Tube Adaptivity for Mesh Fission/Fusion in LS-DYNA®

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Abstract

A new feature named tube adaptivity for sheet metal forming is implemented in LS-DYNA. It conducts adaptive mesh fission/fusion at the beginning of an adaptive step according to a predefined load path and a set of user defined parameters. Automatically mesh refinement is carried out in the neighborhood of the tool path. Tube adaptivity can help in reducing the computational time of incremental forming or roller hemming while maintain the overall accuracy at the place of interest, which can be considered as a major improvement on the original box adaptivity in LS-DYNA.

Introduction

Sheet metal forming has been used in the industry for years for creating metal parts from a blank sheet metal, for example, automobile manufacturers and their suppliers produce many of the parts using sheet metal forming. In recent years, one particular type of sheet metal forming is referred to as incremental sheet metal forming, during which a sheet metal is formed into the final workpiece by a series of small incremental deformations. One example usage of incremental sheet metal forming is for production improvements of parts used in a prototyping or concept vehicle. Due to limited quantity of the concept vehicles (sometimes one), it is impractical to create stamping tools for various parts. Incremental sheet metal forming is generally employed. Generally, incremental sheet metal forming is conducted by connecting a forming tool to a CNC (Computer Numerical Control) machine, a robot or the likes. A load path of the forming tool is therefore predefined. With advent of computer technology, computer aided engineering analysis (e.g., time-marching simulation based on finite element analysis (FEA) technique) have been used for assisting engineers/scientists to design products and manufacturing procedures, for example, sheet metal forming process. In order to capture detailed physical behaviors at the vicinity of drastic changes, finer finite element mesh is required. One prior approach is to have a finer FEA mesh for the entire model. However, this technique requires unrealistic long computation time and much larger computational resources due to huge size of the FEA mesh model. Incremental metal forming process is very a very slow procedure, to numerically simulate such as a process sometimes requires many hours of computation time. As a result, prior art approaches are not adequate. It would, therefore, be desirable to have improved methods and systems for conducting a time-marching simulation for obtaining numerical physical behaviors of sheet metal during a sheet metal forming process having a predefined load path.

Originally in LS-DYNA, mesh fission/fusion associated with a predefined load path is accomplished by attaching two predefined boxes to a moving point in a fixed direction, which is not suitable when the motion is traced back. As an illustration, Figure 1 shows the mesh fission/fusion boxes attached to point P on the tool of the prescribed boundary. LS-DYNA defines that the box is in a fixed direction relative to the point. For instance, the user can define that the box is always on the left hand side of the point.

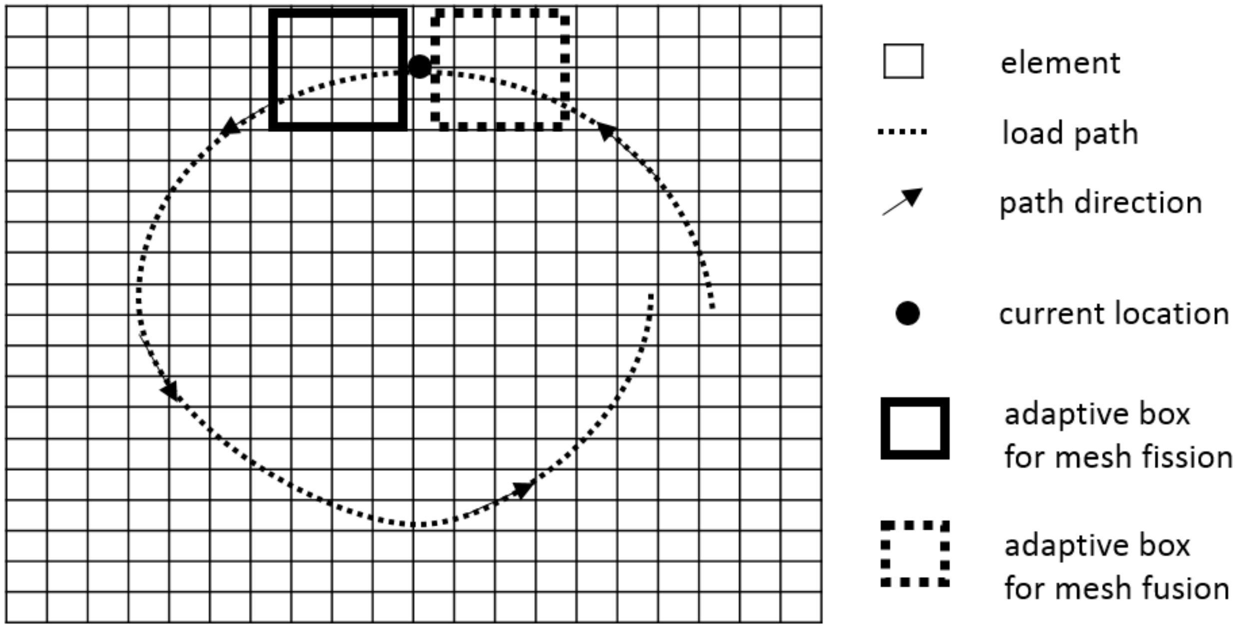


Figure 1: Adaptive boxes on a load path in the current LS-DYNA, mesh is refined in the front and coarsened in the back, which is desirable.

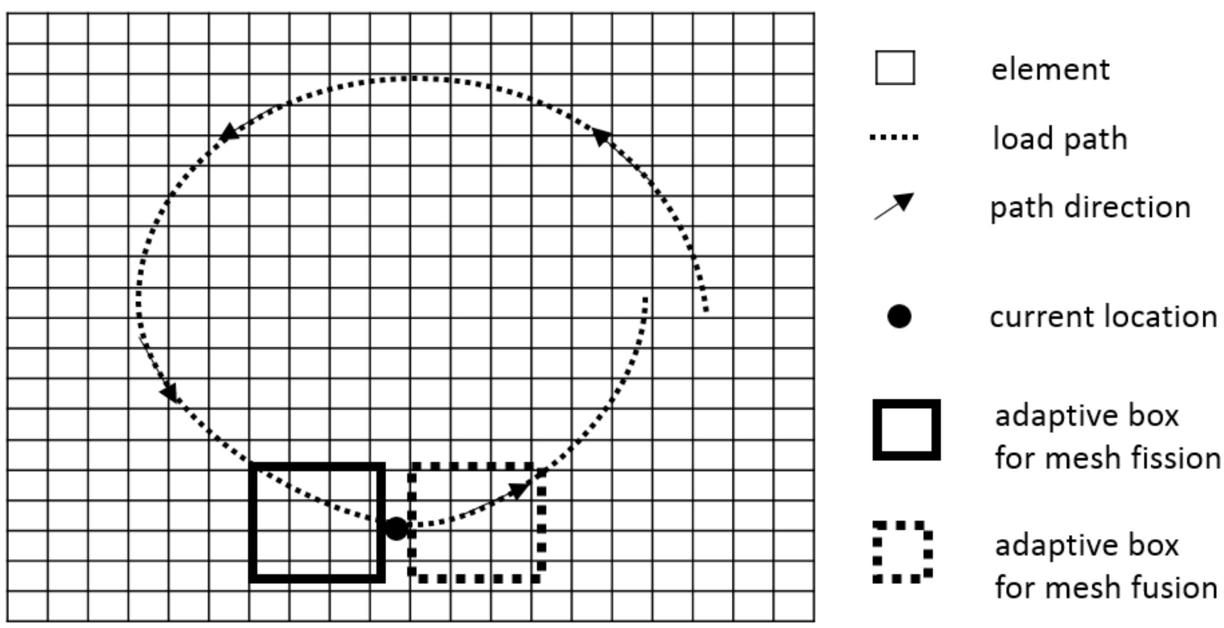


Figure 2: Adaptive boxes on a load path in the current LS-DYNA. Since the path is traced backward, the mesh is coarsened in the front and refined in the back, which is not right.

Wherever the point moves, mesh fission is always conducted on the left adaptive box and mesh fusion is unconditionally enforced on the right adaptive box. Therefore, when the point traces back, the mesh fission/fusion region is flipped, which is not correct, as shown in Figure 2.
To resolve this issue, a new mesh adjustment scheme is proposed and implemented in LS-DYNA. In the new scheme, the mesh is refined in the front of the loading path. The refinement region forms a closed tube with a given radius, whose length is determined by the adaptive interval. As an example, for a given trajectory of the moving point on the boundary, the mesh adjustment at two subsequent adaptive steps are shown in Figure 3 and 4.

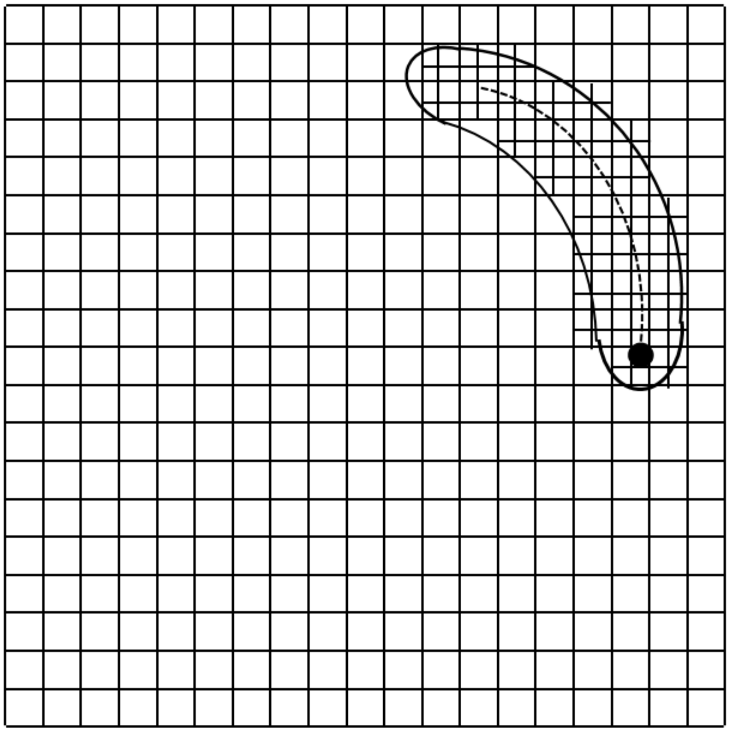


Figure 3. Refined meshes in the tube at the beginning of an adaptive step. The tube region is formed according to the prescribed boundary motion and the user defined radius.

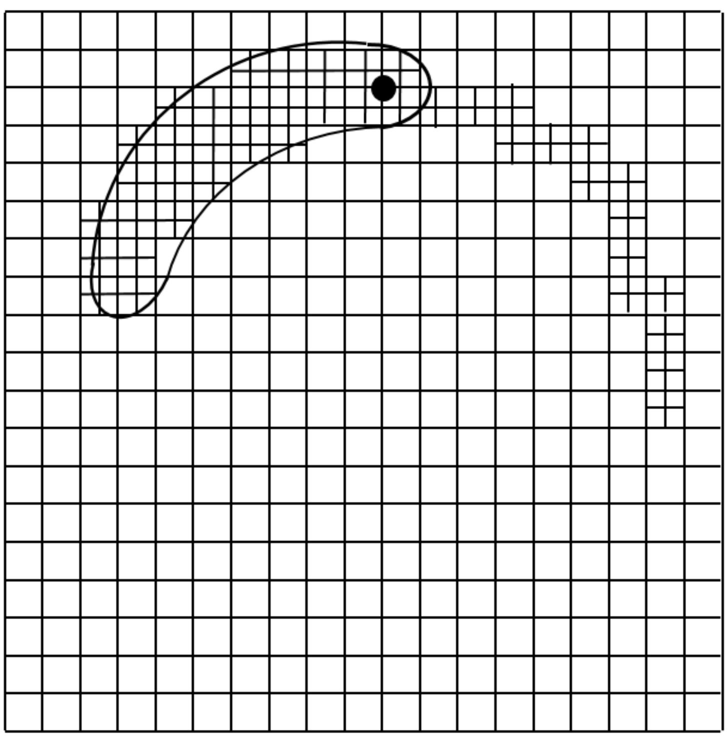


Figure 4: Refined meshes in the tube at the beginning of a subsequent adaptive step. The tube region is formed according to the loading path, adaptive time interval and the user defined radius. Notice that mesh coarsening is carried out outside the tube region, according to curvature of the elements.

This paper is organized as follows. First, the keyword to activate the tube adaptivity is provided. Then through an incremental sheet metal forming example, numerical investigations of the new feature are performed, including its accuracy, efficiency and reliability. Conclusion is drawn in the end.

Activating the New Feature

In order to activate the new feature, aside from the existing keyword *CONTROL_ADAPTIVE, a new keyword named *DEFINE_BOX_NODES_ADAPTIVE is to be included, as shown below:

```
*CONTROL_ADAPTIVE
$  ADPFREQ    ADPTOL    ADPOPT    MAXLVL    TBIRTH    TDEATH     LCADP    IOFLAG
      0.04       1.0         2         2       0.0      13.6         0         1
$  ADPSIZE    ADPASS    IREFLG    ADPENE     ADPTH    MEMORY    ORIENT   MAXEL
                   1         0       0.0       0.0
$  IADPN90    IADPGH    NCFREQ    IADPCL    ADPCTL    CBIRTH    CDEATH   LCLVL
        -1         0         4         0       0.8       0.0      13.6

*DEFINE_BOX_NODES_ADAPTIVE

$       ID      NODE       LCX       LCY       LCZ     ITYPE    RADIUS    NPIECE

         2    114116         1         2         3         2       6.0         8

$      PID     LEVEL

         7         2
```

The existing keyword *CONTROL_ADAPTIVE defines the adaptive time interval (ADPFREQ), which will also serve as the time interval for the tube adaptivity. The reader may refer to LS-DYNA keyword manual for the rest of the parameters in *CONTROL_ADAPTIVE.

Here we shall focus on the new keyword *DEFINE_BOX_NODES_ADAPTIVE, in which, NODE is the reference node user id; LCX, LCY, LCZ are the curve id defining the loading path, ITYPE defines the type of the curve; RADIUS is the radius of the adaptive tube; NPIECE defines the number of segments used to approximate the curved path in one adaptive step; PID specifies the part to be applied; LEVEL is the desired mesh level in the adaptive tube.

Numerical Investigation

To test the new feature, a number of simulations were carried out using an example of incremental forming, as shown in Figure 5. A rigid tool with predefined circular loading path will gradually form the Bank part upon a rigid Backing. The distance between the blank and the backing part is 0.6 mm. The dimension of the blank is 180 mm by 180 mm. Surface to surface contact are enforced for the two pairs Tool/Blank and Blank/Backing. A convergence study of the example is first carried out (without the tube adaptivity), to get the optimum mesh size to be used, minimum shell thickness and maximum effective plastic strain in the end of the simulation, which will serve as a guideline for the upcoming investigation. Based on results from the convergence study, the overall effect of the tube adaptivity feature and the best way to choose the parameters in the new keyword are investigated.

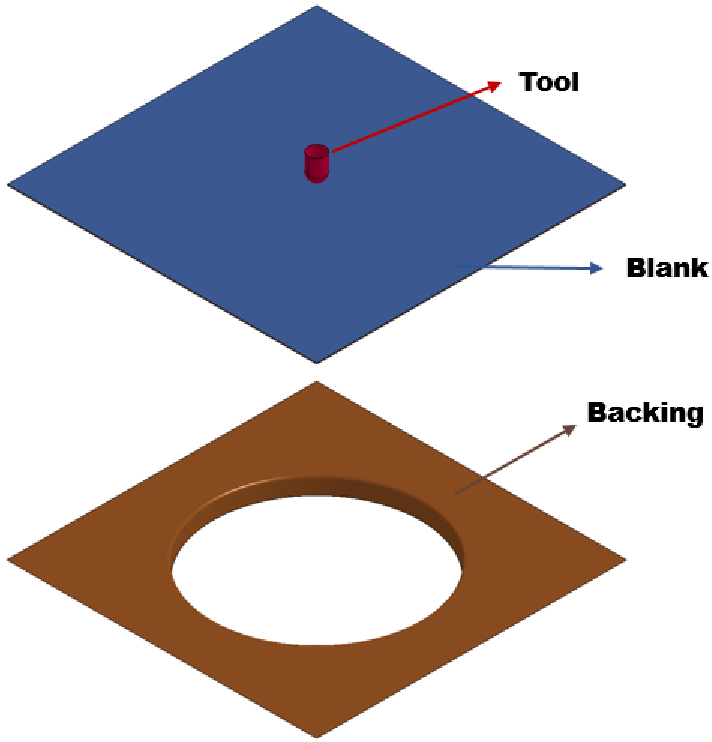
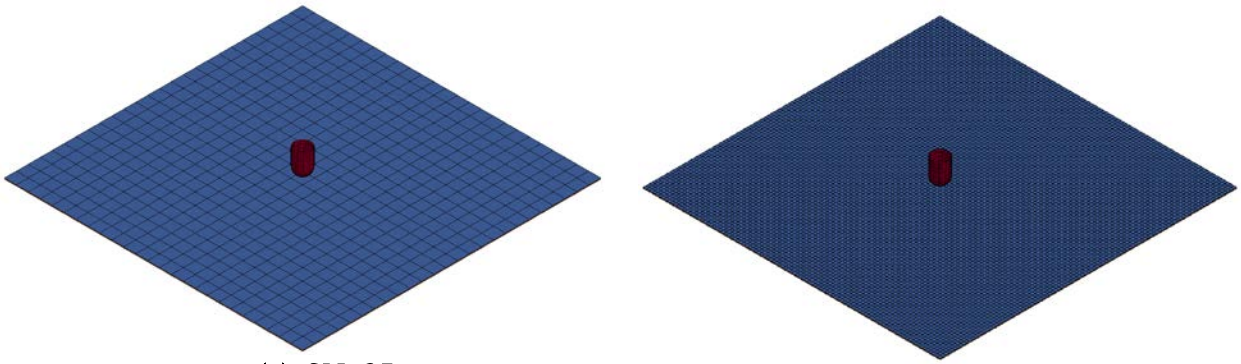


Figure 5. An example of incremental forming: The Tool and Backing are both rigid. Initially, the closest distance between the Blank and Backing is 0.6 mm. A circular loading path is prescribed on the Tool, which will form the Blank into desired shape upon the Backing.

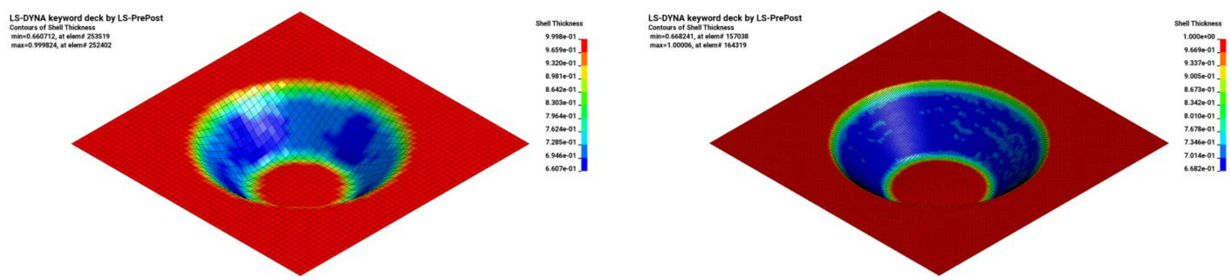
Mesh convergence study (shell thickness, effective plastic strain, simulation time)

A series of simulations are carried out, with different meshes of the blank. The square blank is uniformly discretized into quadrilateral elements, with the side division SN ranging from 25 to 300. Two different meshes with SN being 50 and 100 are given in Figure 6. As an illustration, several contours of the shell thickness and the effective plastic strains are shown in Figure 7 and 8. The minimum shell thicknesses and maximum effective plastic strains versus the number of side divisions in the blank at the end of the simulations are plotted in Figure 9 (a) and (b), respectively, from which, one can see that the problem approximately starts to converge with the number of side division being SN = 200, that is the mesh size being h = 0.9 mm. When the number of division is 200, the minimum shell thickness is 0.6682 mm and the corresponding maximum effective plastic strain is 1.311, which will be taken as the 'exact' solution of the problem. The simulation time is 38049 seconds (10 hours 34 minutes 9 seconds) with 32 MPP procs in an E5-2697 CPU.



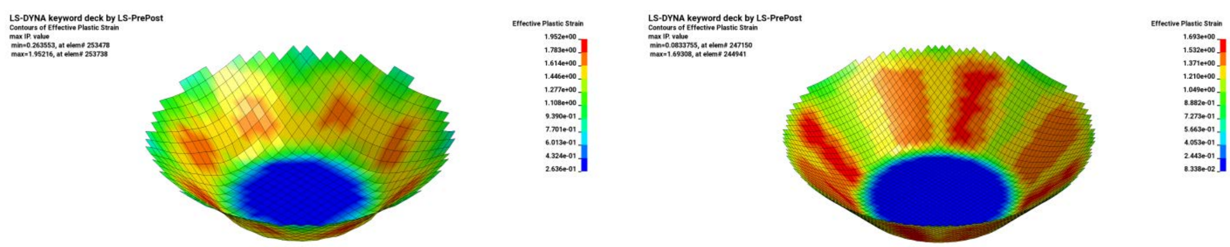
(a) SN=25 (b) SN=100

Figure 6. Different meshes of the blank, discretized into quadrilateral elements.



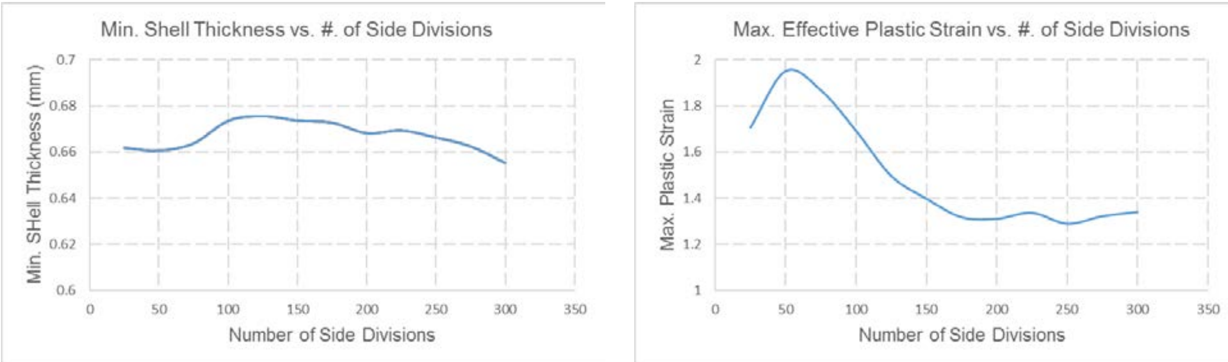
(a) SN = 50 (b) SN = 200

Figure 7. Contours for the shell thickness of the blank at the end of the forming processes.



(a) SN = 50 (b) SN = 100

Figure 8. Contours for the effective plastic strain of the blank at the end of the forming processes.

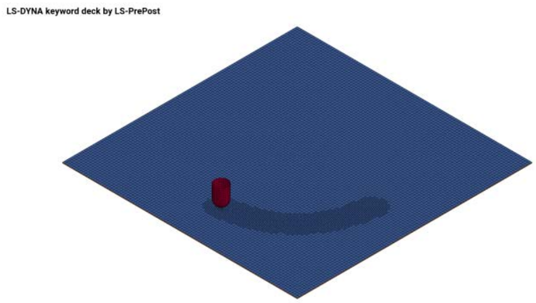


(a) Minimum Shell Thickness (b) Maximum Effective Plastic Strain

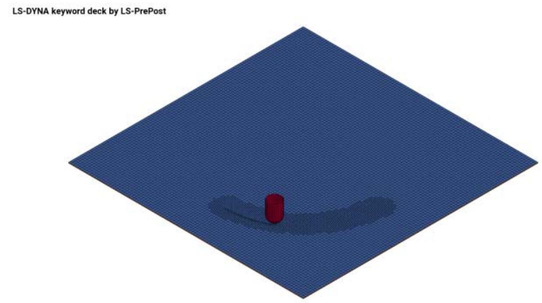
Figure 9. Different meshes of the blank, discretized into quadrilateral elements.

Effect of tube radius (accuracy and efficiency)

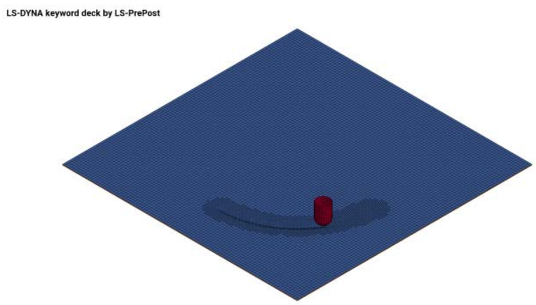
In this example, 2nd level mesh refinement is used in the tube. Thus to have a fair comparison, an initial mesh with side division SN=100 (h=1.8 mm) will be used for the simulations. First, a series of simulations are carried out, with tube RADIUS ranging from 2 mm to 16 mm. For all the simulations, the parameter ADPFREQ is as 0.04s, during which (one adaptive step), the loading path covers approximately 1/3 of a circle. The parameter NPIECE is set to be 8, such that the circular tube region is better captured. As an illustration, Figure 10 shows the meshes of the blank in the first few time steps.



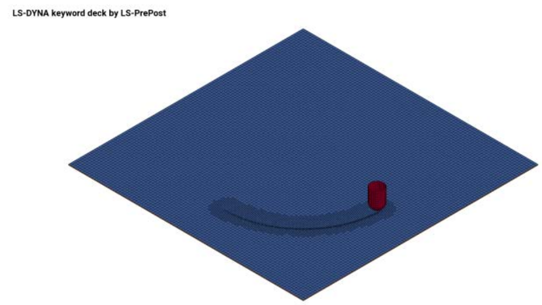
(a) t= 0.21 s



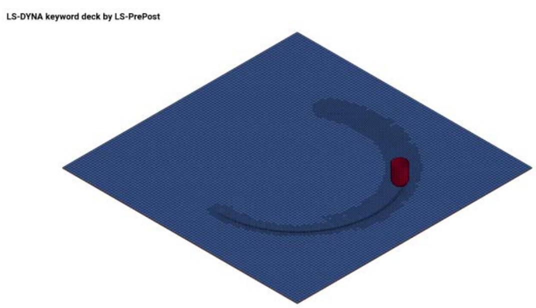
(b) t= 0.22 s



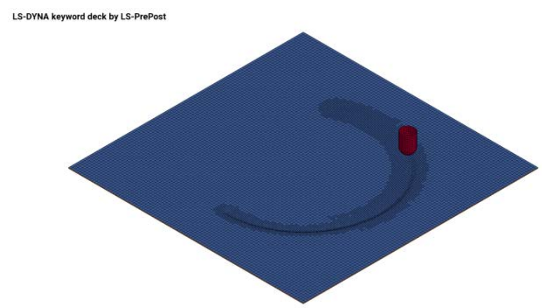
(c) t = 0.23 s



(d) t = 0.24 s



(e) t = 0.25 s



(f) t = 0.26 s

Figure 10. Time sequences of the adaptive meshes for the blank in the first few time steps. Mesh fission/fusion is conducted at the beginning of each time step. Fission is unconditionally enforced inside the tube, while fusion is conditionally applied outside the tube region.

The error percentages of the minimum shell thickness and maximum effective plastic strain, together with the simulation time reduction percentage for each case are summarized in Table 1. One can see that in general, the error in the minimum shell thickness decreases as the radius of the tube increases. When the tube radius is great than 8 mm, the error for the shell thickness is always less than 2%. The overall error for the maximum effective plastic strain is within 6%. The simulation time reduction decreases from 50% to 40% as the radius increases from 2 mm to 16 mm, which is not hard to understand. The larger the radius, the higher the number of elements is obtained during each adaptive step, leading to more computational cost. Overall, one should use a radius large enough to obtain result with acceptable accuracy while not too large as to reduce the computation cost. For the present example, a radius of 10 mm would be a good choice, which is around 5 times of the initial mesh size.

Tube RADIUS (mm)	2	4	6	8	10	12	14	16
Thickness (Difference in Percentage)	6.4	4.4	5.24	1.83	0.30	0.67	0.91	0.60
Effective Plastic Strain (Difference in Percentage)	1.83	3.97	4.73	4.81	3.43	5.26	4.20	6.10
Time Reduction (Percentage)	50.4	49.7	49.0	47.0	46.1	45.0	44.2	39.6

Table 1. The error percentages of the minimum shell thickness and maximum effective plastic strain, together with the simulation time reduction percentage for cases of different radius.

Effect of adaptive time interval

In tube adaptivity, the parameter RADIUS decides the diameter of the tube, while the length of the tube is determined by the adaptive time interval ADPFREQ. A series of simulations were carried out with adaptive time interval ranging from 0.02s to 0.12s and the corresponding parameter NPIECE changing 4 to 24. Other parameters are kept the same. On one hand, the larger the time interval, the less the number of adaptive time steps are to be performed, which seems that it will always reduce the total simulation time. On the other hand, larger adaptive time interval means inside each adaptive time interval, the size of the simulation model is relatively larger, which would otherwise increase the total simulation time. Thus, there should be an optimized adaptive time interval that provides the best option in terms of simulation time. The total simulation times are recorded in Table 2. One can see that the total simulation time decreases when ADPFREQ increases from 0.02s to 0.08s and increases afterwards, which clearly indicates an optimum adaptive time interval close to 0.08s.

ADPFREQ (s)	0.02	0.04	0.06	0.08	0.10	0.12
Simulation Time (s)	21404	20155	20500	20056	20090	20174

Table 2. The total simulation time versus adaptive time interval ADPFREQ.

Conclusion

A new feature of tube adaptivity for sheet metal forming is successfully implemented and available for use. Tube adaptivity enables adaptive mesh fission/fusion at the beginning of an adaptive step according to a predefined load path. A set of user defined parameters can be used to define the details of the mesh adjustment. Tube adaptivity can help in reducing the computational time of incremental forming by 50% while maintain the overall accuracy at the place of interest.