

Advances in LS-DYNA® for Metal Forming (II)

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Abstract

The following will be discussed:

- New features in state output with `*CONTROL_FORMING_OUTPUT`
- Automatic change from shell to thick shell elements with `*CONTROL_FORMING_SHELL_TO_TSHELL`
- Define material hardening behavior in LS-DYNA with `*DEFINE_CURVE_STRESS`
- Uniform mesh refinement inside a curve loop with `*CONTROL_ADAPTIVE_CURVE`
- Vector option in `*CONTROL_FORMING_BESTFI`, and LS-PrePost® 4.5 Best-fit GUI
- Sandwiched part mesh adaptivity
- New capabilities in 2D and 3D trimming of solids, laminates, and 2D trimming of `TSHELL`

New Features in State Output with `*CONTROL_FORMING_OUTPUT`

A few improvements are made according to user's requests:

- 1) The variable `NOUT` is used to specify the number of state outputs but only will work when `Y1 ~ Y4` or `LCID` is used. Now this variable will work alone, starting in Dev Revision 124051, adding to the output capabilities under the keyword.
- 2) A new variable `CIDT` is added to permit the use of a load curve to output states according to simulation time. In the input shown in Figure 1, a load curve ID 999 is specified with four additional states according to simulation time. These four states are added to the state output as shown in Figure 2.
- 3) A negative sign can be added in front of the particular abscissa to skip the state output for that point under the load curve defined by `LCID`, in Dev Revision 112604.

Shell to Thick Shell with `*CONTROL_FORMING_SHELL_TO_TSHELL`

This keyword is created to allow users to easily change the element type from thin shell elements (`*SECTION_SHELL`) to thick shell elements (`*SECTION_TSHELL`), and to generate segments on both top and bottom sides of the thick shells, for use in the `*CONTACT_` definition, for example. The position of the thick shells' mid-plane in reference to the thin shell's surface is determined based on the user specified variable `MIDSF`, in Figure 3. Converted node IDs of the thick shell elements will be the same as those for the thin shells. Element IDs of the thick shell elements will start at 2 (so renumber element IDs of other `PID` accordingly, or use automatic offset). Only one layer of thick shells will be created.

New nodes generated adaptively from their parent nodes with `*BOUNDARY_SPC` are automatically constrained accordingly. Adaptive mesh is supported.

The keyword can be used to just generate TSHELLs from SHELLs, output only nodes and elements associated with TSHELL, or it can be used directly in a full simulation input deck to start a simulation immediately after converting from SHELLs to TSHELLs. In the later case, *SECTION_TSHELL should be defined instead of *SECTION_SHELL for the sheet blank; corresponding material type for the sheet blank (*MAT_037) also needs to be changed to a type that supports solid element formulation (*MAT_024); contact definition needs to use the IDSEGB and IDSEGT created after the conversion.

```

*CONTROL_FORMING_OUTPUT
$ -----1-----2-----3-----4-----5-----6-----7-----8
$      CID      NOUT      TBEG      TEND      Y1/LCID      Y2/CIDT      Y3      Y4
      1116      0      &clstime &endtime      -980      -999
      1117      0      &clstime &endtime      -980      -999
      1118      0      &clstime &endtime      -980      -999
      1119      0      &clstime &endtime      -980      -999

*DEFINE_CURVE
999
1.0e-03
2.0e-03
3.0e-03
4.0e-03

*DEFINE_CURVE
980
13.5,0.0
13.0,0.0
5.0,0.0
3.0,0.0
2.5,0.0
2.0,0.0
1.0,0.0
    
```

Figure 1 Adding state output using CIDT.

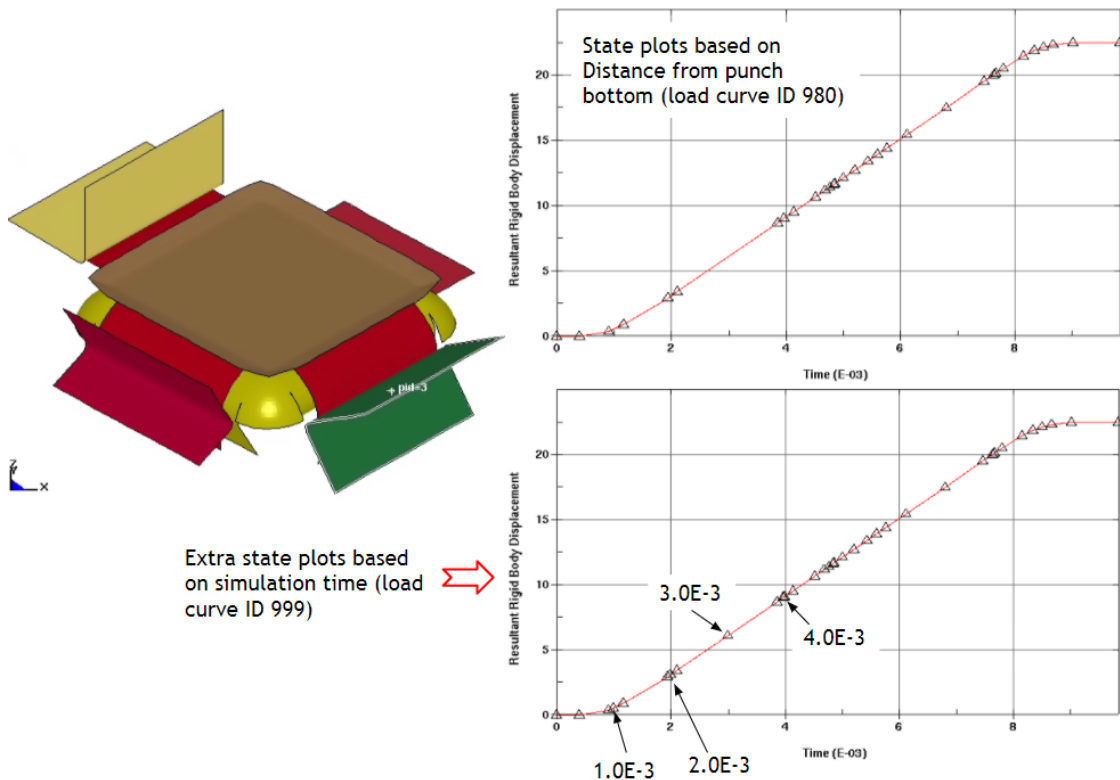


Figure 2 States added according to additional simulation time specified by CIDT.

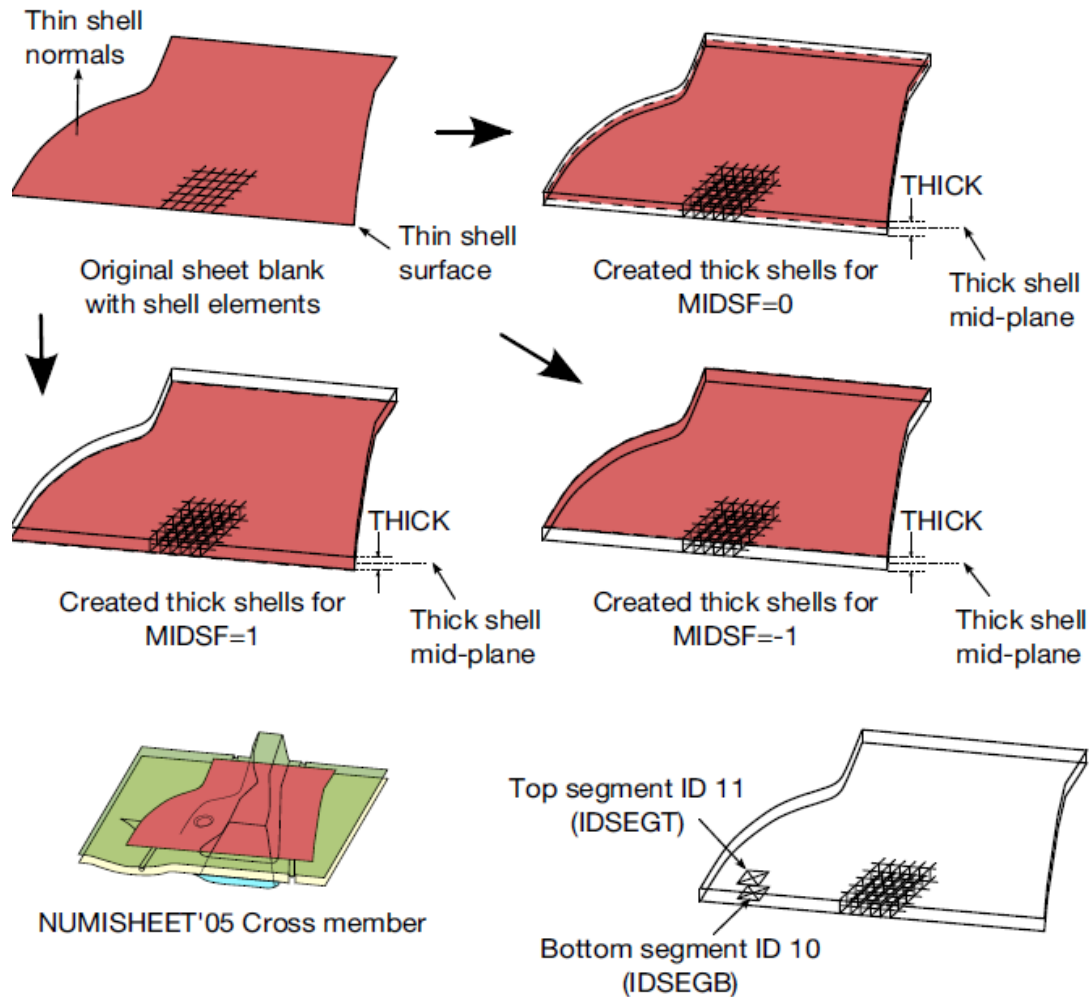


Figure 3 Converting thin shells to thick shells

Define Material Hardening with *DEFINE_CURVE_STRESS

This keyword defines a material hardening curve based on a few commonly used material hardening laws. The hardening curve can also be a weighted combination of some of the laws. The load curve ID for this curve can be referenced in the load curve ID field used by a specific material model. This feature is applicable to all material models with a hardening curve that can be defined by a load curve using *DEFINE_CURVE.

A total of five hardening laws are available, as listed below. In addition, a weighted combination of ITYPE1 and one other type can be defined. The material constants are input through variables P1 to P6, depending on the hardening laws selected, as listed in Table 2.

ITYPE=1

Swift power law: $\sigma = \sigma_0 (\epsilon_0 + \epsilon_p)^n$,

where σ is true effective stress, ϵ_0 is the elastic strain at the initial yield point, σ_0 is a strength coefficient, ϵ_p is true effective plastic strain, and n is the work hardening coefficient.

ITYPE=2

Voce law with form: $\sigma = \sigma_0 + \sigma_{\text{sat}}(1.0 - \epsilon^{-m})$,

where σ_0 is the initial yield stress, σ_{sat} is the stress differential between σ_0 and the saturated stress, and n is a strain coefficient.

ITYPE=3

Voce law with form: $\sigma = \sigma_0 - \sigma_0 e^{-\zeta \epsilon^n}$,

where σ_0 , ζ , and n are material constants.

ITYPE=4

Hockett-Sherby law: $\sigma = \sigma_0 - \sigma_0 e^{-\zeta \epsilon^n}$,

where σ_0 , ζ , and n are material constants.

ITYPE=5

Stoughton-Yoon hardening law: $\sigma = A - B e^{-C \epsilon^m} + D \epsilon^n$,

where A , B , C , m and D are material constants, such that $0 < m < 1.0$ and $D \geq 0.0$.

ITYPE=11

A weighted combination of ITYPE=1 and any of the other ITYPES. Variables w_1 and w_2 are the weighting factors.

Table 1 Material constants for various ITYPES.

ITYPE	P1	P2	P3	P4	P5	P6
1	K	e_0	n			
2	σ_0	R_{sat}	ζ	w_2		
3	A	B	C	H	w_2	
4	A	B	C	H	w_2	
5	A	B	C	M	D	w_2
11	K	e_0	n	w_1		

For validation purpose, we use a single element under uniaxial tension (Figure 4). The resulting hardening curve from this keyword for Stoughton-Yoon law is plotted along with the results from hand-calculation, and they overlap each other (Figure 5). In Figure 6, the results from this keyword and the hand-calculation also overlap for a weighted combination of 0.5 of Swift power law and 0.8 of the Hockett-Sherby law.

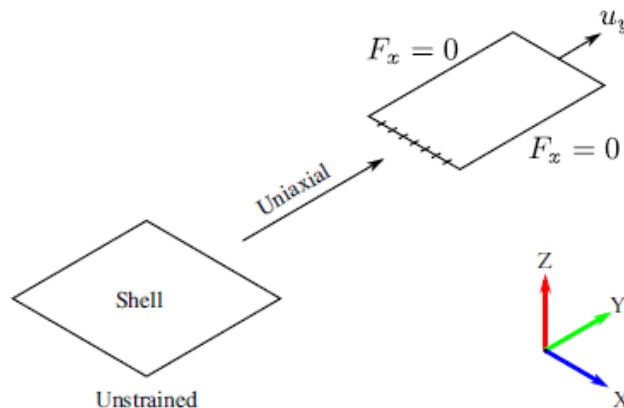


Figure 4 A single element under uniaxial tension is used for validation.

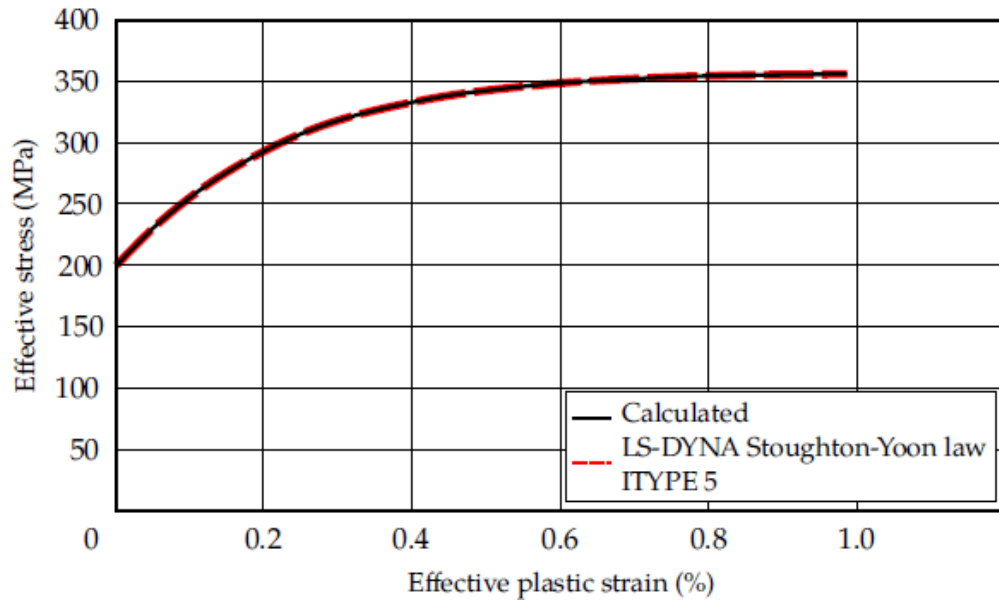
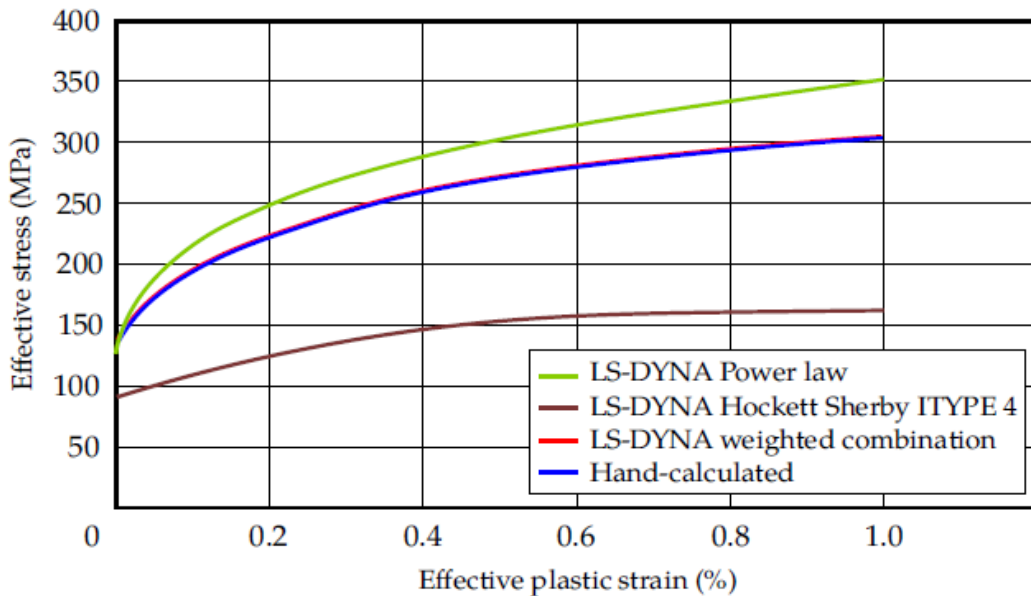


Figure 5 Comparison between Stoughton-Yoon results from LS-DYNA and hand-calculation (A=160.8024, B=71.109, C=4.5058, M=0.9989, D=0.8)



Power law: $\sigma = 350.0(0.01 + \epsilon_p)^{0.22}$,

ITYPE 4 Voce law: $\sigma = 162.2 - 72.2e^{-4.34\epsilon_p^{1.2}}$,

Weighted combination: $\sigma = 0.5 * 350.0(0.01 + \epsilon_p)^{0.22} + 0.8(162.2 - 72.2e^{-4.34\epsilon_p^{1.2}})$.

Figure 6 Resulting hardening curves from LS-DYNA compared with hand-calculated results.

Uniform Mesh refinement inside a Curve Loop with *CONTROL_ADAPTIVE_CURVE

Adding to many existing mesh refinement capabilities along a curve, In Figure 7, the original mesh (Figure 7 left) is refined by six levels inside a curve (in red) loop. This keyword is used together with *DEFINE_CURVE_TRIM_3D to define the curve, and both curve types of TCTYPES of 1 (XYZ data pairs) and 2 (IGES format) are accepted. Note the variable TCTOL must be set to “2”, and a seed node NSEED1 must be defined inside the curve loop. This feature is available starting in Revision 115142.

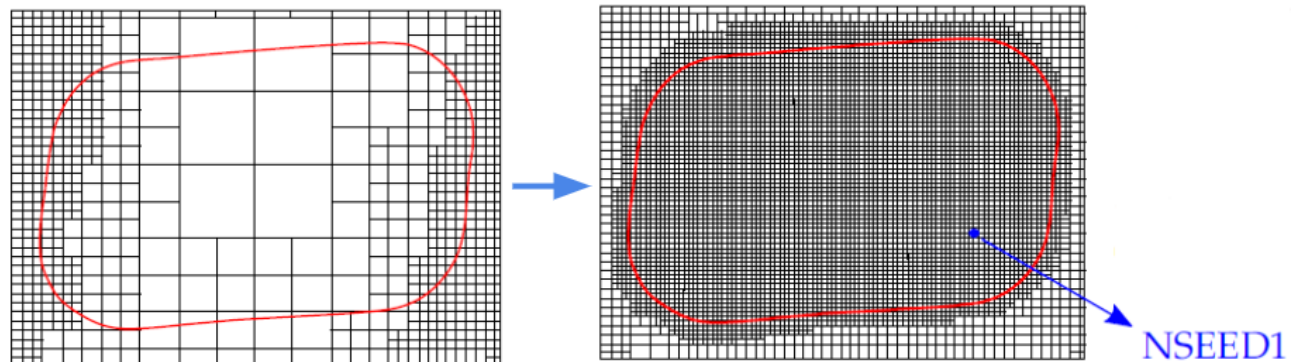


Figure 7 Uniform mesh refinement within a curve loop.

Vector option in *CONTROL_FORMING_BESTFIT and LS-PrePost 4.5 Best-fit GUI

This keyword was developed to rigidly move a part to a target so that they maximally coincide. It has proven to be very useful in sheet metal forming to translate and rotate a spring back part (source) to a scanned part (target) for the purpose of assessing spring back prediction accuracy. The VECTOR option (Dev Revision 112655) was added to allow vector components of the normal distance from the target to the part node to be included in the output file `bestfit.out` under the keyword *NODE_TO_TARGET_VECTOR (Figure 8).

This feature has been also implemented in LS-PrePost 4.5 GUI in Metal Forming Application/eZ Setup to output an input file to run in LS-DYNA for a best-fit simulation, and to process results from the simulation run, as in <http://ftp.lstc.com/anonymous/outgoing/lsprepost/4.5/>.

The best-fit GUI can be activated and follow through to generate an input deck as shown in Figure 9. Results process from a LS-DYNA run include contour plot for part separation between source and target (Figure 10), vector plot (Figure 10), identify separation distance for any point in the part (Figure 11), and section plane cut (Figure 12). The last one is especially useful when the target is also imported into the GUI.

```

*NODE
$ NSKIP=          1
$ GAPONLY=        0
$ IFAST=          1
336991  0.458840E+02  -0.875577E+02  0.169456E+04
336992  0.460404E+02  -0.876008E+02  0.169507E+04
336993  0.463605E+02  -0.876933E+02  0.169617E+04
336994  0.466628E+02  -0.877842E+02  0.169727E+04

*ELEMENT_SHELL_THICKNESS
1218245  4  341061  341058  341059  341059
0.3162278E-01  0.3162278E-01  0.3162278E-01  0.3162278E-01
1218247  4  338694  338695  341058  341061
0.3162278E-01  0.3162278E-01  0.3162278E-01  0.3162278E-01
1218248  4  338695  338696  341055  341058
0.3162278E-01  0.3162278E-01  0.3162278E-01  0.3162278E-01

*NODE_TO_TARGET_VECTOR
336991  0.000000E+00  0.000000E+00  0.000000E+00
336992  0.000000E+00  0.000000E+00  0.000000E+00
336993  0.000000E+00  0.000000E+00  0.000000E+00
336994  0.638517E+00  -0.507506E-01  -0.156754E+00
336995  0.662397E+00  -0.373199E-01  -0.259179E+00
    
```

Figure 8 Option VECTOR adds *NODE_TO_TARGET_VECTOR to the result file "bestfit.out".

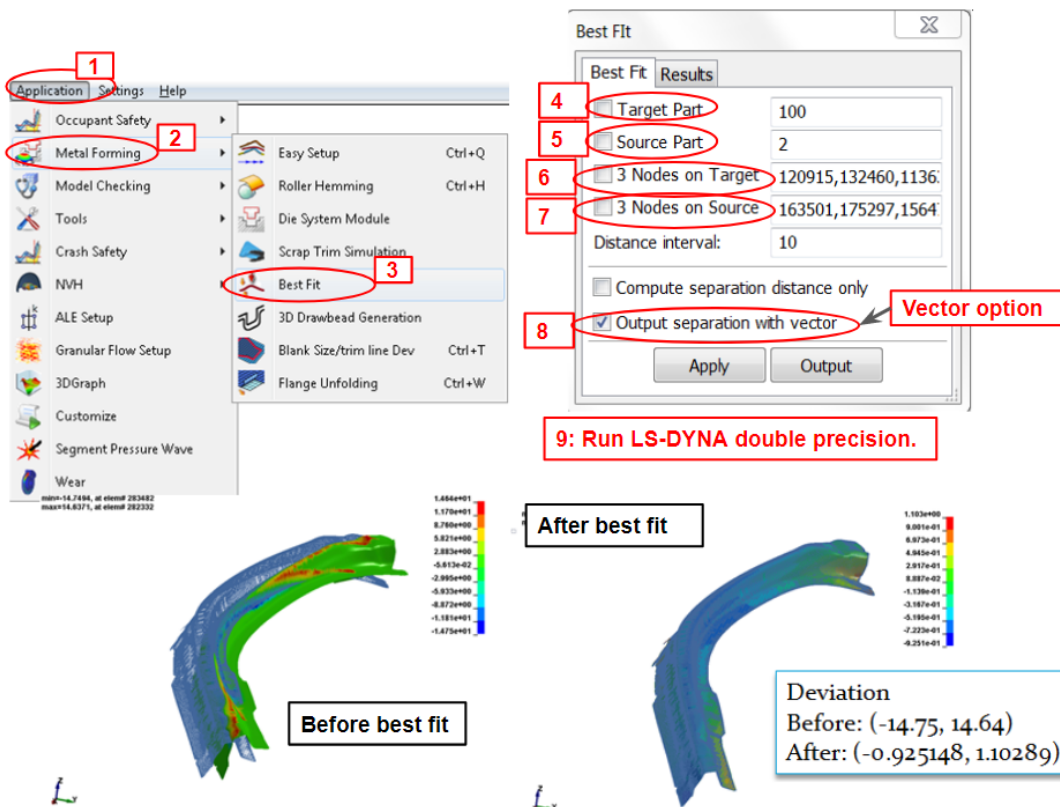


Figure 9 Procedure to set up a best-fit simulation input deck in LS-PrePost 4.5. (GUI developed by Q. Yan).

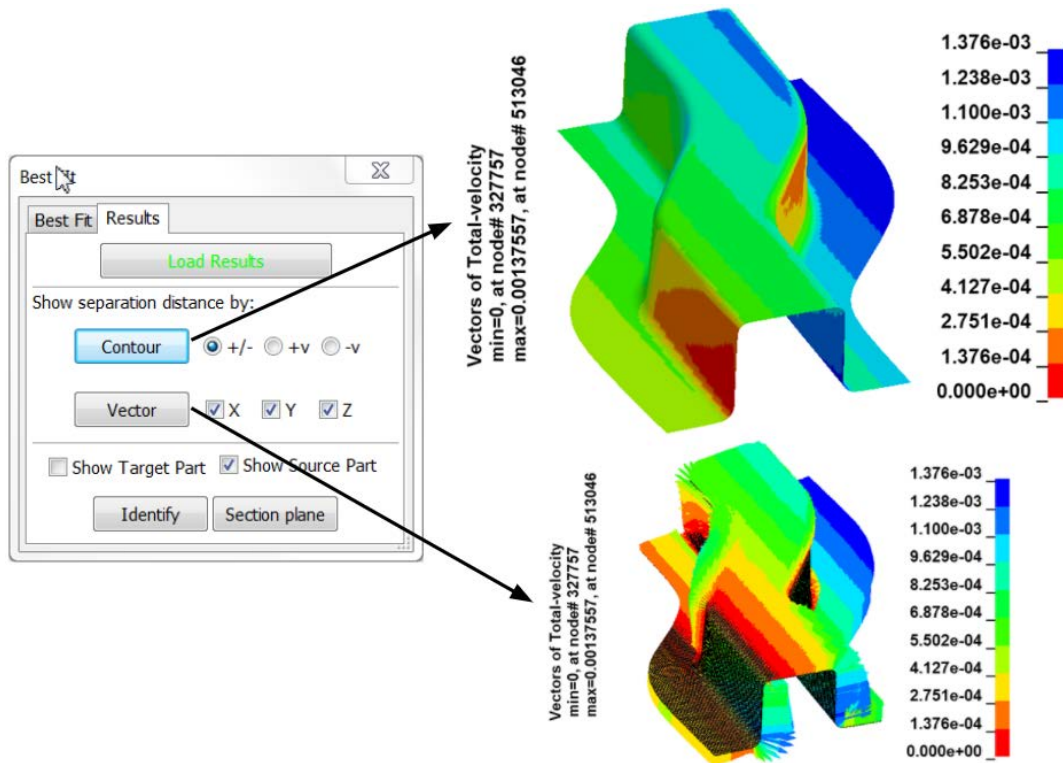


Figure 10 Result process within the GUI: contour and vector plots. (GUI developed by Q. Yan).

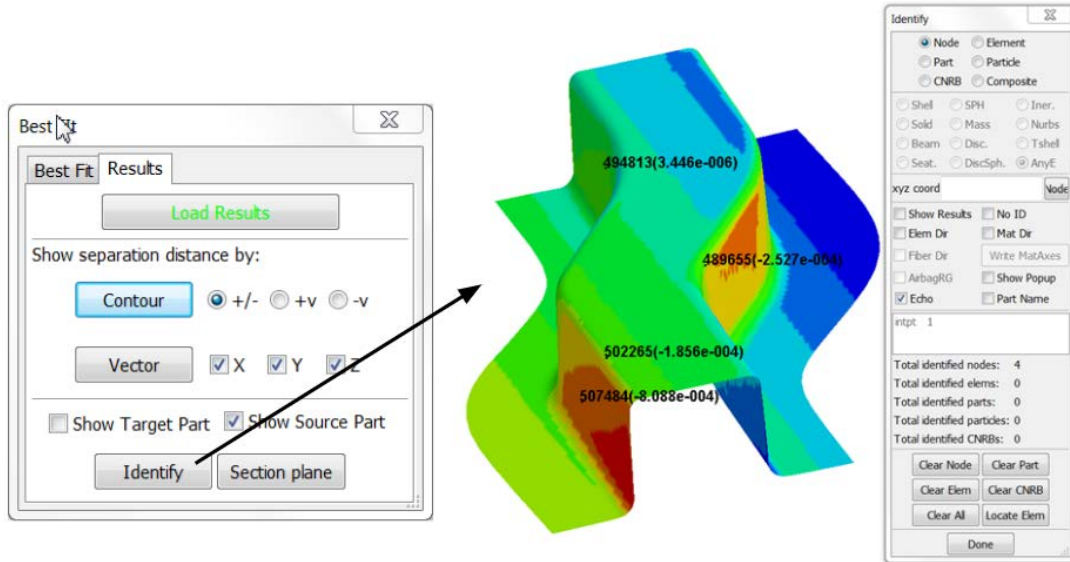


Figure 11 Identifying part deviation in any location. (GUI by Q. Yan).

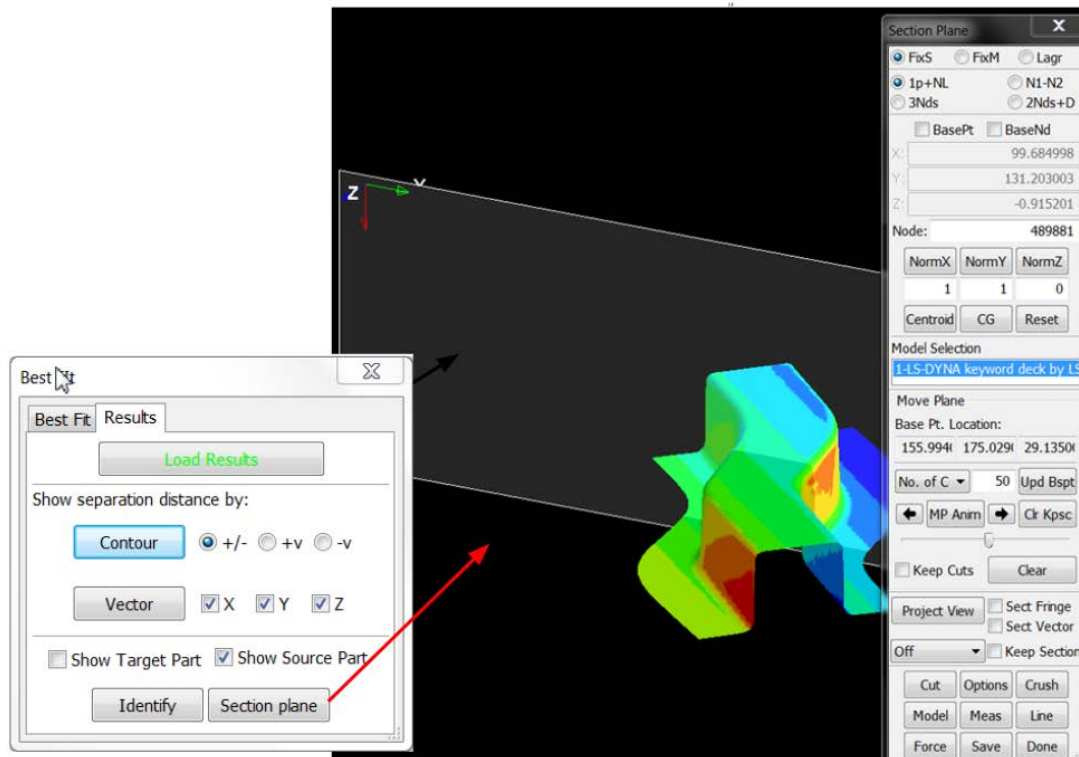


Figure 12 Section plane cut within the GUI. (GUI by Q. Yan).

Sandwiched Part Mesh Adaptivity

Sandwiched parts (also called laminates) consist layers of solid elements (core) sandwiched by one layer of shell elements each on top and bottom surface of the core. Common nodes are used for solid and shell interface. Prior to Dev Revision 116282 mesh adaptivity is limited to only one layer of solid element core with in-plane mesh refinements for both solids and shells (Figure 13); post Dev Revision 116282 improvements were made so that it applies to multiple layers of solid elements (Figure 14).

Mesh refinement is carried through in the part's thickness direction. Shells are discretized into quadrilateral elements and solids into hexahedral ones. The solids are adaptively refined by sweeping the corresponding top and bottom adaptive shells through the thickness (Figure 15). If the shells are discretized into triangular elements and the solids are discretized into wedge elements, then the shells are adaptively refined as more triangular elements and solids refined as more wedge elements. The number of layers of the solids always remains the same. This improvement not only provides more detailed information through more layers of solids in the thickness direction, but also provides more freedom to the material within the solids, i.e., nodes of the solids are no longer solely attached to the shells. Furthermore, the adaptive mesh refinement feature serves to provide better resolution of the simulation results in local areas of interest while keeping the computational cost to an acceptable level.

To activate the mesh adaptivity for sandwiched part, include `*CONTROL_ADAPTIVE` card, set the variable `ADPOPT` to "1" under all `*PART` defining the deformable solids and shells, also set the variable `IFSAND` to "1" in `*CONTROL_ADAPTIVE`.

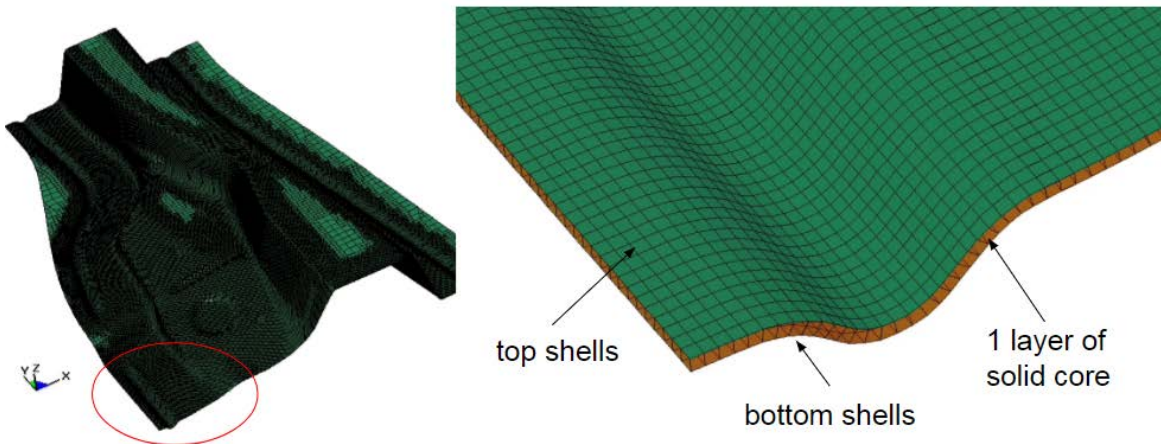


Figure 13 Adaptive refinement for only one layer of solid element as the core prior to Dev Revision 116282.

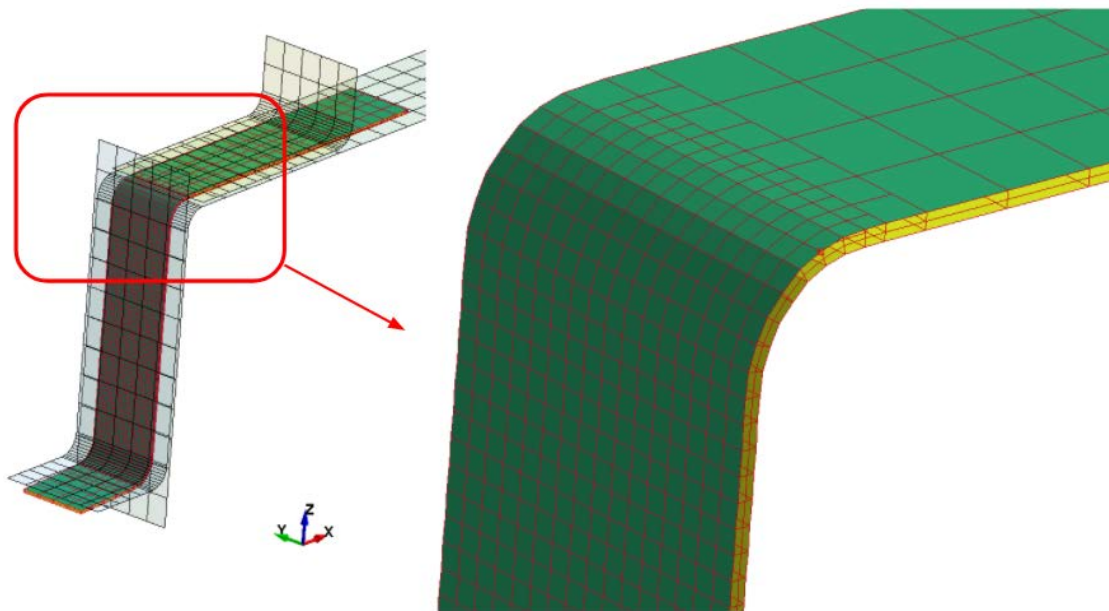


Figure 14 Adaptive refinement for multiple layers of solid elements as the core post Dev Revision 116282.

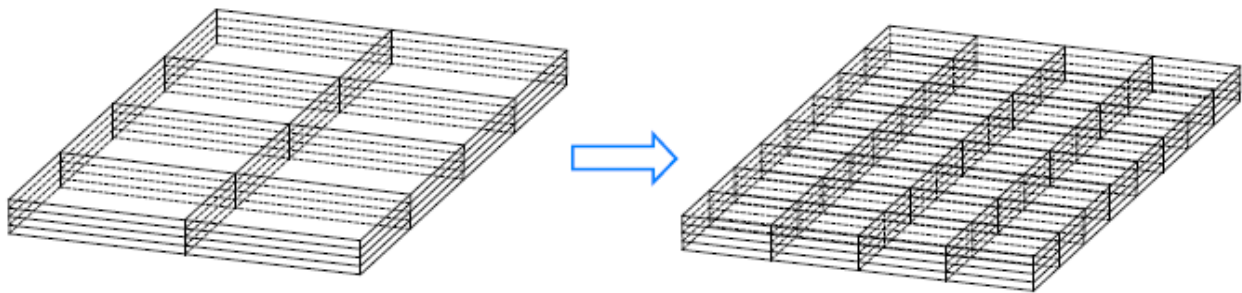


Figure 15 Adaptive refinement "sweeping" through thickness on sandwiched part.

- **New Capabilities in 2D & 3D Trimming of Solids, Laminates, and 2D Trimming of TSHELL**

Listed in Table 1 are a summary of the all the trimmings that can be done in LS-DYNA, with new capabilities are marked by *.

Table 2 Overview of various trimming capabilities (* represents new capability).

	2D (along one direction)	3D (element normal)	2D & 3D Double Trim	Adaptive mesh
Shell	Yes	Yes	Yes	Yes
Solids	Yes	Yes	Yes*	N/A
Laminates	Yes	Yes	Yes*	One layer of solids only*; Multiple layers of solids okay for non-adaptive mesh*.
TSHELL	Yes*	N/A	N/A	N/A

Both 2-D and 3-D double trimming of solids are now available starting in Dev Revision 110140. Both seed point coordinates can be specified in keyword *DEFINE_TRIM_SEED_POINT_COORDINATES to define a seed coordinate for each trimmed part, as shown below, as shown in Figure 16. Note for 3D trimming of solids, the variable TDIR in *DEFINE_CURVE_TRIM needs to be set according to element normal. Also note multiple layers of non-adaptive solids are permitted. Further note *INCLUDE_TRIM must be used when trimming in solids.

Both 2-D and 3-D double trimming of sandwiched part are also available in Dev Revision 110140, as shown in Figure 17. Note the variable ITYP needs to be set as “1” for sandwiched part trimming. Also note for non-adaptive sandwiched part, multiple layers of solids are permitted in the core.

Both 2-D and 3-D trimming of adaptive sandwiched part are available in Dev Revision 108770, with only one layer of solids permitted, as shown in Figure 18. Improvements are also made to automatically refine the mesh along trim curves, which is crucial in achieving smooth trim edges, Figure 19. Note keyword *CONTROL_ADAPTIVE_CURVE must not be used as it applies to shells only.

2-D trimming of TSHELL is available in Dev Revision 107957, Figure 20. Note by definition, TSHELL has only one layer of solid elements, and is defined by keyword *SECTION_TSHELL. Note also *INCLUDE_TRIM (not *INCLUDE) must be used to include the dynain file to be trimmed.

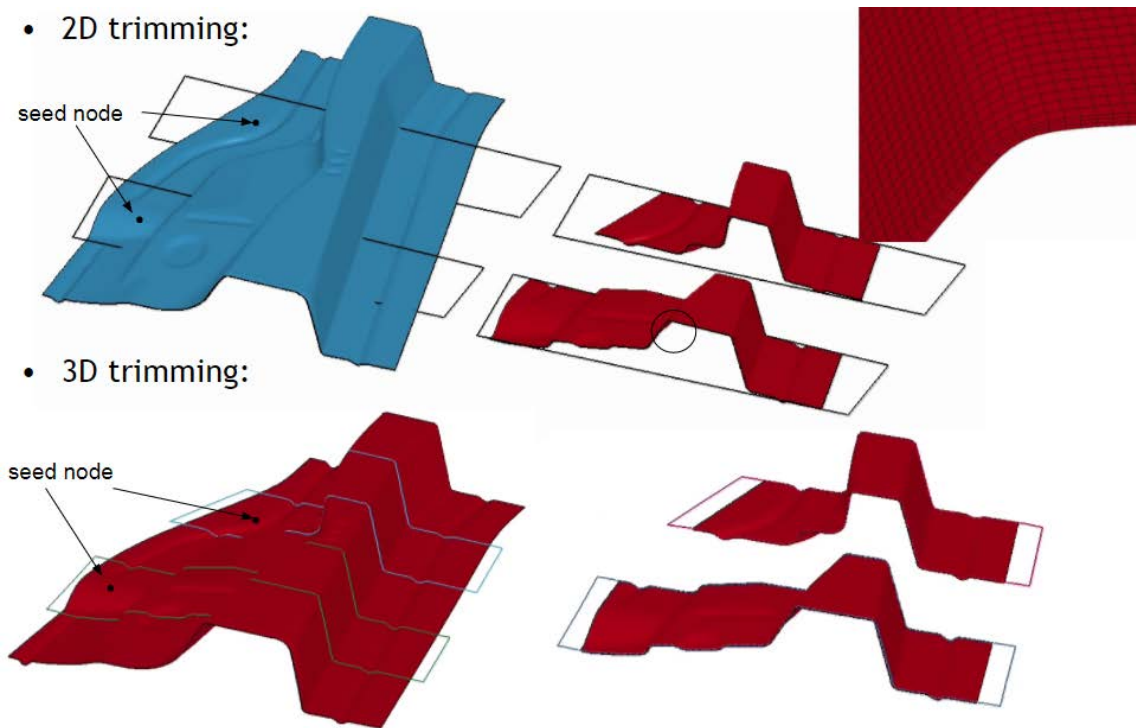


Figure 16 2-D and 3-D double trimming of solids.

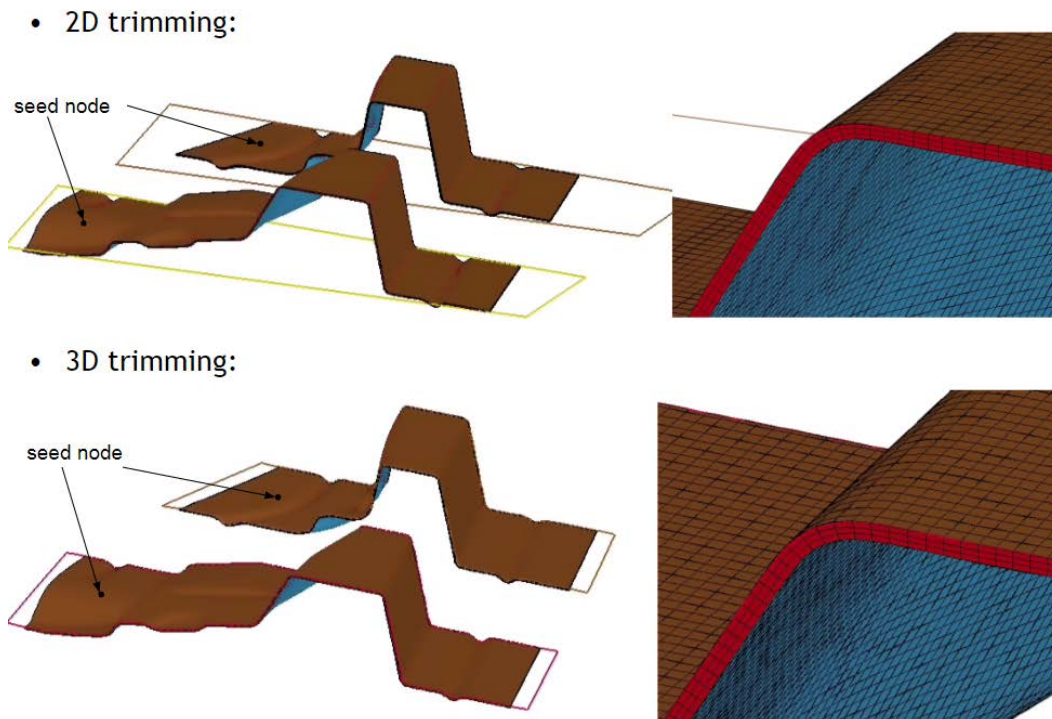


Figure 17 2-D and 3-D double trimming of non-adaptive laminates; multiple layers allowed.

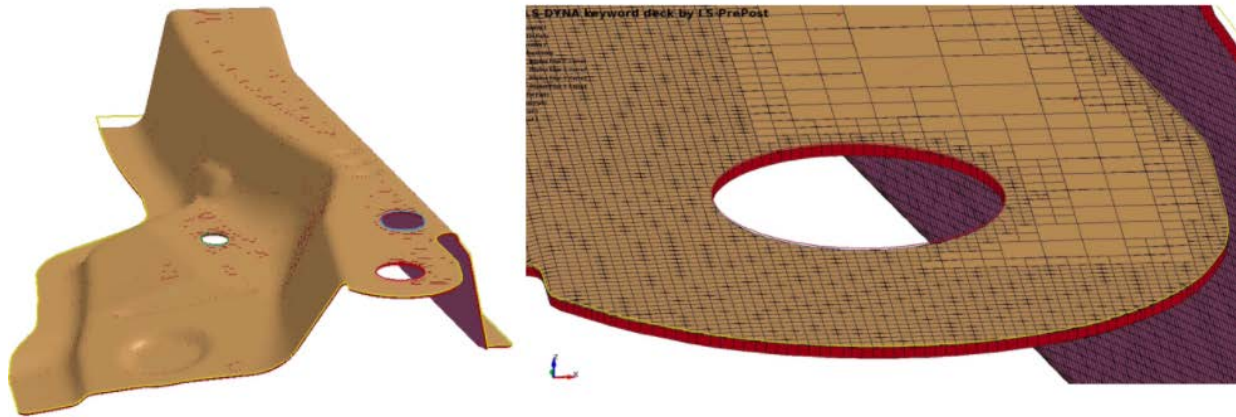


Figure 18 2-D and 3-D trimming of adaptive laminates; only one layer of solids allowed.

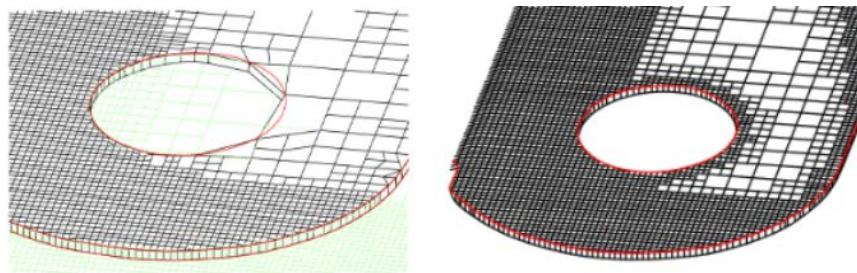


Figure 19 Automatic adaptive refinement along trim curves.

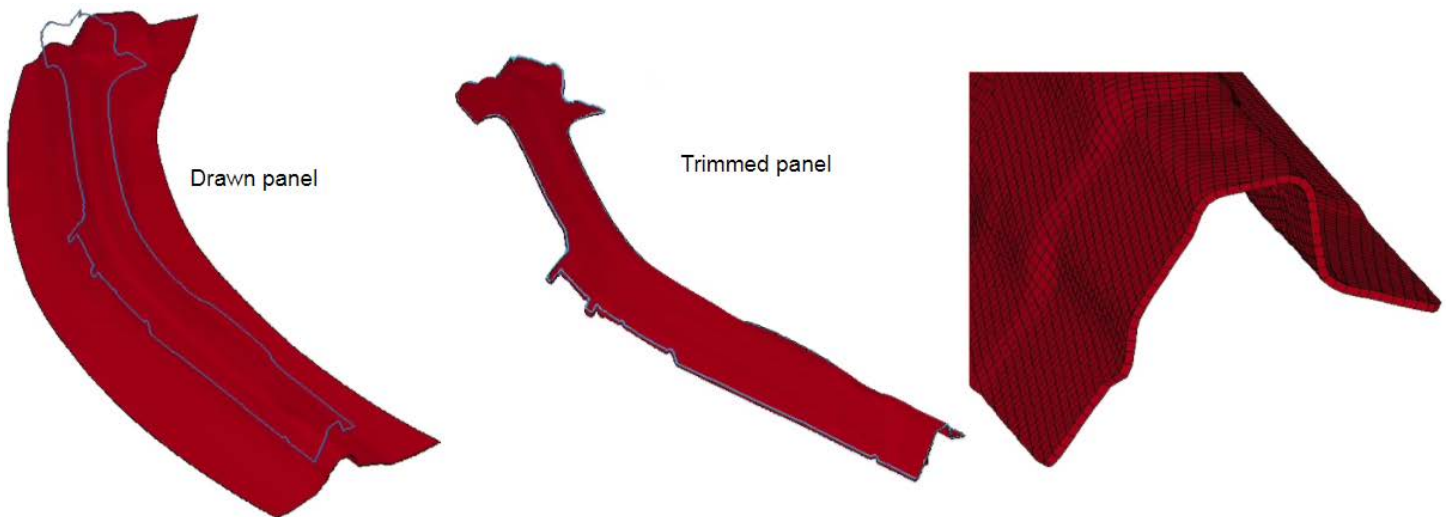


Figure 20 2-D trimming of TSHELL.

References

LS-DYNA User's Manual I.