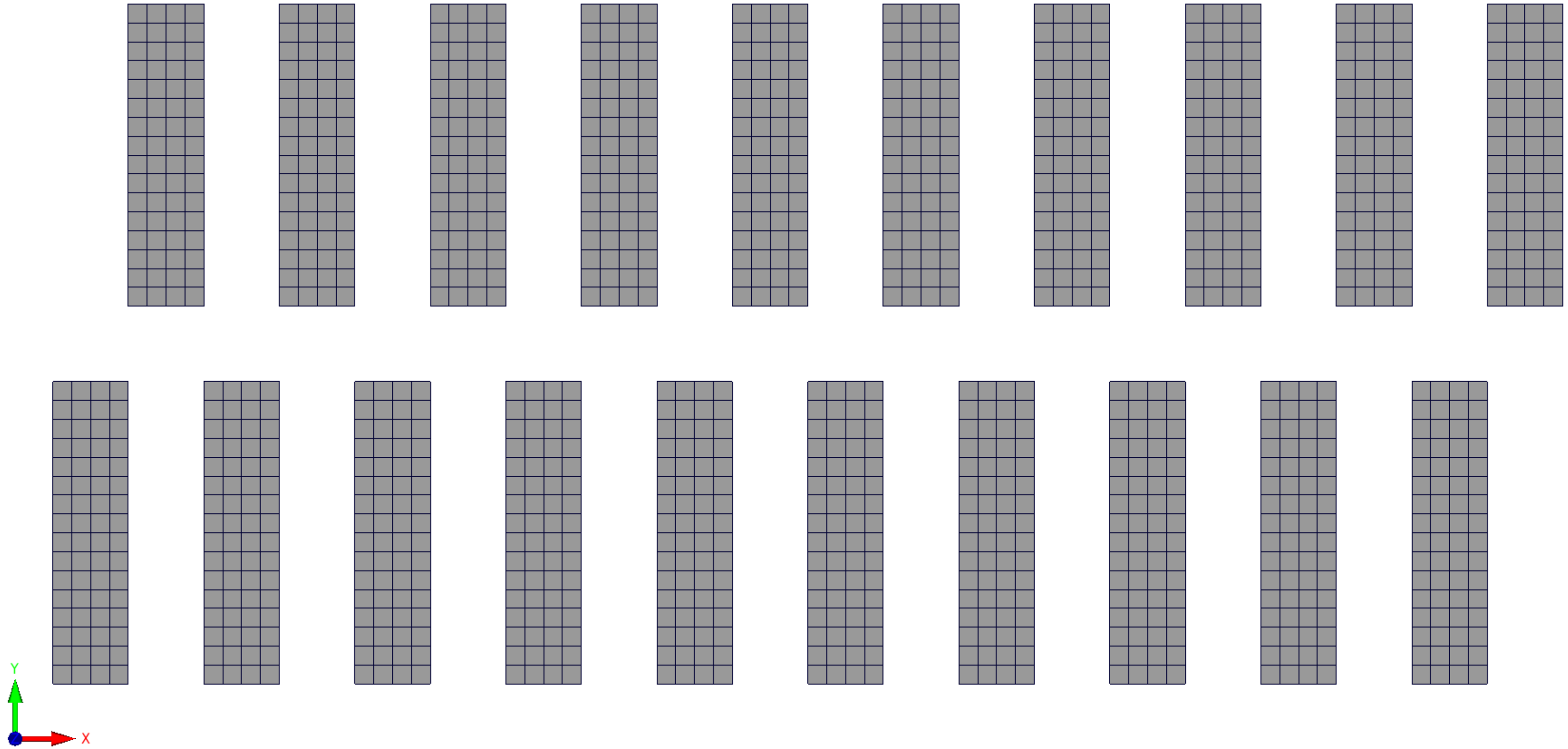
Le=1.0mm



From A80 tensile test to blocks

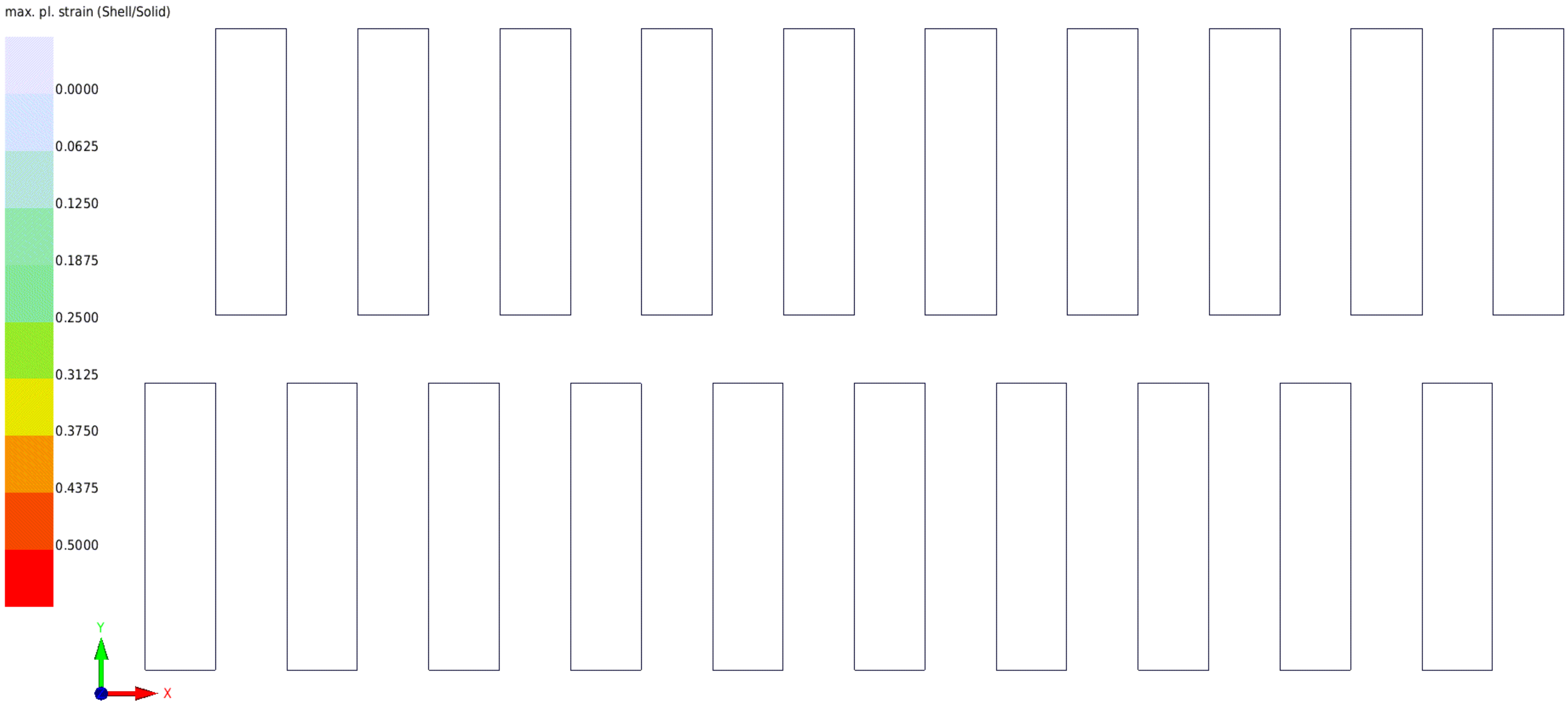
Le=2.5mm





From A80 tensile test to blocks

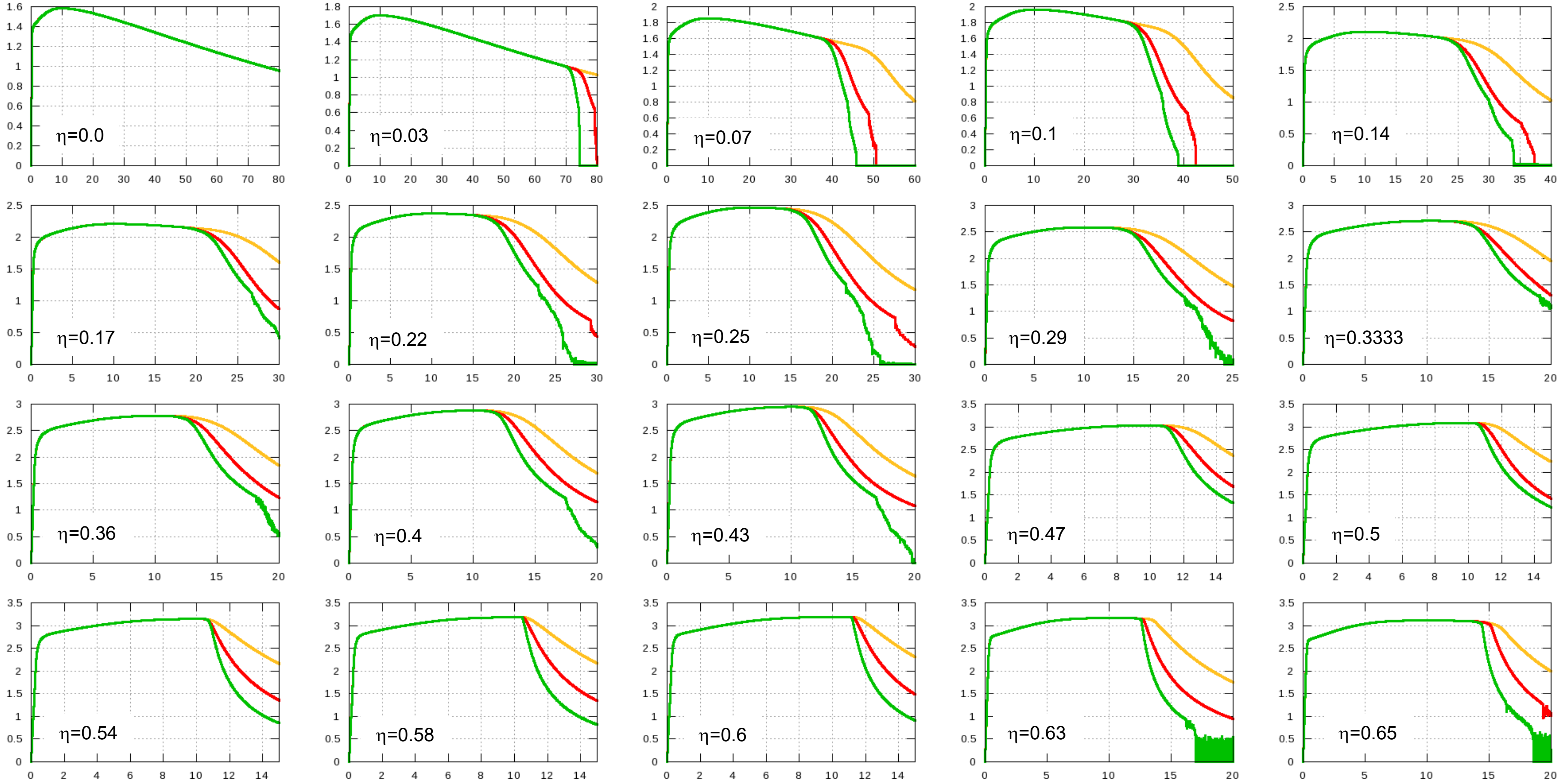
Deformation up to fracture



Y-force vs time

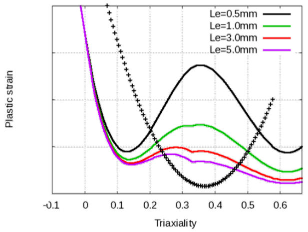
No regularization

Le=0.5mm
Le=1.0mm
Le=2.5mm

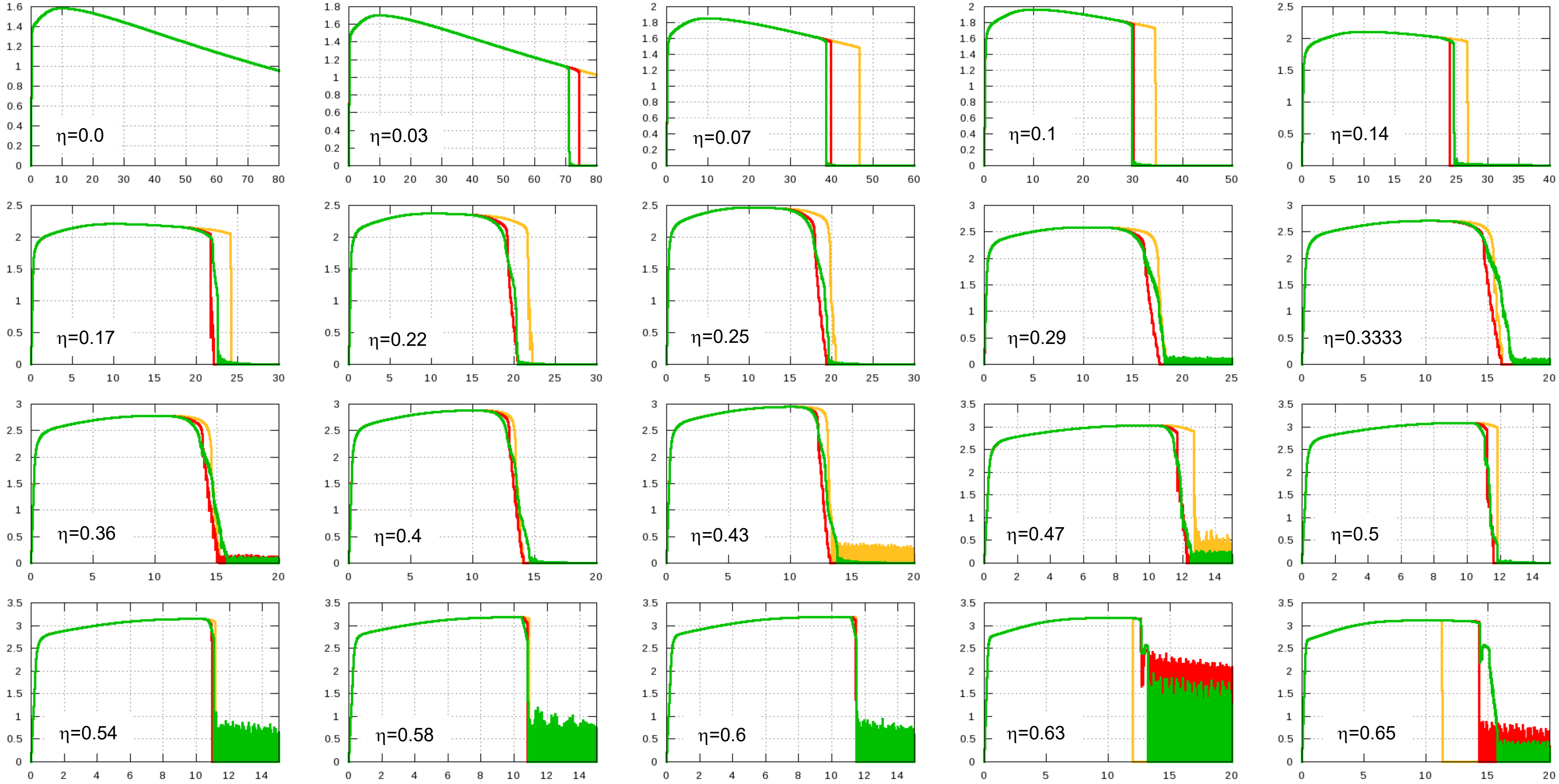


Y-force vs time

SHRF=1, BIAXF=0

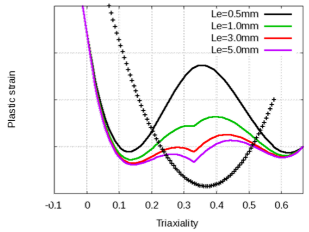


Le=0.5mm
Le=1.0mm
Le=2.5mm

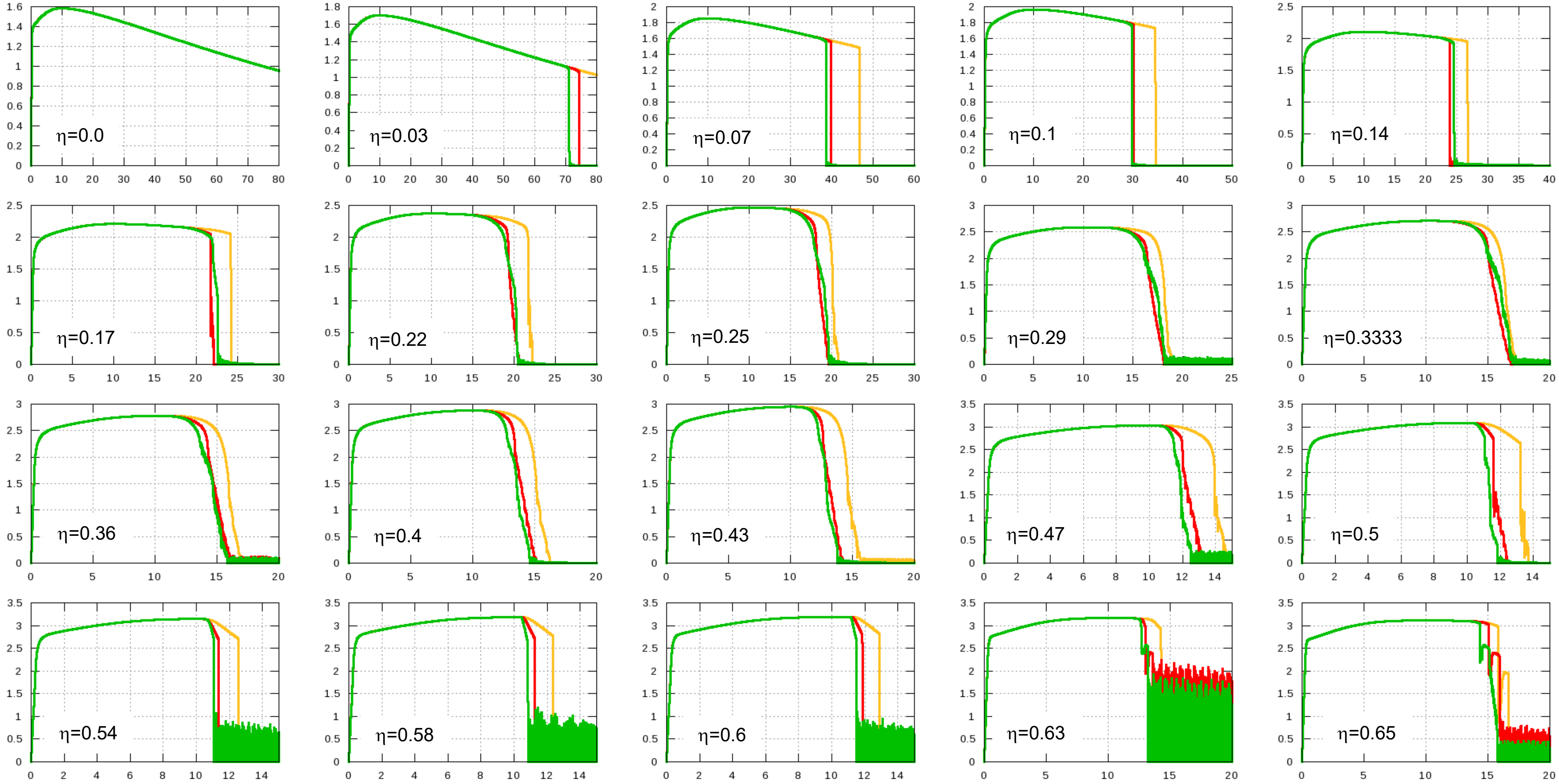


Y-force vs time

SHRF=1, BIAXF=1

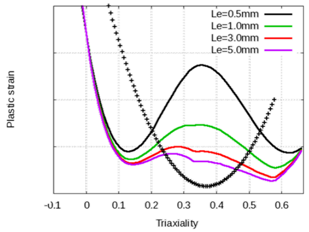


Le=0.5mm
Le=1.0mm
Le=2.5mm



Y-force vs time

Table (1/3 eqv. 0.57735)



Le=0.5mm
Le=1.0mm
Le=2.5mm

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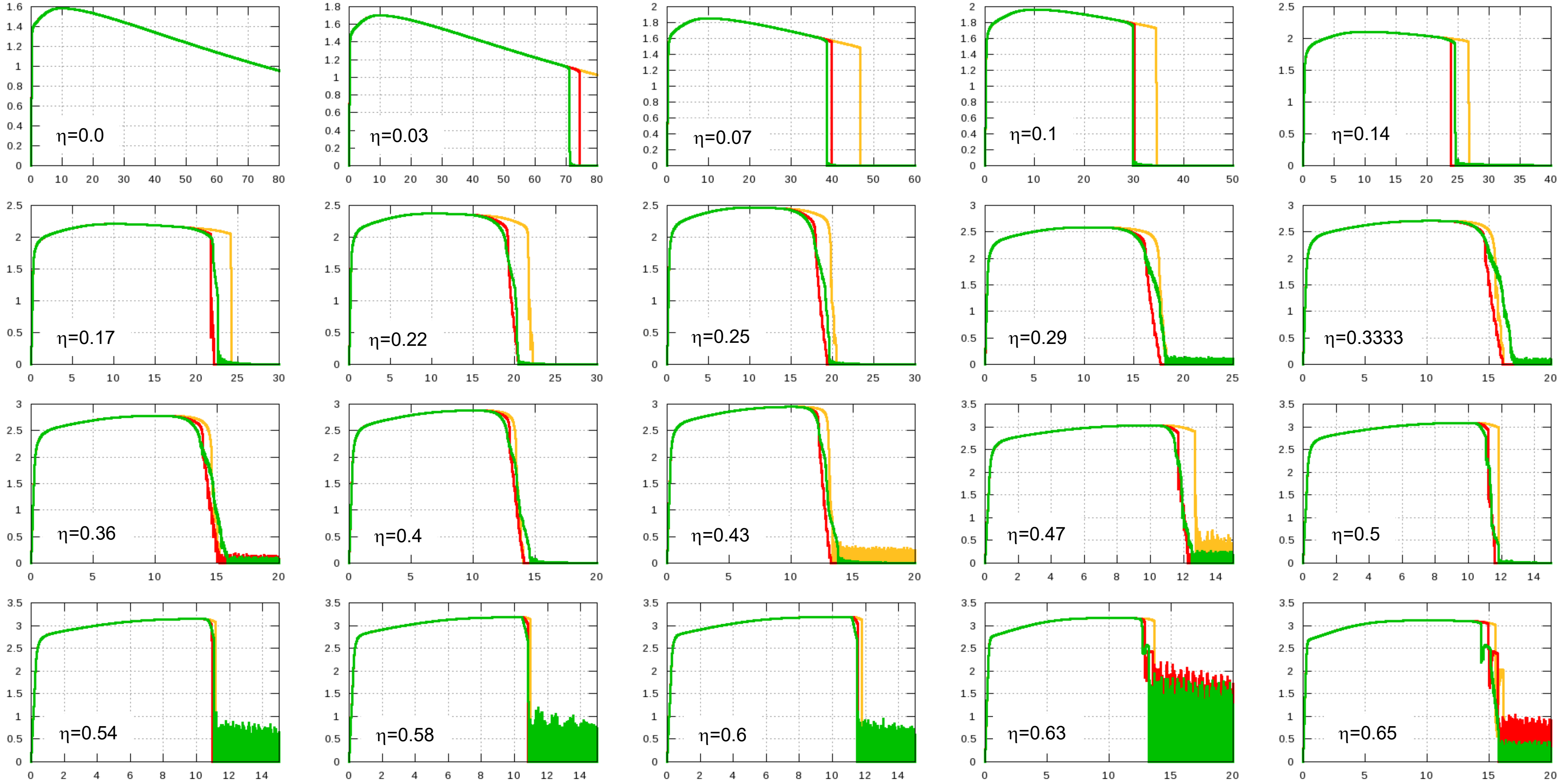
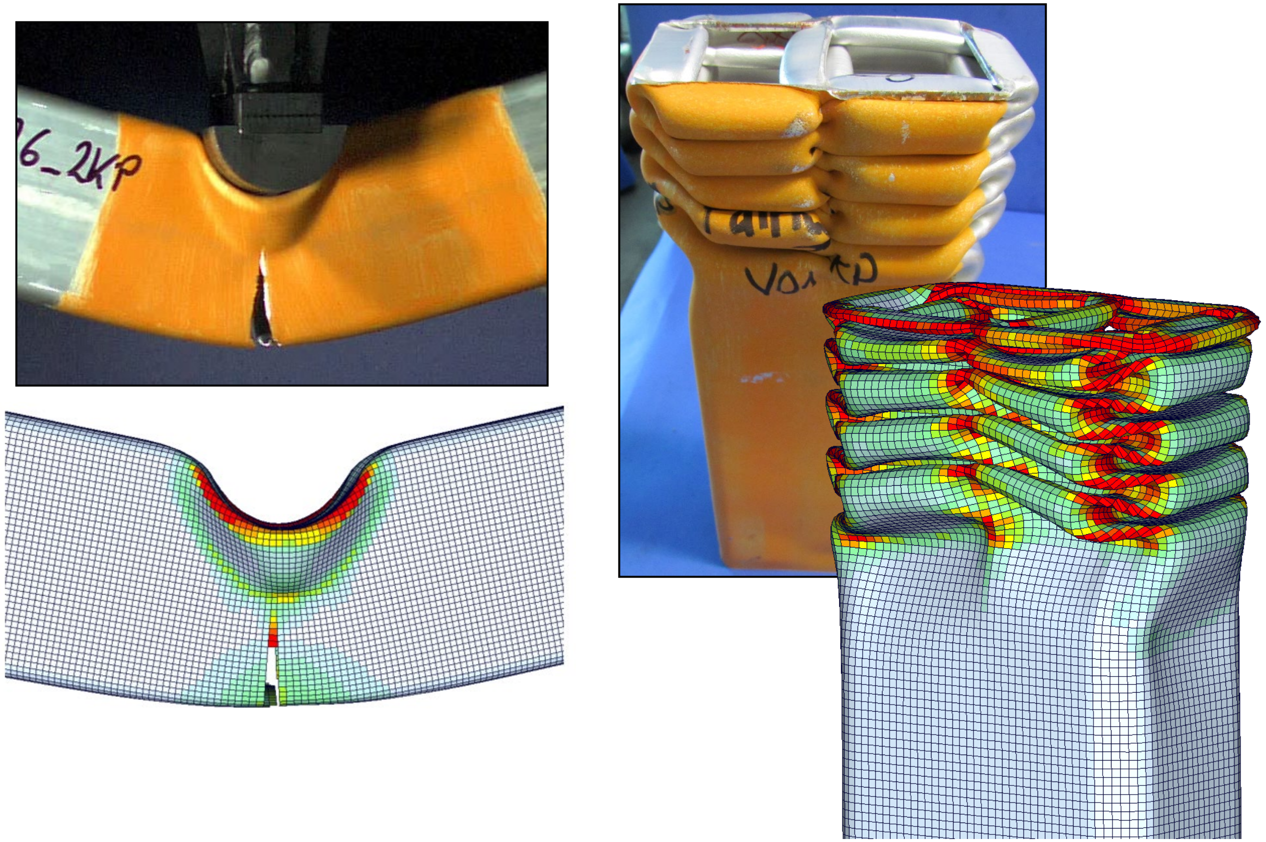
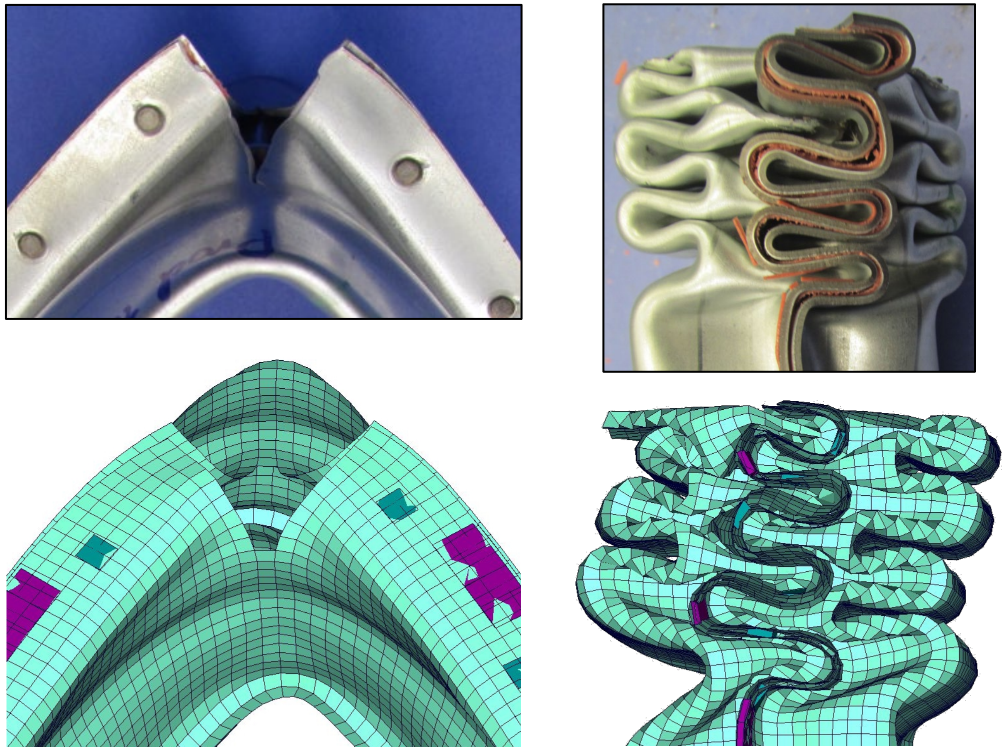


Old method: SHRF and BIAXF

SHRF/BIAXF brought significant improvement but often with contradictory results

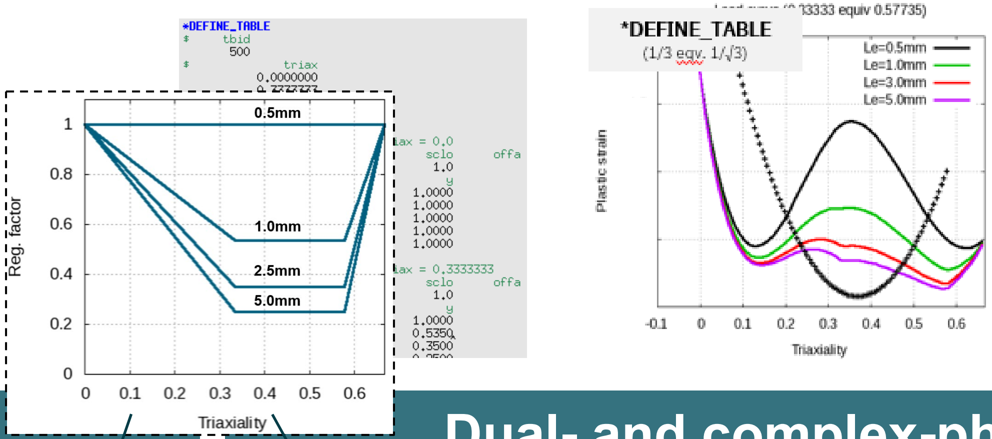
Aluminum extrusions	Dual- and complex-phase steel
SHRF=1.0 BIAXF=0.0	SHRF=1.0 BIAXF=1.0



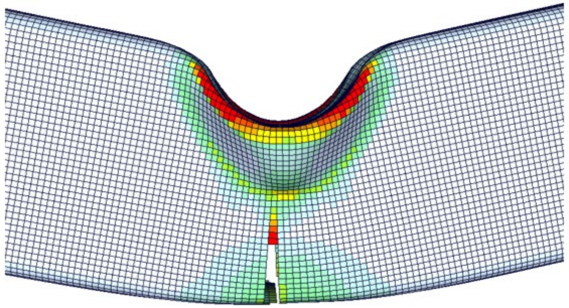


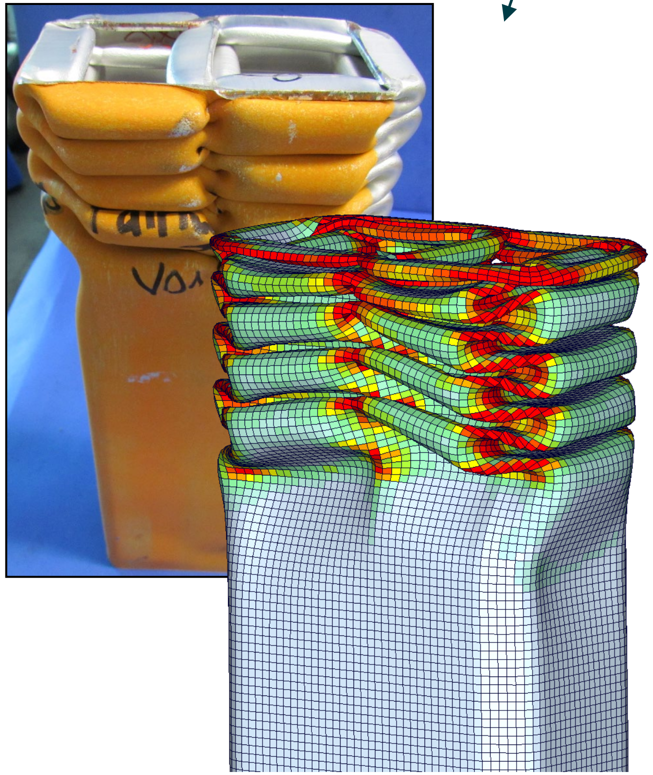
New method: Table

Implemented in R12,
RGTR1 and RGTR2 in dev versions

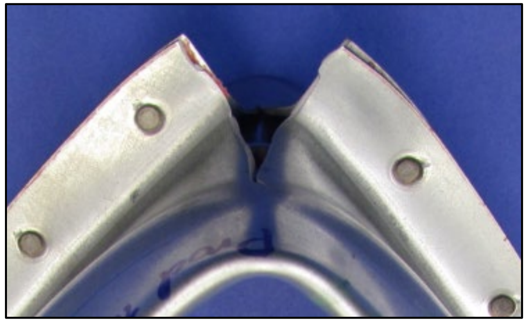


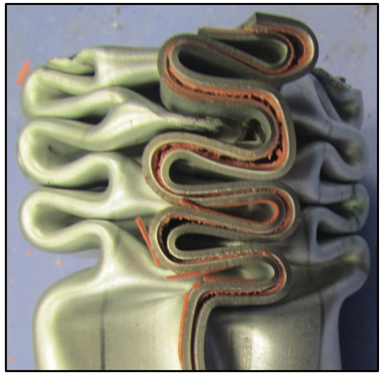
Aluminum extrusions

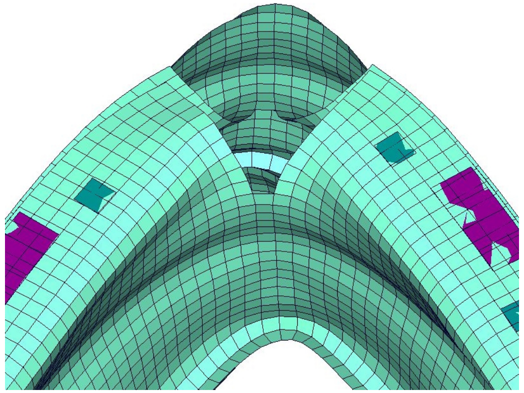


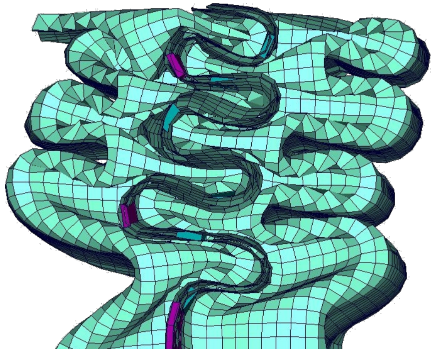


Dual- and complex-phase steel









Conclusions

Conclusions

- Spurious mesh dependence is stress state dependent
- Swift’s plastic instability criterion predicts the onset of mesh dependence very accurately
- Regularization cannot help in geometrical mesh dependence, but can compensate for the effects of spurious mesh dependence
- Triaxiality-dependent regularization removes the ambiguity of using different values of SHRF and BIAXF for different materials
- It also brings significant benefits when mapping from forming to crash simulations
- A new feature is available in *MAT_ADD_DAMAGE_GISSMO through flags RGTR1 and RGTR2
- More investigation is necessary for stress states between triaxiality 0.0 and 1/3

Thank You

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