Simulation of Sheet Metal Forming using Solid Elements in LS-DYNA

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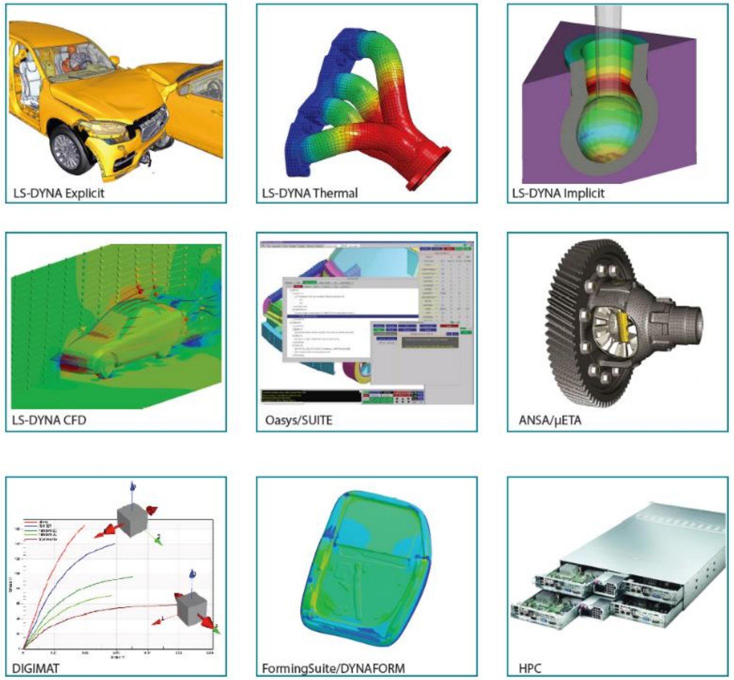
Contact – DYNAmore Nordic



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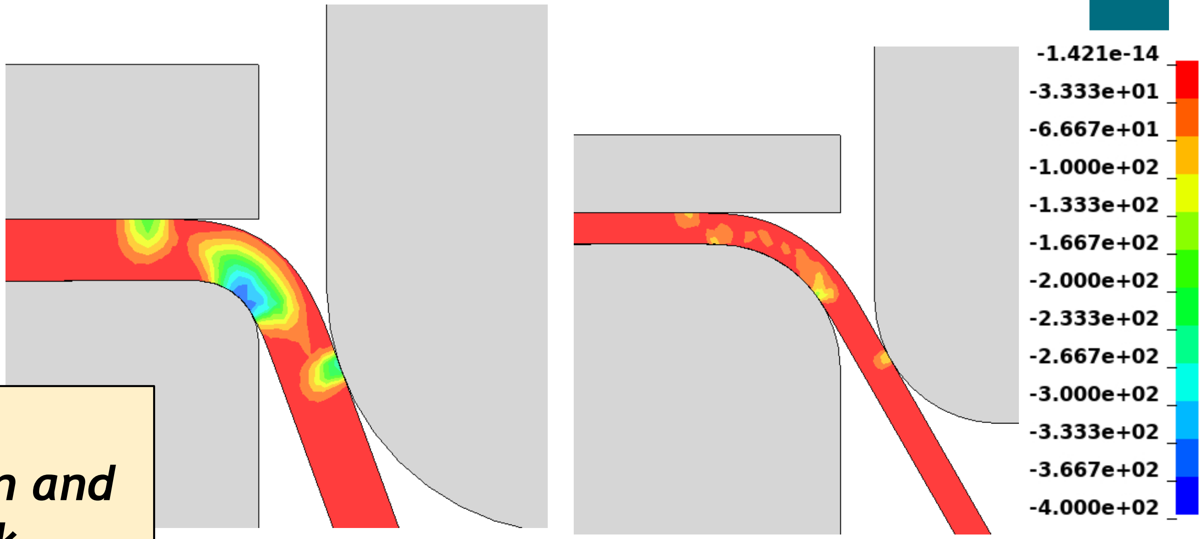
Agenda

- Motivation
  - Why go for solids?
  - What are the obvious hurdles?
- Model specifics for solid elements
  - Element type
  - Contacts
  - Mass Scaling
- Material models for solid elements
  - Hill
  - YLD 2000
- Sheet metal forming specifics
  - Trimming
- Preprocess
  - Dynaform
  - LS-PREPOST
- Postprocessing
  - Thinning
  - FLD

Why go for solids?

- Plane stress condition is not applicable
  - Decreasing radii introduces stresses in the thickness direction



Remember!
A thick sheet can be thin and a thin sheet can be thick.

Why go for solids?

- Plane stress condition is not applicable
  - Decreasing radii introduces stresses in the thickness direction
- Stretch/bend relation is low, ironing
  - Thickness changes are caused by membrane straining for shells

***CONTROL_SHELL**

Purpose: Provide controls for computing shell response.

Card Summary:

Card 1. This card is required.

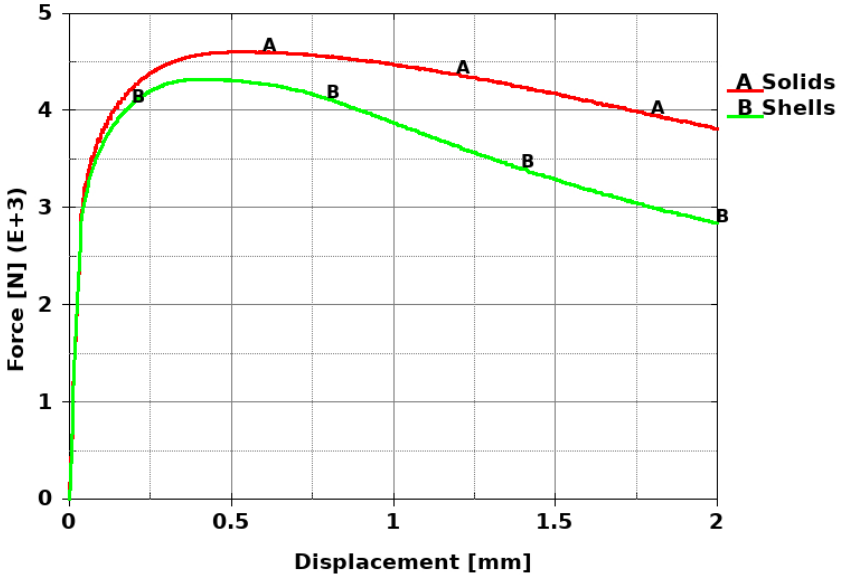
WRPANG	ESORT	IRNXX	ISTUPD	THEORY	BWC	MITER	PROJ

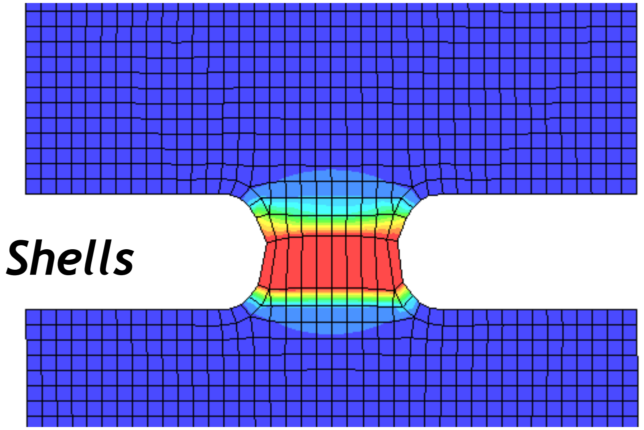
Card 2. This card and all the following cards are optional.

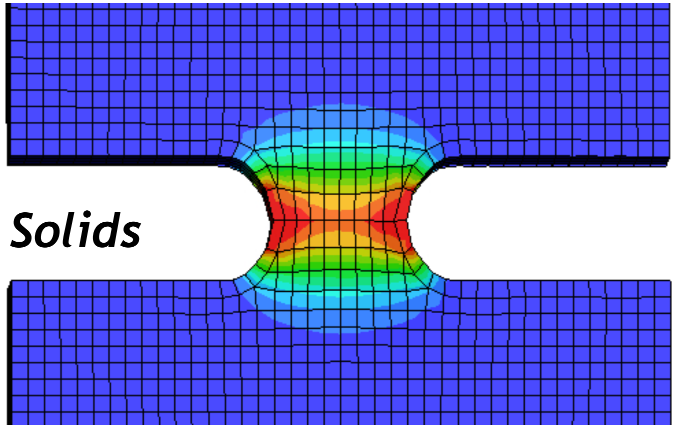
ROTASCL	INTGRD	LAMSHT	CSTYP6	THSHEL			

Why go for solids?

- Plane stress condition is not applicable
  - Decreasing radii introduces stresses in the thickness direction
- Stretch/bend relation is low, ironing
  - Thickness changes are caused by membrane straining for shells
- Failure modelling
  - Localisation through the thickness generates a 3D stress state.







What are the obvious hurdles?

- Timestep
  - Need to discretize the thickness
- Number of elements
  - The model size increases ***#elements_through_the_thickness*** times
- Possibility to timescale/masscale
  - Masscaling in % to meet 0.5 e-6 s of timestep

Shell	Solid
1.67e-7	5.6e-8

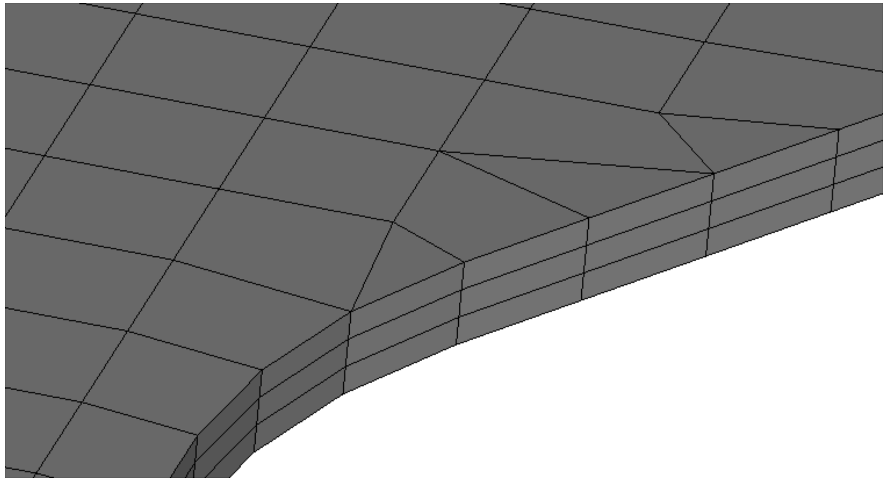
Timestep 2mm thickness steel sheet with 5 intp. through the thickness

Shell	Solid
500 %	840 %

Mass scaling to meet 0.5e-6 s timestep

Model specifics when using Solid Elements – Element type

- Element type
  - Elements are easily created by element extrusion
    - 4 node shell becomes 8 node Hex
    - 3 node triangles becomes 6 node Pentas
- Use Underintegrated constant stress element type 1 for forming
  - If fully integrated element is used during forming use -1/-2 to avoid shear locking for bad aspect ratio elements
- Use Fully integrated element type 2 for springback
- Use **ESORT=1** on ***CONTROL_SOLID** to automatically sort elements



***CONTROL_SOLID**

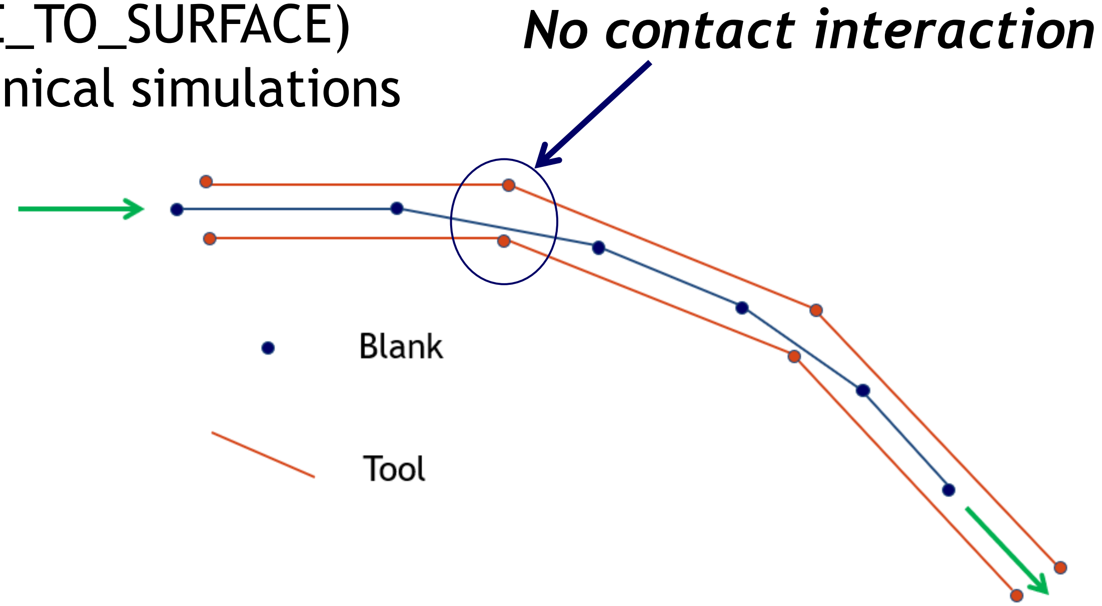
VARIABLE	DESCRIPTION
ESORT	Automatic sorting of tetrahedral and pentahedral elements to avoid use of degenerate formulations for these shapes. See *SECTION_SOLID. EQ.0: No sorting (default) EQ.1: Sort tetrahedron to type 10; pentahedron to type 15; cohesive pentahedron types 19 and 20 to types 21 and 22, respectively.

Model specifics when using Solid Elements – Contacts

Contact interfaces for forming in 3D:

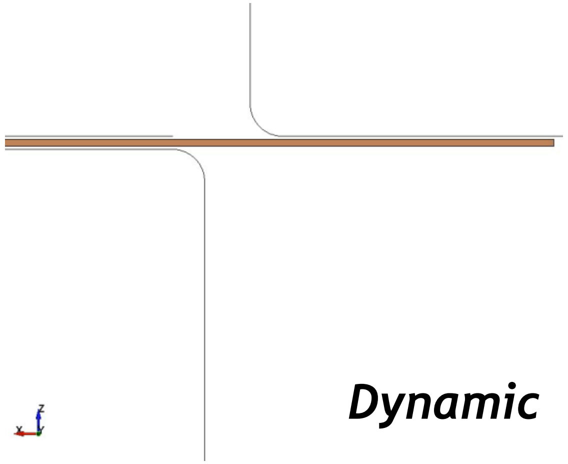
- *CONTACT_FORMING_NODES_TO_SURFACE
- *CONTACT_FORMING_ONE_WAY_SURFACE_TO_SURFACE

- Tools are on the master side
- Blank is the slave side
- Master side thickness disabled
- .._ONE_WAY_ is unsymmetric contact (NODE_TO_SURFACE) that can be used for coupled thermo-mechanical simulations
- If blank self contacts:
  - *CONTACT_AUTOMATIC_SINGLE_SURFACE

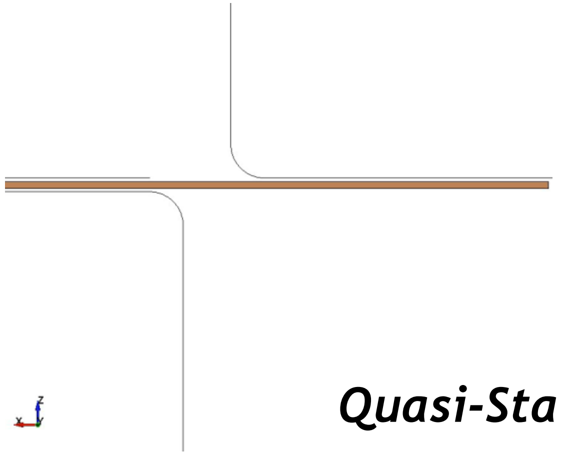


Model specifics when using Solid Elements – Mass and timescaling

- Shorter simulation time is obtained by either of:
  - Increasing the tool movement velocity ⇒ Timescaling
  - Increasing the mass of deformable parts ⇒ Masscaling
- These two “solutions” are equivalent. Both reduces CPU-time while increasing dynamic effects
  - Check your internal/kinetic energy ratio
  - Check the overall behaviour. Does the behaviour look dynamic?
  - Convergence check



Dynamic

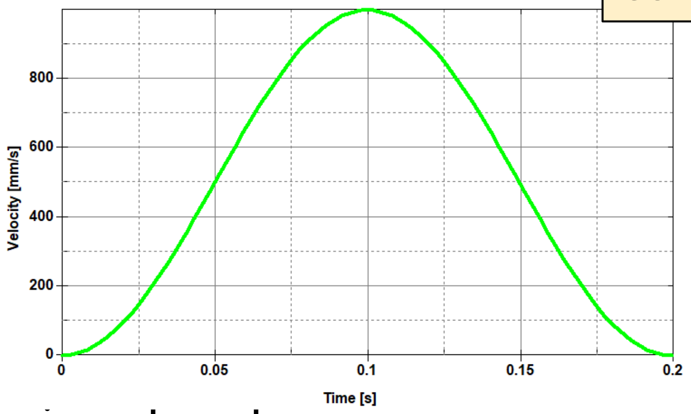


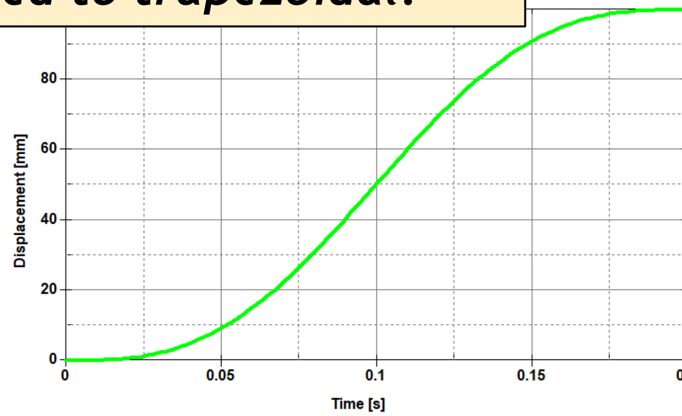
Quasi-Static

Model specifics when using Solid Elements – Mass and timescaling

- How to get rid of dynamics
  - Make sure the tools are not hitting the blank in full speed
  - Use “Smooth” tool velocity curves
  - Decrease the maximum speed
  - Reduce masscaling
  - Switch to selective masscaling
    - Masscaling effect on rigid body motion is reduced
    - Selective mass- scaling is CPU intensive

Doubles the termination time compared to trapezoidal!





*CONTROL_TIMESTEP (1)

1	DTINIT	TSSFAC	ISDO	TSLIMT	DT2MS	LCTM	ERODE
	0.0	0.9000000	0	0.0	-2.200e-06	0	0
2	DT2MSF	DT2MSLC	IMSCL	UNUSED	UNUSED	RMSCL	
	0.0	0	1	0	0	0.0	

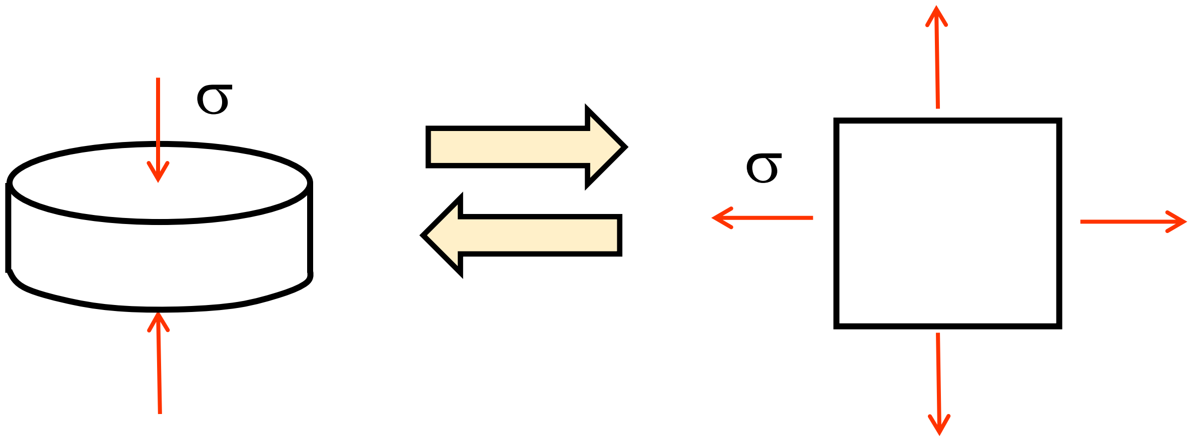
IMSCL=1: Activates selective mass-scaling
IMSL < 0: |IMSCL| is a `*SET_PART` that will undergo selective mass-scaling

Material models for SMF with solid elements

- Two variants will be presented
  - *MAT_103/*MAT_ANISOTROPIC_VISCOPLASTIC – Hill yield criterion
  - *MAT_133/*MAT_BARLAT_YLD2000 – Barlat YLD 2000 yield criterion
- Both include
  - Isotropic elasticity
  - Anisotropic plasticity
  - Optional kinematic hardening
  - Explicit for forming simulation and Implicit for springback
- Other options of material models exist
  - *MAT_33 – 6 parameter Barlat criteria
  - *MAT_122_3D – Hill yield criteria with orthotropic elasticity
  - *MAT_125 – Transversely anisotropic Hill criteria with Ushida Uemori kinematic hardening
  - *MAT_199 – YLD2004 Barlat criteria with up to 18 parameters
  - …

Material parameter identification

- Fully 3D stress formulated Yield criteria require material data in the through thickness direction
- Although the sheet is considered to be “thick”, such data is generally not available.
  - Use in-plane tensile test data (with assumptions)
  - Inverse modeling
  - Additional test e.g. layered compression/biaxial



$$s_{ij} = \frac{\sigma}{3}\begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & -2 \end{bmatrix}$$

Material models for solid elements - *MAT_103/*MAT_ANISOTROPIC_VISCOPLASTIC

- Hill 48 Yield criterion

$$F(\sigma_{22}-\sigma_{33})^2+G(\sigma_{33}-\sigma_{11})^2+H(\sigma_{11}-\sigma_{22})^2+2L\sigma_{23}^2+2M\sigma_{31}^2+2N\sigma_{12}^2=\sigma_f^2$$

$$F=G=H=\frac{1}{2}\text{ and }L=M=N=\frac{3}{2}\text{ yields isotropic yield criteria}$$

- Isotropic/kinematic mixture hardening with parameter **alpha**
  - 0 is pure kinematic and 1 is pure isotropic
- Hardening input by load curve or table(viscoplastic)

Material models for solid elements - *MAT_103/*MAT_ANISOTROPIC_VISCOPLASTIC

σ_{00}	σ_{45}	σ_{90}	R_{00}	R_{45}	R_{90}	σ_b	R_b
45	40	50	0.8	1	1.2	55	0.9

$$F(\sigma_{22}-\sigma_{33})^2+G(\sigma_{33}-\sigma_{11})^2+H(\sigma_{11}-\sigma_{22})^2+2L\sigma_{23}^2+2M\sigma_{31}^2+2N\sigma_{12}^2=\sigma_f^2$$

Solving for stresses

$\boldsymbol{\sigma_{00}}$: $G+H=\left(\frac{\sigma_f}{\sigma_{00}}\right)^2$

$\boldsymbol{\sigma_{45}}$: $F+G+2N=\left(\frac{\sigma_f}{\sigma_{45}}\right)^2$

$\boldsymbol{\sigma_{90}}$: $F+H=\left(\frac{\sigma_f}{\sigma_{90}}\right)^2$

$\boldsymbol{\sigma_b}$: $F+G=\left(\frac{\sigma_f}{\sigma_b}\right)^2$

No description for L and M

Biaxial test gives no additional information

Solving for R values

$\boldsymbol{R_{00}}$: $\frac{H}{G}=R_{00}$

$\boldsymbol{R_{45}}$: $\frac{G+F-2N}{-2G-2F}=R_{45}$

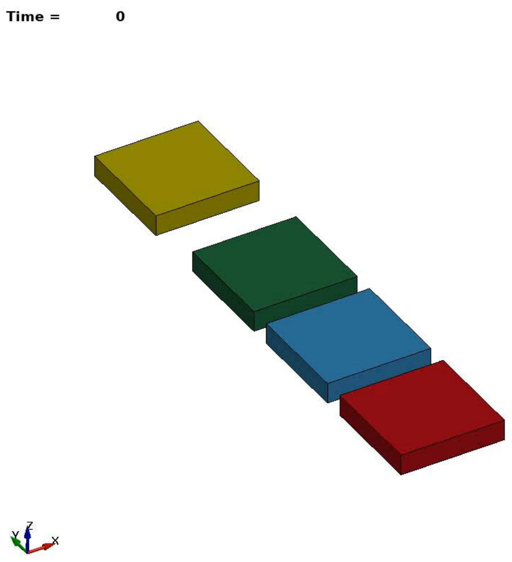
$\boldsymbol{R_{90}}$: $\frac{H}{F}=R_{90}$

$\boldsymbol{R_b}$: $\frac{G}{F}=R_b$

Material models for solid elements – *MAT_103/*MAT_ANISOTROPIC_VISCOPLASTIC

σ_{00}	σ_{45}	σ_{90}	R_{00}	R_{45}	R_{90}	σ_b	R_b
45	40	50	0.8	1	1.2	55	0.9

- Choosing σ_{00} as reference direction yields F=0.37, G=0.555, H=0.444, L=1.5, M=1.5, N=1.3888



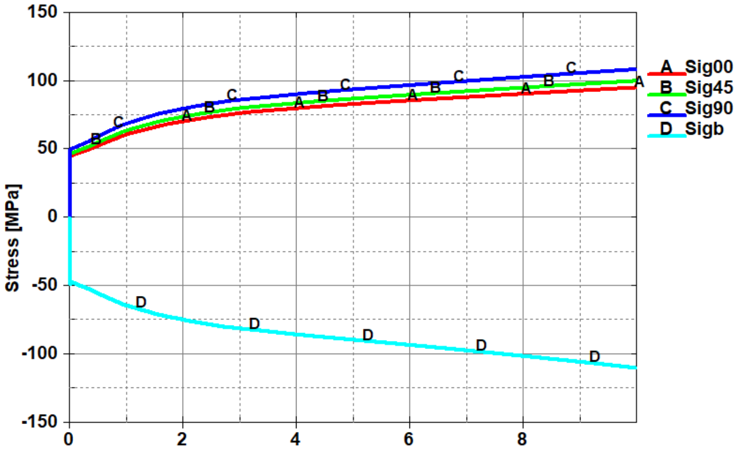
Solving for stresses

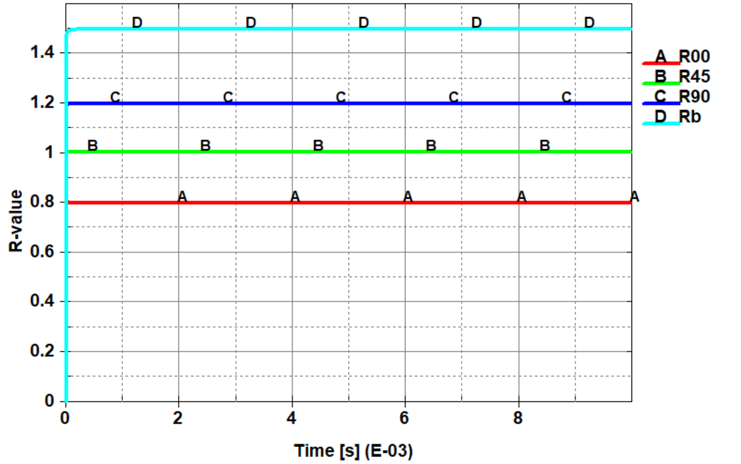
From tests

$$\sigma_{00} = 45$$
$$R_{00} = 0.8$$
$$R_{45} = 1.0$$
$$R_{90} = 1.2$$

From Hill

$$\sigma_{45} = 46.8$$
$$\sigma_{90} = 50.$$
$$\sigma_b = 46.8$$
$$R_b = 1.5$$





Material models for solid elements – `*MAT_133/*MAT_BARLAT_YLD2000`

- Published by Barlat et. Al 2003

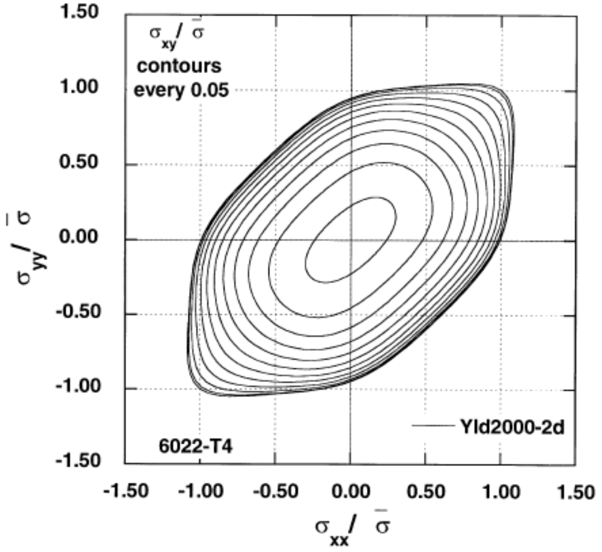
(Barlat et. al. 2003, Plane stress yield function for aluminium alloy sheets - Part 1:Theory)

$$\Phi' + \Phi'' = 2(\bar{\sigma})^a$$

$$where \quad \Phi' = |X_1' - X_2'|^a \qquad \Phi'' = |2X_2'' + X_1''|^a + |2X_1'' + X_2''|^a$$

$$and \quad X' = L's \qquad X'' = L''s$$

F. Barlat et al. / International Journal of Plasticity 19 (2003) 1297–1319




```
Fit to Barlat yld2000-2d material ID= 4

  Alpha_1=    0.7492E+00
  Alpha_2=    0.1275E+01
  Alpha_3=    0.6707E+00
  Alpha_4=    0.9731E+00
  Alpha_5=    0.9583E+00
  Alpha_6=    0.6864E+00
  Alpha_7=    0.8739E+00
  Alpha_8=    0.8523E+00

Comparison of test data with fit for material ID= 4

  Yield stress in 00 direction:
    Test data=   0.4339E+02 Fitted data=   0.4339E+02
  Yield stress in 45 direction:
    Test data=   0.4987E+02 Fitted data=   0.4987E+02
  Yield stress in 90 direction:
    Test data=   0.3990E+02 Fitted data=   0.3990E+02
  R-value in 00 direction:
    Test data=   0.8000E+00 Fitted data=   0.8000E+00
  R-value in 45 direction:
    Test data=   0.1100E+01 Fitted data=   0.1100E+01
  R-value in 90 direction:
    Test data=   0.1200E+01 Fitted data=   0.1200E+01
```

- Formulated with 8 unknown parameters which can be reduced to 6 or 7 anisotropy parameters by assuming symmetry in the linear transformation matrices.
- Can be used for thermo- mechanical simulations with temperature dependent anisotropy parameters.
- Material parameter identification in the material model.
- Isotropic/kinematic mixture hardening with parameter **`beta`**
  - 0 is pure isotropic and 1 is pure kinematic
- Kinematic hardening according to Chaboche-Roussilier
- Hardening input through load curve, table (viscoplastic) or 3D table (temperature dependent and viscoplastic)

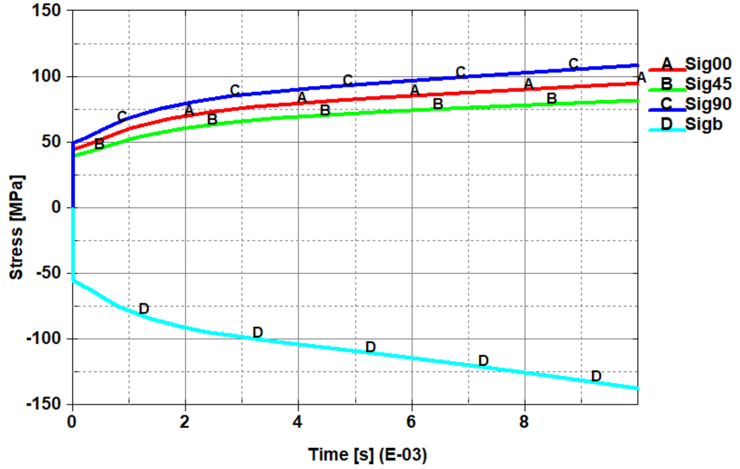
Generalizing to 3D - **`*MAT_133/*MAT_BARLAT_YLD2000`**

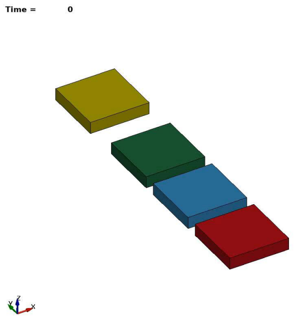
- From R12, **`*MAT_133`** is extended to 3D according to Dunand et al. 2012 – Experiments and modeling of anisotropic aluminium extrusions under multi-axial loading – Part 1: Plasticity.
- Keeping the original α_1 - α_8 and adding α_9 - α_{12} for the out of plane shear stresses.
- Utilizing $s'_{zz} = -\left(s'_{xx} + s'_{yy}\right)$ and $s''_{zz} = -\left(s''_{xx} + s''_{yy}\right)$ and assuming symmetry with respect to x, y and z is possible to reduce the transformations to 8 parameters.
- Formulation properties:
  - Reduces to YLD 2000 2d for the plane stress case.
  - For plane stress calibration, the anisotropic parameters are the same.
  - It is convex
  - Pressure independent
  - It does not reduce to an isotropic function for α_i = 1. except for the plane stress case.

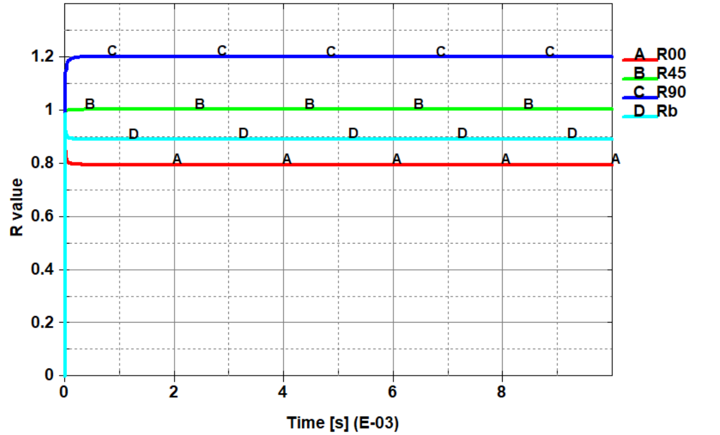
Material models for solid elements – ***MAT_133/*MAT_BARLAT_YLD2000**

σ_{00}	σ_{45}	σ_{90}	R_{00}	R_{45}	R_{90}	σ_b	R_b
45	40	50	0.8	1	1.2	55	0.9

```
*MAT_BARLAT_YLD2000
$#     mid        ro         e        pr       fit      beta      iter    iscale
          17.80000E-9  210000.0       0.3       1.0       0.0       0.0       0.0
$#       k        e0         n         c         p      hard         a
       0.0       0.0       0.0       0.0       0.0        -2       8.0
$#   sig00     sig45     sig90       r00       r45       r90
      45.0      40.0      50.0       0.8       1.0       1.2
$#   sigxx     sigyy     sigxy       dxx       dyy       dxy
      55.0      55.0       0.0       1.0      -0.9       0.0
$#    aopt    offang        p4    htflag       hta       htb       htc       htd
       0.0       0.0       0.0         0         0         0         0         0
$#    null      null      null        a1        a2        a3
       0.0       0.0       0.0       0.0       0.0       0.0
$#      v1        v2        v3        d1        d2        d3   usrfail
       0.0       0.0       0.0       0.0       0.0       0.0         0
```



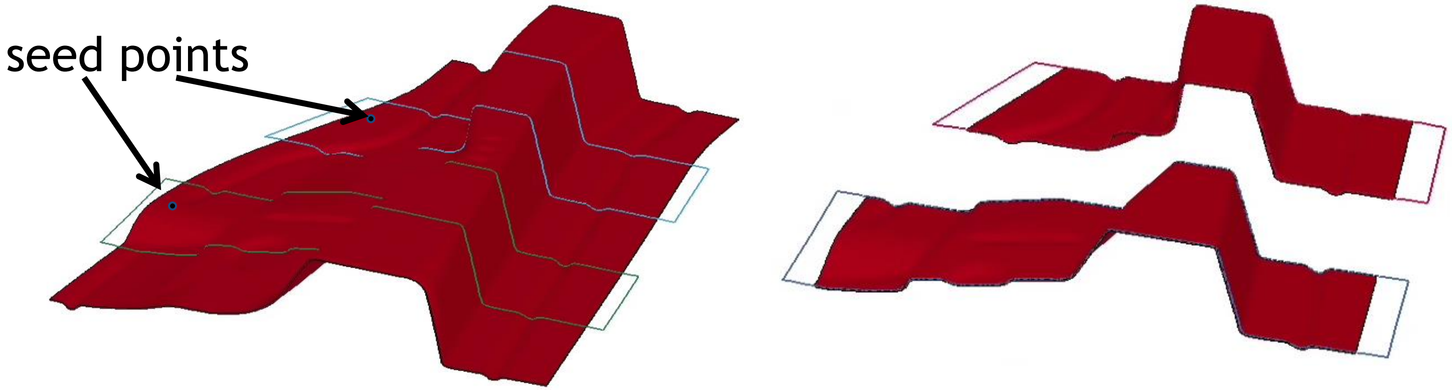




Sheet metal forming specifics - Trimming

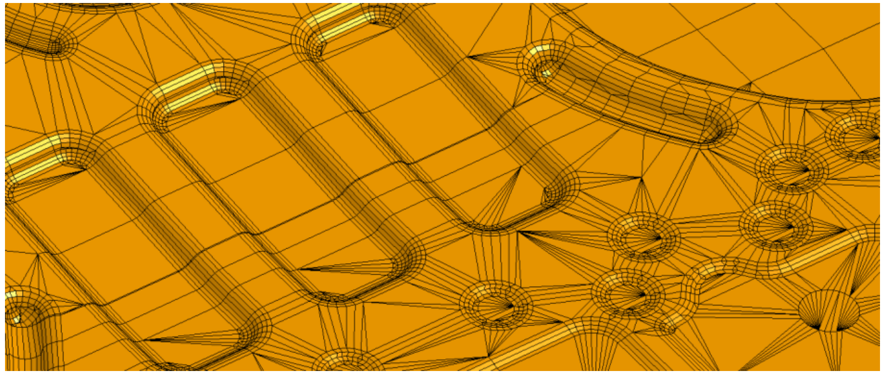
- Trimming is done as usual with ***DEFINE_CURVE_TRIM_NEW** for 2D trim and ***DEFINE_CURVE_TRIM_3D** for laser cutting.
- Parts to be trimmed are defined in ***ELEMENT_TRIM**
- If necessary, seed points are defined using ***DEFINE_TRIM_SEED_POINT_COORDINATES**
- Adaptive refinement along the trim curve is not available

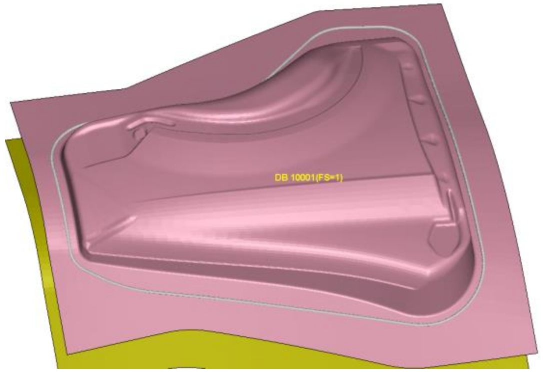
	2D (along one direction)	3D (element normal)	2D & 3D Double Trim	Adaptive mesh
Shell	Yes	Yes	Yes	Yes
Solids	Yes	Yes	Yes	N/A

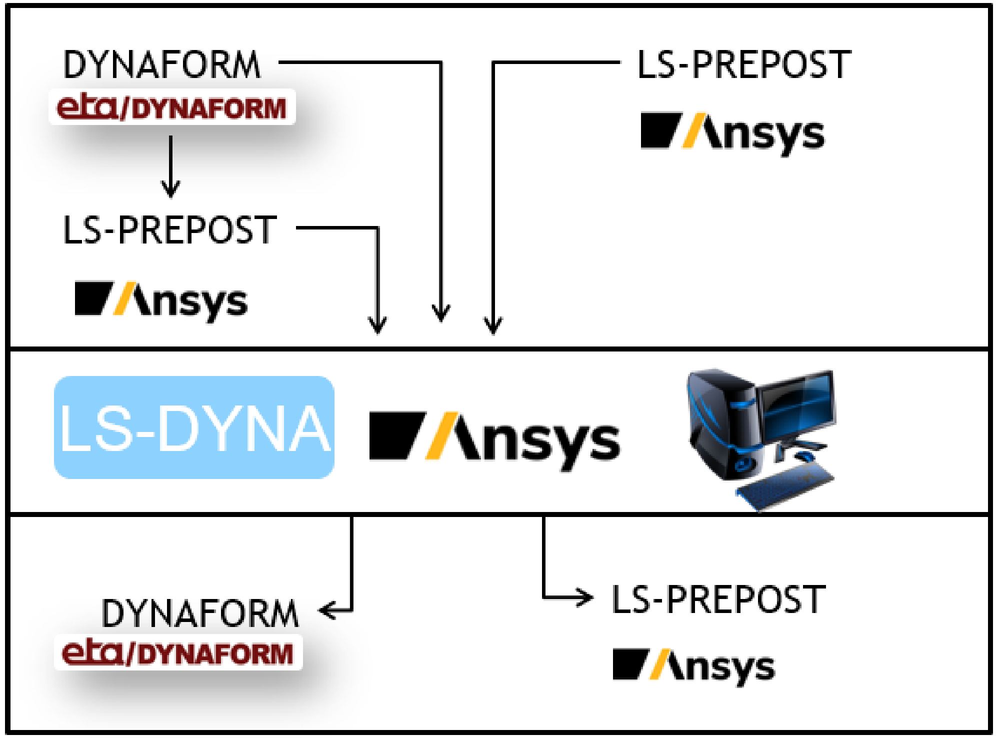


Preprocessing General

- Tools modeled as rigid using shells
  - IGES/STEP
  - Outer surfaces
- Tool movement
  - Tailored pre- processors
- Blankholder force
  - Constant
  - Gas/Coil springs
- Contacts with friction
- Drawbeads
  - Analytical/Physical

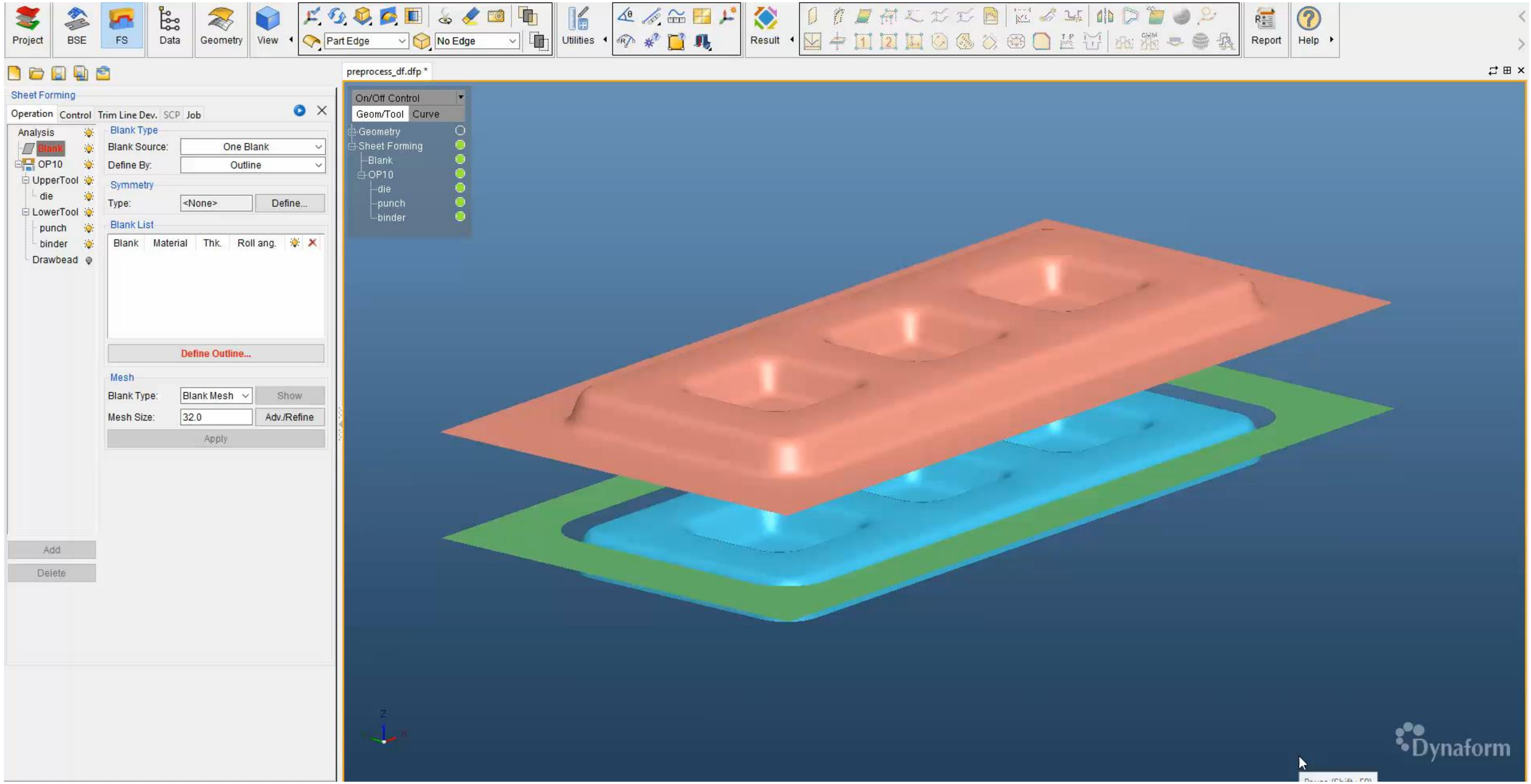






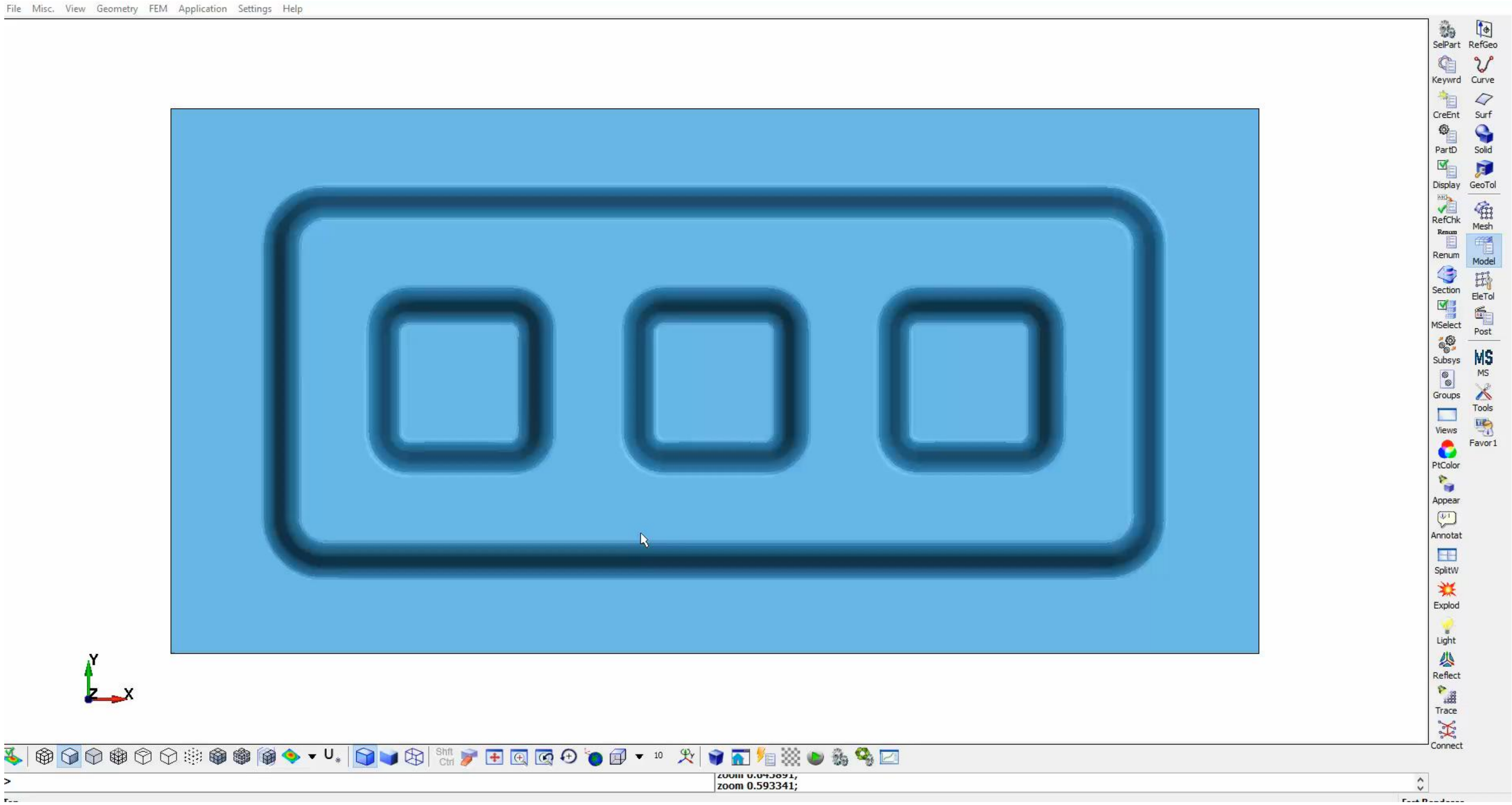
Pre- processing - Dynaform

- In Dynaform, using shells or solids is seamless.



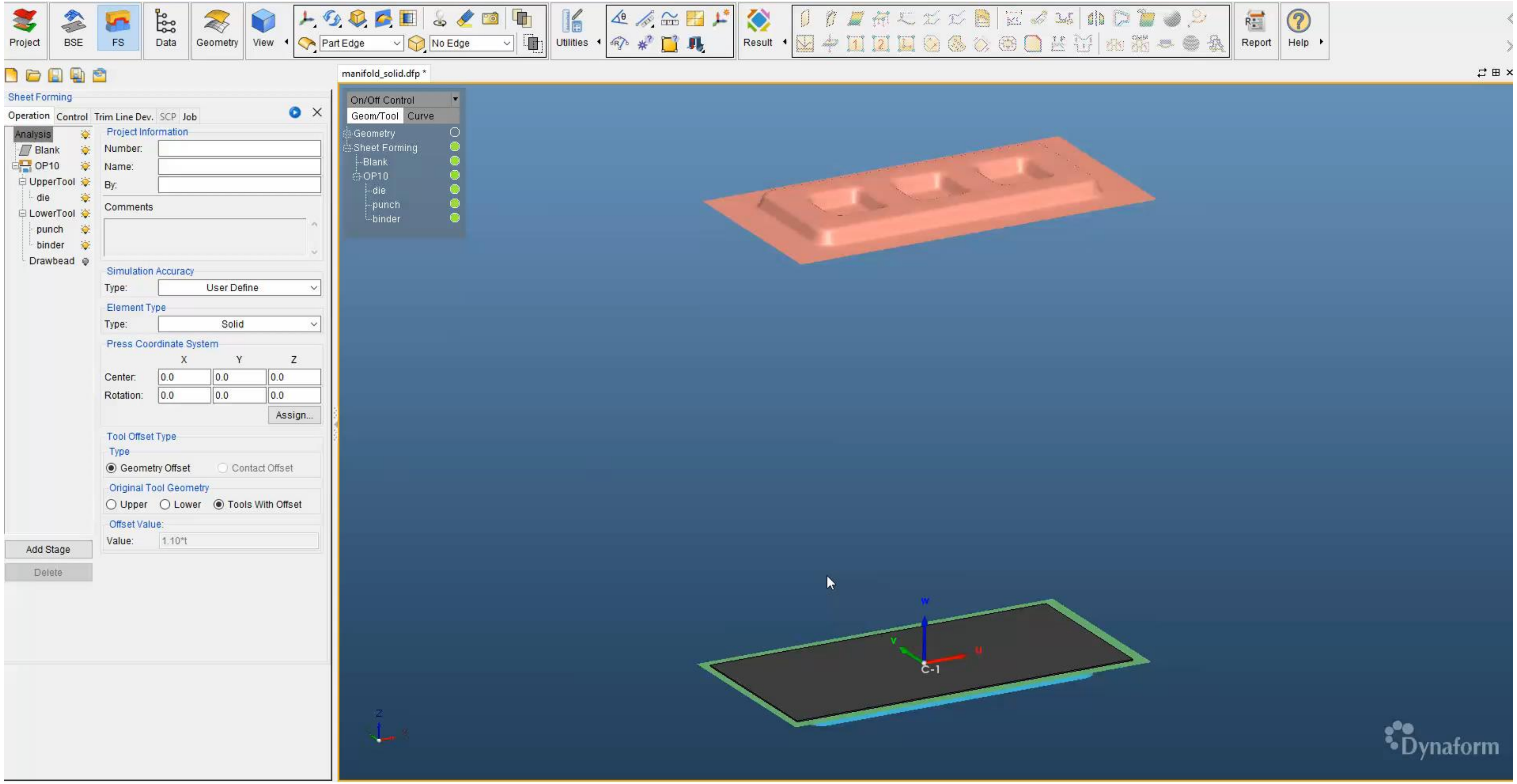
Pre- processing – LS-PREPOST

- Using LS-PREPOST (or similar) is less tailored, but parameterization can reduce manual work substantially.



Postprocessing - Dynaform

- Postprocessing is done in the same way for shells and solids



Postprocessing – LS-PREPOST

- To be able to fringe plot the thickness and FLD, LS-PREPOST needs information on what is the top and bottom surface.
- This is done using the novel keyword ***DEFINE_FORMING_SOLID_SURFACE** where the upper and lower surfaces of the blank is identified by ***SET_SEGMENT**
- The keyword is implemented in LS-DYNA from version R13 and v4.9 of LS-PREPOST.
- The keyword file need to be imported into the postprocessing session.

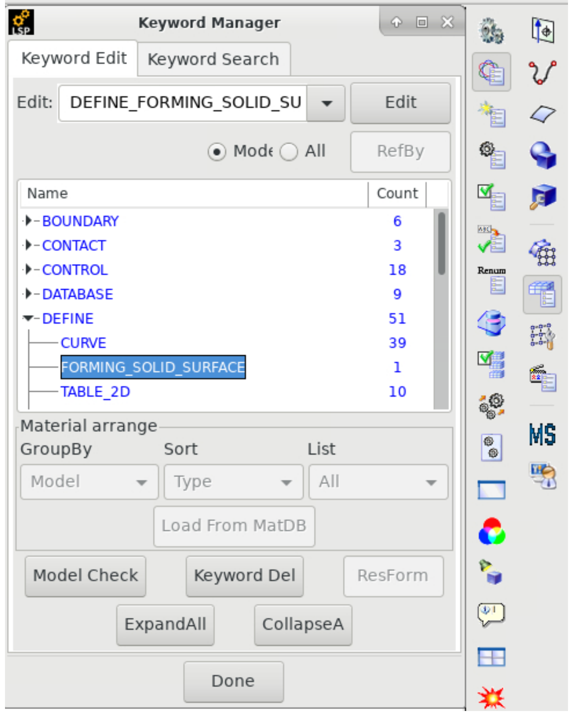
```
*DEFINE_FORMING_SOLID_SURFACE
$#      spid   ssetlow   ssetupp
           1         4         3
```

Surface pair ID

Upper and lower surface segment sets

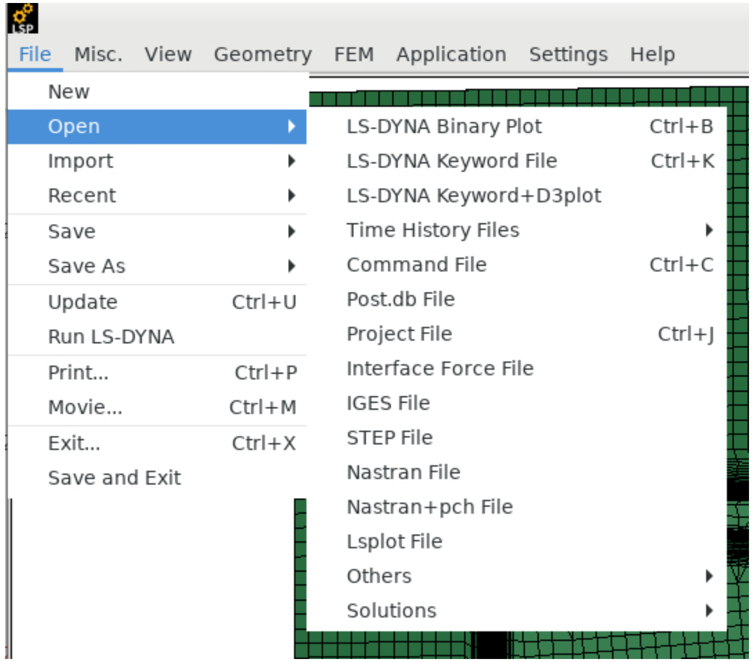
Postprocessing – LS-PREPOST

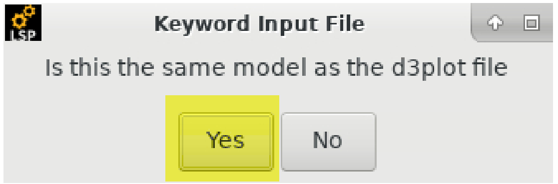
Define upper and lower surface segment sets



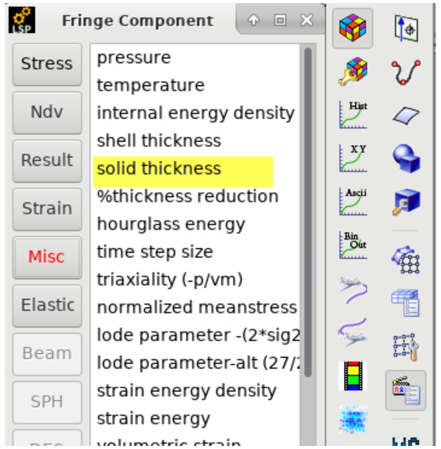
NOTE! This can be done after the simulation is done!

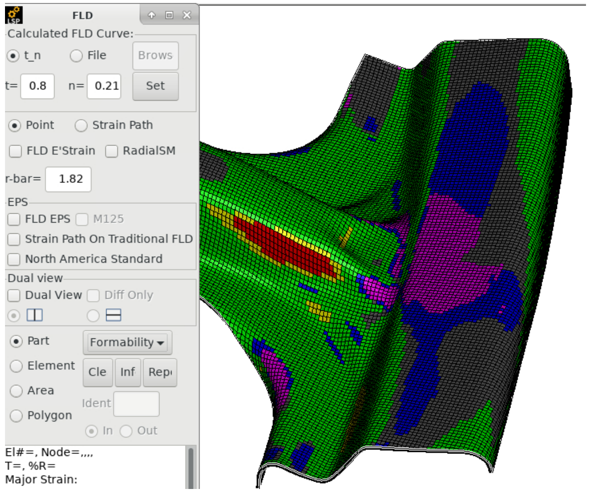
Open the keyword file in the postprocessing session



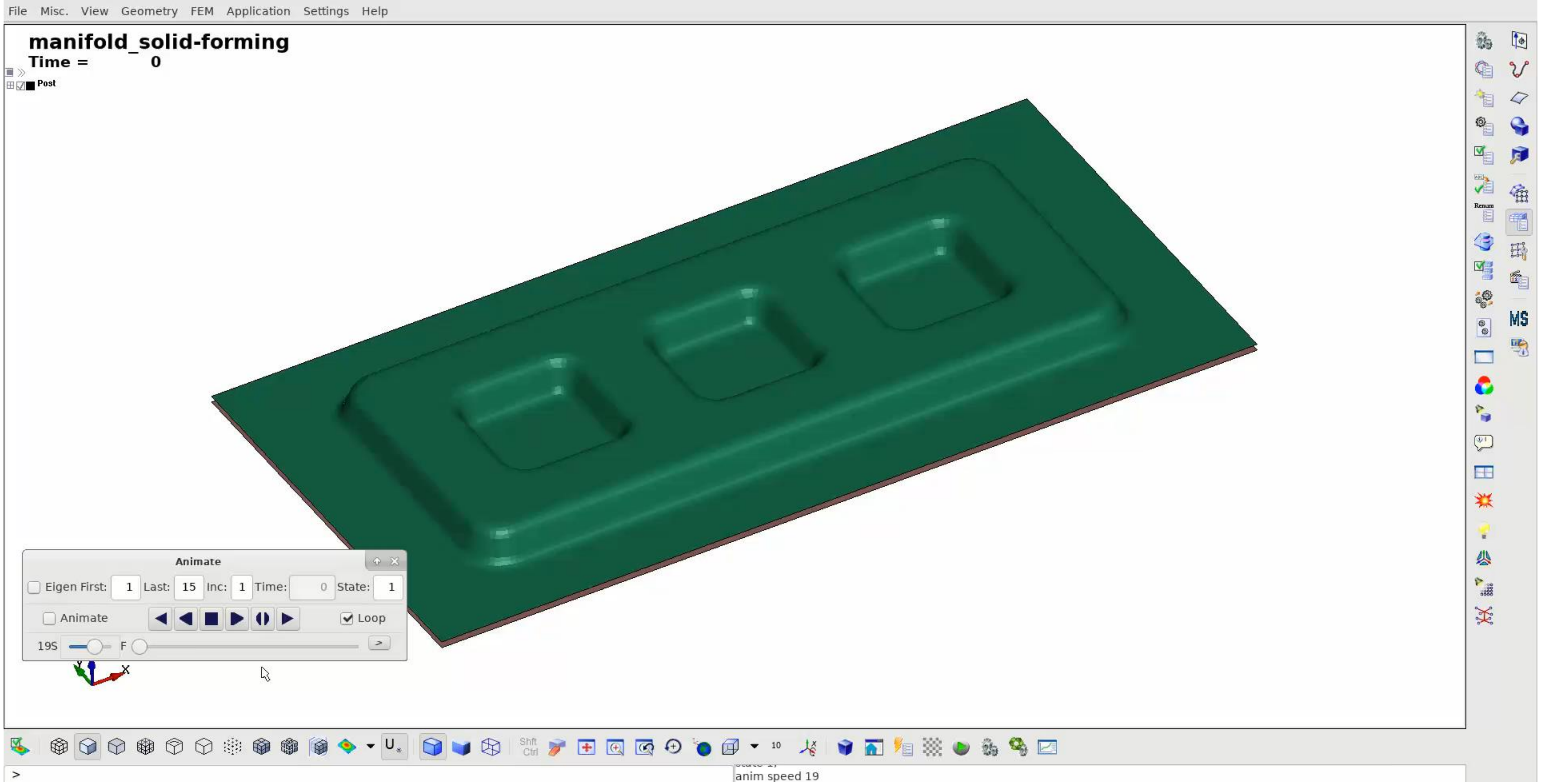


Plot solid thickness and FLD





Postprocessing – LS-PREPOST



Conclusion

- Solid elements is necessary if the plane stress condition does not apply or where the thinning is not correctly described by the membrane strains.
- The challenges with using solid elements is the increase in model size and the reduction in timestep.
- The basic setup is the same as with shells regarding boundary conditions, contacts, element types and constraints.
- The material models need to be formulated in 3D. Here, finding material parameters through the thickness can be an issue.
- LS-DYNA has several suitable material models, but YLD2000 has a very convenient formulation where the input is the same as for the plane stress case.
- Preprocessing can be done by “any” preprocessor but tailored software makes it a lot easier.
- Evaluating blank thickness and FLD with solids in LS-PREPOST are accomplished using the novel keyword **`*DEFINE_FORMING_SOLID_SURFACE`**.

Thank you!

Your LS-DYNA distributor and more