Numerical simulation of a pyramid steel sheet formed by single point incremental forming using solid-shell finite elements

SheMet'13

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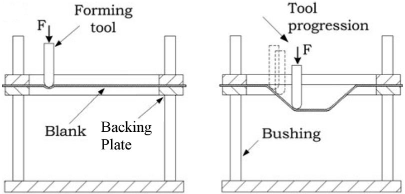
Single point incremental forming

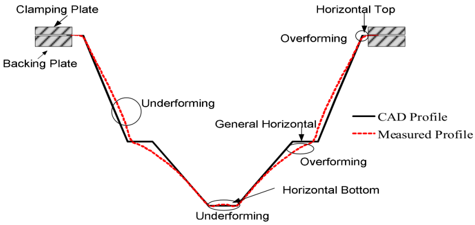
- A sheet metal is deformed by a small tool.
- The tool could be guided by a CNC (milling machine, robot).
- Dieless, with high sheet formability.
- For rapid prototypes, small batch productions, etc.



[Henrard et al., 2010]

Motivations

- Geometrical inaccuracy.
- Process mechanics.
- Increased formability.



[Behera et al., 2011]

Motivations

- Geometrical inaccuracy.
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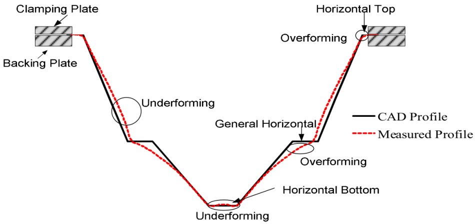
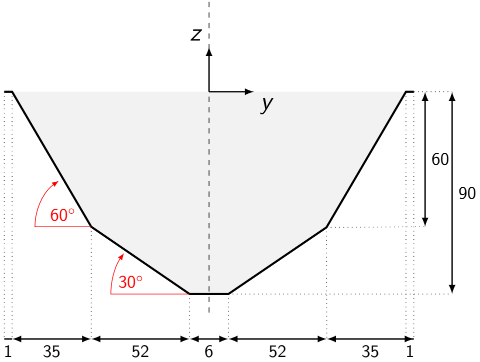
- Through the thickness gradient are important.
- 2D constitutive laws cannot be used.
- New advances on element formulation in FE codes.

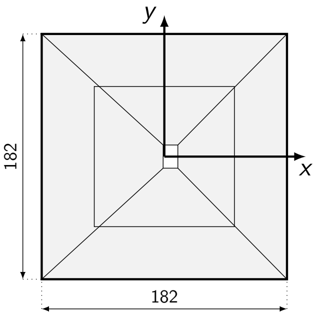


[Behera et al., 2011]

Simulations

- Material: DC01 ferritic steel (1 mm thickness).
- Two slope pyramid:





Constitutive modeling

- Isotropic elasto-plastic constitutive law.
- Voce and Armstrong-Frederick isotropic/kinematic hardening.

$$\sigma_Y = \sigma_{Y0} + K\left(1 - \exp\left(-n\epsilon^P\right)\right)$$

$$\dot{\mathbf{X}} = C_x\left(X_{sat}\dot{\boldsymbol{\epsilon}}^P - \dot{\epsilon}^P\mathbf{X}\right)$$

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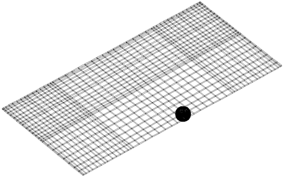
- Material parameters:

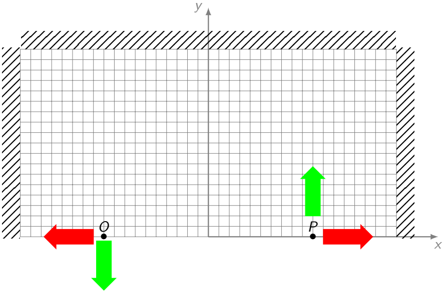
$$\begin{array}{lclllcl}
\sigma_{Y0} & = & 158\,\mathrm{MPa} & & C_x & = & 257 \\
K & = & 255\,\mathrm{MPa} & & X_{sat} & = & 4\,\mathrm{MPa} \\
n & = & 13 & & & &
\end{array}$$

- Identification through *classical* (tensile, monotonic/Bauschinger shear) tests.

Mesh and boundary conditions

- FE code: LAGAMINE.
- Displacement-controlled implicit simulation.
- One layer with 2248 (coarse) and 4282 (fine) elements.
- Symmetry and rotational boundary conditions:

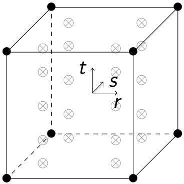




Solid-shell element

SSH3D

- Enhanced assumed strain (EAS).
- Assumed natural strain (ANS).
- In-plane full integration and 5 IP through-the-thickness.

Shell element $\longleftrightarrow$  $\longleftrightarrow$ *Brick element*

Solid-shell

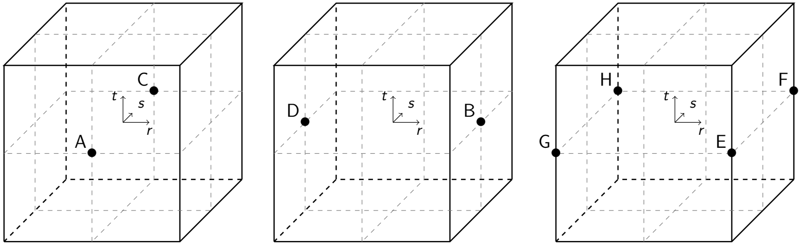
Assumed natural strain

$$\begin{tikzcd}
\mathbf{U} \arrow[r, "\mathbf{B}"] \arrow[dr, bend right, "\mathbf{B}^{ANS}"] & \boldsymbol{\epsilon}^{com} \arrow[d, "\text{linear interpolation}"] \\
& \boldsymbol{\epsilon}^{ANS}
\end{tikzcd}$$

Assumed natural strain

$$
\begin{tikzcd}
\mathbf{U} \arrow[r, "\mathbf{B}"] \arrow[dr, bend right, "\mathbf{B}^{ANS}"'] & \boldsymbol{\epsilon}^{com} \arrow[d, "\text{linear interpolation}"] \\
& \boldsymbol{\epsilon}^{ANS}
\end{tikzcd}
$$

Sampling points (transverse shear and transverse normal strains):



Enhanced assumed strain

Enhanced strain field

$$\boldsymbol{\epsilon} = \boldsymbol{\epsilon}^{com} + \boldsymbol{\epsilon}^{EAS}$$

$$\boldsymbol{\epsilon}^{com} = \Delta^{s}\mathbf{u} = \mathbf{B}(r, s, t)\mathbf{U}$$

$$\boldsymbol{\epsilon}^{EAS} = \mathbf{G}(r, s, t)\boldsymbol{\alpha} = \frac{|\mathrm{J}_0|}{|J(r, s, t)|}\mathbf{F}_0^{-T}\mathbf{M}(r, s, t)\boldsymbol{\alpha}$$

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$$[\mathbf{M}] =$$

$$\begin{bmatrix}
r & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & rs & rt & 0 & 0 & 0 & 0 & 0 & 0 & 0 & rst & 0 & 0 & 0 & 0 & 0 \\
0 & s & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & rs & st & 0 & 0 & 0 & 0 & 0 & 0 & rst & 0 & 0 & 0 & 0 \\
0 & 0 & t & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & rt & st & 0 & 0 & 0 & 0 & 0 & rst & 0 & 0 & 0 \\
0 & 0 & 0 & r & s & 0 & 0 & 0 & 0 & rt & st & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & rs & 0 & 0 & 0 & 0 & 0 & rst & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & r & t & 0 & 0 & 0 & 0 & rs & st & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & rt & 0 & 0 & 0 & 0 & 0 & rst & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & s & t & 0 & 0 & 0 & 0 & rs & rt & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & st & 0 & 0 & 0 & 0 & 0 & rst
\end{bmatrix}$$

03 EAS modes

Enhanced assumed strain

Enhanced strain field

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0 & 0 & 0 & r & s & 0 & 0 & 0 & 0 & rt & st & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & rs & 0 & 0 & 0 & 0 & 0 & rst & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & r & t & 0 & 0 & 0 & 0 & rs & st & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & rt & 0 & 0 & 0 & 0 & 0 & rst & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & s & t & 0 & 0 & 0 & 0 & rs & rt & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & st & 0 & 0 & 0 & 0 & 0 & rst
\end{bmatrix}$$

11 EAS modes

Enhanced assumed strain

Enhanced strain field

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$$\left[\begin{array}{cccccccccccccccccccccccccccccc}
r & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & rs & rt & 0 & 0 & 0 & 0 & 0 & 0 & 0 & rst & 0 & 0 & 0 & 0 & 0 \\
0 & s & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & rs & st & 0 & 0 & 0 & 0 & 0 & 0 & rst & 0 & 0 & 0 & 0 \\
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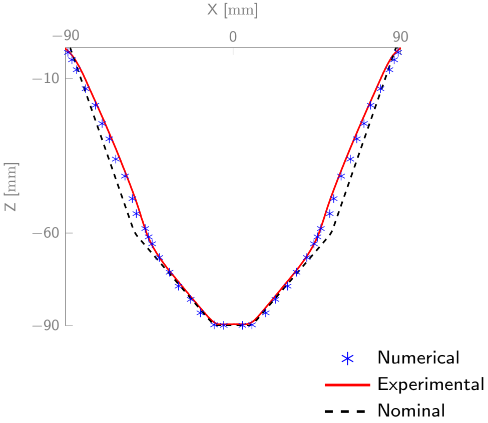
0 & 0 & 0 & r & s & 0 & 0 & 0 & 0 & rt & st & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & rs & 0 & 0 & 0 & 0 & 0 & rst & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & r & t & 0 & 0 & 0 & 0 & rs & st & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & rt & 0 & 0 & 0 & 0 & 0 & rst & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & s & t & 0 & 0 & 0 & 0 & rs & rt & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & st & 0 & 0 & 0 & 0 & 0 & rst
\end{array}\right]$$

24 EAS modes

Shape results

Numerical/experimental (DIC) comparison $Y = 0$



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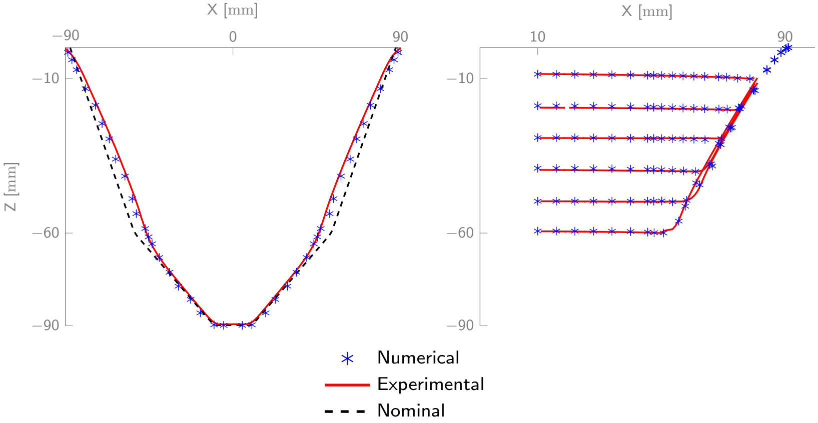

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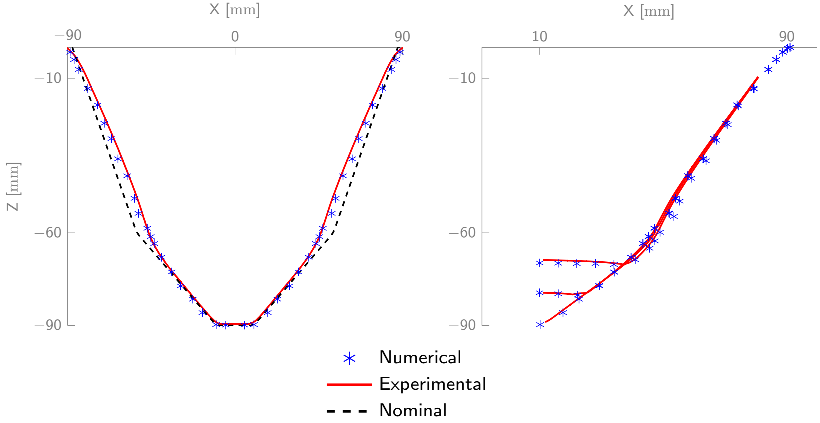
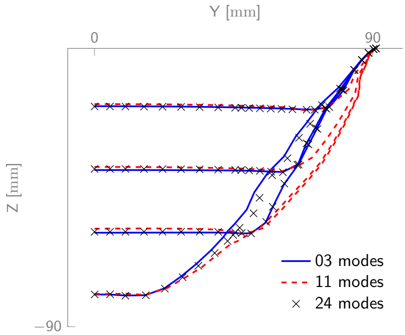
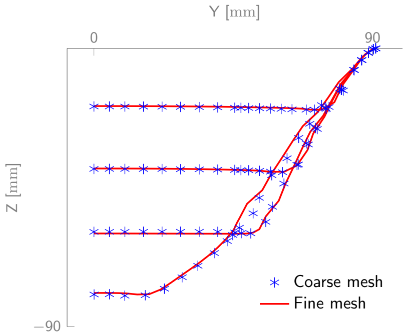


EAS and mesh influence

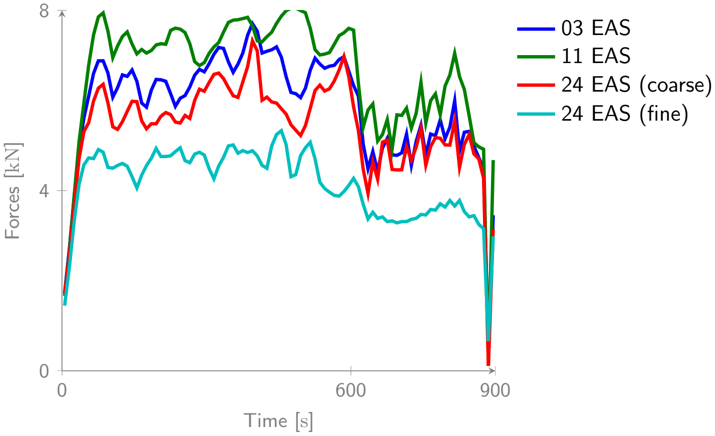
- Strong EAS mode influence.
- Small mesh influence.





Force evolution

- Both EAS modes and mesh influence.



Conclusions

- EAS modes influence the accuracy of the results.
- The elements are subjected to deformation modes reproduced only using the EAS technique.
- ANS version has no effect on both the shape and the force.
- Material identification procedure important.

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Future work

- Identify the most important EAS modes.
- Improve identification procedure to consider out-of-plane stresses.

Acknowledgments

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References

Behera, A. K., Vanhove, H., Lauwers, B., Duflou, J., Mar. 2011. Accuracy Improvement in Single Point Incremental Forming through Systematic Study of Feature Interactions. Key Engineering Materials 473, 881–888.

Henrard, C., Bouffioux, C., Eyckens, P., Sol, H., Duflou, J., van Houtte, P., Van Bael, A., Duchêne, L., Habraken, A. M., Dec. 2010. Forming forces in single point incremental forming: prediction by finite element simulations, validation and sensitivity. Computational Mechanics 47 (5), 573–590.