The Effect of Element Formulation on the Prediction of Boost Effects in Numerical Tube Bending

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Abstract. This paper presents advanced FE models of the pre-bending process to investigate the effect of element formulation on the prediction of boost effects in tube bending. Tube bending experiments are conducted with 3” (OD) IF (Interstitial-Free) steel tube on a fully instrumented Eagle EPT-75 servo-hydraulic mandrel-rotary draw tube bender. Experiments were performed in which the bending boost was varied at three levels and resulted in consistent trends in the strain and thickness distribution within the pre-bent tubes. A numerical model of the rotary draw tube bender was used to simulate pre-bending of the IF tube with the three levels of boost from the experiments. To examine the effect of element formulation on the prediction of boost, the tube was modeled with shell and solid elements. Both models predicted the overall strain and thickness results well, but showed different trends in each of the models.

INTRODUCTION

The pre-bending of tubular parts used for hydroforming is standard industrial practice for creating complex automotive structural components. By reducing the work done on a tube during pre-bending, improvements in hydroforming formability will occur [1,2].

It is important to understand the deformation which a tube undergoes during the pre-bending process. Mandrel-rotary draw tube bending has been shown to be an accurate method of pre-bending for components that are to be hydroformed [3, 4]. The application of increased levels of boost during the bending process has been shown (experimentally and numerically) to reduce thinning and major strains at the outside bend radius of a tube. The inside bend radius shows an increase in thickening and minor strains with increasing boost [1-3, 5]. This effect is due to additional tube material being forced into the bend region at higher boost levels.

In previous work, high boost (HB) numerical models have not been validated due to a lack of experimental data. Numerical models have been accurately validated for normal bends and low boost conditions using plane-stress shell element models [1-3]. The purpose of this work is to validate the HB models using plane-stress shell element models. This boost condition is important because of the potential improvement it can have on a tubes’ formability during hydroforming. In addition to plane-stress shell element models, a solid element model of the bending operation is also examined. The solid model approach is considered because of the recent work done by Simha et al. [6] on the Extended Stress-Based Flow Limit Curve (XSFLC) approach, which is a full three dimensional stress state failure criterion. Although, the tube bending operation is predominantly in the plane-stress regime, the subsequent hydroforming operation creates through-thickness stress components due to tube/die contact. The hydroforming numerical models require the stress history from the bending operation, thus the success of the failure criteria is dependent on the accurate modeling of the pre-bending operation.

This study was conducted using Interstitial-Free (IF) steel tube. Although IF steel has a low strength, it was selected for this study because a HB condition could be achieved in experimental bending. The tube considered had an OD of 76.2mm (3.0”) and an average wall thickness of 1.74mm.

Uniaxial tensile tests were conducted to extract the material properties of the IF tube. The tests were conducted on specimens cut along the longitudinal axis of a straight tube and at different positions along the circumference. Three levels of bending boost were


774
achieved experimentally and modeled for a bend with an R/D ratio (centre-line bend radius to tube diameter) of 2.0.

EXPERIMENTAL TUBE BENDING

Mandrel-Rotary Draw Tube Bending Process

The mandrel rotary draw tube bending experiments were conducted with a fully instrumented Eagle EPT-75 Servo Hydraulic tube bender at the University of Waterloo. The instrumentation is used to accurately control the bending process and provide valuable feedback on the boundary condition.

Figure 1 is a schematic of the tooling and loading conditions involved in the rotary-draw tube bending process. The process is accomplished by drawing the tube around the bend die with the tools shown in Fig. 1. A more detailed description of the process is given in [1-3,5].

To reduce the effect of the weld seam in bending and allow symmetry to be used during numerical modeling, the weld seam is always positioned vertically at the CLR.

Bending Boost

By changing the displacement of the pressure die relative to the arc length swept by the centre-line radius (CLR) of the bend die, a so called “bending boost” is applied. In a normal bend, the pressure die displaces the same distance as the arc length that is swept by the CLR. This is referred to as the “medium boost” (MB) case where the ratio of the displacements is 100%. The calculation for boost is shown below in (1),

$$\%Boost = \frac{Pressure\; Die\; Disp.}{Arc\; Length\; Swept\ by\ CLR} \times 100\%$$ (1)

Experimentally, three levels of boost were considered: “low boost” (LB) bends at 95.3%; MB bends at 100.3%; and, HB bends at 104.7%. The boost values were extracted from the data acquired through the instrumentation and taken as the average of approximately 10 bends.

To ensure that HB was achieved without the tube slipping relative to the pressure die, a boost collet was used to couple the end of the tube to the pressure die. The collet system is shown in Fig. 2.

Experimental Results

Strain and Thickness Measurement Convention

The engineering strain and thickness were measured from the locations on the pre-bent tubes, as shown in Fig. 3. The engineering strain was measured using circle grid analysis, while the thickness was measured with an ultrasonic gauge.

As shown in [2], it is expected that the outside of the bend region will show the greatest effect of bending boost on the strain and thickness distribution and will be examined for this work. The inside of the bend region was also examined, but due to the excessive wear in this region, the circle grid quality was too low for accurate strain measurements and only thickness was measured.
FIGURE 3. Strain and thickness measurement locations

The strain distribution for each boost case was measured from two tubes. The results were then curve-fit with a 6th order polynomial. The scatter in the measured strain data is roughly ±3.0% strain as indicated by error bars in Fig.4. Figure 4 shows the experimental results for the outside of the bend region strain of an MB bend case.

Results

Figure 5 shows the curve-fit experimental results of the strain distributions at the outside of the bend region for the three different boost conditions. The major strain is tensile, acts along the longitudinal direction of the tube, and is the sum of the membrane and bending strain. The minor strain is compressive and acts in the hoop direction of the tube.

The strain distributions in Fig. 5 show that an increase in boost reduces the major strain. To quantify the results, the average strain (εavg) for the steady state region of the bend (20°<θ<70°) is calculated.

FIGURE 4. Outside of the bend region strain distributions for an MB bend case

The average results can be found in Table 1. The minor strains are unaffected by boost and have an approximate value of $ε_{avg}=-0.09$ for all boost conditions.

The thickness distributions of the inside and outside of the bend regions are shown in Fig. 6. As expected, the outside of the bend region experiences thinning due to the tensile strain, while the inside of the bend region thickens due to the compressive strain. Increase in boost level results in a higher thickness on both the inside and outside of the bend. Similar to the average strain calculation, the average thickness ($t_{avg}$) and the % reduction in thickness are summarized in Table 1.

FIGURE 5. Outside of the bend region experimental strain distribution for all boost cases

FIGURE 6. Outside and inside of the bend region experimental thickness distribution for all boost cases
TABLE 1. Experimental strain and thickness results

<table>
<thead>
<tr>
<th>Boost Condition</th>
<th>Outside of the Bend</th>
<th>Inside of the Bend</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Average Major Strain ($\epsilon_{avg}$)</td>
<td>Average Thickness ($t_{avg}$)/% Reduction</td>
</tr>
<tr>
<td>LB</td>
<td>0.29</td>
<td>1.49 / 14.3%</td>
</tr>
<tr>
<td>MB</td>
<td>0.26</td>
<td>1.51 / 13.3%</td>
</tr>
<tr>
<td>HB</td>
<td>0.24</td>
<td>1.54 / 11.3%</td>
</tr>
</tbody>
</table>

NUMERICAL TUBE BENDING

Material Model

The material model used in the simulations was generated from uniaxial tensile tests. The specimens were cut along the longitudinal direction of the tube at different locations along the circumference, as shown in Fig 7. The 6 and 3/9 o’clock positions resulted in different curves due to the roll forming process [7]. The engineering stress-strain was converted to true stress-strain and curve-fit to generate an average curve. This curve was then converted to true stress vs. plastic strain up to 0.25 strain with an extrapolation up to 1.0 strain. The *MAT_PIECEWISE_LINEAR_PLASTICITY [8] material definition was used in the simulation and is shown in Fig 7.

Numerical Model

A numerical simulation of the mandrel rotary draw tube bending operation was developed using the explicit dynamic finite element code, LS-DYNA v970. Half-symmetry models were run to reduce computational requirements. The bender tools (Fig. 1) were modeled as rigid surfaces with 4-noded shell elements. The tooling meshes can be seen in Fig. 8.

The contact definition used between the tube and bender tools was *CONTACT_FORMING_ONE_WAY_SURFACE_T O_SURFACE [8]. The coefficient of friction (COF) used for the numerical models was determined from twist-compression tests that were performed on DP600 steel at the University of Waterloo. The pressure, clamp and bend die were unlubricated with $\mu=0.08$ while the lubricated wiper die had $\mu=0.04$. The mandrel COF was not tested experimentally and approximated at $\mu=0.06$.

The tooling loads and displacement histories used in the experiments were prescribed in the simulations. All models were bent to a final angle of 90°.

Shell Element Tube Model

The shell element tube model used Belytschko-Tsay plane stress fully-integrated (7 point) quadrilateral elements with a Von-Mises yield criterion. The tube is meshed with fine elements in the bend region and coarse elements outside of the bend region (Fig. 9). The elements within the bend region are approximately 2.4mm x 2.4mm which results in a total of 12,916 elements and 2.4mm x 7.1mm in the coarse region which produces 2,500 elements. The bend model was run over 30 milliseconds which resulted in 6.3 hours of processor time. An implicit springback simulation was run after bending.
Solid Element Model

For the solid element tube model, 8-noded constant stress solid elements were used. To create the solid element tube model, the shell element model was used and extruded to create the five through-thickness solid element tube model. This created a total of 77,080 elements. The bend model was run over 10 milliseconds which resulted in 14.2 hours of processor time. Implicit springback was run after bending.

Numerical Results

The engineering strain and thickness along the outside of the bend region and thickness along the inside of the bend region were manually extracted using the post-processor, LS-PREPOST at 10° increments from 0° to 90°. For the shell element model, the major and minor engineering strains at the appropriate shell surface (lower) and element thickness were extracted. For the solid models, the major and minor engineering strains were calculated by manually measuring the longitudinal and hoop dimensions at the appropriate solid elements. Thickness was also measured manually. The shell and solid model strain and thickness results are shown with the experimental data in Fig. 10 and Fig. 11.

Both the solid and shell model predicted the expected trend of reduced outside of the bend major strain distribution for increased levels of boost. Minor strain is unaffected by the level of boost for both models. The thickness distributions shows the expected trends for both models with reduced thinning at the outside of the bend and increased thickening at the inside of the bend with increasing boost.
NUMERICAL MODEL VALIDATION

To compare the results of the different element formulations against the experimental data, the average strain ($\varepsilon_{\text{avg}}$) and thickness ($t_{\text{avg}}$) were quantified for $20^\circ<\theta<70^\circ$ steady-state region as for the experimental data.

Strain Distribution

Figure 12 plots the major and minor strain ($\varepsilon_{\text{avg}}$) against the amount of boost. The ±3.0% strain error bars are included for the experimental results.

Both shell and solid models indicate the expected reduction in major strain with increasing boost. Both models under-predict the major strain. Overall, the major strain for the solid model indicates a better correlation to the experimental results than the shell model, but as the boost level increases, the solid results deviate from the experimental data, which is undesirable since HB is of significant interest. Although the solid models perform better according to Fig. 12, the non-steady-state portion for all of the boost curves between $60^\circ<\theta<85^\circ$ (Fig. 11) consistently show a decreasing trend that was not observed in the experiments. This trend is not observed for the shell models.

The observed “valley” (steady-state region) in major strain (Fig.5) for all boost cases of the experimental data is not captured in Fig. 12. By comparing the experimental and predicted major strain curves in Fig. 10 and 11, one can see that the predicted curves do not capture this “valley”. This trend is important because it represents local areas of greater strain which must be captured for successful modeling of failure in hydroforming. The “valley” effect could also be a result of the polynomial curve-fit used for the experimental strain distribution data.

The minor strain is generally unaffected by the level of boost as expected from the experiments. The shell model predicts the minor strain better than the solid model, but because the minor strain is low, the difference between the two is negligible. Both models under-predict the minor strain for all boost cases.

Thickness Distribution

Figure 13 plots the inside and outside of the bend region average thickness ($t_{\text{avg}}$) against the level of boost. It should be noted that the initial thickness used in both numerical models (1.74mm) is an average that was measured over multiple points of the circumference for an unbent tube. Therefore, the initial tube thickness at the 3 (inside of the bend) and 9 o’clock (outside of the bend) positions (Fig. 7) is slightly different than 1.74mm.

The thickness prediction for the outside of the bend region using shell elements has a better correlation.
with the measured data. The shell model thickness
trend slightly deviates with increasing boost. The
solid model trend does not match the measured trend,
but converges at higher boost.

For the inside of the bend region, the shell model
indicates an overall better prediction than the solid
model. The shell model predicts the trend correctly
with an increase in thickening of approximately
0.04mm for all boost levels. The solid model shows
increasing deviation from the experimental results
with an under-prediction at low boost to over-
prediction at high boost. Since the inside of the bend
region is not as prone to hydroforming failure, the
result is acceptable.

CONCLUSIONS

The following conclusions can be made:

- The application of increased boost in the
  experiments shows that the major strain at the
  outside of the bend is reduced. The minor strain
  is unaffected by boost. The thinning at the outside
  of the bend is also reduced while the inside of the
  bend thickens with increasing boost. These trends
  are advantageous for subsequent hydroforming.

- For the outside of the bend region, the solid model
  predicts the major strain better than the shell
  model, but deviates as boost increases. Both shell
  and solid models under predict the minor strain.
  For $60^\circ < \theta < 85^\circ$, the solid model does not
  accurately predict the trends of the experimental
data.

- The “valley” in major strain on the outside of the
  tube is not captured by either of the numerical
  models. This may be due to the polynomial used
  for the curve-fit.

- The thickness reduction at the outside of the bend
  region is predicted well at MB and HB by both
  models.

- The inside of the bend thickness is over predicted
  by the shell model and follows the experimental
trend. The solid model predicts the thickness
  change well but shows increasing deviation as
  boost increases.

- Accurate coefficients of friction need to be
determined experimentally for the IF steel and
  incorporated into the numerical models as this
  may affect how they perform.

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