Advance in Sheet Metal Forming
- Failure Criteria, Friction, Scrap Trimming and Adaptive Meshing

Li Zhang & Xinhai Zhu
Livermore Software Technology Corporation

Abstract

Some of the new features developed since the last conference will be discussed.

1) *Directional and pressure sensitive friction model for metal forming*
       Developed together with Ford Motor Research and Advanced Engineering Laboratory, this feature enables definition of Coulomb frictions in any directions in the sheet plane. The friction coefficients can also be scaled based on the contact pressure incurred during the stamping process.
2) *Failure criterion for the non-linear strain path for *MAT_036*
       Developed as a part of the ASP-NSP project, the previously known Formability Index (F.I.) is now implemented together with *MAT_036. Verification of the model will be discussed.
3) *Contact-based scrap trimming function*
       Developed together with Ford Motor Company, this powerful feature allows realistic scrap trimming simulation and contact-based kinematic and dynamic transfer from the trim steels to the trimmed scraps.
4) *Pre-adaptive along curves for line-die simulation*
       Developed together with Chrysler LLC, a region of user specified size can now be defined for mesh adaptivity along a curve for subsequent line-die simulation.

A Directional and Pressure Sensitive Friction Model

Developed together with Ford Motor Research and Advanced Engineering Laboratory, the keyword *DEFINE_FRICTION_ORIENTATION [1] enables the definition of Coulomb frictions in any directions in the sheet plane, using the variable LCID. Currently, one edge of all elements representing a sheet blank must be aligned in the direction specified by the vector [V1, V2, V3]. Regardless of the initial directions of the elements as defined by the 'n1-n2' scheme, all of the element directions will be reoriented automatically in the solver to align with the vector specified. The element directions can be checked or verified in LS-PrePost® 3.2, via menu option *EleTol/EleEdit/Direction(or Ident)* for keyword format files, or via menu option *EleTol/EleEdit/Ident* for D3PLOT format files. The friction coefficients can also be scaled based on contact pressure formed during the stamping process, using the variable LCIDP.

Shown in *Figure 1*, verification is done based on a simple model of pulling on one edge of a flat sheet blank clamped in between two rigid plates. The bottom plate is fixed while the top plate is applied a concentrated load in the normal direction to press the blank against the bottom plate. The specifications of the friction characteristics and the loading conditions are listed below:

Pulling direction: 330° (-30°);
Blank area: 3906.25mm²;
Applied forces (normal) total: 562.75N at 0.09 sec. and 1125.5N at 0.18 sec, linear ramp;

Directional friction characteristics: as shown in Figure 2;
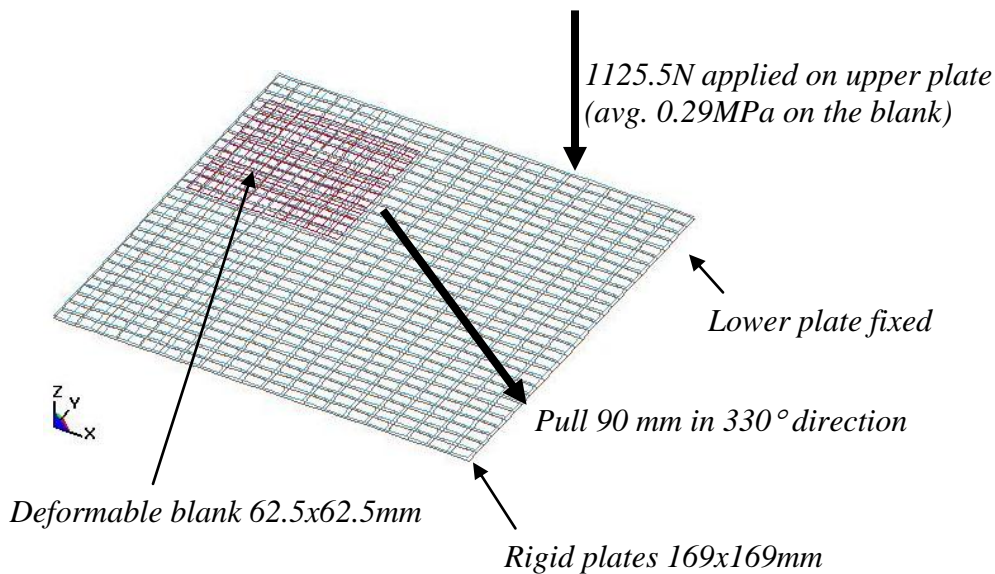*Pressure sensitive friction coefficient scale factor: as shown in Figure 3;*
Theoretical frictional forces:
   at 0.09 sec, F_x=17.28N, F_y=9.98N, F_{total}=19.96N;
   at 0.18 sec, Fx=68.2N, Fy=39.4N, F_{total}=78.8N;

Pulling and applied normal forces output are shown in *Figure 4*, at half of the time and the total time. Interface pressures are captured at the same time interval for verification of the friction values, as shown in *Figure 5*. A comparison of the pulling forces between theoretical and simulated is shown in *Table 1*. It is noted that the elements along the boundary of the flat blank get slightly higher pressures while the corner elements get the most pressure, consistent with the finite elements edge condition. The slight discrepancies between the predicted pulling and the calculated forces are attributed to the dynamic effect in the system.

A more versatile, MPP enabled orthotropic friction model, activated by *_ORTHO_FRICTION* [1] option in *CONTACT…, was later developed in place of this feature.

1125.5N applied on upper plate
(avg. 0.29MPa on the blank)

Lower plate fixed

Pull 90 mm in 330° direction

Deformable blank 62.5x62.5mm

Rigid plates 169x169mm
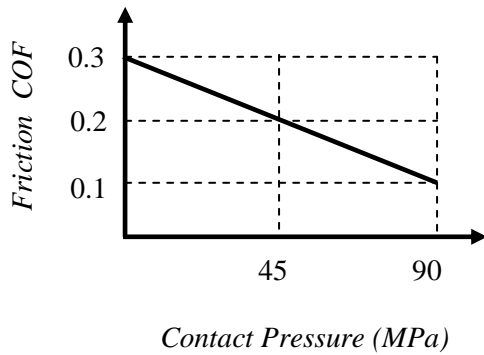
Figure 1. A rigid plate - blank system

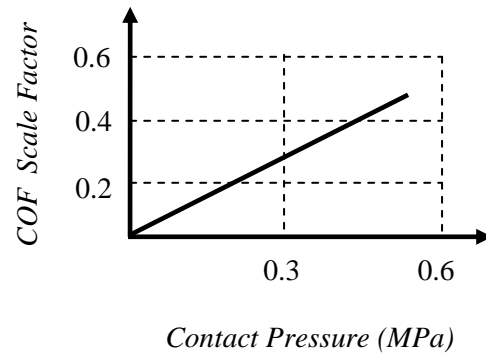*Figure 2. Directional Friction Characteristics*　　*Figure 3. Pressure Dependent Characteristics*

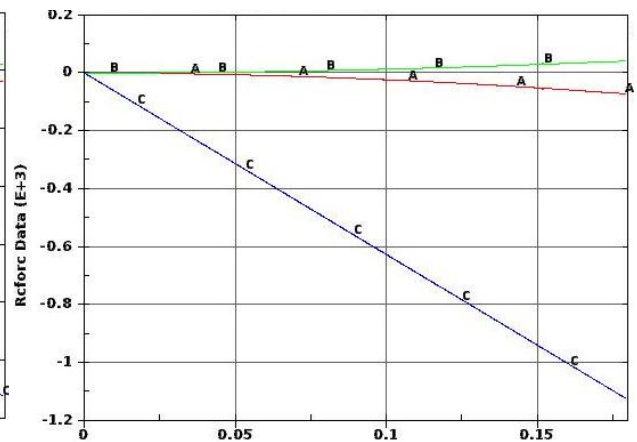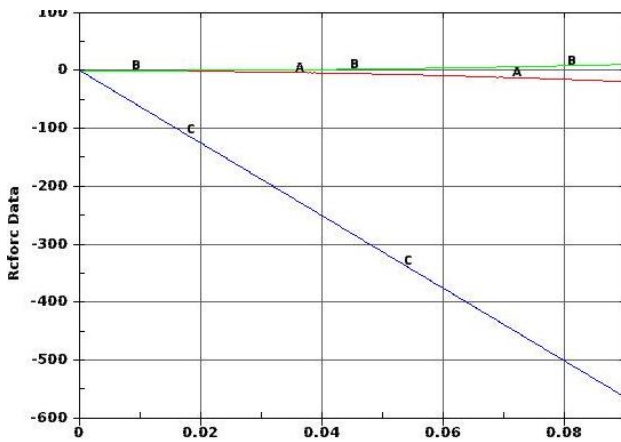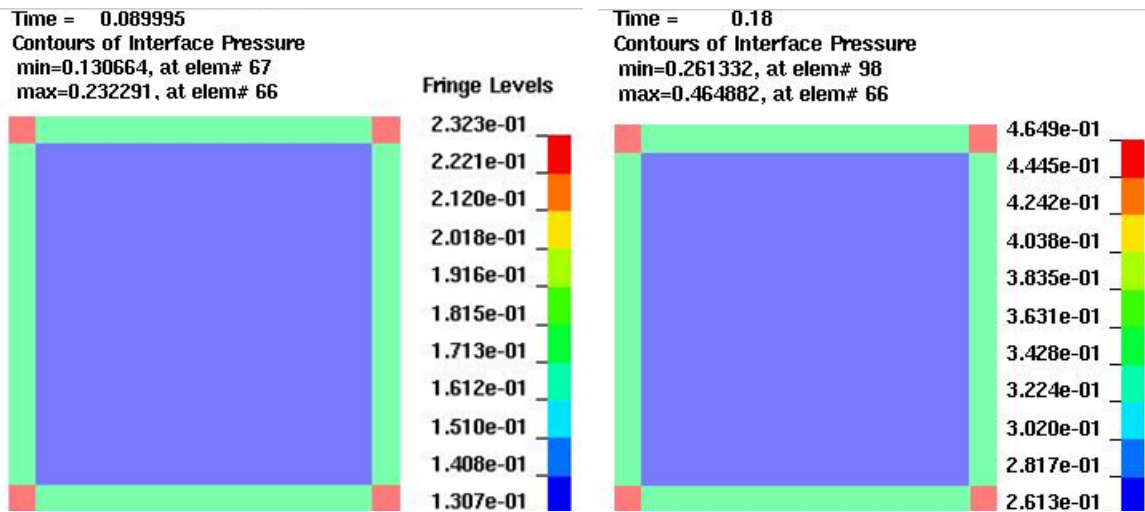*Figure 4. Force Output at 0.09 sec. and 0.18 sec.*

Figure 5. Interface Pressure at 0.09 sec. and 0.18 sec.

Comparison	F_x (Newton @ t/2, t)	F_y (Newton @ t/2, t)	% Deviation F_x @ t/2, t	% Deviation Fy @ t/2, t
Theoretical	*17.29, 68.23*	*9.98, 39.4*	*7.6, 4.5*	*8.2, 4.8*
Simulated	*18.6, 71.5*	*10.8, 41.3*		

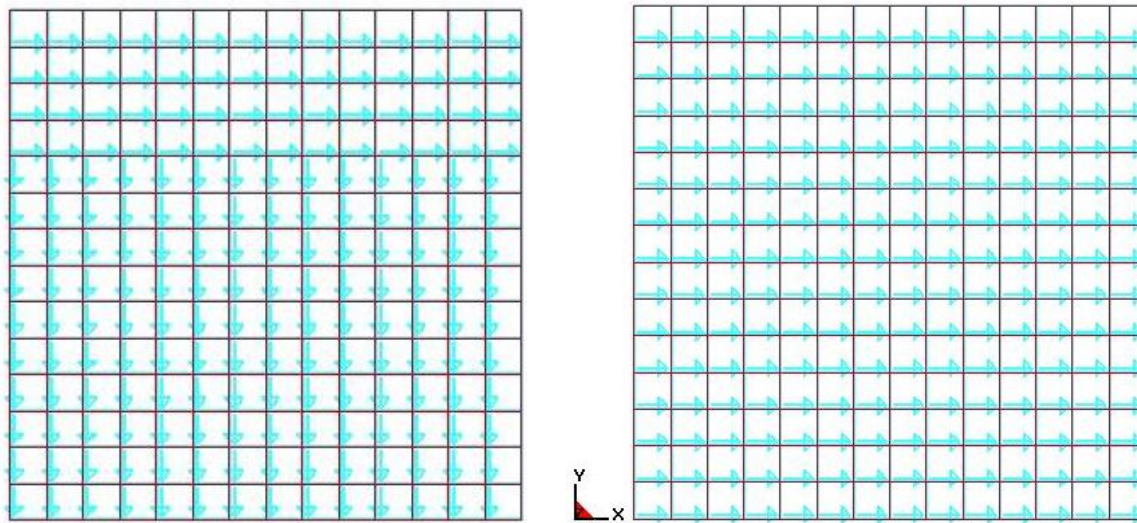*Table 1. Comparison between theoretical and simulation*

Figure 6. Checking element directions on incoming mesh (left) and on D3PLOT files (right) with LS-PrePost v3.2

A Path Independent Failure Criterion for *MAT_036

Following the development and implementation in *MAT_037, the Formability Index (F.I.) is now implemented with *MAT_036 [1]. The F.I. handles sheet metal necking failure, especially under the condition of nonlinear strain paths. In this section, forming limit curves are reconstructed using three distinctive strain paths: uni-axial tension, plane strain and equi-biaxial. As shown in *Figure 7*, a single shell element, having been strained first in these three paths, is further strained in these three paths. The limit strains are recovered when the F.I. reaches the value of 1.0 at the secondary straining, as shown in *Figure 8*. The new forming limit curves, illustrated in dashed curves, are also included in the figure.

To activate the F.I. in LS-DYNA, an option *_NLP* is added to *MAT_036. A new variable, NLP, is used to defined forming limit curve for the linear strain path. The F.I. information is stored in a history variable #9, so it is necessary to set the variable NEIPS to 10 in *DATABASE_EXTENT_BINARY, and set MAXINT to NIP used in *SECTION_SHELL. Necking failure starts when the F.I. of the minimum IP value across the section, viewable via

history variable #9, reaches the value of 1.0. Similar to the _NLP option in *MAT_037, one can plot the F.I. history using LS-PrePost.
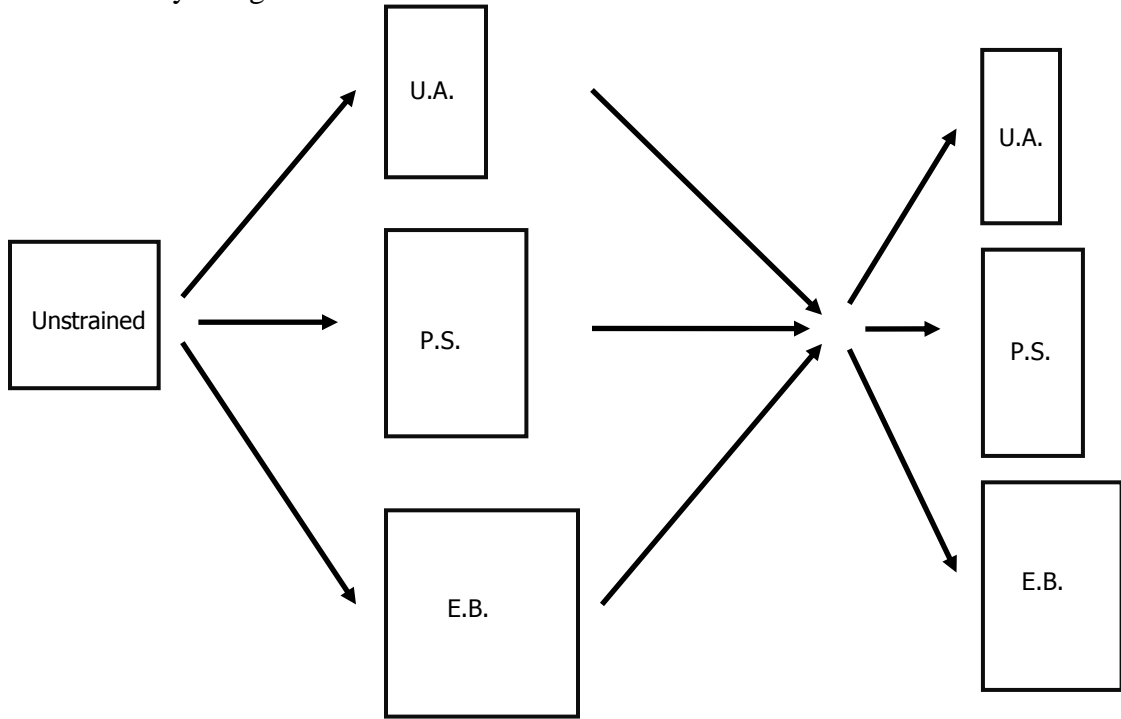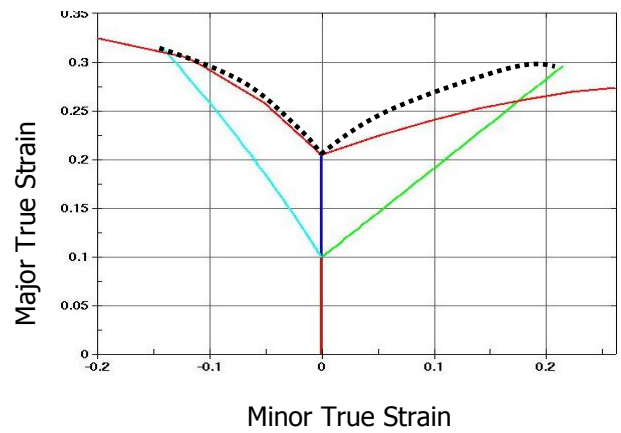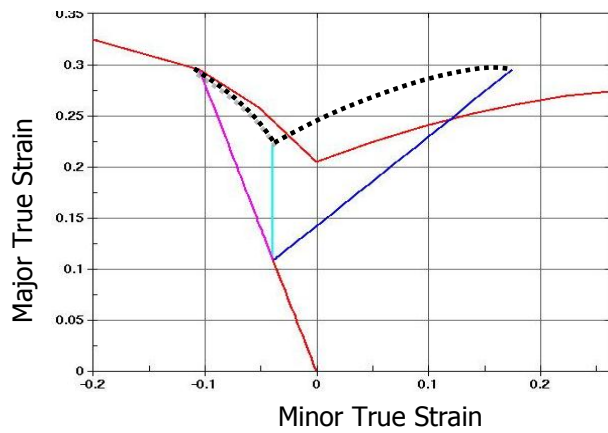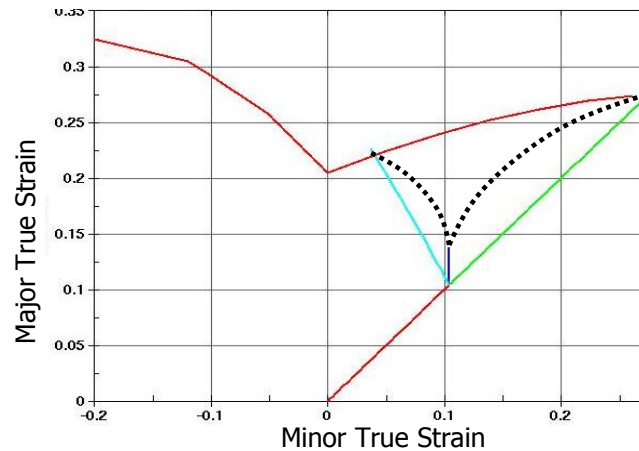

Figure 7. Straining of a single element

Figure 8. Forming Limit Curves for different strain paths (m=8, r=0.8, 0.6, 0.55)

A Contact-based Scrap Trimming Feature

Developed in conjunction with Ford Motor Company, this powerful feature allows realistic scrap trimming simulation and contact-based kinematic and dynamic transfer from the trim steels to the trimmed scraps. The keyword responsible for this application is *CONTROL_FORMING_SCRAP_FALL [1]. As shown in Figure 9, the trim steel is moved with a load curve LCID in a direction defined by a variable VECTID, towards the scrap piece, defined by a variable PID. A variable NDSET, consists of the nodes along the trim edge, is also defined, which is used to determine the contact between the trim steel and edges (trim lines) of the scrap piece. The nodes along the trim edge are initially fixed (automatically by the solver), and are released as the trim steel edge comes into contact within a specified tolerance, defined by a variable DEPTH. Contacts are defined between the trim steel and the scrap piece so kinematics and dynamics can be carried over from the trim steel to the scrap piece. Contacts are also defined between the scrap and the rest of the die structure (not shown), taking into account edge-to-edge contact condition dominant in this type of application, so the scrap would fall properly within the structure. As implied, the parent piece is not necessary but can be defined for viewing purpose.

Applications of the keyword in 11 production trimming conditions show realistic and promising potential. The keyword can currently handle complex trimming condition including direct, aerial cam, scrap cutters, segmented trim, and by-pass trimming involving direct and aerial cam, etc. As one of the cases used for validation of the feature, as shown in Figure 10, trim steel #2, a direct trim in global Z responsible to trim scrap piece #2, and trim steel #1, an aerial cam trim in a direction defined by a local vector #1, responsible to trim scrap piece #1, form a severe by-pass trimming condition in the area indicated. In Figure 11, the results of the trimming and deformation of the scrap piece is shown. Such information can be used to further design the timing of the trim and trim steel shapes in the by-pass area leading to a more favorable trimming condition. The keyword can also be used to determine and compare the falling speeds of the scraps in different die structure configurations.
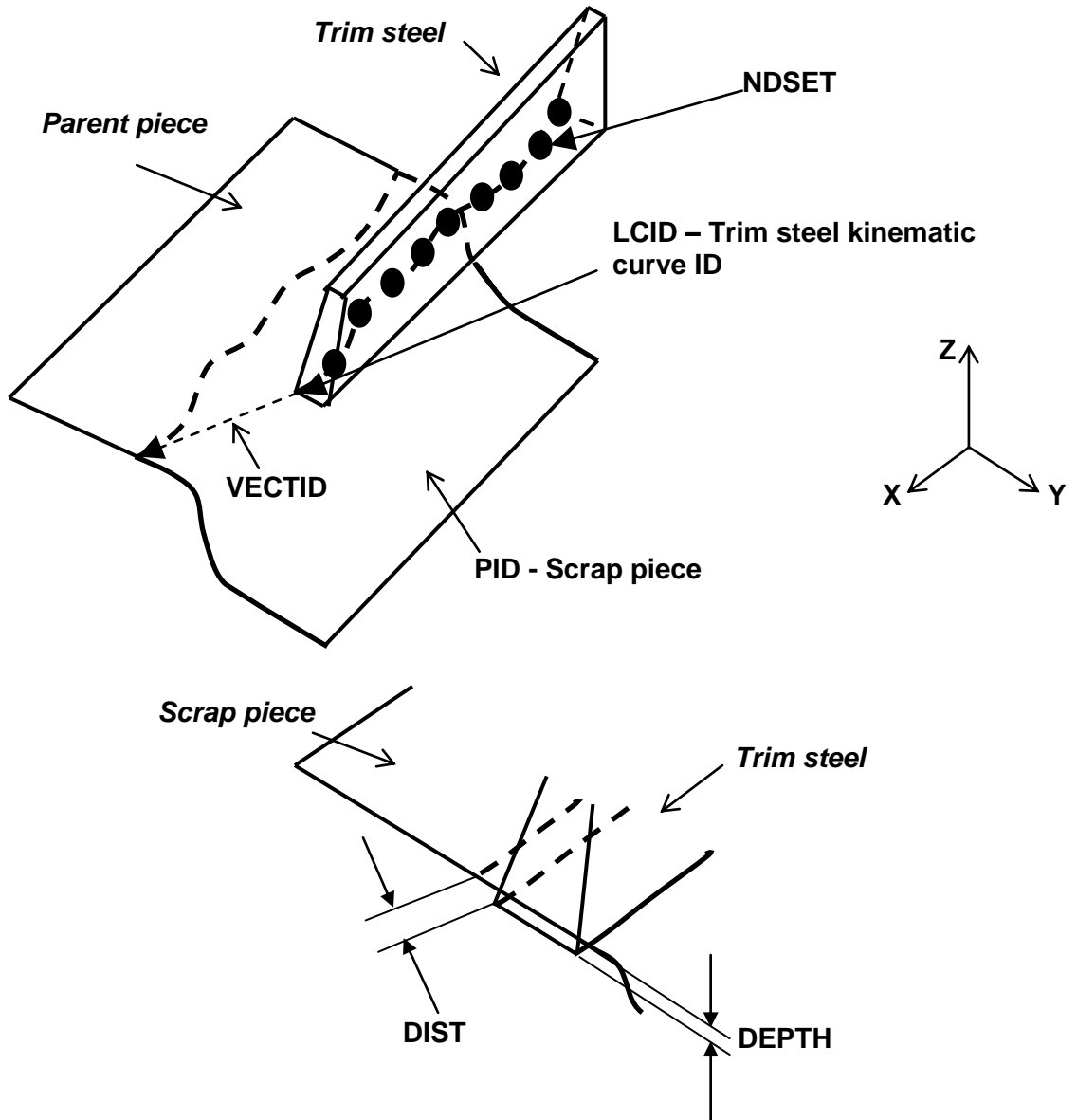
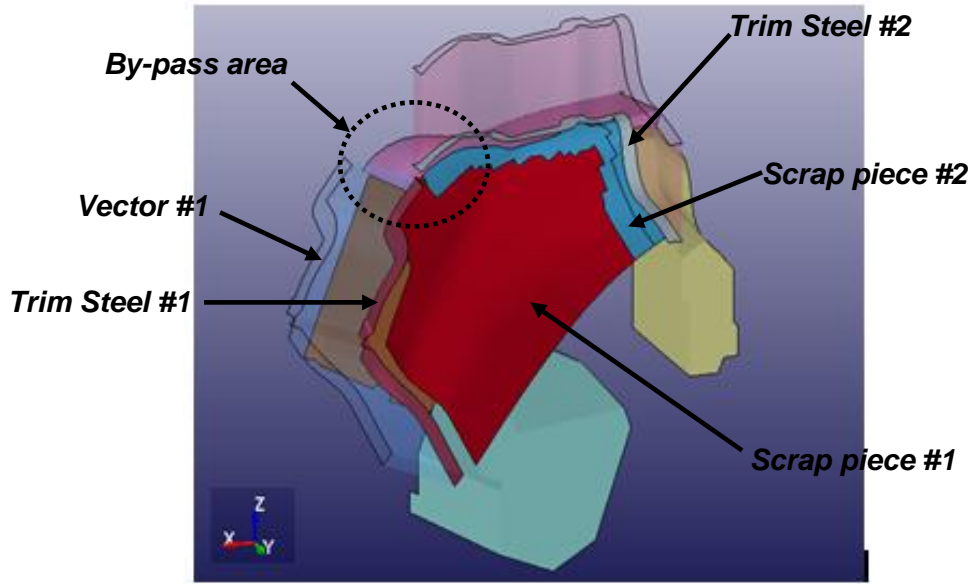*Figure 9. Defining a scrap trimming with *CONTROL_FORMING_SCRAP_FALL*

Figure 10. A by-pass trimming case involving direct and aerial cam
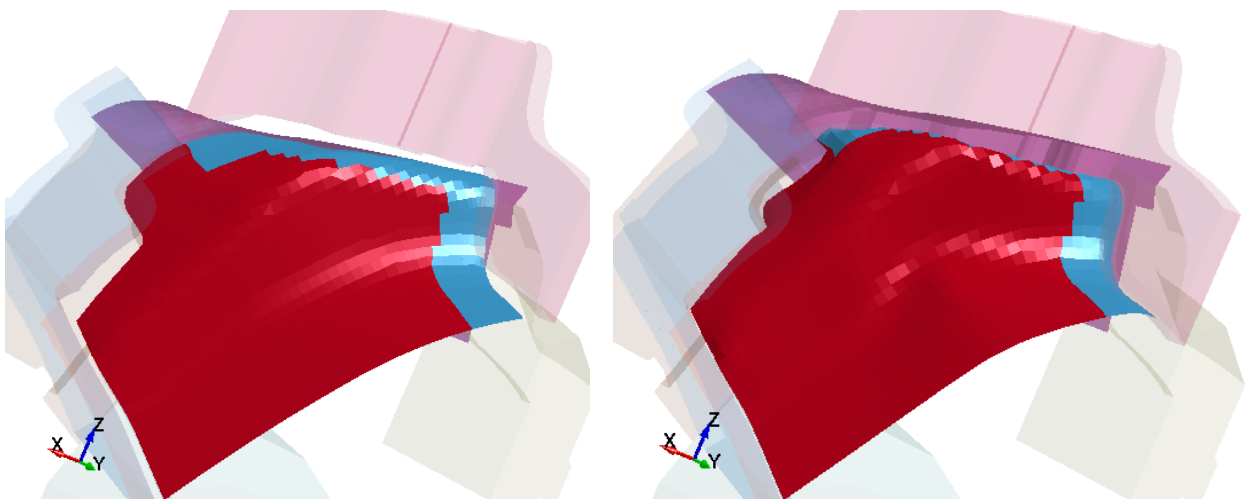*(Courtesy of Ford Motor Company)*

Figure 11. Scrap deformation of the by-pass trimming
(Courtesy of Ford Motor Company)

Mesh Refinement for Along Curves

During line die simulation, frequently the feature lines, for example, the hood break line separating class-A surface and secondary flange along a fender outer panel, has a relatively gentle curvature coming out of draw die. Mesh along this feature line is typically not refined enough going into the next stage of line die forming. A new feature utilizing keywords *DEFINE_CURVE_TRIM_3D [1] and *CONTROL_ADAPTIVE_CURVE can now be used together to refine the mesh along user defined curves in the same input for the line die

simulation. Mesh is refined in the beginning of the simulation, prior to tooling contact. Optionally, the refinement can be done alone, by setting ENDTIME to 0.0 in *CONTROL_TERMINATION, and the resulting dynain file can be used for further forming.

When the keyword *ELEMENT_TRIM is absent, the variable TCTOL (shown in Figure 12) in *DEFINE_CURVE_TRIM_3D is used to control the mesh refinement width. The variables of 'N' and 'SMIN' in *CONTROL_ADAPTIVE_CURVE define the levels of the adaptivity and minimum element size allowed. These variables give users options to refine mesh in the area needed and yet limit the number of elements going into the line die simulation.
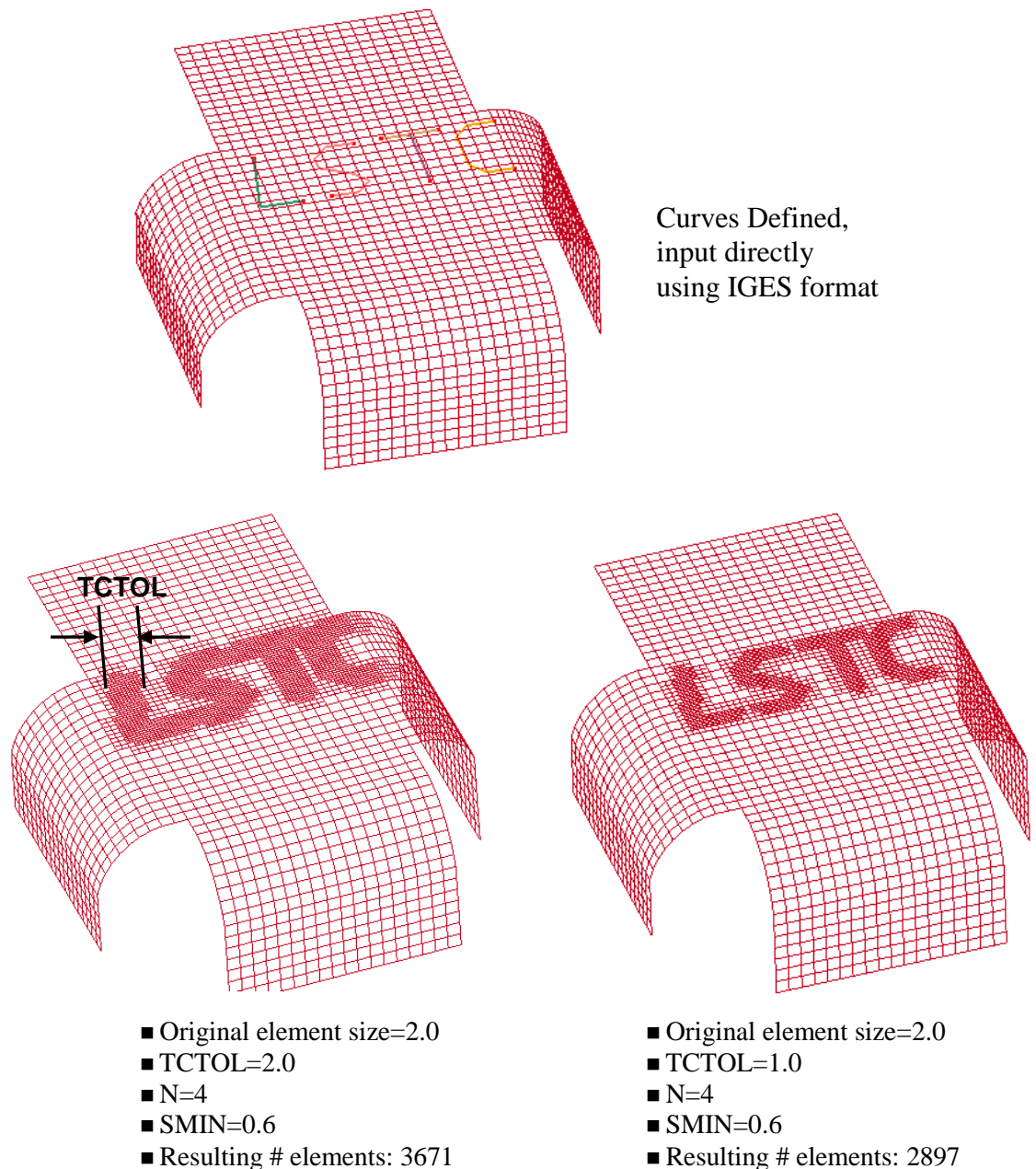

Curves Defined, input directly using IGES format

- Original element size=2.0
- TCTOL=2.0
- N=4
- SMIN=0.6
- Resulting # elements: 3671

- Original element size=2.0
- TCTOL=1.0
- N=4
- SMIN=0.6
- Resulting # elements: 2897

Figure 12. Mesh adaptivity along curves

This feature was developed in conjunction with Chrysler LLC, and is available in Metal Forming Application/eZ Setup/Flanging in LS-PrePost 4.0.

Conclusion

Working with engineers and researchers of the metal forming industry, LSTC has developed features to address issues in friction and necking failure under nonlinear strain path for Barlat 1989 yield criterion, both applicable to Aluminum sheet stamping. A new feature related to scrap trimming and shedding can potentially improve stamping plant productivity significantly. Finally, mesh pre-adaptivity along curves enables accurate and faster line die simulation. At LSTC, we are committed to advancing sheet metal forming simulation technology, benefiting our current and future users.

References

1) LS-DYNA User's Manual R6.0.0 (Volume I), ftp://user:computer@ftp.lstc.com/manuals.