Accurate Single Point Incremental Forming Simulations using Solid-Shell Elements

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Presentation contents

1. Introduction
2. Simulations
3. Results
4. Conclusions
Single point incremental forming

- A sheet metal is deformed by a small tool.
- The tool could be guided by a CNC (milling machine, robot).

[Henrard et al., 2010]
Single point incremental forming

- **Dieless**, with high sheet formability.
- Easy shape generation.
- For rapid prototypes, small batch productions, etc.

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

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

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

![Diagram of a two slope pyramid with dimensions and angles indicated.]
Constitutive modeling

- Isotropic elasto-plastic constitutive law (HILL3D_KI.F).
- Voce and Armstrong-Frederick isotropic/kinematic hardening.

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

\[
\dot{X} = C_x \left( X_{sat}\dot{\epsilon}^P - \dot{\epsilon}^P X \right)
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\]

- Material parameters:

\[
\begin{align*}
\sigma_{Y0} & = 158 \text{ MPa} \\
K & = 255 \text{ MPa} \\
C_x & = 257 \\
X_{sat} & = 4 \text{ MPa} \\
n & = 13
\end{align*}
\]

- Identification through *classical* (tensile, monotonic/Bauschinger shear) tests (OPTIM).
Mesh and boundary conditions

- Displacement-controlled implicit simulation.
- One layer with 2248 elements.
- Symmetry and rotational boundary conditions (`BINDS.F`):
Solid-shell element

Formulation

- Large aspect ratios $\rightarrow$ locking
- Enhanced Assumed Strain (EAS)
- Assumed Natural Strain (ANS)

Shell element $\leftrightarrow$ Solid-shell $\leftrightarrow$ Brick element
Assumed natural strain

\[ \mathbf{U} \xrightarrow{\mathbf{B}} \varepsilon^{\text{com}} \]

\[ \mathbf{B}^{\text{ANS}} \]

\[ \varepsilon^{\text{ANS}} \xrightarrow{\text{linear interpolation}} \]

Sampling points (transverse shear and transverse normal strains):
Assumed natural strain

\[ U \xrightarrow{B} \epsilon_{\text{com}} \]

Linear interpolation

\[ B^{\text{ANS}} \]

\[ \epsilon_{\text{ANS}} \]

Sampling points (transverse shear and transverse normal strains):

\[ A \rightarrow C \rightarrow B \rightarrow E \rightarrow F \]

\[ D \rightarrow G \rightarrow H \]

\[ s \rightarrow t \rightarrow r \]
Enhanced assumed strain

\[ \epsilon = \epsilon^{com} + \epsilon^{EAS} \]

\[ \epsilon^{com} = \Delta^s u = B(r, s, t)U \]

\[ \epsilon^{EAS} = G(r, s, t)\alpha = \frac{|J_0|}{|J(r, s, t)|} F_0^{-T} M(r, s, t)\alpha \]
Enhanced assumed strain

Enhanced strain field

\[ \epsilon = \epsilon^{\text{com}} + \epsilon^{\text{EAS}} \]

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\[ [M] = \]

03 EAS modes
Enhanced assumed strain

\[ \epsilon = \epsilon^{\text{com}} + \epsilon^{\text{EAS}} \]

\[ \epsilon^{\text{com}} = \Delta^s u = B(r, s, t)U \]

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11 EAS modes
## Enhanced assumed strain

### Enhanced strain field

\[
\epsilon = \epsilon^{\text{com}} + \epsilon^{\text{EAS}}
\]

\[
\epsilon^{\text{com}} = \Delta^s u = B(r, s, t)U
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\epsilon^{\text{EAS}} = G(r, s, t)\alpha = \frac{|J_0|}{|J(r, s, t)|} F_0^{-T} M(r, s, t)\alpha
\]

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

24 EAS modes
Solid-shell element... in LAGAMINE

- Enhanced Assumed Strain (EAS) modes: 24
- Assumed Natural Strain (ANS) version: 4
- In-plane integration: full
- Stabilization technique: reduced* Yes

SSH3D.F

RESS3.F
Running simulations

Not easy...

- Complex toolpath and small contact zone.
- Several time increments.
- Simulations can take **weeks**.
Running simulations

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- Several time increments.
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### NIC machine

- Near 1000 cores and 5 Tb memory.
- LAGAMINE (and PREPRO) compiled in Linux.
- Possibility of using other machines (Lemaître-UCL,...)
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Shape results

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

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

![Graph showing numerical, experimental, and nominal results for Y = 0.](image)

- **Numerical**
- **Experimental**
- **Nominal**
Numerical/experimental (DIC) comparison $Y = 0$
EAS and mesh influence

- Strong EAS mode influence.
- Small mesh influence.
Force evolution

- Both EAS modes and mesh influence.

![Graph showing force evolution over time for different EAS modes and mesh settings. The x-axis represents time in seconds (0-900), and the y-axis represents forces in kN. The graph includes lines for 03 EAS, 11 EAS, 24 EAS (coarse), and 24 EAS (fine).]
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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.
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.

Future work

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