Multigrid Preconditioned Solvers for Some Elastoplastic Type Problems

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Outline

- Motivation
- Single yield plasticity
  - Modeling
  - Algorithm for isotropic hardening
  - Numerical results
- Multi yield plasticity
  - What is multi yield?
  - Difficilties in symbolic calculations
- Conclusions and outlook

Motivation

Computing solutions numerically avoids e.g. expensive crash tests:

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Literature:

- Plasticity: Carstensen, Han/Reddy
- Variational inequalities: Ekeland/Teman, Glowinski et al.
- FEM and multigrid: Braess, Bramble, Brenner/Scott, Hackbusch

Modeling

Find $u \in W^{1,2}(0,T;\ H_0^1(\Omega)^n)$, $p \in W^{1,2}(0,T; L^2(\Omega, \mathbb{R}^{n\times n}))$,
$\sigma \in W^{1,2}(0,T; L^2(\Omega, \mathbb{R}^{n\times n}))$, $\alpha \in W^{1,2}(0,T; L^2(\Omega, \mathbb{R}^{m}))$ such that

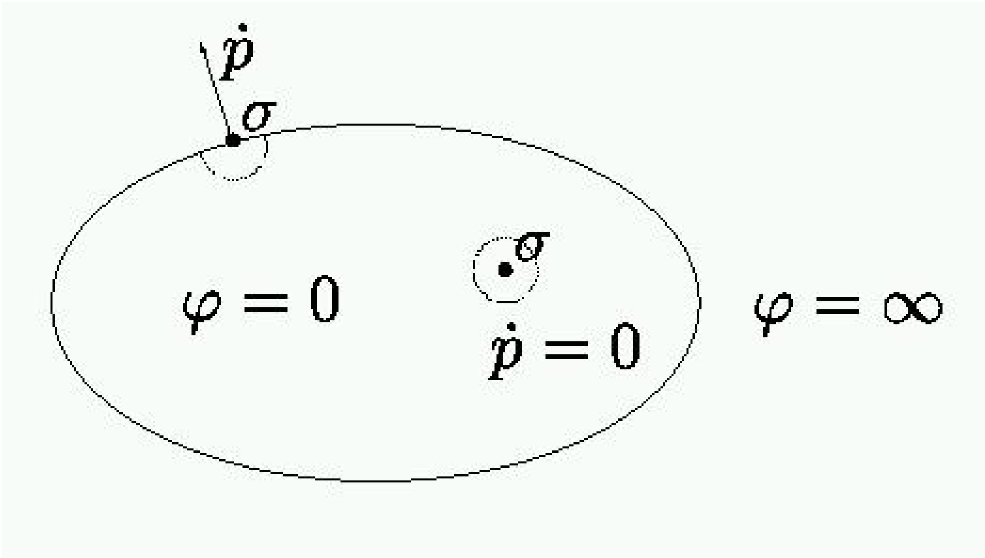
$$
\begin{aligned}
-\operatorname{div}\sigma &= b \\
\sigma &= \sigma^T \\
\varepsilon(u) &= \frac{1}{2}\left(\nabla u + (\nabla u)^T\right) \\
\varepsilon(u) &= \mathbb{C}^{-1}\sigma + p \\
\varphi(\sigma,\alpha) &< \infty \\
\dot{p} : (\tau - \sigma) - \dot{\alpha} : (\beta - \alpha) &\leq \varphi(\tau,\beta) - \varphi(\sigma,\alpha)
\end{aligned}
$$

are satisfied in the variational sense with $(u, p, \sigma, \alpha)(0) = 0$ for all (τ, β).
b and $\mathbb{C}^{-1}$ are given, $b(0) = 0$.

Normality law

Formulas without α (perfect plasticity)

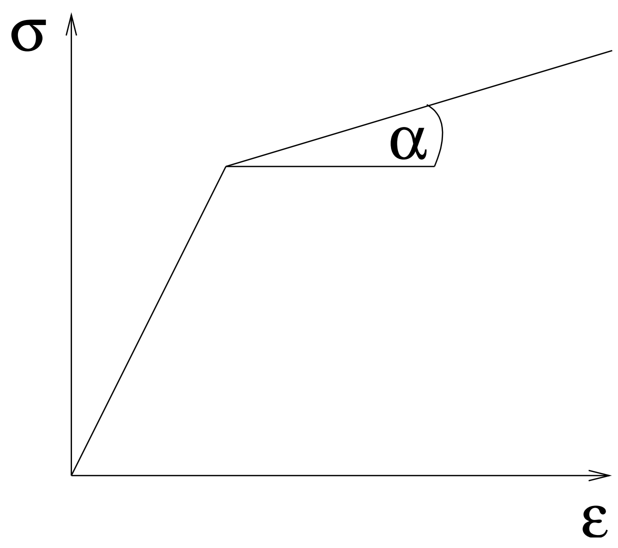
$$\begin{aligned} \varphi(\sigma) &< \infty \\ \dot{p} : (\tau - \sigma) &\leq \varphi(\tau) - \varphi(\sigma) \end{aligned}$$



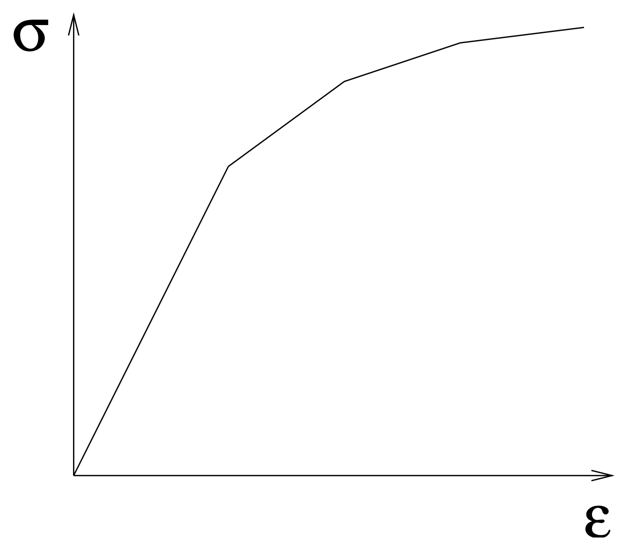
Numeric-analytic steps

- Time discretization: $t_1 = t_0 + \Delta t$
- Reformalution of the problem using functional-analytic arguments (switching arguments in variational inequalities using a dual functional)
- Equivalent minimization problem

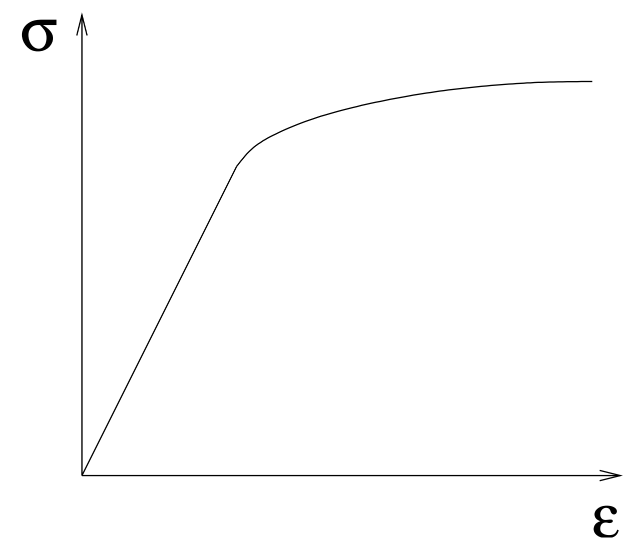
Hysteresis curves



Single yield



Multi yield



Reality

Minimization problem for isotropic hardening

The minimization problem is

$$f(u,p) := \frac{1}{2}\int_\Omega \mathbb{C}[\varepsilon(u)-p] : (\varepsilon(u)-p)dx + \frac{1}{2}\int_\Omega (\alpha_0 + \sigma_y H|p-p_0|)^2 dx + \int_\Omega \sigma_y |p-p_0| dx - \int_\Omega b(t)\, u\, dx$$

under the constraint $\mathrm{tr}(p-p_0)=0$

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New variable: $\tilde{p} = p - p_0$

A differentiable approximation of $|\tilde{p}|$:

$$|p|_\epsilon := \begin{cases} |p| & \text{if } |p| \geq \epsilon \\ \frac{1}{2\epsilon}|p|^2 + \frac{\epsilon}{2} & \text{if } |p| < \epsilon \end{cases}$$

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Minimization strategy in each time step:

$$u^{k+1} = \mathrm{argmin}_v \min_q \bar{f}(v,q) = \mathrm{argmin}_v \tilde{f}(v, q_{\mathsf{opt}}(v))$$

Then $p = p_0 + \tilde{p}$

Minimization in u

FEM-Discretization of the unconstrained objective is equivalent to

$$\frac{1}{2}(Bu-\tilde{p})^T \mathbb{C}(Bu-\tilde{p}) + \frac{1}{2}\tilde{p}^T \mathbb{H}(|\tilde{p}|_\epsilon)\tilde{p} - bu \longrightarrow \min!$$

Matrix notation:

$$\frac{1}{2}\begin{pmatrix} u \\ \tilde{p} \end{pmatrix}^T \begin{pmatrix} B^T\mathbb{C}B & -B^T\mathbb{C} \\ -\mathbb{C}B & \mathbb{C}+\mathbb{H} \end{pmatrix} \begin{pmatrix} u \\ \tilde{p} \end{pmatrix} + \begin{pmatrix} -b - B^T\mathbb{C}p_0 \\ \mathbb{C}p_0 \end{pmatrix}^T \begin{pmatrix} u \\ \tilde{p} \end{pmatrix} \longrightarrow \min!$$

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Necessary condition:

$$\begin{pmatrix} B^T\mathbb{C}B & -B^T\mathbb{C} \\ -\mathbb{C}B & \mathbb{C}+\mathbb{H} \end{pmatrix} \begin{pmatrix} u \\ \tilde{p} \end{pmatrix} + \begin{pmatrix} -b - B^T\mathbb{C}p_0 \\ \mathbb{C}p_0 \end{pmatrix} = 0$$

The Schur-Complement system in u with the matrix

$$S = B^T(\mathbb{C} - \mathbb{C}(\mathbb{C}+\mathbb{H})^{-1}\mathbb{C})B$$

is solved by multigrid preconditioned conjugate gradient method.

Minimization in $\tilde{p}$

The objective in each integration point writes as

$$F(\tilde{p}) = \frac{1}{2}\tilde{p}^T \mathbb{C}\tilde{p} + p_0^T \mathbb{C}\tilde{p} - \tilde{p}^T \mathbb{C}\varepsilon(u) + \frac{1}{2}\sigma_y^2 H^2 |\tilde{p}|^2 + \sigma_y(1 + \alpha_0 H)|\tilde{p}|_\epsilon$$

$\tilde{p}$ is determined by a modified Newton Algorithm in each integration point.

Are there symbolic methods (as in the unregularized case)?

What about the constraint?

Constraint $\operatorname{tr} \tilde{p} = 0$

in 2D: $\tilde{p}_{22} = -\tilde{p}_{11}$, in 3D: $\tilde{p}_{33} = -\tilde{p}_{11} - \tilde{p}_{22}$.

Projection matrix P: $\tilde{p} = P\bar{p}$

$$\text{2D: } P = \begin{pmatrix} 1 & 0 \\ -1 & 0 \\ 0 & 1 \end{pmatrix}, \qquad \text{3D: } P = \begin{pmatrix} 1 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 \\ -1 & -1 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 1 \end{pmatrix}$$

Modified Newton system:

$$P^T F''(\tilde{p}) P \bar{p} = P^T F'(\tilde{p})$$

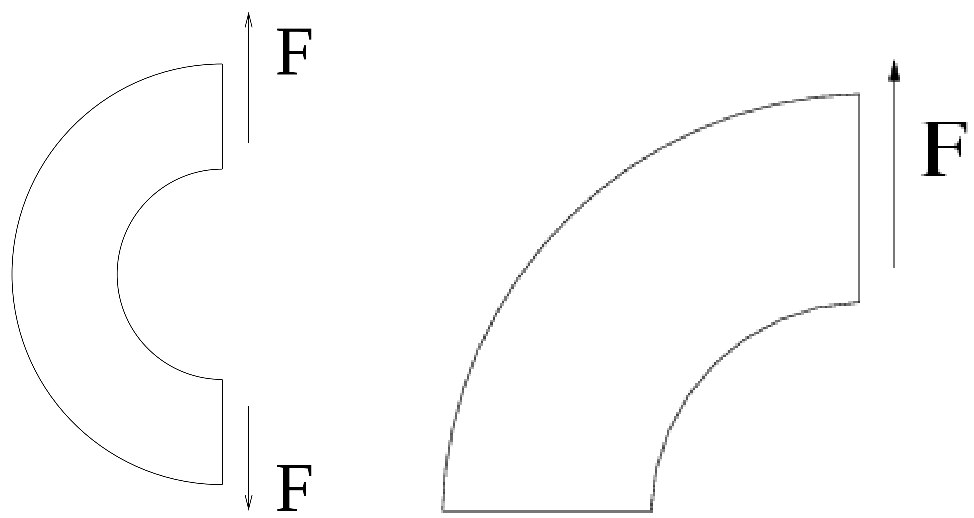
Modified Schur-Complement Matrix:

$$S = B^T(\mathbb{C} - \mathbb{C}P(P^T(\mathbb{C} + \mathbb{H})P)^{-1}P^T\mathbb{C})B$$

Numerical results - Quarter of a ring

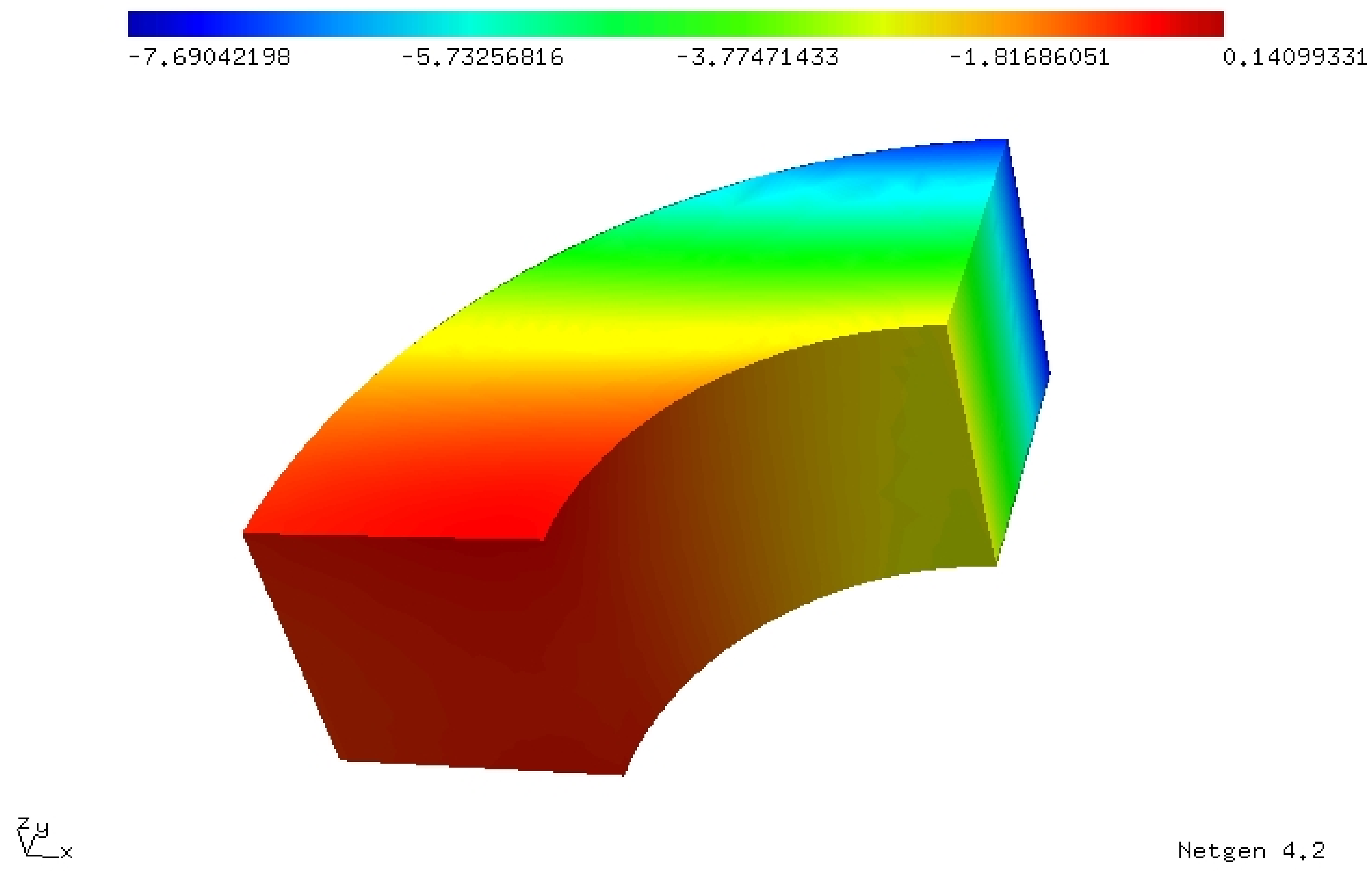
FEM shape functions: u piecewise quadratic, p piecewise constant

Symmetric problem:



Constants:
E=1, $\nu = 0.2$, H = 0.01, $\sigma_y = 1$, F = 0.25

Number of time steps: 10



Displacement in x-direction

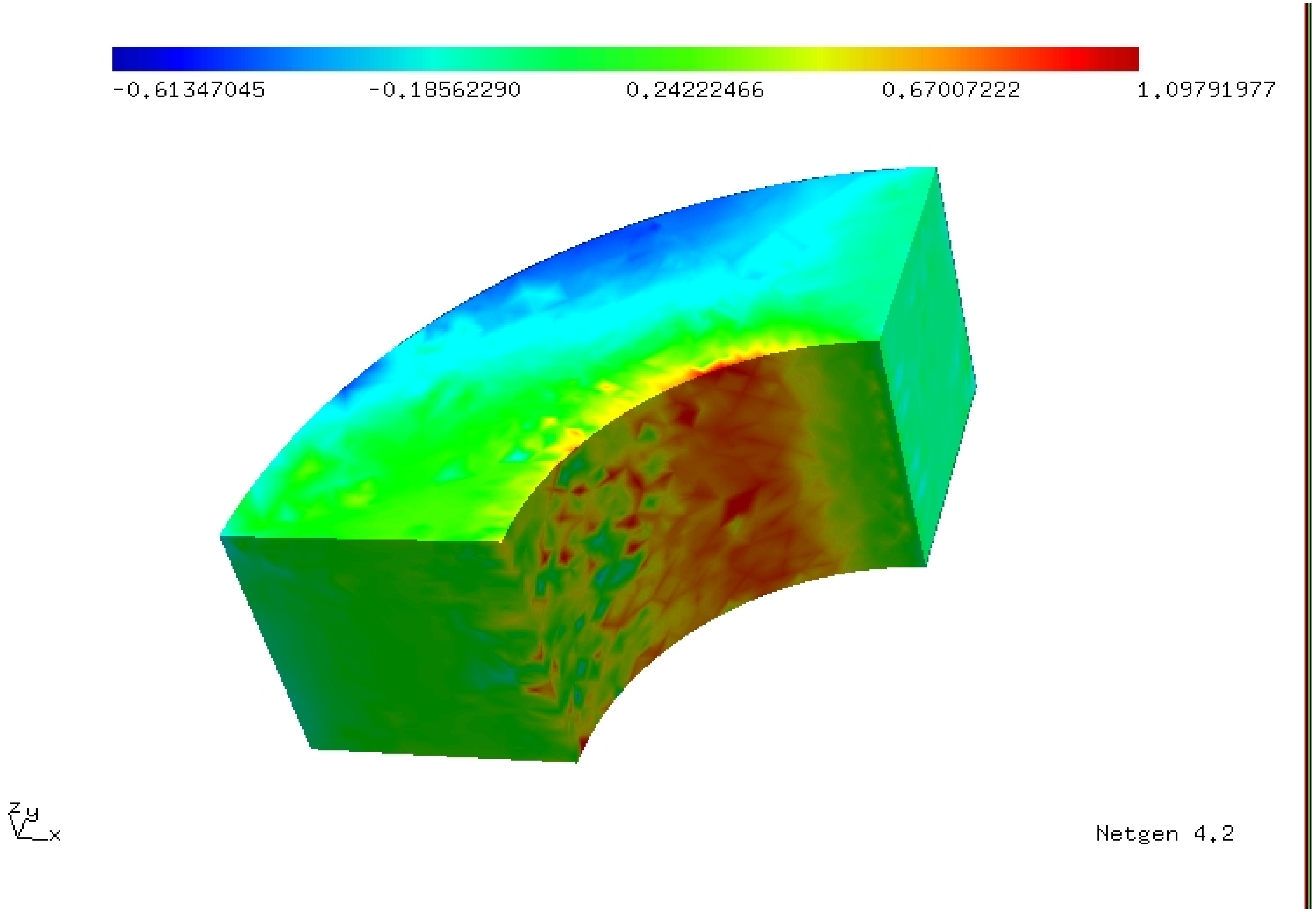


Figure 1: Stress in x-direction: σ_{11}

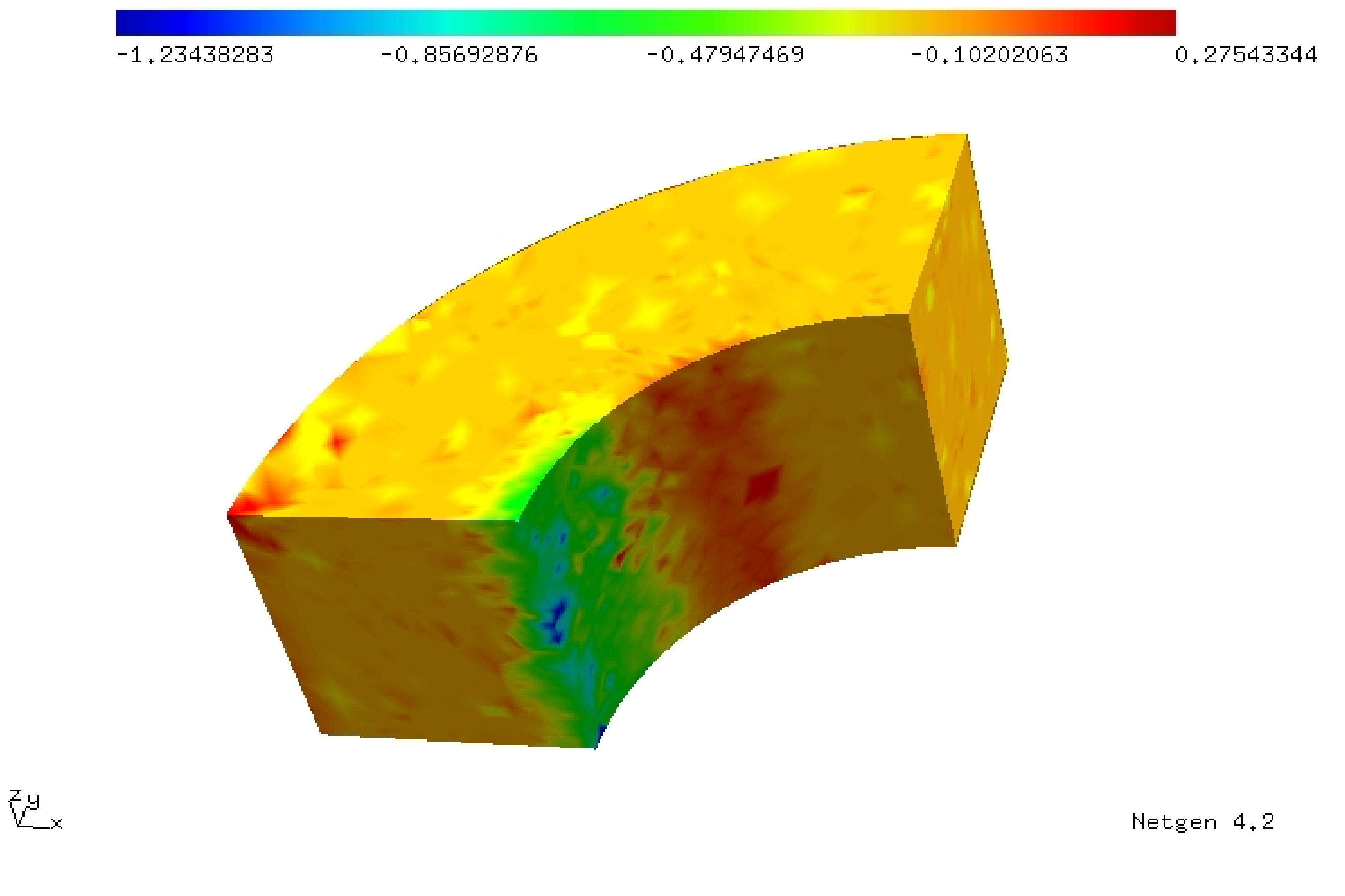


Figure 2: Plastic part of the strain in x-direction: p_{11}

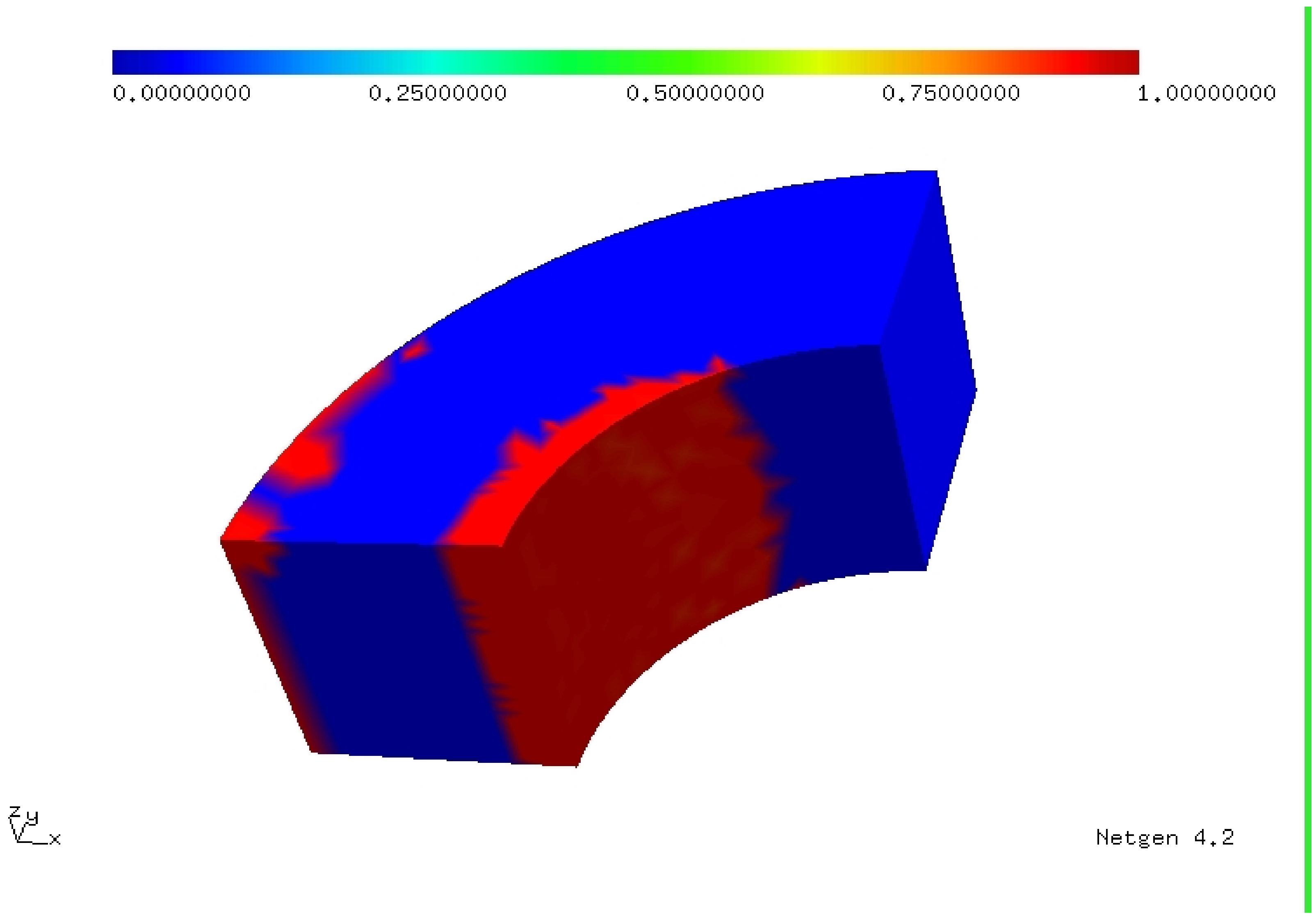


Figure 3: Plasticity domain

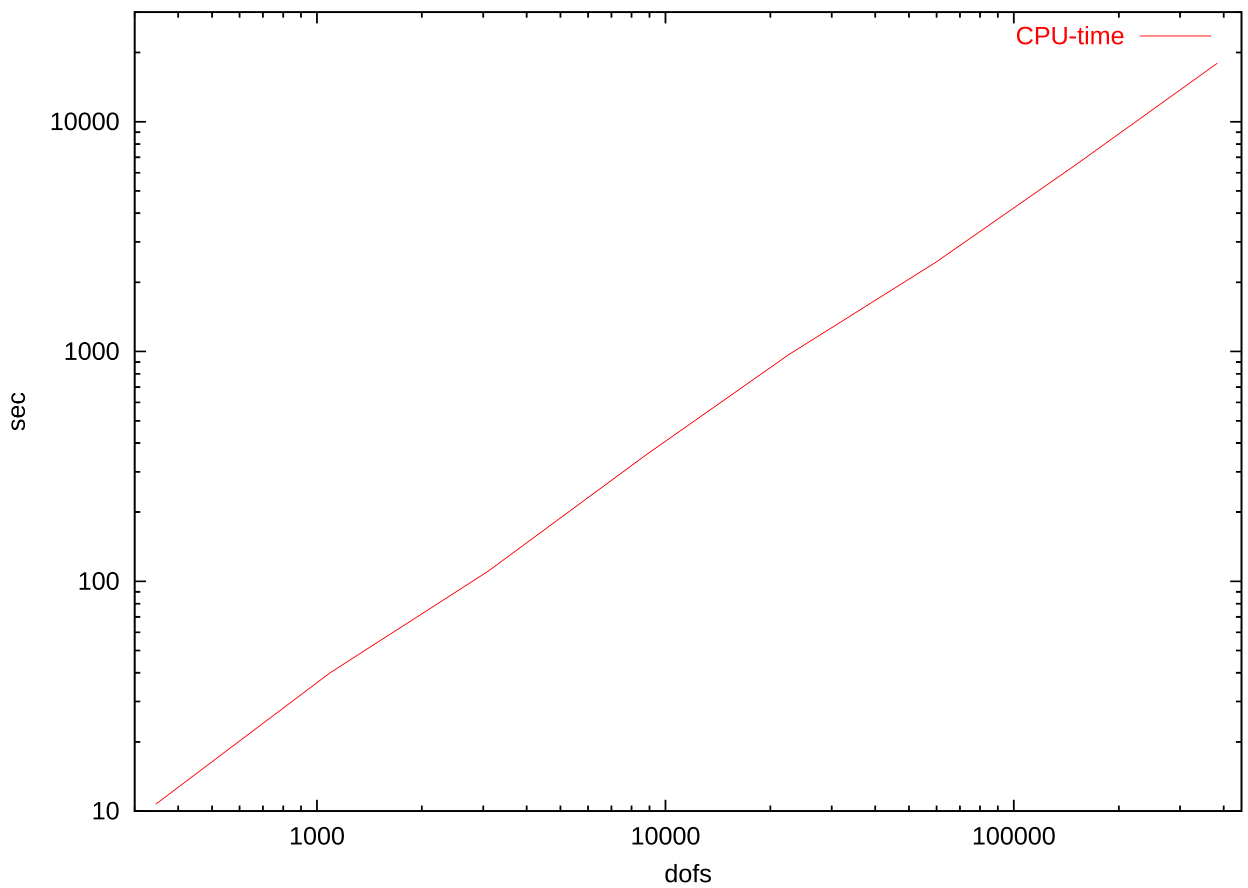


Figure 4: CPU-Time

Conclusions and outlook

We have considered:

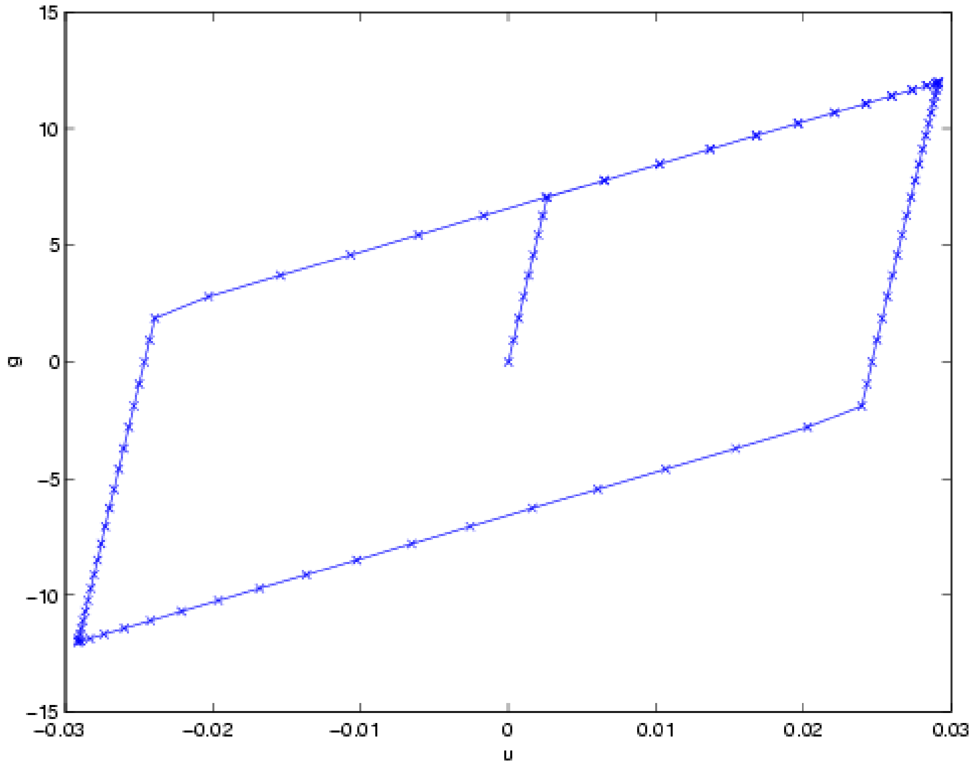
- Problem formulation and discretization
- Regularized minimization problem of isotropic hardening
- Minimization: 3D time-dependent algorithm

Future Work:

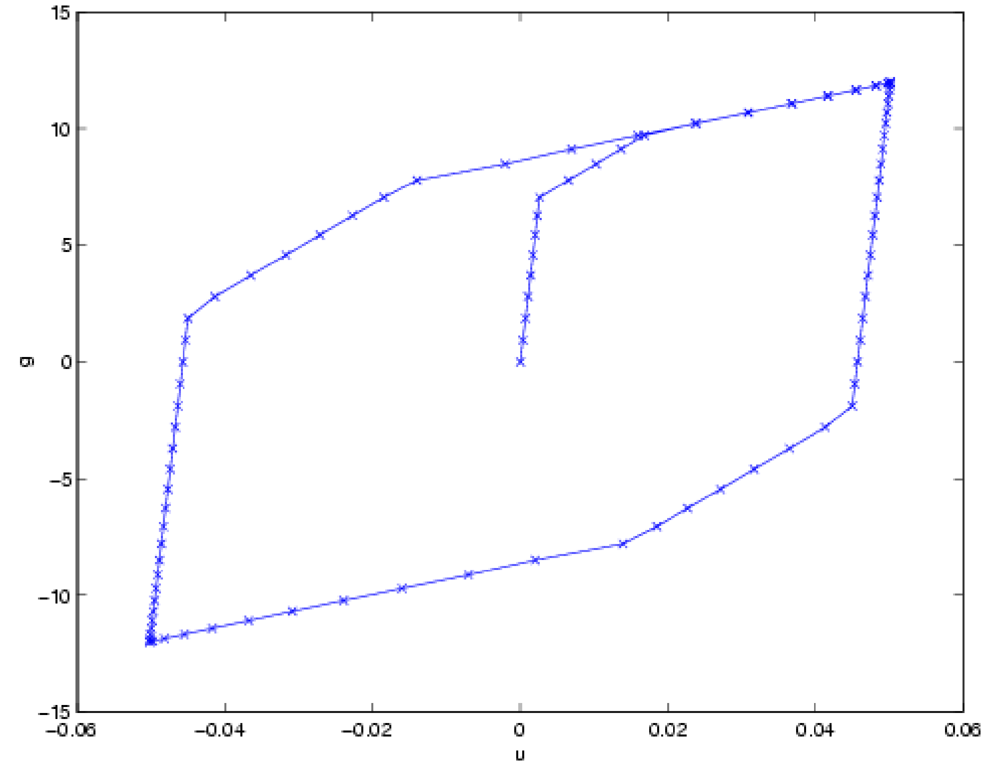
- Convergence proof
- Other hardening laws (multi-yield plasticity)
- Direct solver needed in inverse problems of plasticity
- Minimize p using symbolic methods?

Why Multi-yield (Two-yield) model?

- More realistic hysteresis stress-strain relation in materials!



Kinematic hardening model.



Two-yield hardening model.

Direct minimization problem

Kinematic hardening model:

$$f(Q) = \frac{1}{2}(\mathbb{C} + \mathbb{H})Q : Q - Q : A + \sigma^y ||Q|| \to \text{min}$$

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$$f\begin{pmatrix} Q_1 \\ Q_2 \end{pmatrix} = \frac{1}{2}\begin{pmatrix} \mathbb{C} + \mathbb{H}_1 & \mathbb{C} \\ \mathbb{C} & \mathbb{C} + \mathbb{H}_2 \end{pmatrix}\begin{pmatrix} Q_1 \\ Q_2 \end{pmatrix} : \begin{pmatrix} Q_1 \\ Q_2 \end{pmatrix} - \begin{pmatrix} Q_1 \\ Q_2 \end{pmatrix} : \begin{pmatrix} A_1 \\ A_2 \end{pmatrix} + \sigma_1^y ||Q_1|| + \sigma_2^y ||Q_2|| \rightarrow \text{min}$$

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minimizer $(P_1, P_2) = ?$

Direct minimization problem: Two-yield model - analytical approach

Lemma: Let $f(P) = \min_Q f(Q), P = (P_1, P_2)$, If $P_1 \neq 0, P_2 \neq 0 \Rightarrow ||P_2||$ is a root of a 8-th degree polynomial.

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Mininum condition on P: $0 \in \partial f(P) \Leftrightarrow A - (\hat{\mathbb{C}} + \hat{\mathbb{H}})P \in \partial || \cdot ||_{\sigma^y}(P)$

In case $P_1 \neq 0, P_2 \neq 0$ is $\partial || \cdot ||_{\sigma^y}(P) = \{\sigma_1^y \frac{P_1}{||P_1||}, \sigma_2^y \frac{P_2}{||P_2||}\}$

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$$\begin{pmatrix} \mathrm{dev}\, A_1 \\ \mathrm{dev}\, A_2 \end{pmatrix} - \begin{pmatrix} (2\mu + h_1)\mathbb{I} & 2\mu\mathbb{I} \\ 2\mu\mathbb{I} & (2\mu + h_2)\mathbb{I} \end{pmatrix} \begin{pmatrix} P_1 \\ P_2 \end{pmatrix} = \begin{pmatrix} \sigma_1^y \frac{P_1}{||P_1||} \\ \sigma_2^y \frac{P_2}{||P_2||} \end{pmatrix}$$

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Subst. $\xi_1 = ||P_1||, \xi_2 = ||P_2||$ with $A, B, C, D, E, F, G, H, I, J \in \mathbb{R}$

$$A + B\xi_1 + C\xi_1^2 - (G + H\xi_1 + I\xi_2 + J\xi_1\xi_2)^2 = 0$$
$$D + E\xi_2 + F\xi_2^2 - (G + H\xi_1 + I\xi_2 + J\xi_1\xi_2)^2 = 0$$

MAPLE $\Rightarrow$ 8-th degree polynomial in $\xi_2 \Rightarrow$ no analytical formula!

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Gröbner basis?

Direct minimization problem: Two-yield model - iterative approach

Algorithm (*): Given $tolerance \geq 0$.

(a) Choose $(P_1^0, P_2^0) \in \text{dev}\,\mathbb{R}^{d\times d}_{sym} \times \text{dev}\,\mathbb{R}^{d\times d}_{sym}$, set $i := 0$.

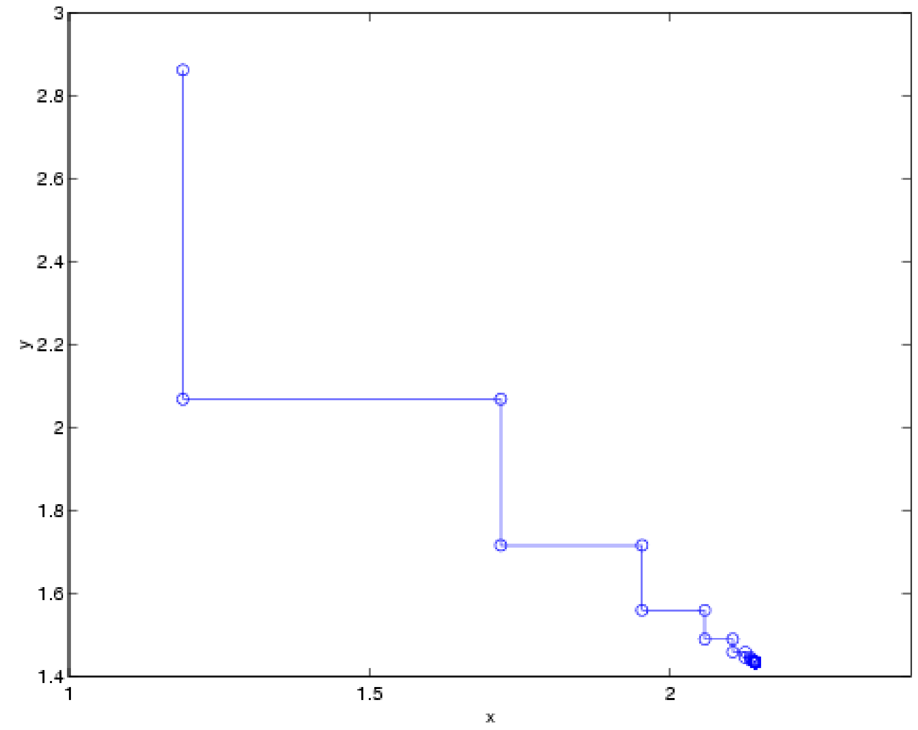
(b) Find $P_2^{i+1} \in \text{dev}\,\mathbb{R}^{d\times d}_{sym}$ s. t.

$$f(P_1^i, P_2^{i+1}) = \min_{Q_2 \in \text{dev}\,\mathbb{R}^{d\times d}_{sym}} f(P_1^i, Q_2).$$

(c) Find $P_1^{i+1} \in \text{dev}\,\mathbb{R}^{d\times d}_{sym}$ s. t.

$$f(P_1^{i+1}, P_2^{i+1}) = \min_{Q_1 \in \text{dev}\,\mathbb{R}^{d\times d}_{sym}} f(Q_1, P_2^{i+1}).$$

(d) If $\frac{||P_1^{i+1} - P_1^i|| + ||P_2^{i+1} - P_2^i||}{||P_1^{i+1}|| + ||P_1^i|| + ||P_2^{i+1}|| + ||P_2^i||} > tolerance$ set $i := i + 1$ and goto (b), otherwise output (P_1^{i+1}, P_2^{i+1}).



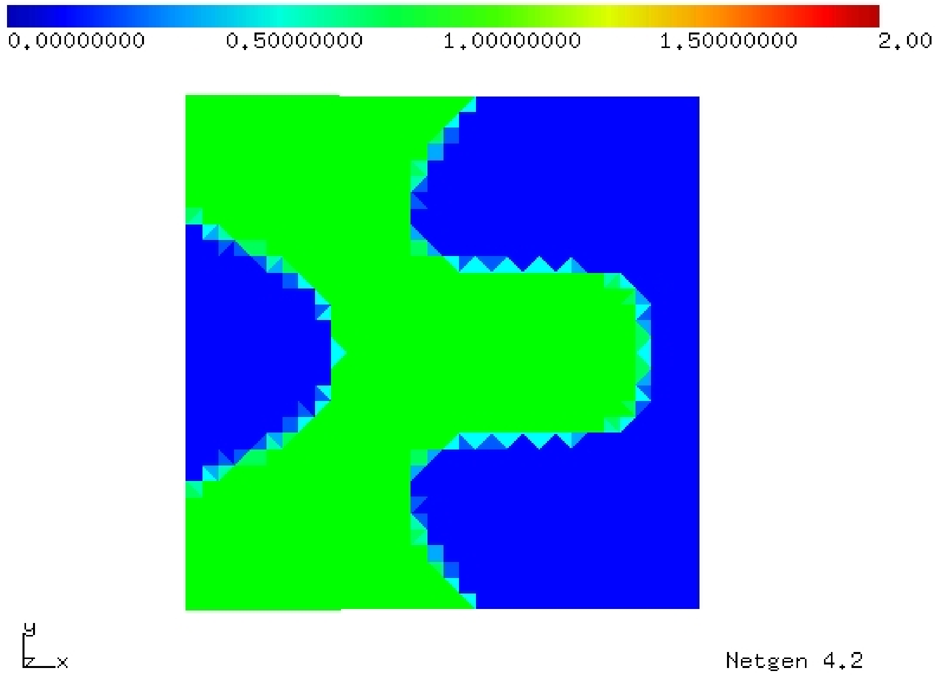
The approximations $P_1^i = (x^i, 0; 0, -x^i)$, $P_2^i = (y^i, 0; 0, -y^i)$, $i = 0, 1, \ldots$ of Algorithm (*) in the $x - y$ coordinate system.

- global convergence with the rate $1/2$:

$$||P_1^i - P_1||^2 + ||P_2^i - P_2||^2 \leq C_0 \cdot q^i$$

NGSOLVE calculations

Elastoplastic domains (blue -elastic, green - first plastic, red - second plastic)



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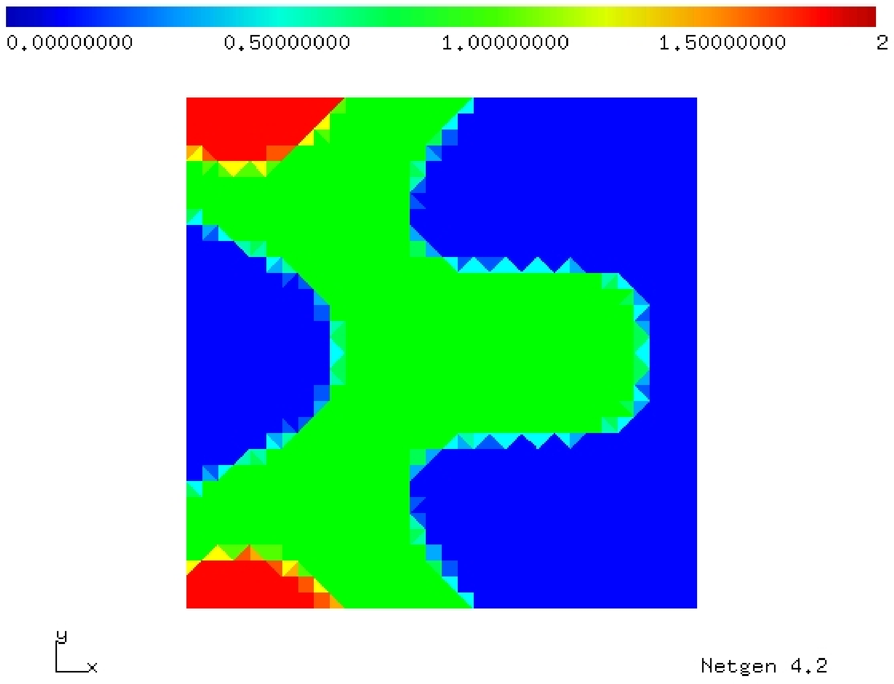

Two-yield hardening model.

Future work

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- *Generalization to isotropic hardening or combined kinematic-isotropic hardening.*
- *Exact analytical formulas. (with F1302/F1303/F1304/F1305)*
- *Nonlinear hardening models, big deformations. (with F1308)*