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Taco Holder Laboratory Project

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Taco Holder Laboratory Project

Abstract

In this project, undergraduate mechanical engineering students designed and executed a laboratory exercise to fabricate a taco holder using 22 ga. (0.031 in.) stainless steel sheet metal. The taco holder, measuring 10 in. by 4 in., features three 60-degree bends, each spaced 2.5 inches apart. The primary objective was to develop a repeatable laboratory procedure that introduces students to the principles of sheet metal bending, including force measurement, springback compensation, and the influence of tool geometry on final part accuracy. This paper describes the complete process, from equipment modification to experimental validation and simulation, providing a comprehensive framework for future educational use.

The scientific goal of the taco holder lab was to investigate the behavior of sheet metal during v-bending, focusing on how parameters such as applied force, v-die geometry, and punch configuration affect material deformation, springback, and overall product quality. By using a taco holder as a prototype, the project connects modeling with hands-on fabrication, offering insights into the practical challenges when translating simulation outputs into manufacturing.

To perform the bending operations, students modified a 60-degree press brake attachment to fit a hydraulic shop press. These modifications included cutting the die to a 1-ft length, altering the bottom tab design, and drilling mounting holes to ensure the die was securely attached to the press. This setup facilitated the creation of consistent bends while allowing for precise measurement of applied forces. An Imada digital force gauge was integrated into the punch and die assembly to monitor the force required for each bend. Calculations determined that a bend allowance of 0.9 in. was necessary to account for material stretching, and a force of 1,184 N was required to achieve the desired bend angle for the stainless steel sheet.

A key challenge during the fabrication process involved determining the bend sequence. Given the proximity of the three bends, maintaining adequate clearance was crucial to ensure accurate and consistent bending. After evaluating multiple approaches, students found that initiating the bends from one end and proceeding sequentially yielded the best results, preventing interference and ensuring accurate angle formation. In addition to the physical fabrication, students modeled the taco holder using SOLIDWORKS and performed simulations of the bending process using Ansys Mechanical's Static Structural Analysis system. The experimental bending forces were compared with theoretical predictions and Ansys simulations, allowing students to evaluate the accuracy of computational models against real-world data.

The paper includes a detailed tutorial for Ansys simulations and the new laboratory manual developed during the project, both of which are provided as appendices. This paper describes the laboratory's implementation, the technical challenges encountered, and the quantitative results from both experimental and simulated analyses. It also assesses student learning outcomes, engagement, and feedback, highlighting how the project enhances understanding of sheet metal forming processes and the practical considerations involved in manufacturing complex geometries.

Introduction

Sheet metal bending is a cornerstone of modern manufacturing, playing a critical role in industries ranging from automotive to consumer electronics. Among the various bending techniques, v-bending stands out for its versatility and precision. In v-bending, a punch presses a flat sheet of metal into a V-shaped die, inducing controlled plastic deformation to achieve the desired bend angle. As Groover[1] emphasizes, this method is essential for transforming flat stock into components with exact geometries and tolerances.

A central challenge in v-bending is managing the material's elastic recovery, known as springback. When the bending force is removed, the metal tends to partially revert toward its original shape, often resulting in deviations from the intended angle. Research by Eltantawie[2] and Kumar et al.[3] has shown that accurate prediction and compensation for springback are vital for ensuring product precision. To address this, the applied force must be calibrated carefully so that it not only achieves the desired bend but also overcomes the inherent elastic resistance of the material, as detailed by Salem and Meslameni[4].

Key parameters influencing the v-bending process include the geometry of the V-die, the thickness and material properties of the sheet metal, and the magnitude of the applied force. Each factor directly affects the final bend quality—impacting aspects such as bend radius, angle accuracy, and surface integrity. An optimized bending process must consider these parameters to minimize waste, improve consistency, and ensure that the finished parts meet stringent quality standards.

This project was developed to immerse students in the intricacies of sheet metal bending through a practical, hands-on lab experience. By fabricating a taco holder, students are guided through a complete manufacturing cycle—from cutting a flat sheet to executing multiple precise bends. The lab emphasizes the measurement of key process variables, including the force and displacement of the V-bending punch, enabling students to collect and analyze graphical data for each bend. This data-driven approach not only reinforces theoretical models—such as bend allowance calculations and springback compensation—but also highlights the real-world challenges of achieving repeatable and accurate manufacturing outcomes.

In essence, this project bridges the gap between theory and practice, providing students with a robust understanding of material behavior and process dynamics in sheet metal bending. By engaging directly with the equipment and processes, students gain valuable insights into the optimization and quality control measures that are indispensable in industrial manufacturing.

Method of Approach and Evaluation

Students began by defining the design criteria for a taco holder that is functional and manufacturable. Prior to experimentation, students reviewed principles of material science and mechanics of deformation to form expectations about how sheet metal behave under bending conditions. Students ensured that settings for hydraulic pressure, punch speed, and v-die alignment were optimized. Students conducted a series of experiments where they varied key parameters such as force and bending speed to observe their impact on the bend quality and material behavior. Based on observed outcomes, students refined their process parameters to achieve more accurate and consistent results.

The final taco holder products were evaluated for geometric precision, uniformity of bends, and repeatability. The lab was evaluated on its ability to enhance critical thinking through real-time troubleshooting. Student feedback was gathered to assess the perceived value of real-world interaction versus simulation tools like Ansys. The outcomes were compared with those from modeling labs, emphasizing the learning from handling materials and machinery.

Theory

The v-bending process is a fundamental technique in sheet metal forming, where a punch forces the metal into a V-die to create a permanent bend. In the context of fabricating a taco holder, this process not only demonstrates basic principles of metal deformation but also serves as a project that connects theoretical models with hands-on manufacturing practice. In this section, we detail the key equations governing bend allowance, springback, and the v-bending force, providing a framework for predicting and controlling the bending process.

Bend allowance is the length of the arc along the bend line that accounts for the material's deformation during bending. This equation helps in determining the developed length of the sheet metal before bending, ensuring that the final product meets the design specifications. It is given by the equation $A_b = (\pi\alpha / 180)(R + K_{ba}\, t)$ where $\alpha = 180 - \alpha_b'$ (degrees) is the bend angle, R (mm) is the bend radius, K_{ba} (equal 0.5 if $R > 2t$) is a factor to estimate stretching and t (mm) is the sheet metal thickness, see Groover[1] and Kalpakjian and Schmid[5]. In this case where the taco holder has three 120-degree bends, we have a total bend allowance

$$A_b = (3 \cdot \pi \cdot 120° / 180°)(3.175 + 0.5 \cdot 0.7874) = 22.4\ mm = 0.882\ inch \quad (1)$$

Springback is the elastic recovery of the material after the bending force is removed, resulting in a slight change from the intended bend angle. We define springback as

$$SB = \alpha' - \alpha_b' \quad (2)$$

Where α' (degrees) is the included angle of the finished sheet metal part and $\alpha_{b'} = 60$ degrees is included angle of the bending punch tool, see Figure 1.

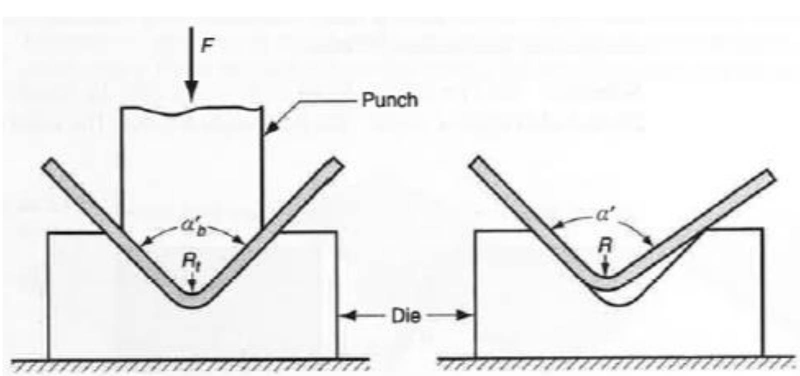

Figure 1. Springback in bending, from Groover[1].

The force required for v-bending is determined by the interplay of material properties, sheet thickness, and die geometry. This equation is derived from the balance of moments and forces required to plastically deform the metal, accounting for the constraints imposed by the die geometry and the inherent material resistance to bending . The bending force can be determined from

$$F = K_{bf}\, TS\, w\, t^2 \,/\, D = 1.33 \cdot 587 \cdot 101.6 \cdot 0.7874^2 \,/\, 26.1 = 1884\ N \tag{3}$$

where K_{bf} = 1.33 for V-bending is a constant accounting for differences in an actual bending process, *TS* is ultimate tensile strength of the stainless-steel sheet metal, *w* is width of the part in direction of the bend axis and *D* is the dimension of the die opening.

Experimental Set-Up

The experimental setup is designed to be adaptable to a variety of shop environments, allowing similar outcomes using different tools and techniques. While this project utilizes a hydraulic shop press and specialized measurement equipment, the core processes—cutting, bending, and data collection—can be replicated with alternative methods that are accessible to many shop facilities. This flexibility encourages students to think creatively and explore multiple approaches to achieve the same manufacturing goals.

Material Preparation

Students begin by cutting a 9.5 in. x 4 in. piece of 22-gauge (0.031 in.) stainless steel sheet metal. In this setup, a bandsaw is used for cutting; however, other cutting tools can achieve similar results. For example, facilities with a sheet metal shear can quickly produce clean, straight cuts, while those without advanced equipment may use aviation snips for manual cutting. For higher precision, waterjet or laser cutting systems can be used if available. Alternatively, for readers working with plastic sheets to produce a similar taco holder, a plastic sheet can be cut with a fine-toothed saw, a hot knife, or a CNC router.

Bending Process

The bending process in this experiment is performed using a pneumatic-assisted hydraulic shop press with a 60-degree v-punch and die assembly. The die has a 60-degree v-groove, is 12 inches long to accommodate the full length of the sheet, and the punch is similarly 12 inches long with a 1/8-inch radius edge to ensure consistent bends while minimizing material damage. However, these specific tools are not required to complete the project.
In workshops without access to a hydraulic press, several alternative bending methods can be employed:

- A hand-operated press brake can provide sufficient force to bend thin sheet metal.
- A box-and-pan brake or other sheet metal bender can produce clean, repeatable bends.
- For smaller-scale operations, a sturdy bench vise combined with v-shaped angle iron can approximate the die and punch geometry, enabling accurate manual bending.

- For facilities using thermoplastics instead of metal, a thermal strip heater or similar plastic sheet bender can soften the material for precise bends. While plastic achieves the same taco holder shape, it does not exhibit the same springback behavior or force-displacement relationship, thus limiting the pedagogical value related to mechanical deformation.

Positioning and Accuracy

To ensure consistent and repeatable bends, mechanical offsets are used to position the sheet metal relative to the die centerline. For the first and third bends, an offset of 3.166 inches from the die center is used, while the second bend is positioned at 6.333 inches. These offsets ensure uniform spacing between each bend. In environments where precise offsets cannot be mechanically set, markings on the sheet metal or physical stop blocks can be used to maintain positional accuracy.

Since the taco holder requires three closely spaced bends, the order of operations is critical. This project adopts a sequential bending approach, beginning at one end and working toward the other. This sequence ensures sufficient clearance for each bend and reduces handling errors. Students using different bending setups should consider their specific machine's clearance and workspace when determining the optimal bending sequence.

Data Collection

Force and displacement measurements are crucial for analyzing the bending process and comparing experimental results with theoretical predictions. In this project, an Imada digital force gauge is mounted between the press and punch to record the force applied during each bend. Data is collected using Force Recorder Standard software and exported to an Excel spreadsheet for analysis. A displacement gauge is also mounted to measure the vertical travel of the punch. This data enables the creation of force vs. displacement graphs for each bend, providing insights into material deformation and springback.

For those without access to a specialized force gauge, alternative force measurement methods include:

- Standard load cells paired with data acquisition systems can accurately measure bending forces.
- Analog force gauges, while less precise, can still provide useful measurements.
- In the absence of direct measurement, theoretical calculations based on material properties and punch geometry can estimate the required bending force.

Similarly, displacement can be measured with alternative tools, including:

- Simple dial indicators can track punch travel accurately.
- After each bend, digital calipers can measure the depth of deformation manually.
- For advanced setups, linear potentiometers connected to a data logger provide continuous displacement readings.

Ansys Mechanical Simulations

An Ansys Mechanical simulation for the bend is important to predict the deformation of the sheet metal, bending force parameters, stress on the sheet metal after the bend, and spring back angle that deviates from the bend angle due to elasticity. This analysis is preferably done before the experimental fabrication of the Taco-Holder to assist with making predictions of the force requirements and the durability of the finished part.

Three Ansys simulations were completed for the taco holder project to give results for the three bends on the sheet, see Figure 2. First bend at one end, second bend inverted in the middle and third bend at the other end of the sheet.

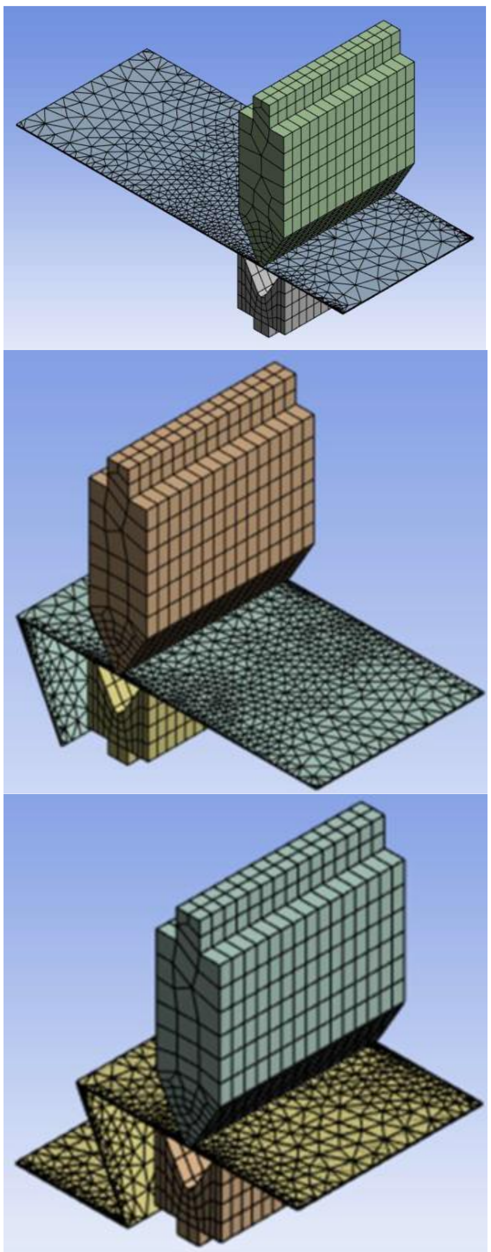

Figure 2. Finished mesh for punch, die and sheet assembly for three bends

Results from the Ansys simulation are compared with those from the theory session to ensure comprehensiveness of data and estimate tolerance for the finished part. The predicted spring back from the Ansys simulation were 0.8602º, 0.5291º, and 0.1803º respectively with an average of 0.5232º, which compares to the theoretical value 0.75º (as calculated in the Theory section of Appendix 2) with a difference of 30%.

Results

From the results of each bend, see Figures 3-5, we can compare how similar they are to each other and see how each bend follows similar force vs displacement patterns. Each bend should take the same amount of force to complete each bend and allow for limited spring back to occur to produce the correct angle. Unfortunately, the press brake does not allow for a shut-off once a certain force is reached so, each bend will have a different max force applied to it. To ensure spring back is neglected we had to put more than 1884 N of force on each bend.

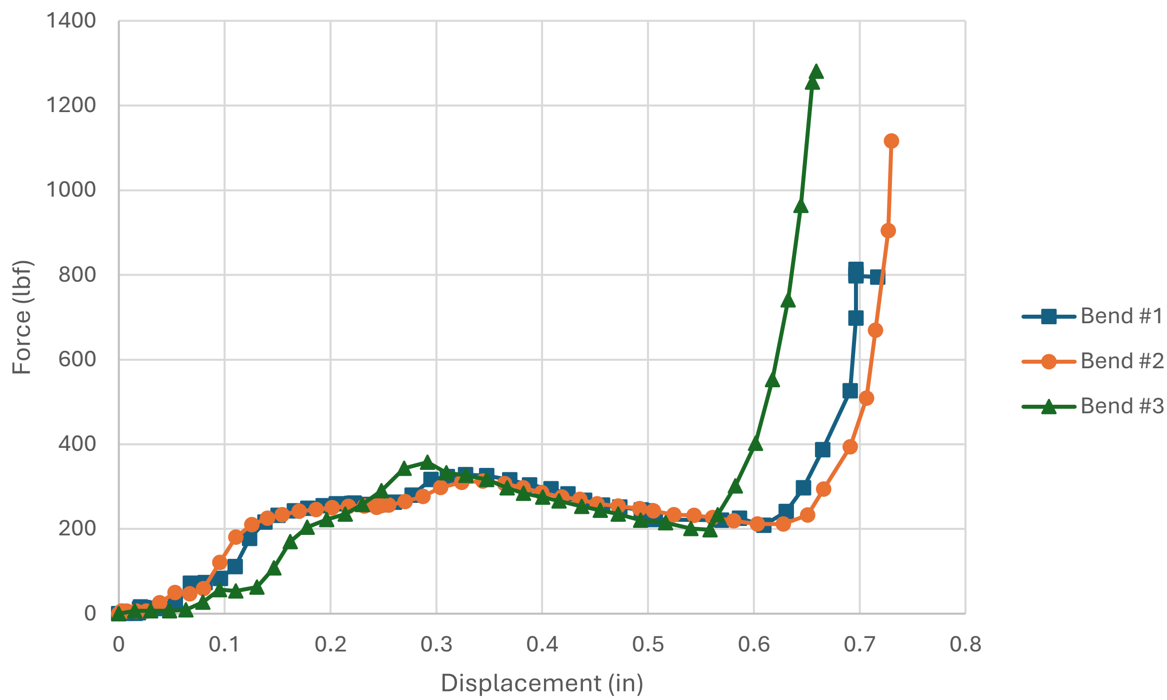

Figure 3. Force versus punch displacement for bend #1 – bend #3.

Student Involvement

Students involved with the project learned valuable skills in relation to experimenting and developing labs. They had the opportunity to compare theory, simulated and experimental measurements which backed up what they learn in classes. The students also had the chance to apply knowledge they had gained in classes such as Mechanics of Materials, and Manufacturing Processes.

The students were given a purchased taco holder to emulate. The first step in this project was to figure out the length of the stainless-steel sheet that was needed. This was done through trial and error and comparing each attempt to the original using scrap metal. The students' first attempts at bending the sheet involved drawing lines where each bend needed to be and lining it up with the punch and die by hand. This method led to bends that were not perfectly aligned and caused the taco holders to be wobbly on a flat surface.

The students brainstormed ideas on how to more accurately bend the sheet and get a stable taco holder. The idea that they came up with was to create a jig. The jig was a precisely cut L beam that was flush against the die, and the sheet would be placed flush against the L beam. This reduced the error from lining up the sheet by hand and resulted in less wobbly taco holders. There were also issues with the metal not being cut precisely and the students brainstormed a plan to improve the accuracy of the cuts. The simple solution was to just use a vertical band saw to cut precisely the dimensions that were needed.

Students also gained experience using Ansys Mechanical to simulate the bends of the taco holder. They were able to model the punch, die, and sheet in SOLIDWORKS, and simulate the bend in Ansys to determine the simulated spring back. They also took the data from each bend, modeled a bent sheet in SOLIDWORKS and performed the second and third bends using this process.

Student Engagement and Learning

In this innovative project, students immersed themselves in a hands-on learning experience by designing and fabricating a taco holder. The project was structured around the practical application of a v-die combined with a hydraulic press, transforming raw sheet metal into a functional and aesthetically pleasing taco holder.

Students were actively involved from the outset. They began by researching and sketching design ideas, which helped them understand the principles of geometry and ergonomics necessary for a functional taco holder. Once a design was finalized, they moved into the practical phase:

- Students discussed material choices and layout plans. This collaboration encouraged peer-to-peer learning and critical thinking.
- Each student had the opportunity to operate the hydraulic press. They adjusted the v-die setup, experimented with different order of bending, and observed firsthand how variations in pressure affected the metal's deformation.
- As challenges arose—such as ensuring uniform bends and preventing metal warping—students experimented with adjustments to machine settings and die positions, fostering an iterative approach to problem solving.

The taco holder project was more than a fabrication exercise; it was a lesson in the principles of sheet metal bending:

- Students learned how the v-die’s geometry influences the bend radius and overall shape of the metal.
- Operating the hydraulic press taught students about force application, pressure, and the importance of consistent feed rates.
- Through observation and measurements, students understood how sheet metal responds to stress.
- The project highlighted the need for precision in measuring, cutting, and bending, reinforcing attention to detail.

The taco holder lab goes beyond modeling exercises by providing students with a hands-on experience that bridges the gap between simulation and real-world manufacturing. While tools like Ansys Mechanical are excellent for predicting behavior through numerical models, this lab immerses students in the physical process of sheet metal fabrication:

- Students witness how sheet metal behaves under force. They experience phenomena such as springback and material deformation, which are critical for understanding real-world manufacturing tolerances.
- Operating a hydraulic press and a v-die and punch develops essential skills in machine handling.
- Students take a design concept and turn it into a physical product.
- Working with machinery and sharp metal pieces reinforces the importance of safety protocols.

Student Assessment

This project was incorporated into the fall 2024 Manufacturing Processes course, contributing 15% of the final grade. Students were evaluated through three progress reports and a final written report, which included an abstract, theory, results, conclusions, references, a lab manual for future classes, and an Ansys tutorial.

The project directly supported Outcome C of the course: "Discuss and explain machining." Through hands-on experience with press brakes and measurement tools, students applied engineering analysis to real-world manufacturing. Additionally, the use of Ansys for simulations provided valuable skills applicable to their future careers.

By reproducing this project, future students can enhance their understanding of machining processes, improve efficiency through simulation-based adjustments, and gain practical experience comparing experimental results with theoretical predictions.

Table 1: Manufacturing processes course inventory for university student learning outcomes

OUTCOMES	Significant	Moderate	Minimal
Intellectual Pursuit			
ABET: An ability to identify, formulate, and solve complex engineering problems by applying principles of engineering, science, and mathematics.		**X**	
Discuss and explain casting processes.	**X**		
Discuss and explain hot and cold working of metals.		**X**	
Discuss and explain joining: soldering, brazing and welding bonding.	**X**		
Discuss and explain machining.	**X**		
Discuss and explain plastic processing: molding and extruding.	**X**		

Conclusion

This project successfully demonstrated the principles of sheet metal bending through theoretical calculations, experimental procedures, and simulation using Ansys Mechanical. The project allows students to familiarize themselves with Anys and be able to complete simulations of the bends to allow for theoretical results before the experimental aspect of the project is completed. It also allows students to gain valuable hands-on experience in measuring, cutting, and bending operations. Students are able to see manufacturing processes worked out and understand how to enhance each procedure. By measuring force and displacement data, students will be able to compare the results of the process of each bend and see how the experimental aspect of the process corresponds to the theoretical side and simulations.

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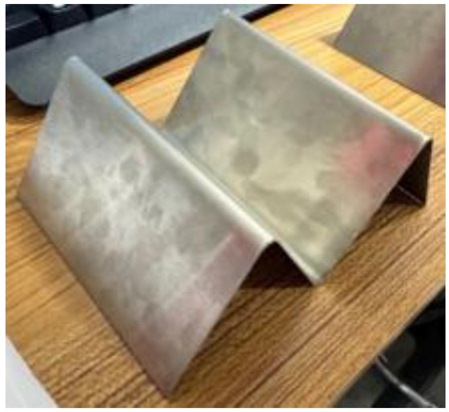
5. Kalpakjian, S. and Schmid, S.R., Manufacturing Processes for Engineering Materials. 4th Ed., Prentice Hall, 2003.

Appendix 1: Lab Manual for V-Bending Project

Manufacturing Processes
<u>Taco Holder V-Bending Lab</u>



Introduction

In this lab you will create your own taco holder from 22 Ga. (0.031 inch) thick stainless-steel sheet. A rectangle will be cut out of a larger piece of sheet metal with a band saw. A brake press with a punch and die attached will then be used to make three bends to form the taco holder. Your creation will then be compared to the original.

Length: *9.5 inch*
Width: *4 inch*
Bend Angle: *60 degrees*

Equations and Theory

Bend allowance is defined as:

$$A_b = (\pi\alpha / 180)\,(R + K_{ba}t) \tag{1a}$$

Where $\alpha = 180° - \alpha_b'$ (degrees) is the bend angle, R (mm) is the bend radius, K_{ba} (0.5 if $R > 2t$) is a factor to estimate stretching and t (mm) is the sheet metal thickness. In this case where the taco holder has three 120-degree bends, there's a *total* bend allowance of:

$$A_b = ((3 \cdot \pi \cdot 120°) / 180)\,(3.175 + 0.5 \cdot 0.7874) = 22.4\ mm = 0.882\ inch \tag{1b}$$

Springback is defined as:

$$SB = (\alpha' - \alpha_b') / \alpha_b' \tag{2}$$

Where α' (degrees) is the included angle of the finished sheet metal part and $\alpha_b' = 60$ degrees is the included angle of the bending punch tool.

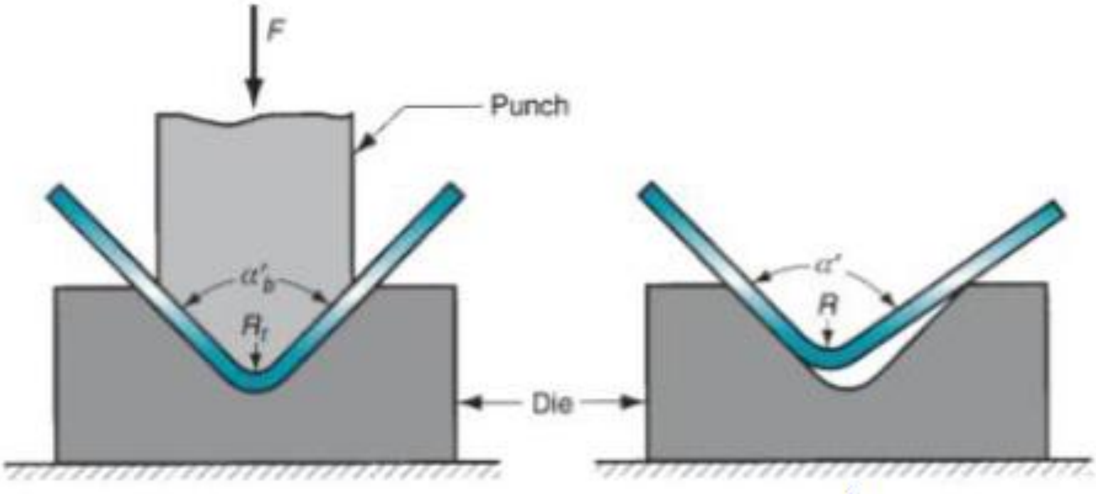


Figure 1: Springback in bending, from Groover[1]

The bending force can be determined from:

$$F = K_{bf} TS w t^2 / D \quad (3a)$$

$$F = 1.33 \cdot 587 \cdot 101.6 \cdot 0.7874^2 / 26.1 = 1884.23\ N = 423.59 \text{ lbf} \quad (3b)$$

Where K_{bf} = 1.33 for V-bending is a constant accounting for differences in an actual bending process, *TS* is ultimate tensile strength of the stainless-steel sheet metal, *w* is width of the part in the direction of the bend axis and *D* is the dimension of the die opening.

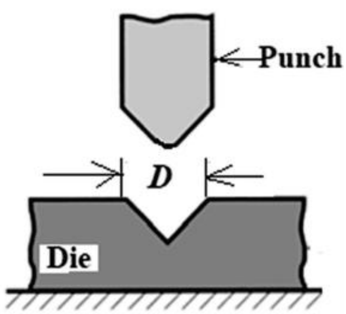


Figure 2: Die Opening dimension D, from Groover[1]

Setup

1. **Make sure to wear safety glasses at all times.**
2. Take a picture of all the tools and the equipment that are being used to complete this lab. Use the sheet of 22 Ga. stainless steel.
   Using a ruler, trace with a thin sharpie the pattern of a 9.5 x 4-inch rectangle. Make sure that the lines are not at an angle, and as close to 90 degrees as possible.

Procedure

Cutting Stainless Steel

3. Using the band saw, cut out the 9.5 x 4-inch sheet and deburr sharp edges, using a file. Use a wooden scrap piece as a push stick to not cut yourself. It is vital that the cuts are as straight as possible-- remeasure sheet at end, if wrong, cut again. **Take a picture of your metal sheet showing its dimensions.**

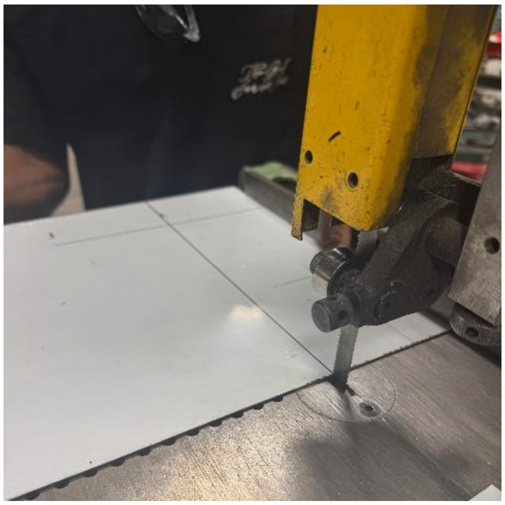


Figure 3: Band Saw Cutting Sheet Metal

Setting Up Force Gauge Program

4. Open the program "Force Recorder Standard" and connect force gauge to computer. A screen will pop up to create a folder and file name. Name file: "V Bending Taco Holder- 'Group Name'". After you should get the screen in Figure 4. Zero out the Imada force gauge by hitting "Zero" on screen in Figure 4 or on physical force gauge.

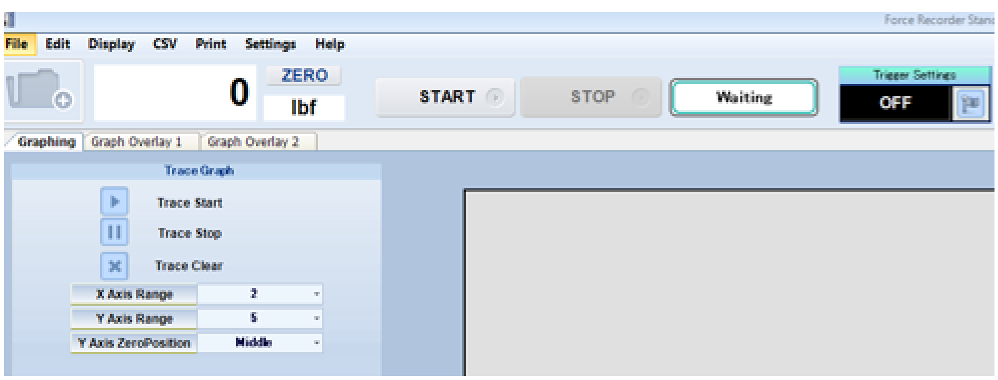


Figure 4a) Main Screen on Force Recorder Standard under "Graphing" tab

IMPORTANT: Click on the setting tab, then "Set up graphing", change the recording rate to 0.5 seconds, then hit OK. If you don't do this, you'll get around 150k data points from the auto set recording rate, see Figure 4b).

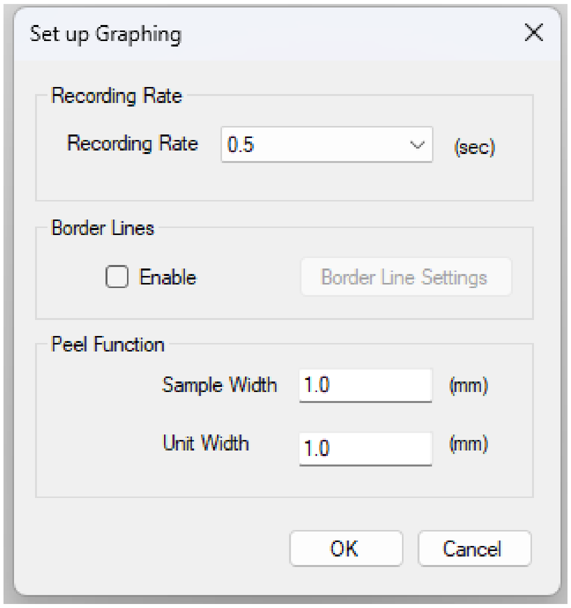


Figure 4b) Change the recording rate to 0.5 sec.

V-Bending Set Up

5. For the first bend, use the smaller L beam (Figure 5). Make sure it is flush against the die, rested on the magnets. Place the sheet metal between the punch and die, and the short end flush against the vertical part of the L beam. **Take a picture of the sheet flush with the L beam and between the punch and die.**


Figure 5. First L beam for 1st bend on left side of punch

Setting Up the Displacement Excel Sheet

6. Open a new Excel document. Label the document as “Displacement of 3 Bends- ‘Group Name’”. Zero out the displacement gauge (Figure 6), make sure it’s in inches. Just before bending, hold down “In/mm... Auto” on the displacement gauge until “automatic mode; one second 2 time” occurs. If you pass “automatic mode; one second 2 time” keep holding down button until the desired sampling rate returns. The displacement gauge will start collecting data automatically, that's ok! You can self-contain the data by selecting a few cells or fix this in post processing.

Figure 6. Displacement indicator (left) and gauge sampling button (right)

Bending Procedure: 1st Bend

7. To record data, the force gauge program and the displacement Excel sheet need to be open at the same time. Use split screen mode. Begin recording the force gauge (hit START) and then start recording the displacement as shown in step 6. MAKE SURE TO CLICK ON THE EXCEL DOCUMENT WHILE BENDING—the displacement gauge won’t record data points otherwise.

Once force and displacement are recording, turn the red knob on the hydraulic press all the way to the right (Figure 7a) and then press and hold the air pressure lever (Figure 7b) to bend the metal until the force gauge reaches 1,000 lb to reduce springback. Once the press reaches 1,000 lb, STOP recording both gauges (Force gauge is set to beep at 1,000lb). Turn the red knob to the left to release the pressure to raise it just enough to remove the holder—turn knob back to the right to ‘lock’ press in place. Save force gauge data as CSV file (Figure 7d) and label accordingly. **Take a picture of the completed first bend.**

Figure 7a) Knob

Figure 7b) Pressure lever

Figure 7c) First bend

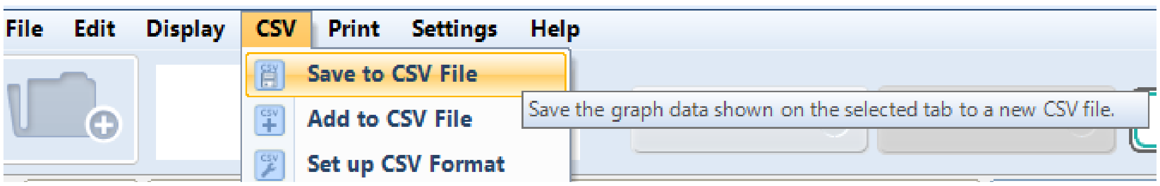


Figure 7d) Save each Force vs Time data as CSV file.

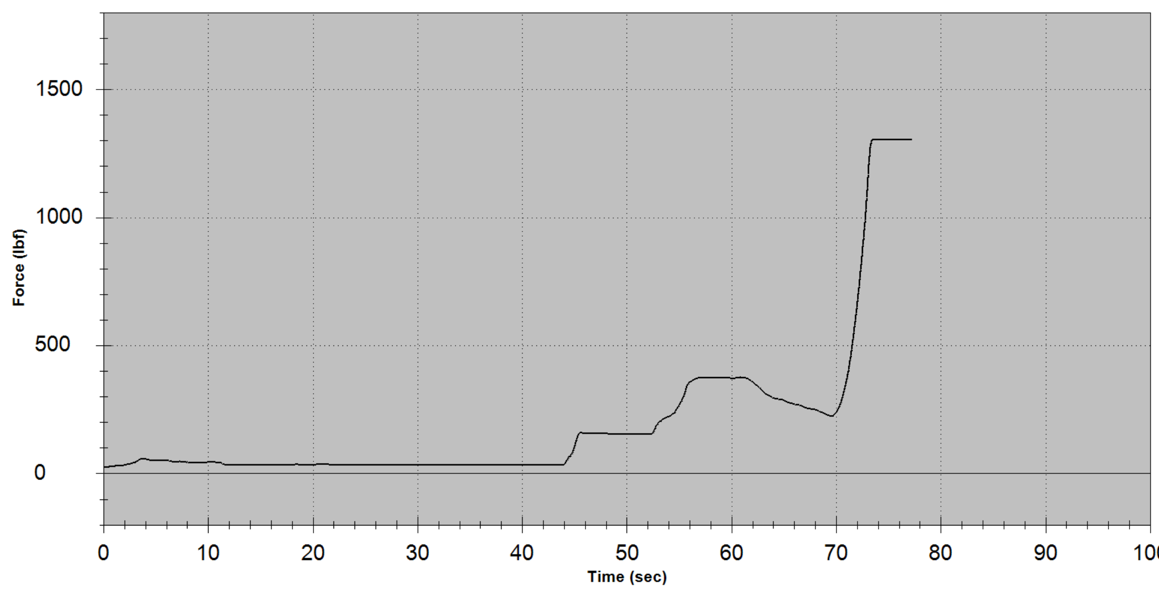


Figure 7e) Example of results from force vs time graph

Bending Procedure: 2^{nd} Bend

8. For the second bend, replace the smaller L beam with the larger L beam as shown (Figure 8a). Make sure it is flush against the die and rested on the magnets. Take the metal taco holder out and flip it over so that it will bend in the opposite direction of the 1st bend. Repeat the measurements and bending from step 7 in a new graph and the same Excel document (Label the displacement data as you go). Save 2^{nd} bend force gauge data as CSV file and label accordingly. **Take a picture of the completed second bend.**

Figure 8a) Large L beam

Figure 8b) Completed second bend

Bending Procedure: 3rd Bend

9. For the final bend, replace the larger L beam with the smaller L beam just like the first bend. Make sure it is flush against the die, rested on the magnets. Take the metal taco holder out and flip it over so that it will bend the same direction as first bend. Repeat measurements and bending from step 7 in a new graph and the same Excel document. Save force gauge data as CSV file and label accordingly. **Take a picture of taco holder.**

Figure 9 Final completed third bend

10. Place your completed taco holder on top of the original reference holder for comparison. **Take a picture of your holder on top of the original.**

Figure 10. Completed taco holder on top of original

Place your completed holder on a protractor and measure the included angle α' of one of the bends. **Take a picture showing the angle of one of the bends**. Calculate the springback (Eq. 2), and record data in Table 1. *For Theoretical springback, calculate the value for original taco holder.

Fill in Actual/Experimental entry for Bending force after post processing data. Taken an average of leveled force (Figure 11).

Table 1: Comparing theoretical and Actual data

	Theoretical	**Actual/Experimental**	**Percent Diff.**
Spring Back			
Bending Force	423.59 lb		

Post Processing: Force vs Displacement Graphs

11. Open the CSV files in Excel. Copy each force data column and place next to/into the corresponding displacement data values.

Erase data from columns that are not recording data or when stopped recording data. (For example, erase the beginning 0's in displacement columns except for the first one).

Make a force vs displacement graph for all 3 bends in the same graph and compare (see example in Figure 11 for one bend). Include theoretical value in graph for comparison. **Take screen shots and label the graph.**

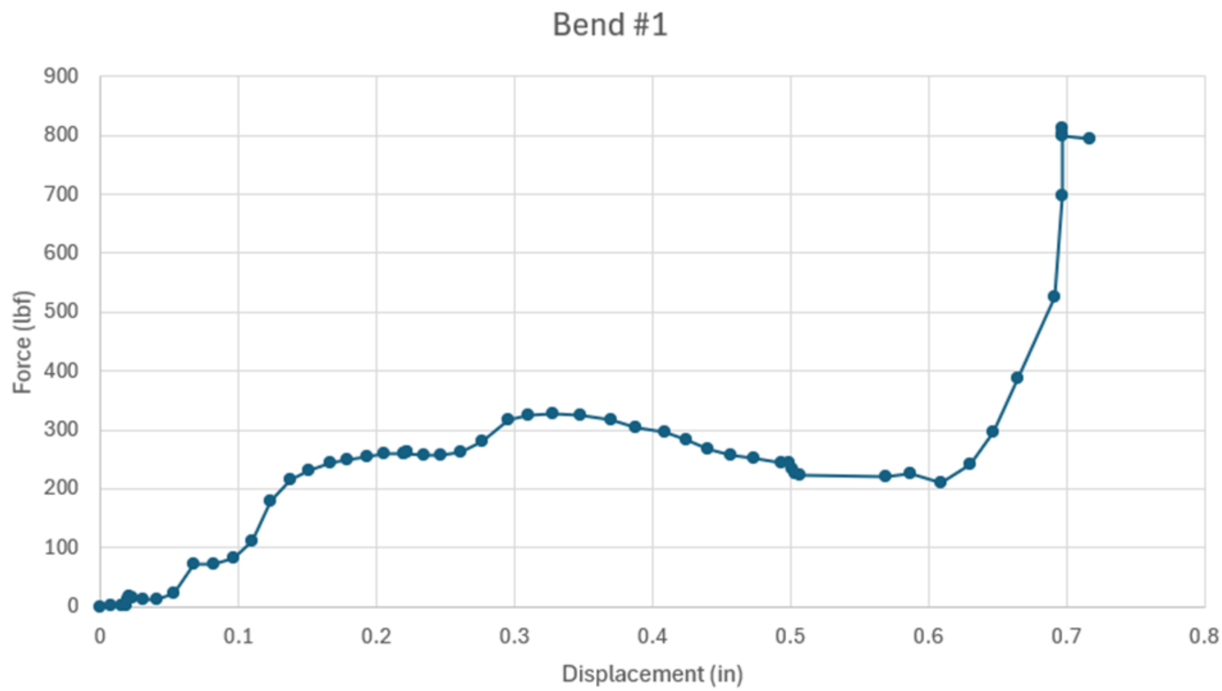


Figure 11 Example force vs displacement graph (see leveled region between 200 and 350lb)

Reference

[1] Groover M. P., Fundamentals of Modern Manufacturing Materials, Processes and Systems. 2nd Ed., Wiley. 2004.

Taco Holder V-Bending Laboratory Grading Sheet

Use Times New Roman Font Size 11. **Names:**………………………………………………

The requested pictures are referred to in the lab manual. This lab will be completed with your lab partner and must show your results and include pictures. Upload lab report to Dropbox.

1. Include picture of all tools and equipment that are being used to complete this lab. (5%)

2. Include picture of the cut piece of metal, showing the dimensions with a ruler. (5%)

3. Include picture of sheet metal flush with L-beam and between punch and die. (5%)

4. Include picture of 1st bend with force gauge showing 1000lbs and sheet in punch & die. (10%)

5. Include picture of 2nd bend with force gauge showing 1000lbs and sheet in punch & die. (10%)

6. Include picture of 3rd bend with force gauge showing 1000lbs and sheet in punch & die. (10%)

7. Include a picture with completed taco holder. (5%)

8. Include a picture with your taco holder on top of the original. (5%)

9. Include a picture showing the angle of one of the bends. (10%)

10. Include screen shot of all three force vs displacement curves for the three bends in one graph. Include theoretical value in graph. (10%)

11. Include Table 1 filled out with your calculated values. (10%)

12. Include a summary (250 words) of the main things that you learned in this lab and different ways that this lab can be improved (250 words) for future students. (15%)

Appendix 2: Ansys Mechanical Simulation for V-Bending Project

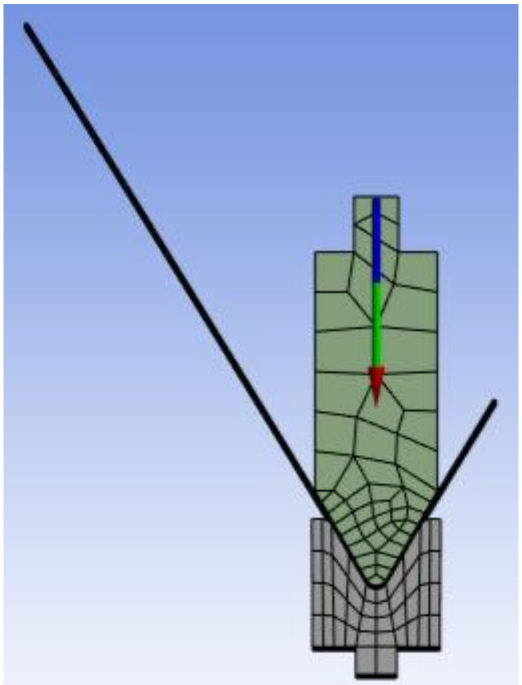
TACO HOLDER

A. Objectives

- Using Ansys Mechanical to simulate V-bending of sheet metal for a taco holder
- Creating mesh and displacements
- Running the calculations
- Using deformations for visualizations
- Comparing Ansys solution with theory

B. Problem Description

We will study V-bending of 22 ga. (0.031 inch) sheet metal for a taco holder using a punch and a die.



C. Launching Ansys Workbench and Selecting Static Structural

1. Start by launching the Ansys Workbench in Ansys 2024 R2. Select Tools>>Options…. from the menu. Select Appearance on the left-hand side. Select Classic Theme as Workbench Theme under Graphics Style for Appearance. Select OK to close the window. Double click on the Static Structural Analysis System.

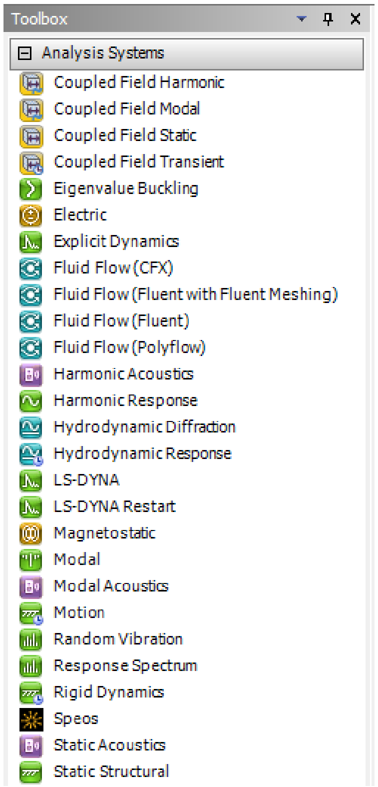


Figure 1 Static Structural Analysis

2. Double click on Engineering Data in the Project Schematic window. Select the Engineering Data Sources tab and select General Non-linear Materials. Highlight Stainless Steel NL under Material in the Outline of Schematic. Click on the plus sign next to Isotropic Elasticity under Property in the Properties of Outline. Make sure that the Young's modulus is 193 GPa. Select the plus sign next to Stainless Steel NL. Click on the Project tab under Tools in the menu.

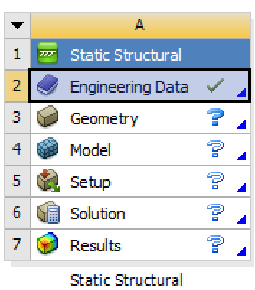


Figure 2a) Selecting Engineering Data

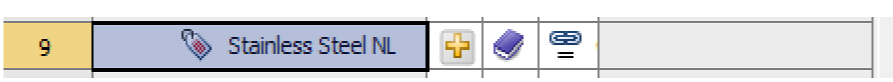


Figure 2b) Highlighting Stainless Steel NL

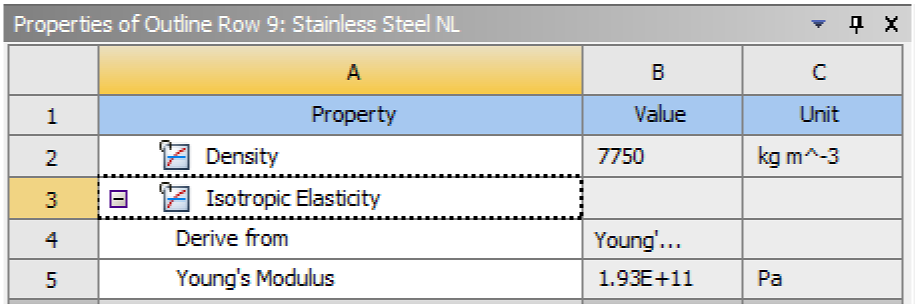


Figure 2c) Properties of Stainless Steel NL

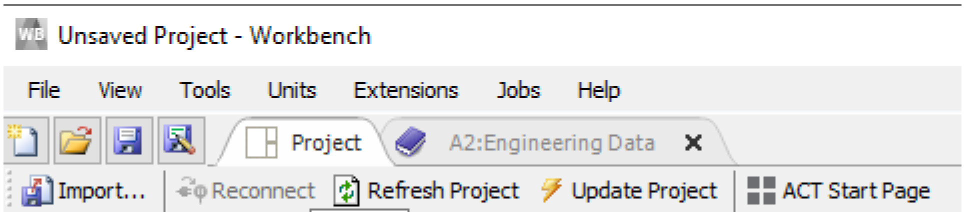


Figure 2d) Returning to the Project

D. Launching Ansys DesignModeler

3. Right click on Geometry in the Project Schematic window and select New DesignModeler Geometry. **Select Units>>Meter in the menu of DesignModeler**. Select File>>Import External Geometry File…. and import the file *FinalAssemblyTacosHolder.x_t*. Click on Generate and Close DesignModeler.

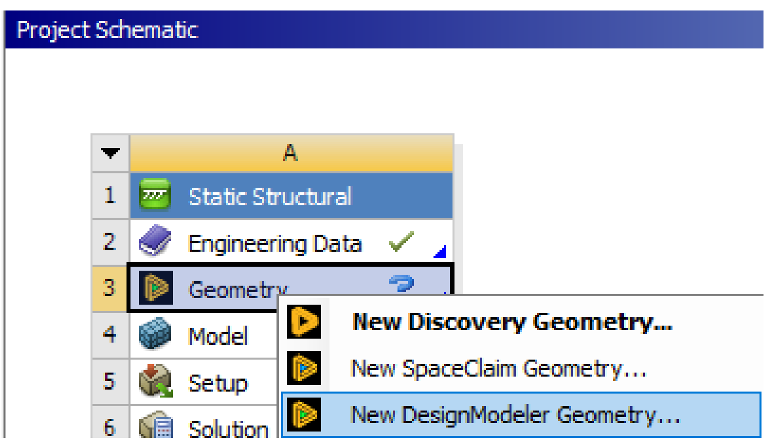


Figure 3a) Selecting the Geometry

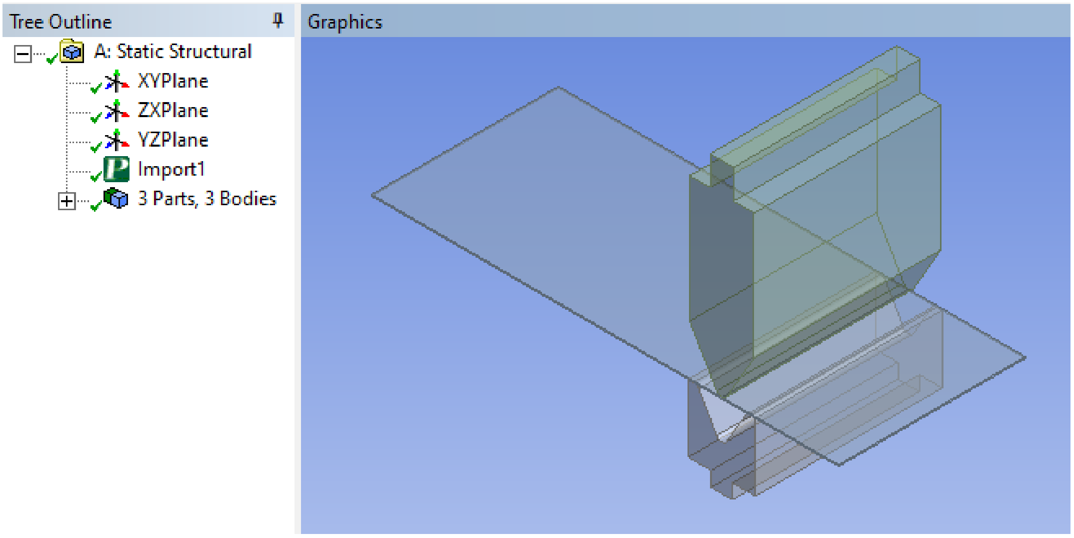


Figure 3b) Die, punch and sheet for taco holder V-bending

E. Launching Ansys Mechanical

4. Double click on Model in the Ansys Workbench Project Schematic to open the Ansys Mechanical window. Select File>>Options… from the menu. Select UI Options under Mechanical on the left-hand side. Select None as Mechanical View under Engineering Data for UI Options. Select OK to close the window. Control-select the punch and die under Geometry in the Outline. Keep Structural Steel as Assignment under Material in Details. Assign Stainless Steel NL as the Material in Details View for the sheet. Make sure that the Stiffness Behavior under Definition in Details for the sheet is Flexible.

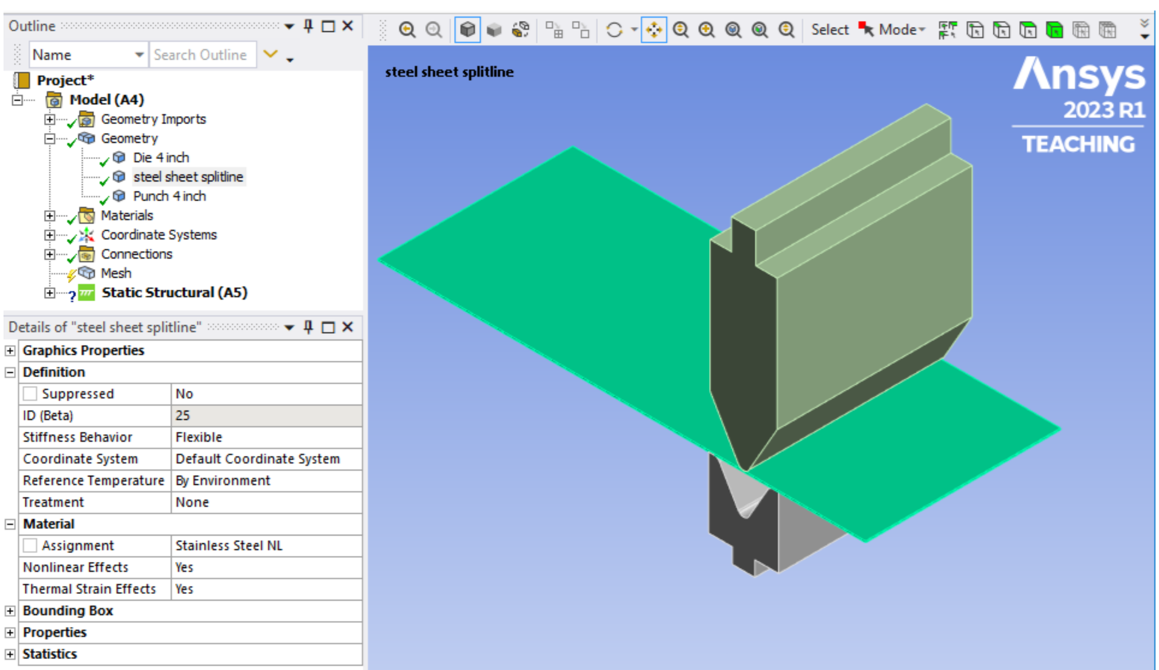


Figure 4 Assigning stainless steel as material for sheet

5. We will include friction between the sheet and the die. Right click on the Sheet under Geometry and select Hide Body. Open Connections and Contacts in the Outline. Select Contact Region under Contacts. Select the seven contact faces of the die and Apply these Faces as Contact under Scope in Details. Right-click on Sheet under Geometry in the Outline and select Show Body. Set units as Metric(mm,kg,.) from Home>>Tools>>Units.

Right click in the graphics window and select View>>Bottom. Control-select and Apply the two bottom faces as Target under Scope in Details and shown in Figure 8.5b). These two faces may already have been preselected. Set the Type to Frictional and set the Friction Coefficient to 0.15 for Sheet To Die. Make sure to assign all the other settings in details as shown in Figure 5c). Rename the contact region to Friction – Die to Sheet.

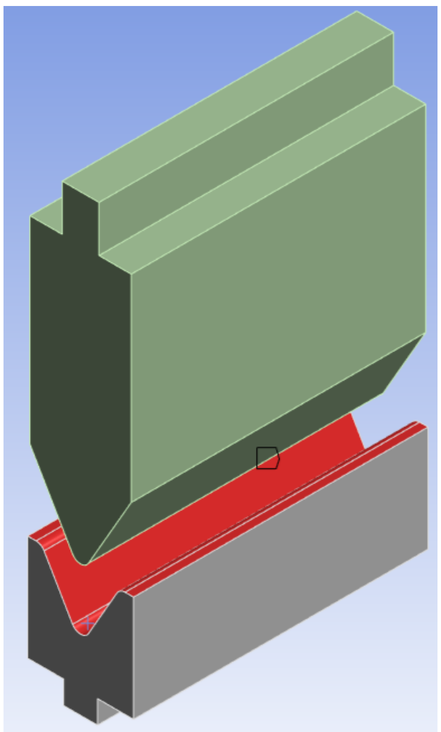


Figure 5a) Contact faces for taco holder die

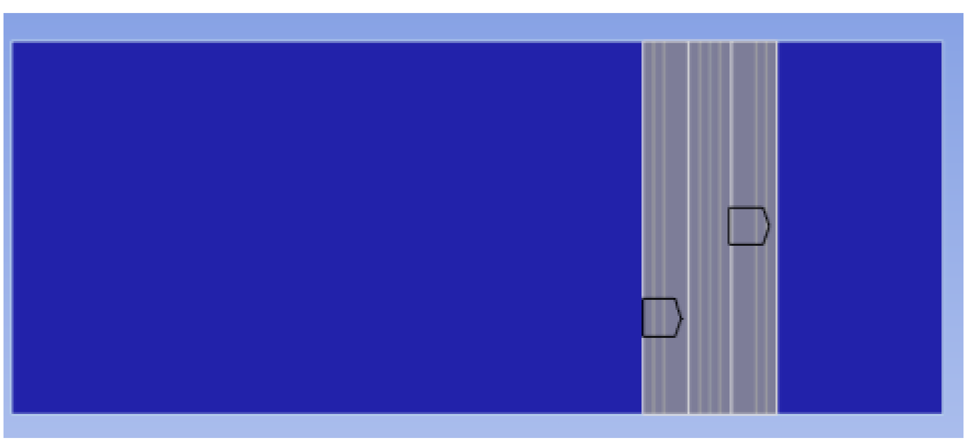


Figure 5b) Contact faces for the taco holder sheet

Details of "Contact Region"

Scope	
Scoping Method	Geometry Selection
Contact	4 Faces
Target	2 Faces
Contact Bodies	Die
Target Bodies	steel sheet splitline
Protected	No
Definition	
Type	Frictional
Friction Coefficient	0.15
Scope Mode	Manual
Behavior	Auto Asymmetric
Trim Contact	Program Controlled
Contact APDL Name	
Target APDL Name	
Suppressed	No
Display	
Element Normals	No
Advanced	
Formulation	Augmented Lagrange
Small Sliding	Off
Detection Method	Program Controlled
Penetration Tolerance	Program Controlled
Elastic Slip Tolerance	Program Controlled
Normal Stiffness	Factor
Normal Stiffness Factor	0.15
Update Stiffness	Program Controlled
Stabilization Damping Factor	0.
Pinball Region	Program Controlled
Time Step Controls	None
Geometric Modification	
Interface Treatment	Add Offset, No Ramping
Offset	0. m
Contact Geometry Correction	None
Target Geometry Correction	None

Figure 5c) Details of contact region between die and sheet for taco holder

6. We will now include friction between the sheet and the punch. Open Connections and Contacts in the Outline. Select Contact Region 2 under Contacts. Select the two upper contact faces of the sheet and Apply these Faces as Contact under Scope in Details. These face may already have been preselected. Right-click on Sheet under Geometry in the Outline and select Hide Body. Control-select and Apply the three bottom faces of the punch as Target under Scope in Details and shown in Figure. Set the Type to Frictional and set the Friction Coefficient to 0.15 for Sheet To Punch. Make sure to assign all the other settings in details as shown in Figure 8.5c). Rename the contact region to Friction – Sheet to Punch. Right-click on Sheet under Geometry in the Outline and select Show Body. Select Isometric View.

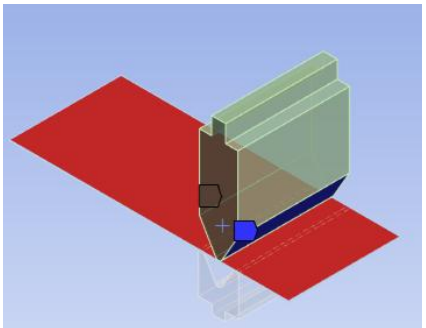


Figure 6 Contact faces for punch and sheet

7. Right click on Mesh in the Outline and select Insert>>Method. Select Body above the graphics window. Select and apply the Sheet as Geometry under Scope in Details, see Figure 7a). Select Tetrahedrons as Method under Definition in Details. Rename the method to Patch Conforming Method Sheet.

Details of "Patch Conforming Method Sheet

Scope	
Scoping Method	Geometry Selection
Geometry	1 Body
Definition	
Suppressed	No
Method	Tetrahedrons
Algorithm	Patch Conforming
Element Order	Use Global Setting
Advanced Improve Options	
Aggressive Thin Face Collapse	Program Controlled
Automatic Node Movement	Program Controlled
Refinement Options	
Refine at Thin Section	No

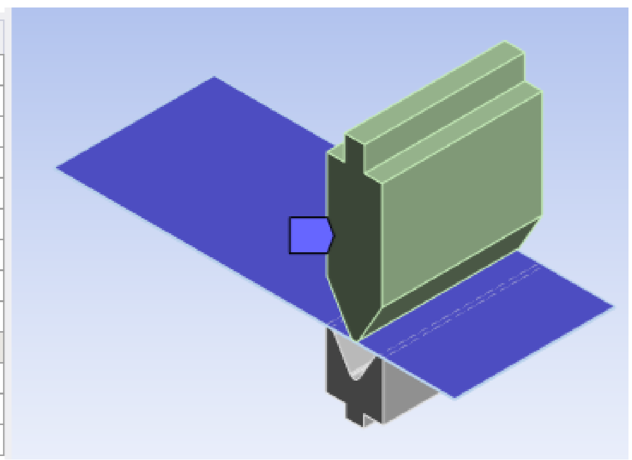


Figure 7a) Tetrahedron method for sheet

Right click on Mesh in the Outline and select Insert>>Sizing. Select Body above the graphics window. Control select and apply punch and die as Geometry under Scope in Details. Set Element Size to 12.0 mm and Rename sizing to Body Sizing Punch and Die.

Details of "Body Sizing Punch and Die" - Si

Scope	
Scoping Method	Geometry Selection
Geometry	2 Bodies
Definition	
Suppressed	No
Type	Element Size
Element Size	12.0 mm
Advanced	
Defeature Size	Default
Behavior	Soft

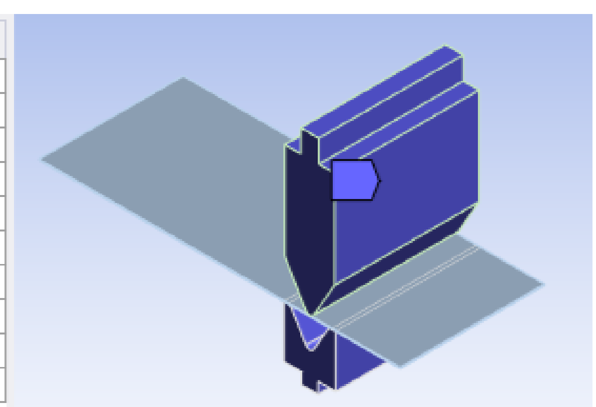


Figure 7b) Body sizing for punch and die

Right-click on Sheet under Geometry in the Outline and select Hide Body. Right click on Mesh in the Outline and select Insert>>Sizing. Select Face above the graphics window. Control select and apply the three lower faces of the punch and the seven faces of the die as Geometry under Scope in Details, see Figure 7c). Set the Element Size to 4 mm and Rename the sizing to Face Sizing Punch and Die. Right-click on Sheet under Geometry in the Outline and select Show Body.

Details of "Face Sizing Punch and Die" - Si:

Scope	
Scoping Method	Geometry Selection
Geometry	10 Faces
Definition	
Suppressed	No
Type	Element Size
Element Size	4.0 mm
Advanced	
Defeature Size	Default
Influence Volume	No
Behavior	Soft

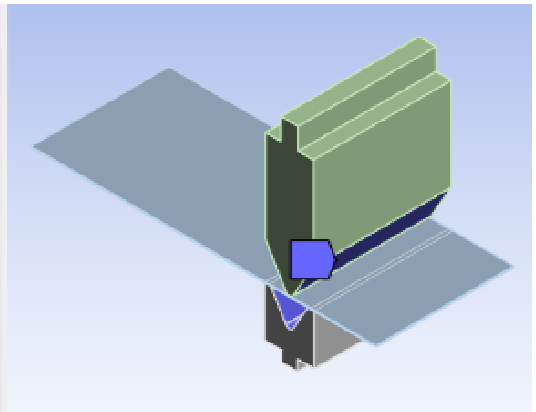


Figure 7c) Face sizing for punch and die

Select isometric view in the graphics window. Right click on Mesh in the Outline and select Insert>>Sizing. Select Edge above the graphics window. **Control select and apply the four longer upper and lower edges of the sheet, see Figure 7d).** Set Type to Number of Divisions and set the Number of Divisions to 100. Select the first Bias type and enter 400 as Bias Factor. Select the two edges furthest away for Reverse Bias. Rename the sizing to Edge Sizing Long Sides.

Details of "Edge Sizing Long Sides" - Sizi

Scope	
Scoping Method	Geometry Selection
Geometry	4 Edges
Definition	
Suppressed	No
Type	Number of Divisions
Number of Divisions	100
Advanced	
Behavior	Soft
Bias Type	----- --- - -
Bias Option	Bias Factor
Bias Factor	400.0
Reverse Bias	2 Edges

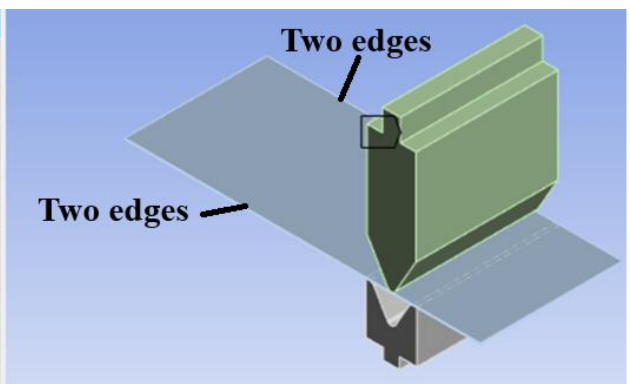


Figure 7d) Edge sizing for longer sides of sheet

Select isometric view in graphics window. Right click on Mesh in the Outline and select Insert>>Sizing. Select Edge above the graphics window. **Control select and apply the four shorter upper and lower edges of the sheet, see Figure 7e).** Set Type to Number of Divisions and set Number of Divisions to 80. Select first Bias type and enter 200 as Bias Factor. Select closest edge for Reverse Bias. Rename sizing to Edge Sizing Short Sides.

Details of "Edge Sizing Short Sides" - Sizi	
Scope	
Scoping Method	Geometry Selection
Geometry	4 Edges
Definition	
Suppressed	No
Type	Number of Divisions
Number of Divisions	80
Advanced	
Behavior	Soft
Bias Type	----- --- - -
Bias Option	Bias Factor
Bias Factor	200.0
Reverse Bias	2 Edges

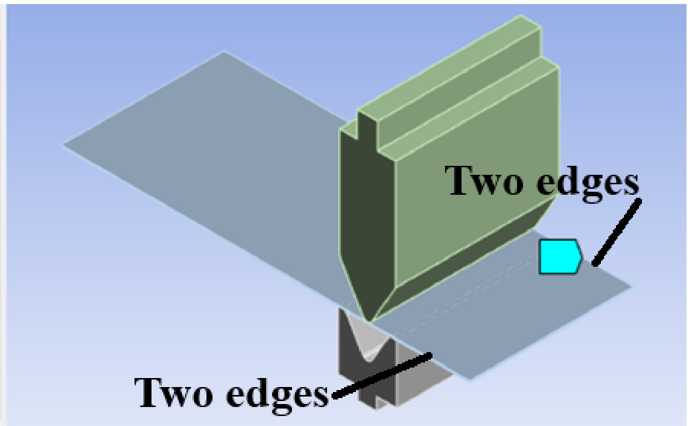


Figure 7e) Edge sizing for shorter sides of sheet

Select isometric view in the graphics window. Right click on the punch under Geometry and Hide Body. Right click on Mesh in the Outline and select Insert>>Sizing. Select Edge above the graphics window. **Select and apply the upper and lower split lines on the sheet, one on each side of the sheet, see Figure 7f).** Set the Element Size to 4.0 mm and Rename the sizing to Edge Sizing Bending Axis.

Details of "Edge Sizing Bending Axis" - S	
Scope	
Scoping Method	Geometry Selection
Geometry	2 Edges
Definition	
Suppressed	No
Type	Element Size
Element Size	4.0 mm
Advanced	
Behavior	Soft
Bias Type	No Bias

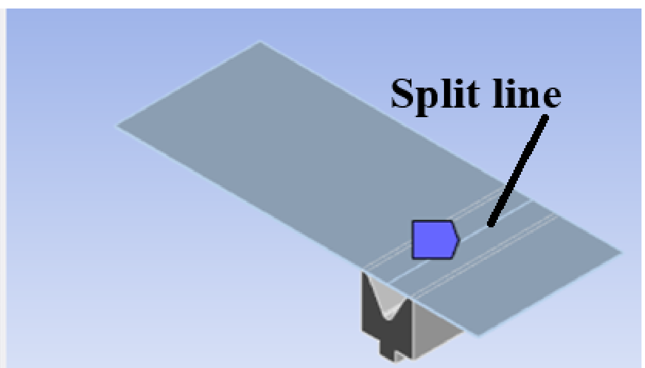


Figure 7f) Edge sizing for short side

Right click on Mesh in Outline and select Generate Mesh. The mesh has 21,809 Nodes and 7,925 Elements. Right click on punch under Geometry and select Show Body.

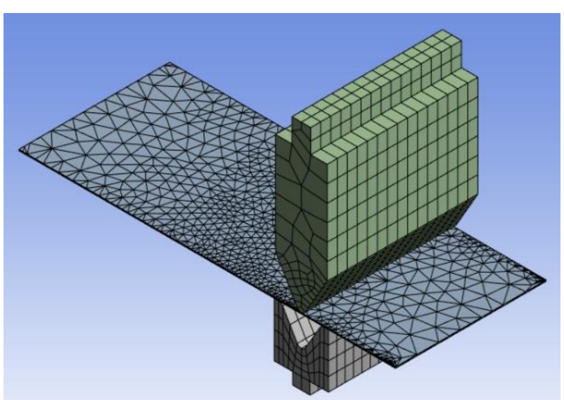
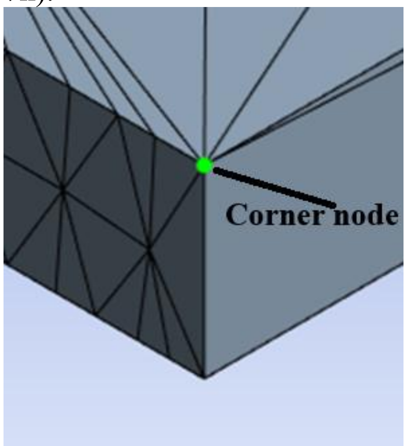


Figure 7g) Finished mesh for punch, die and sheet assembly

Right click on punch under Geometry and select Hide Body. Select isometric view in the graphics window. Zoom in on the corner of the sheet that is closest to you and select the upper corner node of the mesh using  (available above graphics window) on the sheet, see Figure 7h).



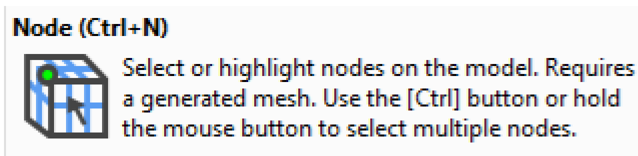


Figure 7h) Selected corner node on meshed sheet

Zoom in on the sheet edge at the split line and **control-select** the node at the intersection of the split line and the edge of the sheet, see Figure 7i).

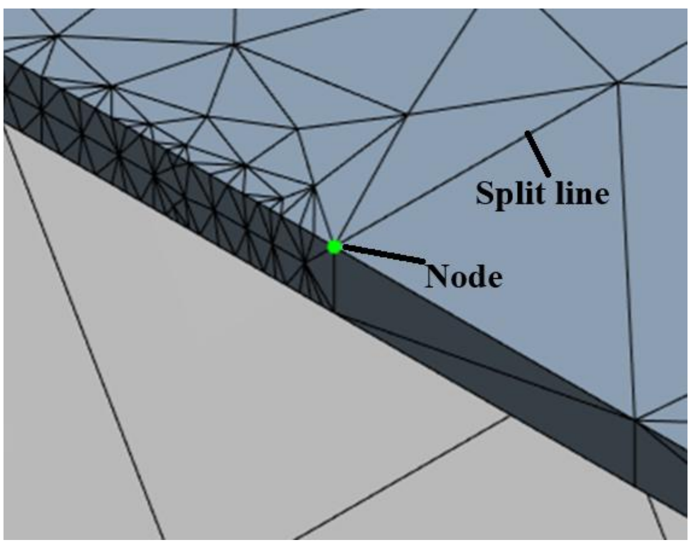


Figure 7i) Control-selected mesh split line node on edge of sheet

Finally, zoom in on the remaining sheet corner on the same edge as the other two mesh nodes that have already been control-selected. Control-select the remaining upper corner node of the mesh, see Figure 7j). Zoom out on the sheet with isometric view in the graphics window. You will now have three-control selected nodes on the sheet as shown in Figure 7j). Right click in the graphics window and select Create Named Selection…. Enter the name Mesh Nodes Long Sheet Edge and select OK to close Selection Name window. Right click on punch under Geometry and select Show Body.

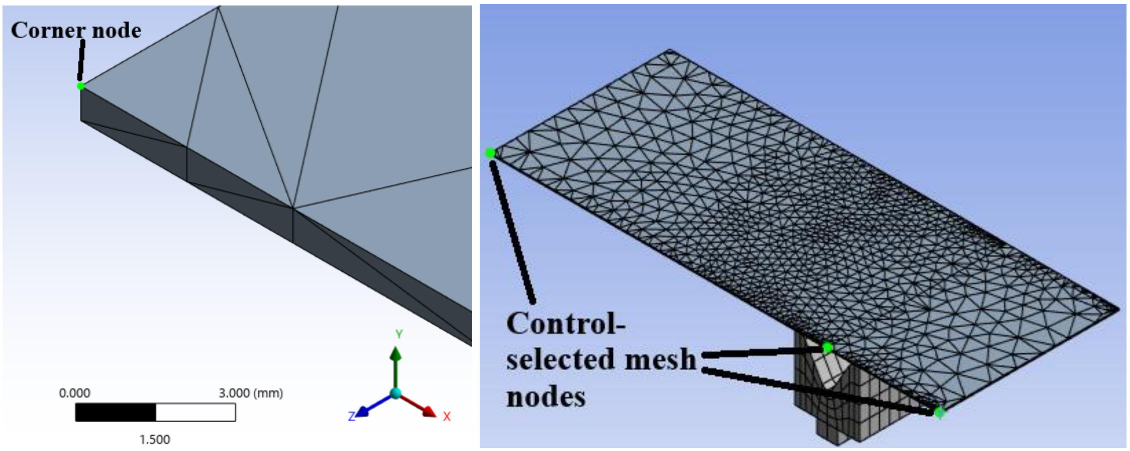


Figure 7j) Corner mesh node and the three control selected mesh nodes on sheet

8. Select Analysis Settings under Static Structural in the Outline. Make sure to assign all the settings as shown in Figure 8.

Details of "Analysis Settings"	
Step Controls	
Number Of Steps	60.
Current Step Number	60.
Step End Time	60. s
Auto Time Stepping	On
Define By	Substeps
Carry Over Time Step	Off
Initial Substeps	100.
Minimum Substeps	1.
Maximum Substeps	100.
Solver Controls	
Solver Type	Direct
Weak Springs	Program Controlled
Solver Pivot Checking	Program Controlled
Large Deflection	On
Inertia Relief	Off
Quasi-Static Solution	Off
Rotordynamics Controls	
Restart Controls	
Nonlinear Controls	
Newton-Raphson Option	Program Controlled
Force Convergence	Program Controlled
Moment Convergence	Program Controlled
Displacement Convergence	Program Controlled
Rotation Convergence	Program Controlled
Energy Convergence (Beta)	Program Controlled
Line Search	Program Controlled
Stabilization	Off
Advanced	
Output Controls	
Output Selection	None
Stress	Yes
Back Stress	No
Strain	Yes
Contact Data	Yes
Nonlinear Data	No
Nodal Forces	Yes
Volume and Energy	Yes
Euler Angles	Yes
General Miscellaneous	No
Contact Miscellaneous	No
Store Results At	All Time Points
Cache Results in Memory (Beta)	Never
Combine Distributed Result Files (Beta)	Program Controlled
Result File Compression	Program Controlled
Analysis Data Management	
Visibility	

Figure 8 Details of analysis settings

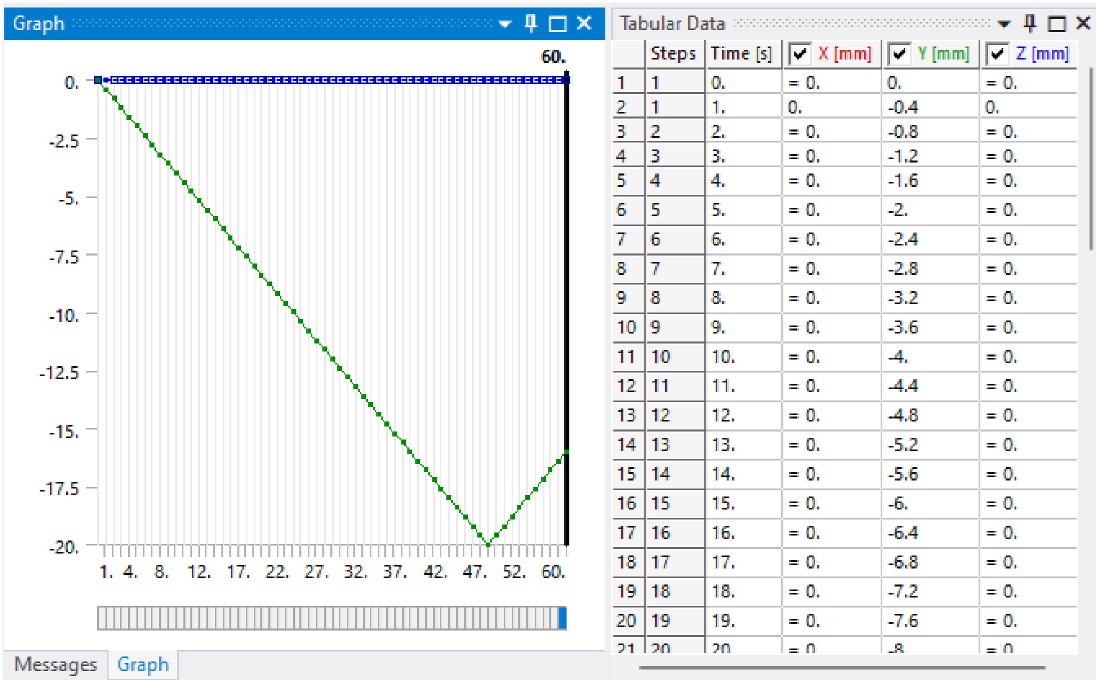
9. Numbers with bold face below needs to be updated with your own values for homework assignment. Right click on Static Structural in the Outline and select Insert>>Displacement. Select the top face of the punch and Apply this face as Geometry. Start an Excel file and enter the values 0 and -0.4 in cells A1 and A2, respectively. Select these two data points and drag these down to row **51**. You should have data point **-20** in row 51. Enter **-19.6** in row **52**. Select **-20** and **-19.6** in rows **51** and **52** and drag these data points to row 61. You should have **-16** in row **61**.

Copy the column of data from Excel and paste the data as Tabular Data as Y Component under Definition in Details of "Displacement", see Figure 8.9a). Enter 0 mm as X and Z Components of Displacement. Right click on Displacement under Static Structural and select Rename. Rename the Displacement to Displacement Punch Y Component.

Table 1 Tabular data for X, Y and Z components of displacement during a total of **60** s

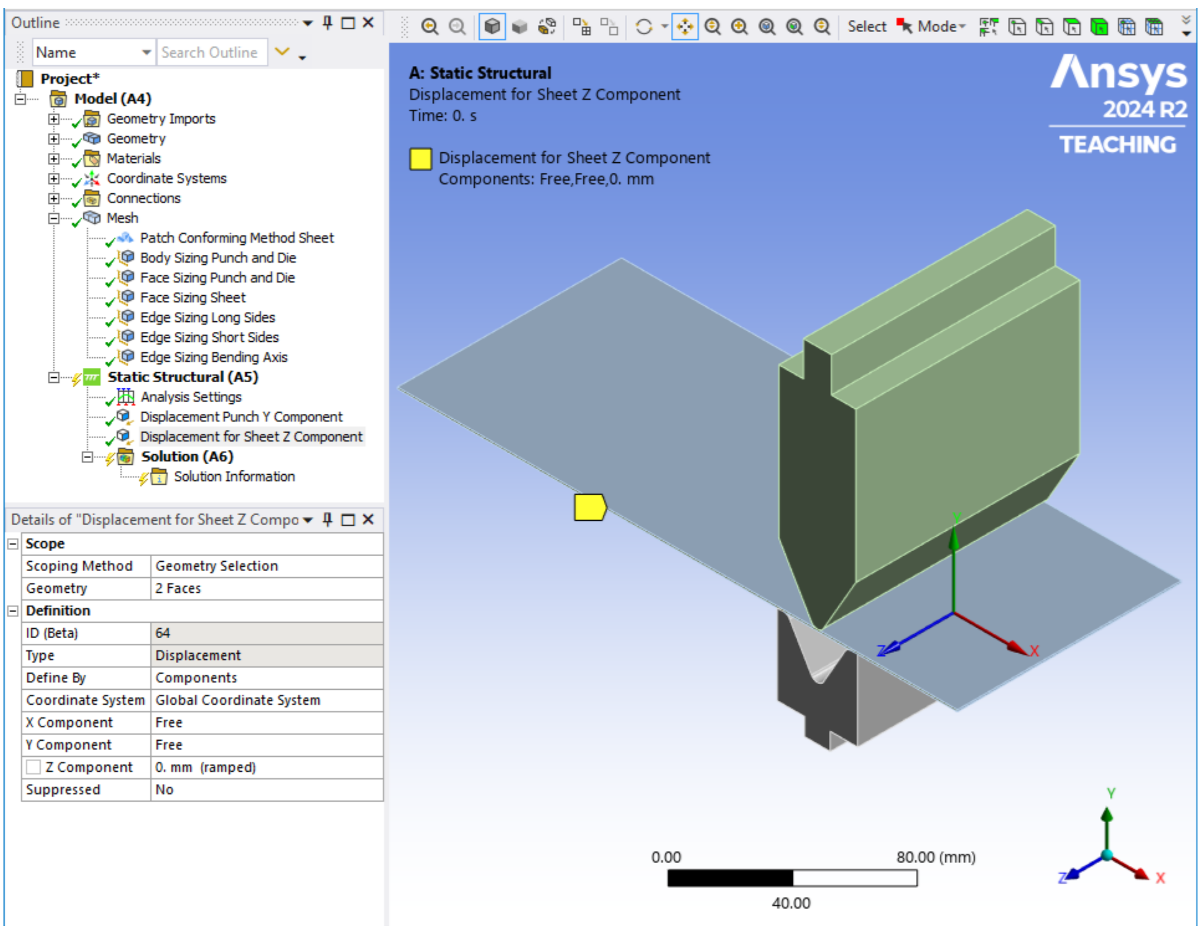
Time [s]	Displacement X [mm]	Displacement Y [mm]	Displacement Z [mm]
0	0	0	0
1	0	-0.4	0
2	0	-0.8	0
3	0	-1.2	0
4	0	-1.6	0
5	0	-2	0
6	0	-2.4	0
7	0	-2.8	0
8	0	-3.2	0
9	0	-3.6	0
10	0	-4	0
11	0	-4.4	0
12	0	-4.8	0
13	0	-5.2	0
14	0	-5.6	0
15	0	-6	0
16	0	-6.4	0
17	0	-6.8	0
18	0	-7.2	0
19	0	-7.6	0
20	0	-8	0
21	0	-8.4	0
22	0	-8.8	0
23	0	-9.2	0
24	0	-9.6	0
25	0	-10	0
26	0	-10.4	0
27	0	-10.8	0
28	0	-11.2	0
29	0	-11.6	0
30	0	-12	0
31	0	-12.4	0
32	0	-12.8	0
33	0	-13.2	0
34	0	-13.6	0
35	0	-14	0
36	0	-14.4	0
37	0	-14.8	0
38	0	-15.2	0
39	0	-15.6	0
40	0	-16	0
41	0	-16.4	0
42	0	-16.8	0
43	0	-17.2	0
44	0	-17.6	0
45	0	-18	0
46	0	-18.4	0
47	0	-18.8	0
48	0	-19.2	0
49	0	-19.6	0
50	0	-20	0
51	0	-19.6	0
52	0	-19.2	0
53	0	-18.8	0
54	0	-18.4	0
55	0	-18	0
56	0	-17.6	0
57	0	-17.2	0
58	0	-16.8	0
59	0	-16.4	0
60	0	-16	0

Right click on Static Structural in the Outline and select Insert>>Displacement. Select the two side faces of the Sheet (both faces that have a normal in the Z direction) and Apply these as Geometry. Enter 0 mm as Z Component of Displacement, see Figure 9b). Rename Displacement to Displacement Sheet Z Component.



	Steps	Time [s]	X [mm]	Y [mm]	Z [mm]
1	1	0.	= 0.	0.	= 0.
2	1	1.	0.	-0.4	0.
3	2	2.	= 0.	-0.8	= 0.
4	3	3.	= 0.	-1.2	= 0.
5	4	4.	= 0.	-1.6	= 0.
6	5	5.	= 0.	-2.	= 0.
7	6	6.	= 0.	-2.4	= 0.
8	7	7.	= 0.	-2.8	= 0.
9	8	8.	= 0.	-3.2	= 0.
10	9	9.	= 0.	-3.6	= 0.
11	10	10.	= 0.	-4.	= 0.
12	11	11.	= 0.	-4.4	= 0.
13	12	12.	= 0.	-4.8	= 0.
14	13	13.	= 0.	-5.2	= 0.
15	14	14.	= 0.	-5.6	= 0.
16	15	15.	= 0.	-6.	= 0.
17	16	16.	= 0.	-6.4	= 0.
18	17	17.	= 0.	-6.8	= 0.
19	18	18.	= 0.	-7.2	= 0.
20	19	19.	= 0.	-7.6	= 0.
21	20	20	= 0	-8	= 0

Figure 9a) Inserting Y component displacement for punch



Scope	
Scoping Method	Geometry Selection
Geometry	2 Faces
Definition	
ID (Beta)	64
Type	Displacement
Define By	Components
Coordinate System	Global Coordinate System
X Component	Free
Y Component	Free
Z Component	0. mm (ramped)
Suppressed	No

Figure 9b) Inserting Z component displacement for sheet

Right click on Static Structural and select Insert>>Commands. Enter the command *NEQIT,100* on the first available line (line 7), see Figure 9c).

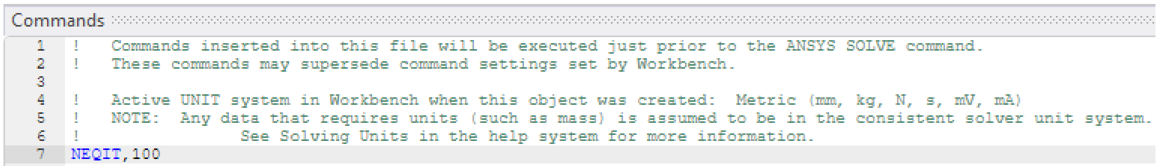


Figure 9c) Command for simulations

Right click on Static Structural in the Outline and select Insert>>Displacement. Select the bottom face of the die and Apply this face as Geometry. Enter 0 mm as X, Y and Z Components of Displacement. Right click on Displacement under Static Structural and select Rename, see Figure 9d). Rename the Displacement as Displacement Die.

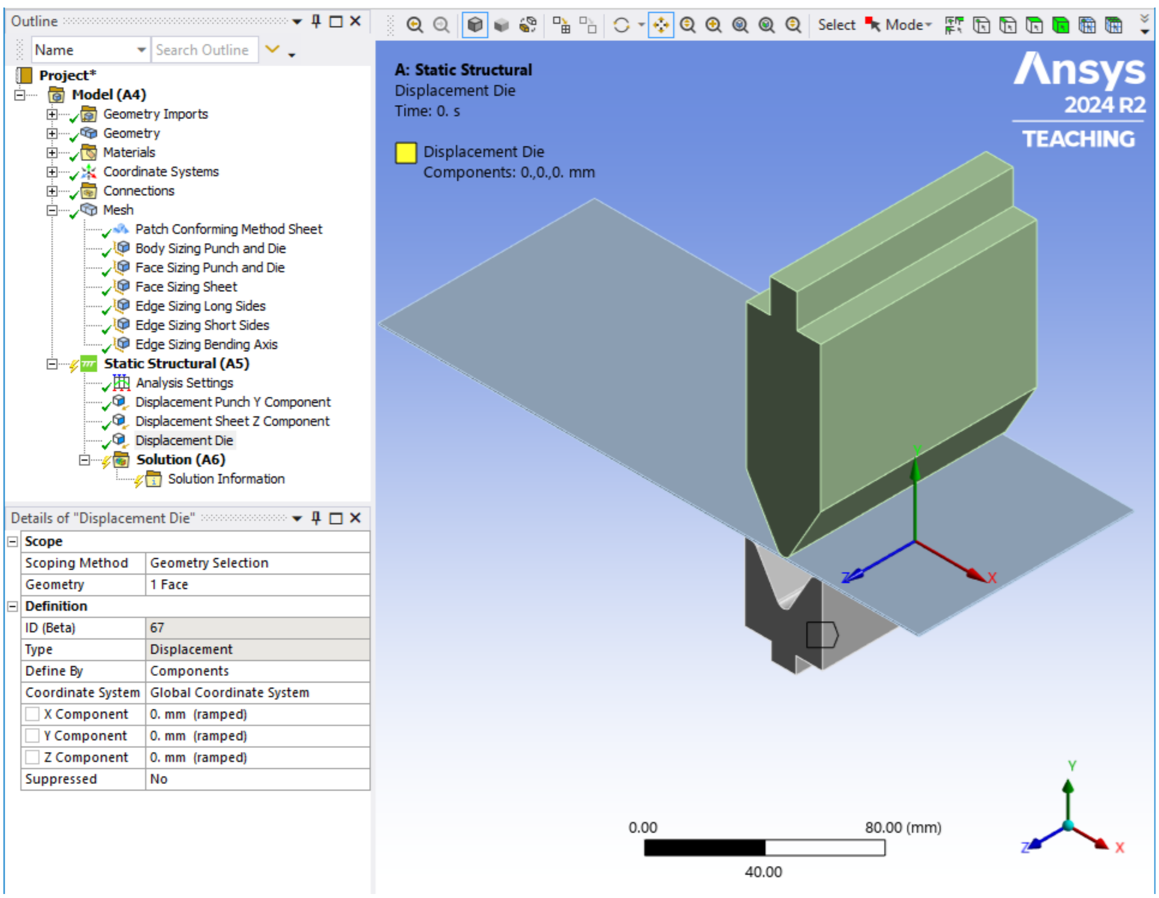


Figure 9d) Inserting die displacement

Right click on Static Structural and select Insert>>Standard Earth Gravity. Select -Y Direction under Definition in Details, see Figure 9e).

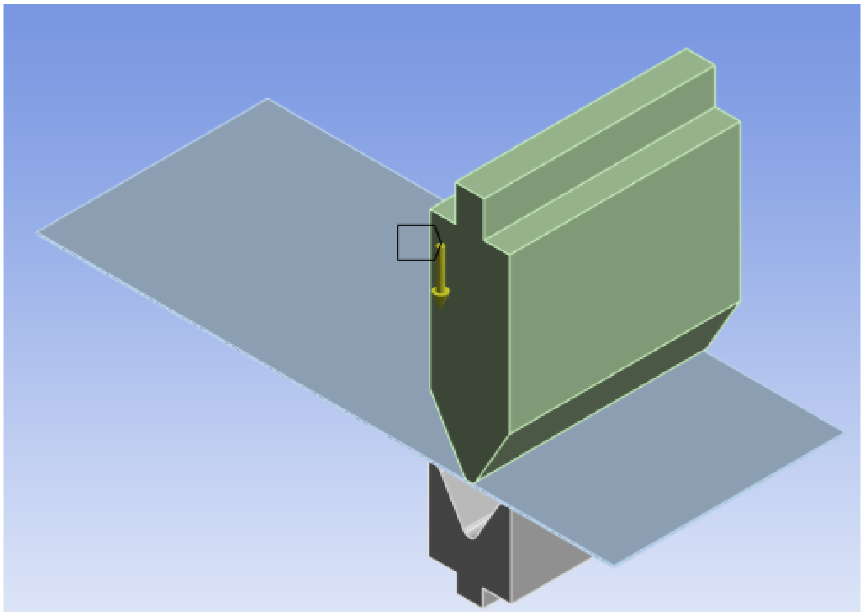
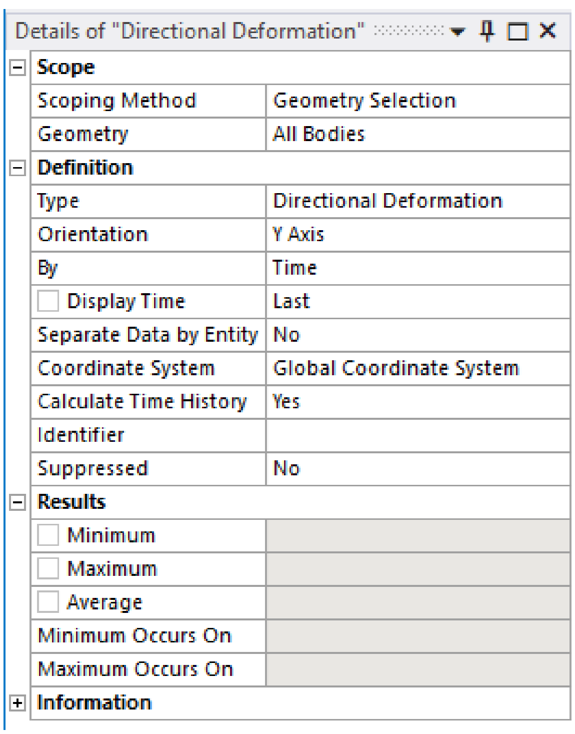


Figure 9e) Inserting gravity

Right click on Solution in the Outline and select Insert>> Deformation>>Total. Right click on Solution in the Outline and select Insert>> Deformation>>Directional. Select Y Axis as Orientation under Definition in Details, see Figure 9f). Rename deformation to Directional Deformation Y Axis. Insert Directional Deformation X Axis in the same way.
Right click on Solution in Outline and select Insert>>Stress>>Equivalent (von Mises). Right click on Solution in the Outline and select Insert>>Contact Tool>>Contact Tool.



Details of "Directional Deformation"

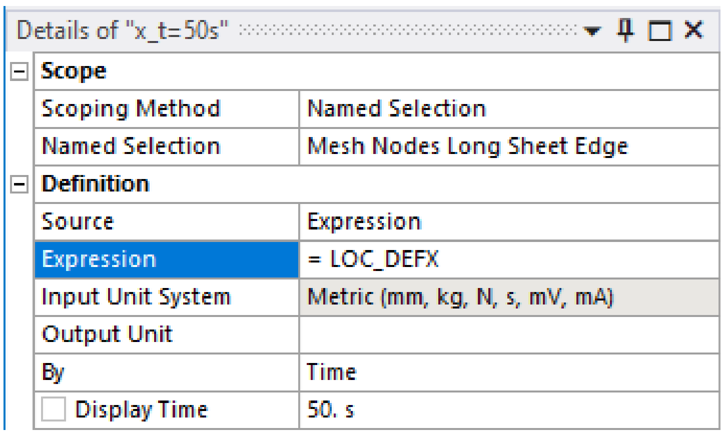
Scope	
Scoping Method	Geometry Selection
Geometry	All Bodies
Definition	
Type	Directional Deformation
Orientation	Y Axis
By	Time
Display Time	Last
Separate Data by Entity	No
Coordinate System	Global Coordinate System
Calculate Time History	Yes
Identifier	
Suppressed	No
Results	
Minimum	
Maximum	
Average	
Minimum Occurs On	
Maximum Occurs On	
Information	

Figure 9f) Details for Directional Deformation Y Axis

Right click on Solution in the Outline and select Insert>>Probe>>Force Reaction. Select Boundary Condition as Location Method under Definition in Details. Select Displacement Punch Y Component as Boundary Condition in Details.

Numbers with bold face below needs to be updated with your own values for homework assignment.

Right click on Solution in the Outline and select Insert>>User Defined Results. Select Named Selection as Scoping Method under Scope in Details and select Mesh Nodes Long Sheet Edge as Named Selection. Enter **50** s as Display Time (only enter number **50**, not units as units will automatically appear) and enter LOC_DEFX (don't enter equal sign) as Expression under Definition in Details. Select Displacement as Output Unit. Right click on User Defined Result under Solution in Outline and select Rename. Enter the name x_t=**50**s. Repeat this step twice to create LOC_DEFY and LOC_DEFZ and enter the names y_t=**50**s and z_t=**50**s.



Details of "x_t=50s"

Scope	
Scoping Method	Named Selection
Named Selection	Mesh Nodes Long Sheet Edge
Definition	
Source	Expression
Expression	= LOC_DEFX
Input Unit System	Metric (mm, kg, N, s, mV, mA)
Output Unit	
By	Time
Display Time	50. s

Figure 9g) Details for user defined results

Repeat this set of three user defined results for the x, y and z coordinates for the deformed sheet but this time select Display Time **60** s and rename the user defined results as x_t=**60**s, y_t=**60**s and z_t=**60**s.

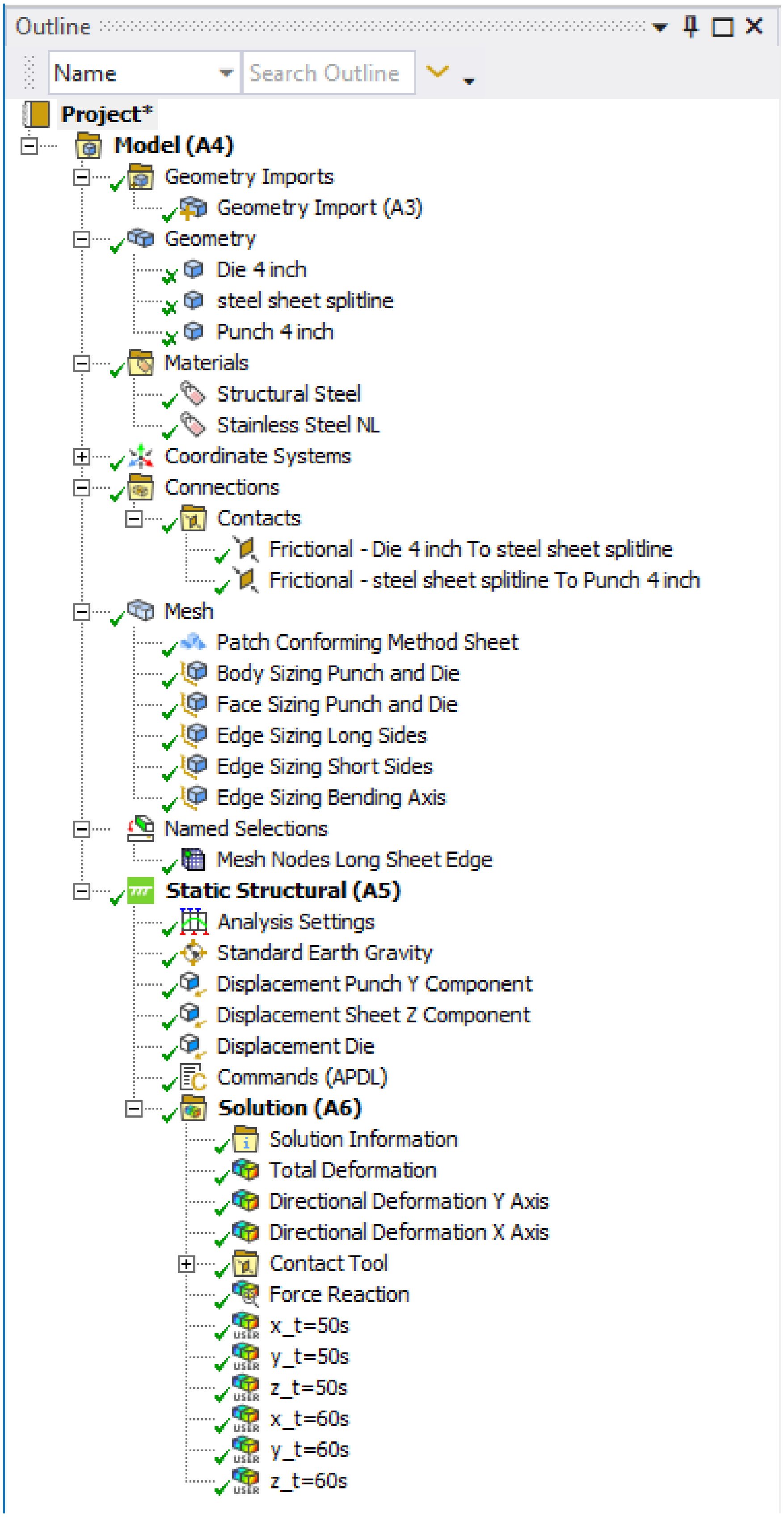


Figure 9h) Completed outline in Ansys Mechanical

Set the number of Cores to 4 under the Home tab in the menu, see Figure 9g). Save the project with the name *Tacos Holder V-bending.wbpj*. Also, go to the Ansys Workbench window and save the project as File>>Archive… with the name *Tacos Holder V-bending.wbpz*. Keep the current options checked in the Archive Options window and click on Archive. Go back the Ansys Mechanical window and select Solve from under the menu.

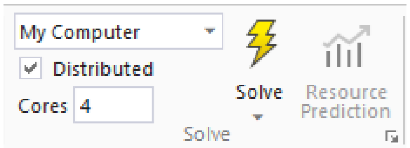


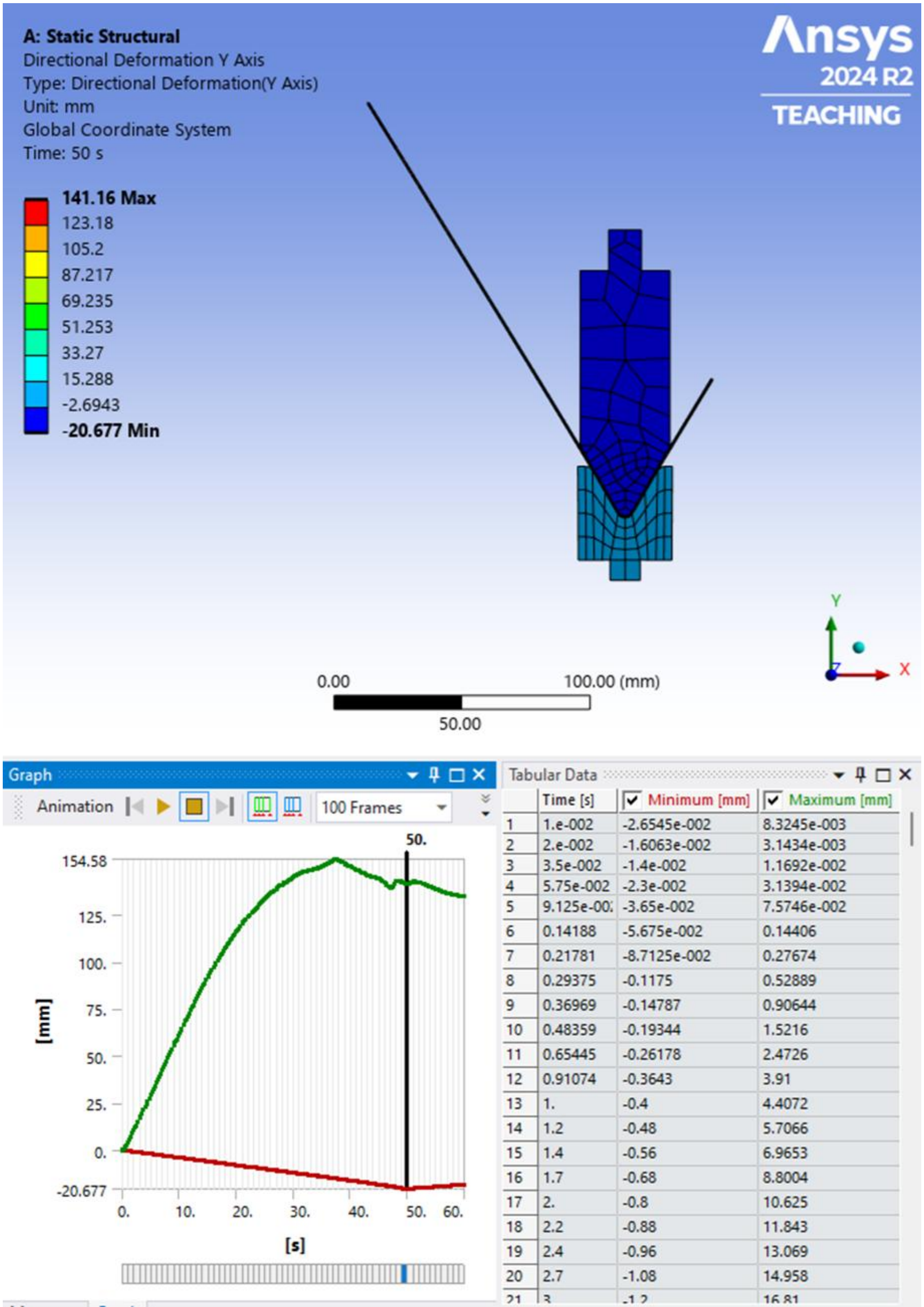
Figure 9g) Details for solver

F. Post-Processing for 1st Bend

10. Numbers with bold face below needs to be updated with your own values for homework assignment.
Double click on Directional Deformation Y Axis under Solution in the Outline. Select 100 Frames as Total number of frames in animation. Select 10 Sec as Play duration for animation. Export Video File and save the file with the name *Tacos Holder V-Bending Directional Deformation Y Axis Video.mp4*. Uncheck box for Average [mm] under Tabular Data. The minimum deformation in the Y direction is -20.667 mm at **50** s. Set Display Time to **50** s in Details of "Directional Deformation Y Axis". Right click on Directional Deformation Y Axis under Solution in Outline and select Retrieve This Result.

Continue setting Display Time **0, 10, 20, 30, 40, 50, 53.3, 56.7** and **60** s and Retrieve This Result for each Display Time. Take screenshots as shown in Figure 8.10b) and keep the height of the die the same in between each screenshot.

Right click on die and punch (one at a time) under Geometry in Outline and select Hide Body. Right click in the graphics window and select View>>Top. Select Equivalent Stress under Solution in the Outline. Set Display Time to **60** s under Definition in Details. Right click on Equivalent Stress and select Retrieve This Result,, see Figure 8.10d). Right click on die and punch (one at a time) under Geometry in Outline and select Show Body.



	Time [s]	Minimum [mm]	Maximum [mm]
1	1.e-002	-2.6545e-002	8.3245e-003
2	2.e-002	-1.6063e-002	3.1434e-003
3	3.5e-002	-1.4e-002	1.1692e-002
4	5.75e-002	-2.3e-002	3.1394e-002
5	9.125e-00	-3.65e-002	7.5746e-002
6	0.14188	-5.675e-002	0.14406
7	0.21781	-8.7125e-002	0.27674
8	0.29375	-0.1175	0.52889
9	0.36969	-0.14787	0.90644
10	0.48359	-0.19344	1.5216
11	0.65445	-0.26178	2.4726
12	0.91074	-0.3643	3.91
13	1.	-0.4	4.4072
14	1.2	-0.48	5.7066
15	1.4	-0.56	6.9653
16	1.7	-0.68	8.8004
17	2.	-0.8	10.625
18	2.2	-0.88	11.843
19	2.4	-0.96	13.069
20	2.7	-1.08	14.958
21	3	-1.2	16.81

Figure 10a) Minimum and maximum Directional deformation Y Axis (front view).

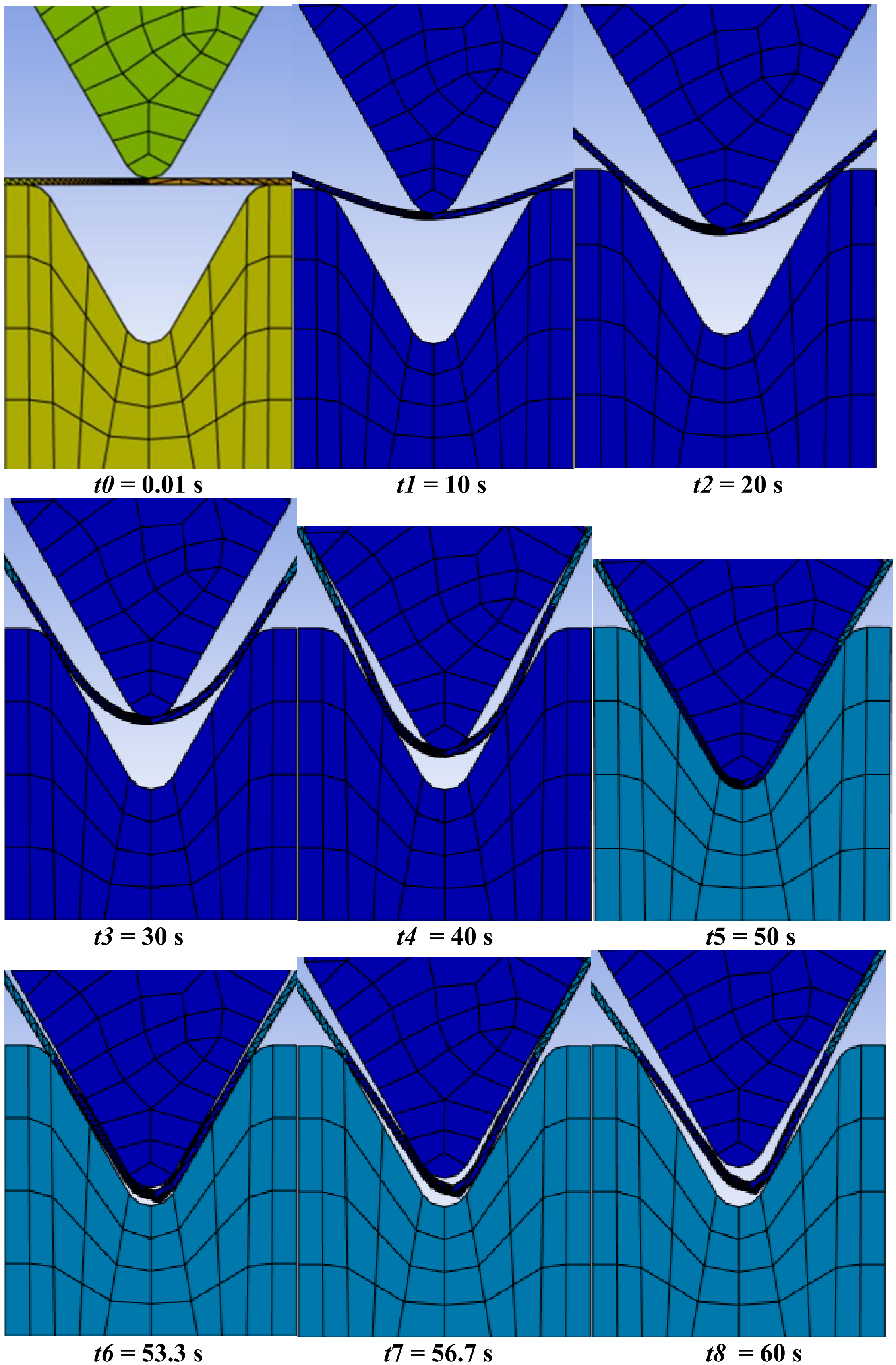


Figure 10b) Directional deformation Y Axis at different times (front view).

Numbers with bold face below needs to be updated with your own values for homework assignment.

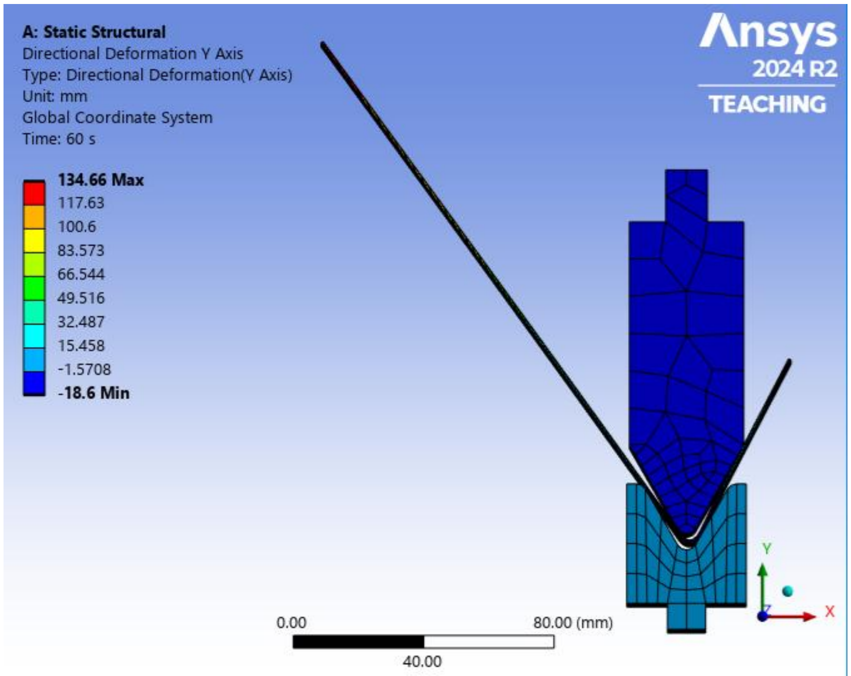


Figure 10c) Final Directional Deformation Y Axis at *t* = **60** s (front view).

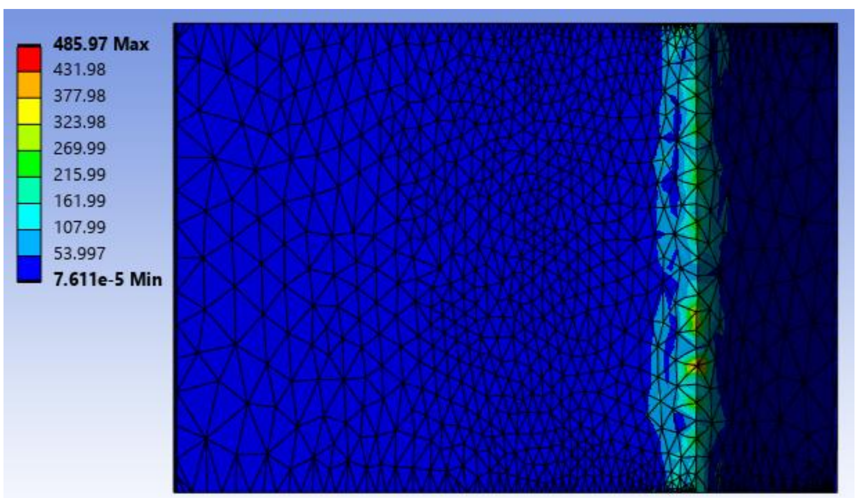


Figure 10d) Equivalent von Mises stress in metal sheet at *t* = **60** s (top view).

Double click on Force Reaction under Solution in the Outline. Uncheck boxes for Force Reaction (X) [N], Force Reaction (Z) [N] and Force Reaction (Total) [N] under Tabular Data. Set Display Time to **50** s in Details of “Directional Deformation Y Axis”. Right click on Force Reaction under Solution in Outline and select Retrieve This Result.

Select the Time [s] column under Tabular Data. Right click and select Copy Cell. Start an Excel sheet and paste the data in column A starting in cell A2. Include a heading labeled Time [s] in cell A1. In the same way, select the **Force Reaction (Y) [N]** column in Ansys Mechanical and copy over the data to column B starting in cell B2 in the Excel sheet and include a label in cell B1. **Numbers with bold face below needs to be updated with your own values for homework assignment.** Label column C in Excel as Bending Stroke (mm) in cell C1 and enter =**20***A2/**50** in cell C2. Select the lower right corner of cell C2 and drag this cell down column C all the way to row **218** corresponding to Time [s] equal **50**. Enter =**20-20***(A**219-50**)/**50** in cell C**219**. Select the lower right corner of cell C**219** and drag this cell down column C all the way to row **271** corresponding to Time [s] equal **60**. The value in cell C**271** will be **16**. Label column D in Excel as Bending Force [N] in cell D1 and enter =ABS(B2) in cell D2. Select the lower right corner of cell D2 and drag this cell down column D all the way to row **271** corresponding to Time [s] equal **60**. Label column E in Excel as Eq. 8.1 (N) in cell E1 and enter =1582 in cell E2. Select the lower right corner of cell E2 and drag this cell down column E all the way to row **271** corresponding to Time [s] equal **60**.

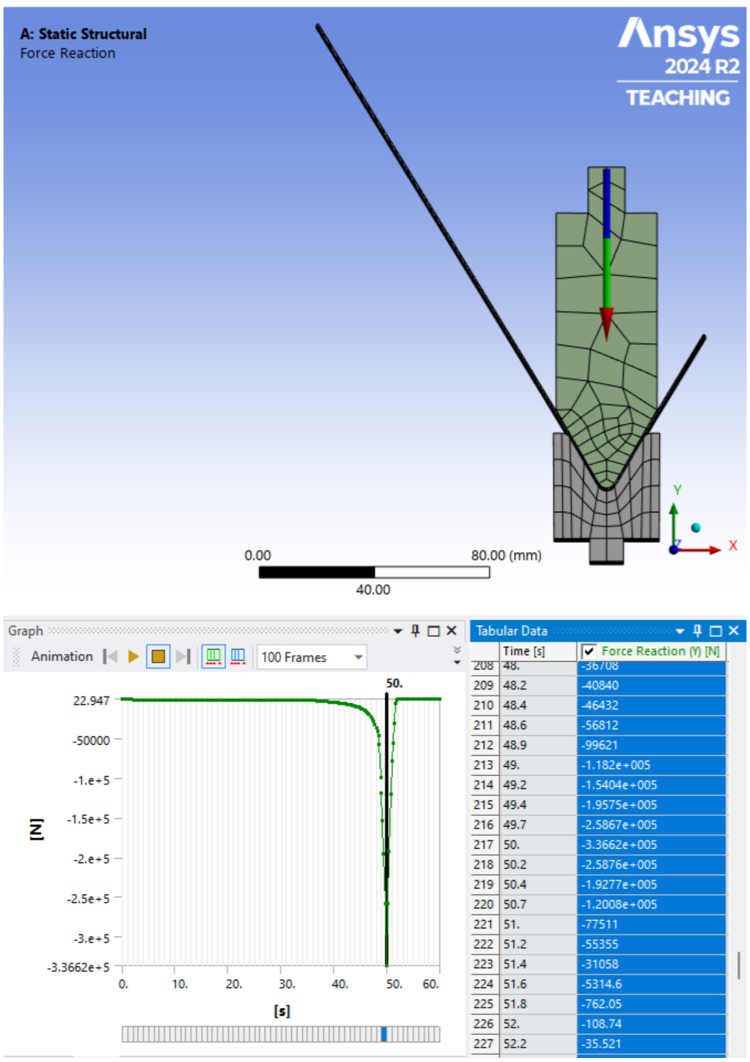


Figure 10e) Maximum force reaction at t = **50** s (front view).

	A	B	C	D	E
1	Time [s]	Force Reaction (Y) [N]	Bending Stroke (mm)	Bending Force [N]	Eq. 8.1 (N)
2	1.00E-02	0.20426	4.00E-03	0.20426	1528
3	2.00E-02	-0.12578	8.00E-03	0.12578	1528
4	3.50E-02	-2.3725	1.40E-02	2.3725	1528
5	5.75E-02	-6.2846	2.30E-02	6.2846	1528
6	9.13E-02	-12.192	3.65E-02	12.192	1528
7	0.14188	-21.221	5.68E-02	21.221	1528
8	0.21781	-37.231	8.71E-02	37.231	1528
9	0.29375	-62.712	1.18E-01	62.712	1528
10	0.36969	-99.541	1.48E-01	99.541	1528
11	0.48359	-159.57	1.93E-01	159.57	1528
12	0.65445	-253.12	2.62E-01	253.12	1528
13	0.91074	-394.1	3.64E-01	394.1	1528
14	1	-441.49	4.00E-01	441.49	1528
15	1.2	-543.5	4.80E-01	543.5	1528
16	1.4	-606.59	5.60E-01	606.59	1528
17	1.7	-670.77	6.80E-01	670.77	1528
18	2	-717.55	8.00E-01	717.55	1528

Figure 10f) Excel sheet with data for V-bending force.

Numbers with bold face below needs to be updated with your own values for homework assignment. Select columns C - E in the Excel sheet. Select Insert>>Charts>>Scatter from the Excel menu. Label the vertical axis as Bending Force (N) and the horizontal axis as Bending Stroke (mm). The maximum bending force (bottoming force) is 336,620 N (75,580 lb) corresponding to stroke **20** mm. Set the vertical scale to logarithmic with lower and upper bounds 10 N and 1,000, 000 N, respectively. Set the horizontal scale to linear with lower and upper bounds 0 mm and **20** mm. Save the Excel file with the name *Bending Force versus Bending Stroke for V-Bending*.

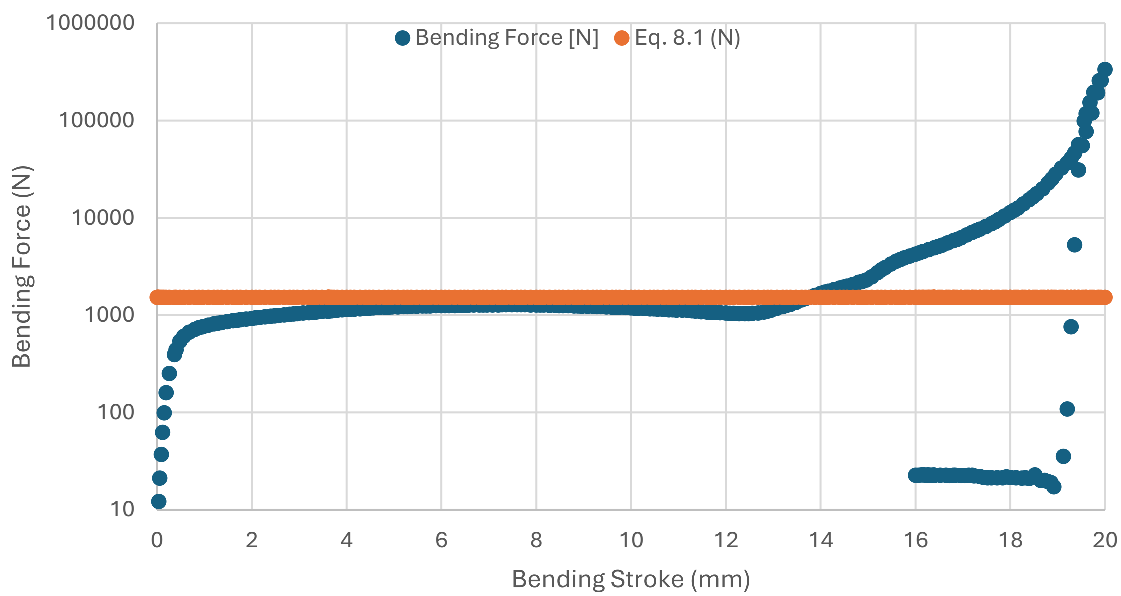


Figure 10g) Excel sheet with data for V-bending force.

Numbers with bold face below needs to be updated with your own values for homework assignment. The steps described on this page have already been completed in the Excel file *Deformed Sheet Coordinates.xlsx* that is available on d2l. This file can be used and updated with your data. Right click on x_t=**50**s under Solution in the Outline and select Export…>>Export Text File. Set Save as type: to Excel File (*.xls) and save the file with the name x_t=**50**s.xls. Repeat this step for y_t=**50**s, z_t=**50**s, x_t=**60**s, y_t=**60**s and z_t=**60**s.

Open the files x_t=**50**s.xls and y_t=**50**s.xls in Excel. Copy column B with the title LOC_DEFY (mm) from the file y_t=**50**s.xls and paste this data column including title to column C in file x_t=**50**s.xls. In the same way, copy column B with the title LOC_DEFZ (mm) from the file z_t=**50**s.xls and paste this data column including title to column D in file x_t=**50**s.xls.

Save the Excel file, Save as type: Excel Workbook (*.xlsx), with the name *Deformed Sheet Coordinates.xlsx*. Insert another row on the Excel sheet as the first row. Label cell A1 as t = **50** s, label cell B1 as x-coord, label cell C1 as y-coord. and label cell D1 as z-coord.

Select cells B3 – B5 on the Excel sheet. Select Sort & filter on the Editing tab under the Excel menu. Select Sort Smallest to Largest, Expand the selection in the Sort Warning window and select Sort in the same window.

Copy columns A and B with the titles Node Numbers and LOC_DEFX (mm) from the file x_t=**60**s.xls and paste these data columns including titles to cell A8 in file *Deformed Sheet Coordinates.xlsx*. In the same way, copy column B with the title LOC_DEFY (mm) from the file y_t=**60**s.xls and paste this data column including title to cell C8 in file *Deformed Sheet Coordinates.xlsx*. Finally, copy column B with the title LOC_DEFZ (mm) from the file z_t=**60**s.xls and paste this data column including title to cell D8 in file *Deformed Sheet Coordinates.xlsx*. Label cell A7 as t = **60** s, label cell B7 as x-coord, label cell C7 as y-coord. and label cell D7 as z-coord.

Select cells B9 – B11 on the Excel sheet. Select Sort & filter on the Editing tab under the Excel menu. Select Sort Smallest to Largest, Expand the selection in the Sort Warning window and select Sort in the same window. Enter Time [s] in cell A13, enter t = **50** s in cell A14 and enter t = **60** s in cell A15.

Enter γ & γ_f (deg.) in cell B13, enter =180*ATAN((C3-C4)/(B4-B3))/PI() in cell B14 and enter =180*ATAN((C9-C10)/(B10-B9))/PI() in cell B15. Enter β & β_f (deg.) in cell C13, enter =180*ATAN((C5-C4)/(B5-B4))/PI() in cell C14 and enter =180*ATAN((C11-C10)/(B11-B10))/PI() in cell C15. Enter α & α_f (deg.) in cell D13, enter =180-C14-B14 in cell D14 and enter =180-C15-B15 in cell D15. Enter SB (deg.) in cell E13 and enter =D15-D14 in cell E14. Enter SB, theory (deg.) in cell F13 and enter =F20 in cell F14. Enter % diff. in cell G13 and enter =100*ABS(E14-F14)/F14 in cell G14.

Enter the remaining theory section with headings and data in rows 17-20 in the Excel file as shown in Figure 8.10h). Enter **60** and **63.8948** in cells A19 and A20. Enter =25.4/8 in cells B19 and B20. Enter =3.175/0.9869 in cells C19 and C20. Enter 0.5 in cells D19 and D20. Enter =(C19+D19*0.7874)*A19/(B19+D19*0.7874) in cell E19 and

=(C20+D20*0.7874)*A20/(B20+D20*0.7874) in cell E20. Enter =E19-A19 in cell F19 and enter =E20-A20 in cell F20.

Select cells B3 – C5 on the Excel sheet. Select Insert>>Charts>>Scatter with Straight Lines and Markers from the Excel menu. Include axis titles, label the horizontal axis as x (mm) and the vertical axis as y (mm). Include legend in the chart and insert cells B9 – C11 in the same graph.

	A	B	C	D	E	F	G
1	t = 50s	x-coord.	y-coord.	z-coord.			
2	Node Number	LOC_DEFX (mm)	LOC_DEFY (mm)	LOC_DEFZ (mm)			
3	20766	-105.29	159.78	56.403			
4	20657	-5.2303	-1.0267	56.403			
5	20862	28.117	52.333	56.403			
6							
7	t = 60s	x-coord.	y-coord.	z-coord.			
8	Node Number	LOC_DEFX (mm)	LOC_DEFY (mm)	LOC_DEFZ (mm)			
9	20766	-116.55	153.33	56.403			
10	20657	-4.0627	0.99372	56.403			
11	20862	25.788	56.404	56.403			
12							
13	Time [s]	γ & γ_f (deg.)	β & β_f (deg.)	α & α_f (deg.)	SB (deg.)	SB, theory (deg.)	% diff.
14	t = 50 s	58.1086	57.9966	63.8948	0.8602	0.75	14
15	t = 60 s	53.5573	61.6877	64.7550			
16							
17	Theory						
18	α (degrees)	R_i (mm)	R_f (mm)	K	α_f (degrees)	SB (degrees)	
19	60	3.175	3.2171	0.5	60.71	0.71	
20	63.8948	3.175	3.2171	0.5	64.65	0.75	

Figure 10h) Data in Excel file *Deformed Sheet Coordinates at t = 50s and 60s.*

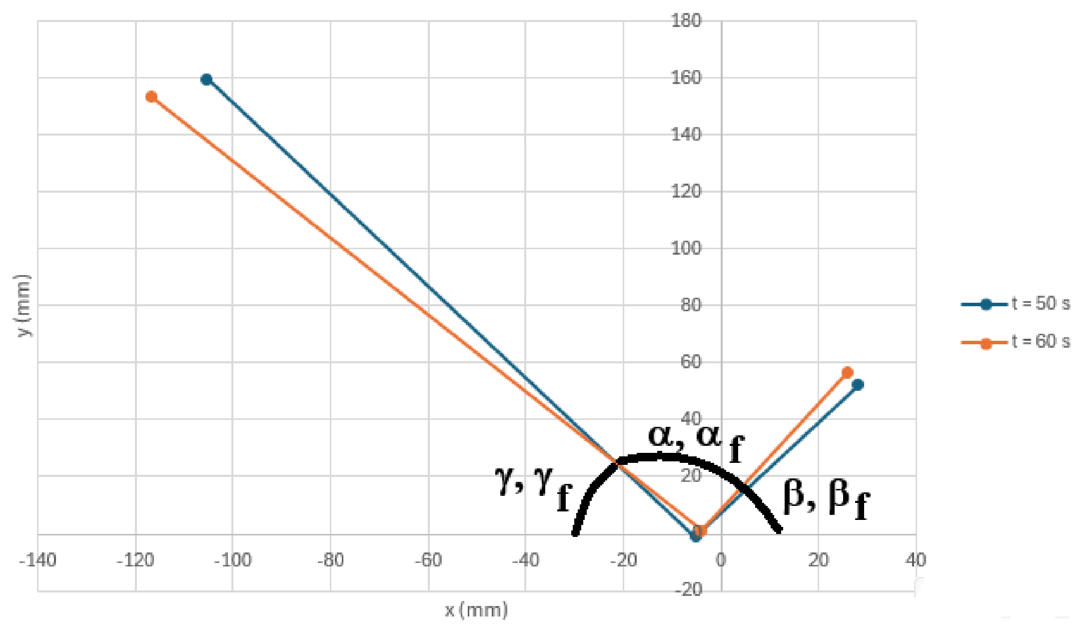


Figure 10i) Geometry of sheet at t = **50** s (bottoming) and t = **60** s after spring back.

G. Ansys Mechanical for 2nd and 3rd Bend

11. Open workbench window. Right click geometry under static structural in project Schematic window. Select Replace Geometry and Browse…. Upload the file SecondBendAssemblyTacoHolder.SLDASM for the second bend or alternatively upload ThirdBendAssemblyTacoHolder.SLDASM to Geometry for the third bend.

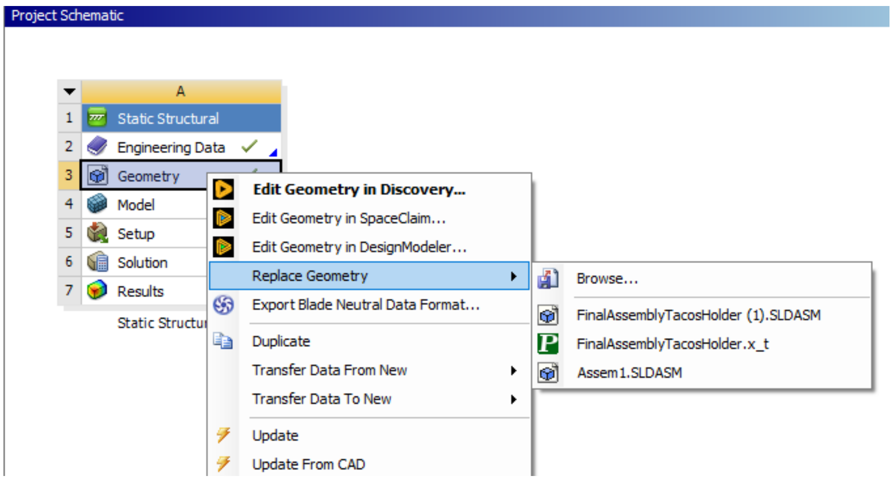


Figure 11 Replacing Geometry

12. Double click on Model in the Ansys Workbench Project Schematic to open the Ansys Mechanical window. Select yes on the Ansys Workbench pop-up. Control-select the punch and die under Geometry in the Outline. Select Structural Steel as Assignment under Material in Details. Assign Stainless Steel NL as the Material in Details View for the sheet. Make sure that the Stiffness Behavior under Definition in Details for the sheet is Flexible.

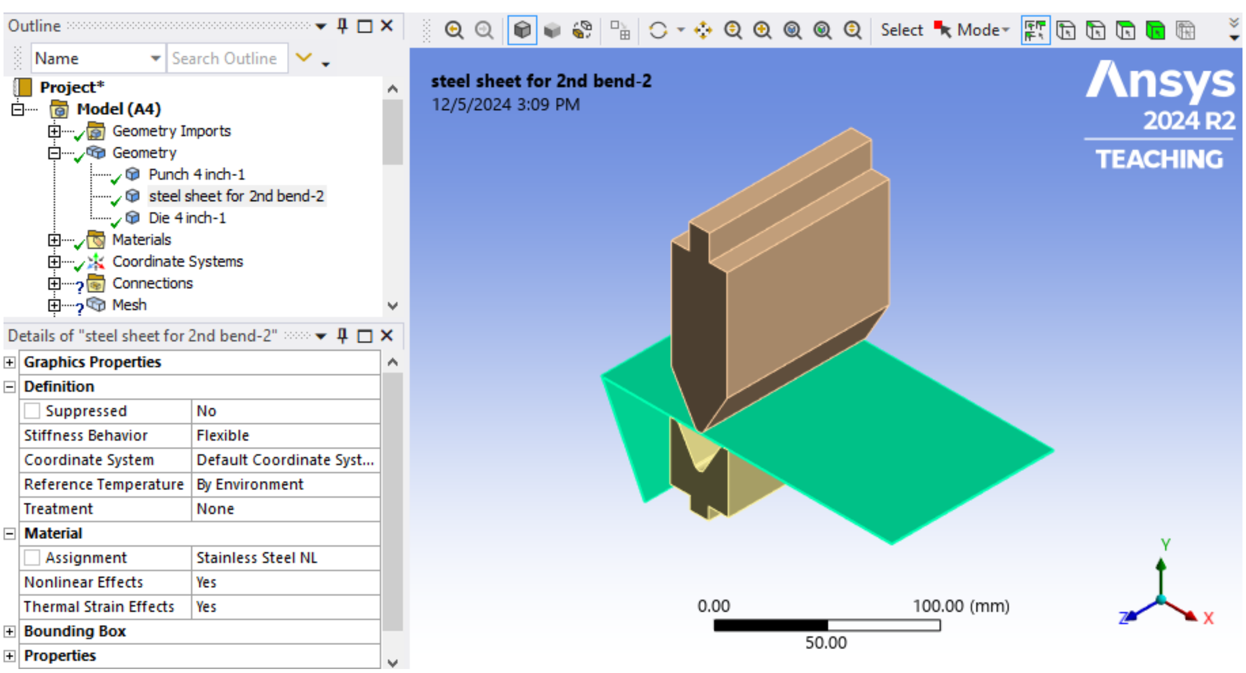


Figure 12 Assigning stainless steel as material for bent sheet.

13. Select and right click on the Sheet under Geometry and select Hide Body. Open Connections and Contacts in the Outline. Delete Contact Region and Contact Region 2. Select Friction – Die to Sheet under Contacts. Select the seven contact faces of the die (see Figure 5a) and Apply these Faces as Contact under Scope in Details. Right-click on Sheet under Geometry in the Outline and select Show Body. Right click in the graphics window and select View>>Bottom. Control-select and Apply the two bottom faces of the sheet as Target under Scope in Details and shown in Figure 13.

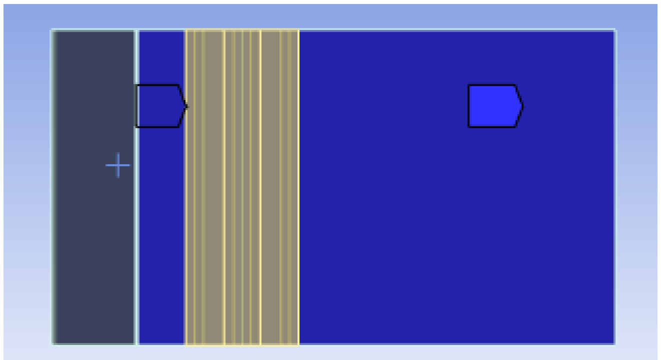


Figure 13. Target faces for the taco holder sheet

14. Open Connections and Contacts in the Outline. Select Friction – Sheet to Punch under Contacts. Select the two upper contact faces of the sheet and Apply these Faces as Contact under Scope in Details. These faces may already have been preselected. Right-click on Sheet under Geometry in the Outline and select Hide Body. Control-select and Apply the three bottom faces of the punch as Target under Scope in Details and shown in Figure. Right-click on Sheet under Geometry in the Outline and select Show Body. Select Isometric View.

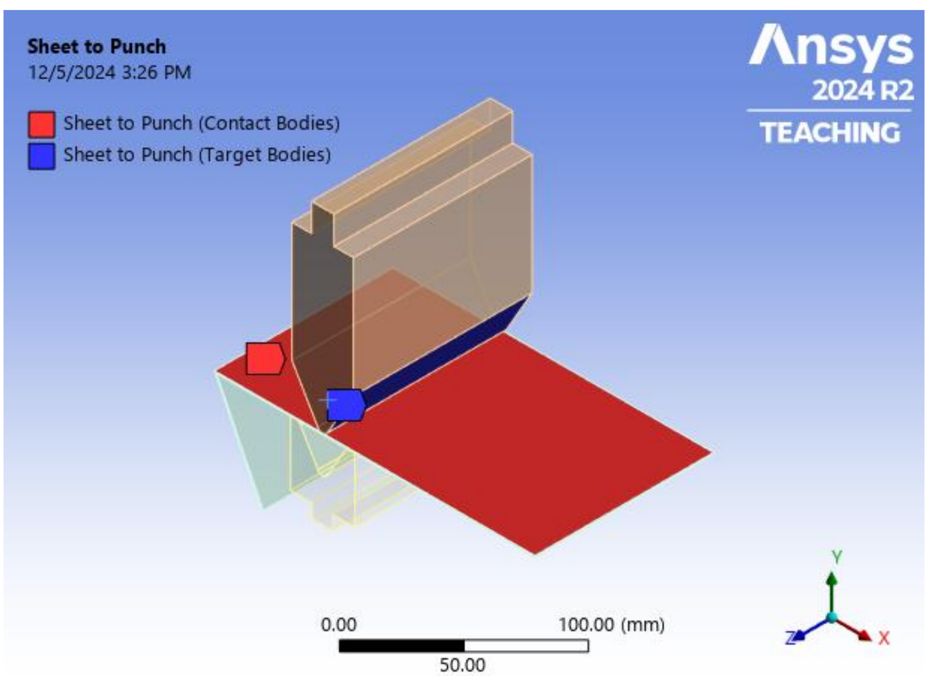


Figure 14. Contact faces for punch and sheet for second bend

15. Open mesh in the outline and select Patch Conforming Method Sheet. Select Body  above the graphics window. Select and apply the Sheet as Geometry under Scope in Details, see Figure 15a).

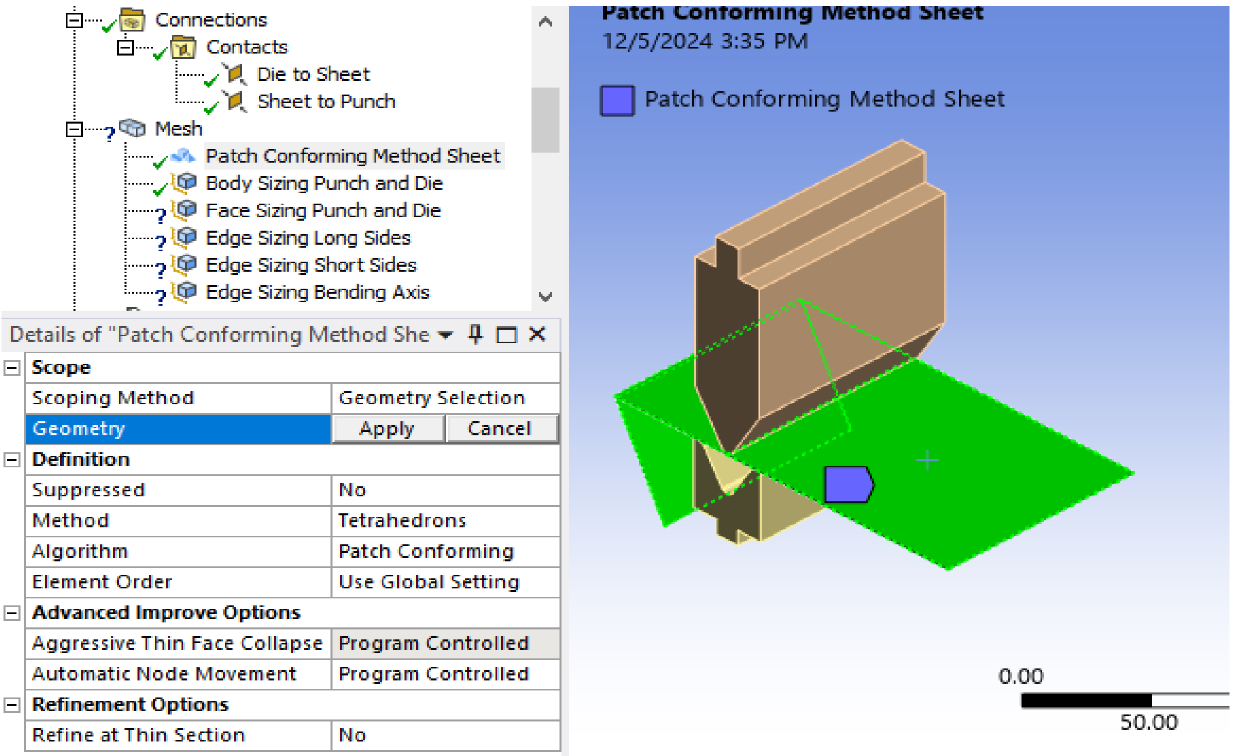


Figure 15a) Selecting sheet metal for Patch Conforming Method Sheet

Under mesh in the outline, select Body Sizing Punch and Die. Control select and apply punch and die as Geometry under Scope in Details.

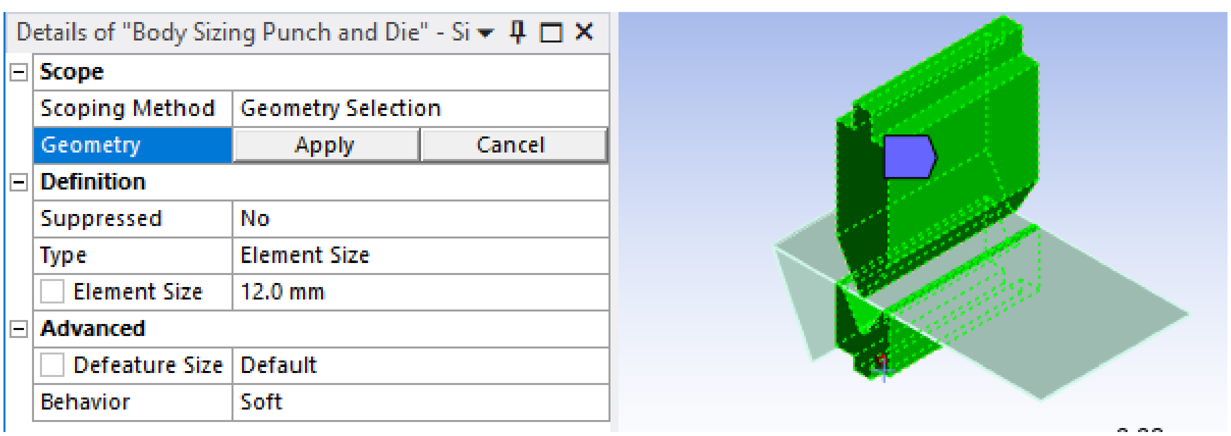
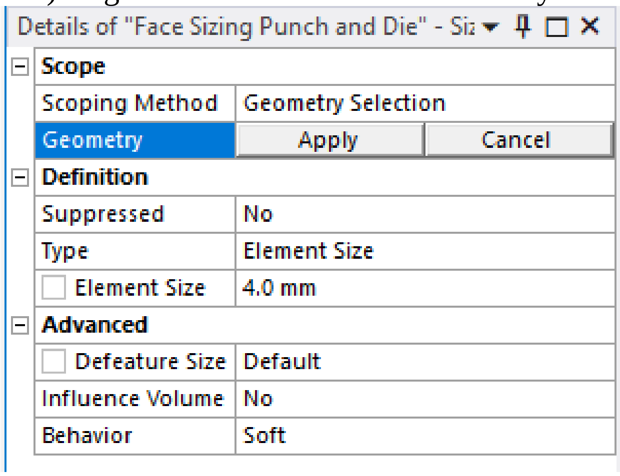


Figure 5b) Body sizing for punch and die

Right-click on Sheet under Geometry in the Outline and select Hide Body. Select Face Sizing Punch and Die. Select Face above the graphics window. Control select and apply the three lower faces of the punch and the seven faces of the die as Geometry under Scope in Details, see Figure 15c). Right-click on Sheet under Geometry in the Outline and select Show Body.



Details of "Face Sizing Punch and Die" - Siz

Scope	
Scoping Method	Geometry Selection
Geometry	Apply / Cancel
Definition	
Suppressed	No
Type	Element Size
Element Size	4.0 mm
Advanced	
Defeature Size	Default
Influence Volume	No
Behavior	Soft

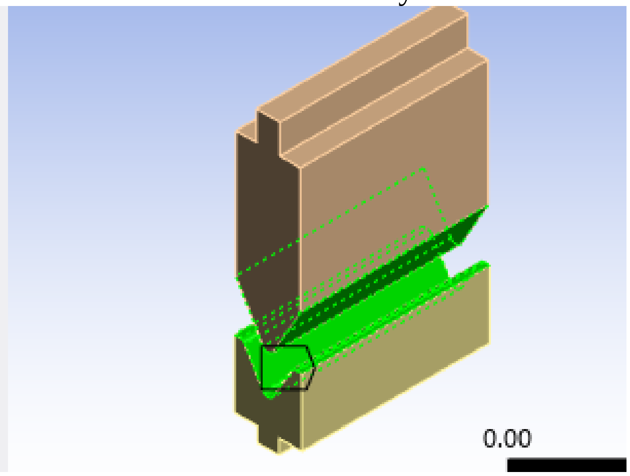
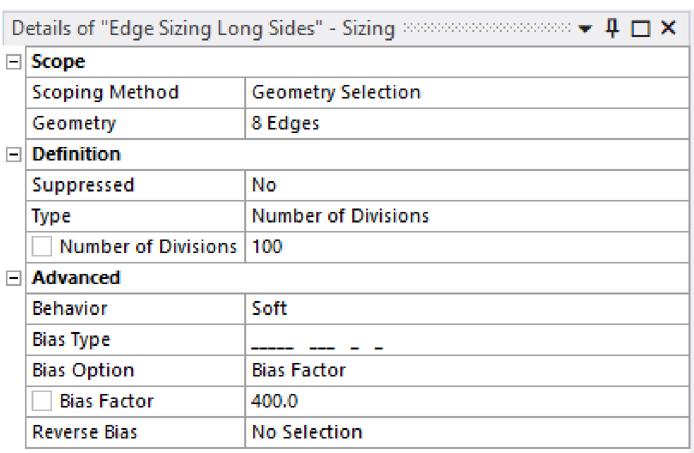


Figure 15c) Face sizing for punch and die

Select Edge Sizing Long Sides. Control select the eight (Twelve for the third bend) edges on the bent side of the sheet parallel to the x axis. Apply the selected edges as geometry in the details of Edge Sizing Long Sides. Zoom in and select the sized edges that do not have a squeezing effect towards the middle (bending axis) of the sheet. Apply the selected edges as reverse bias.



Details of "Edge Sizing Long Sides" - Sizing

Scope	
Scoping Method	Geometry Selection
Geometry	8 Edges
Definition	
Suppressed	No
Type	Number of Divisions
Number of Divisions	100
Advanced	
Behavior	Soft
Bias Type	_____ ___ _ _
Bias Option	Bias Factor
Bias Factor	400.0
Reverse Bias	No Selection

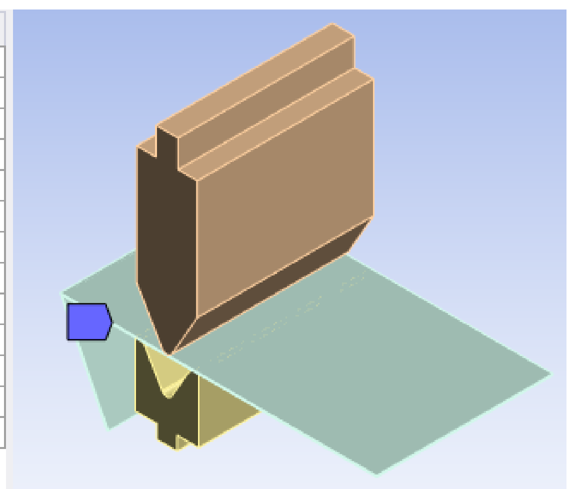


Figure 15d) Edge sizing of bent side of sheet (2nd bend)

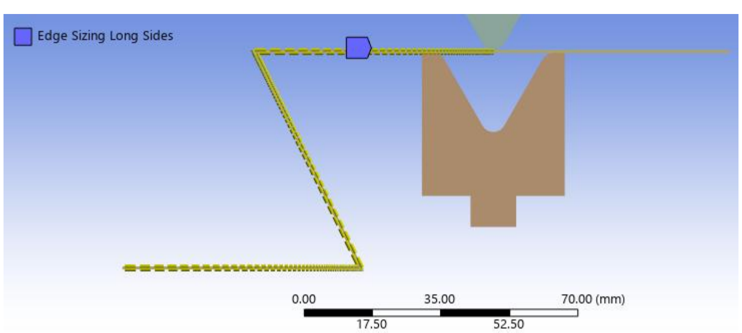


Figure 15e) Edge sizing of bent side of sheet (3rd bend)

Select Edge Sizing Short Sides. Control select the four edges on the flat side of the sheet parallel to the x axis. Apply the selected edges as geometry in the details of Edge Sizing Short Side. Zoom in and select the sized edges that do not have a squeezing effect towards the middle (bending axis) of the sheet. Apply the selected edges as reverse bias.

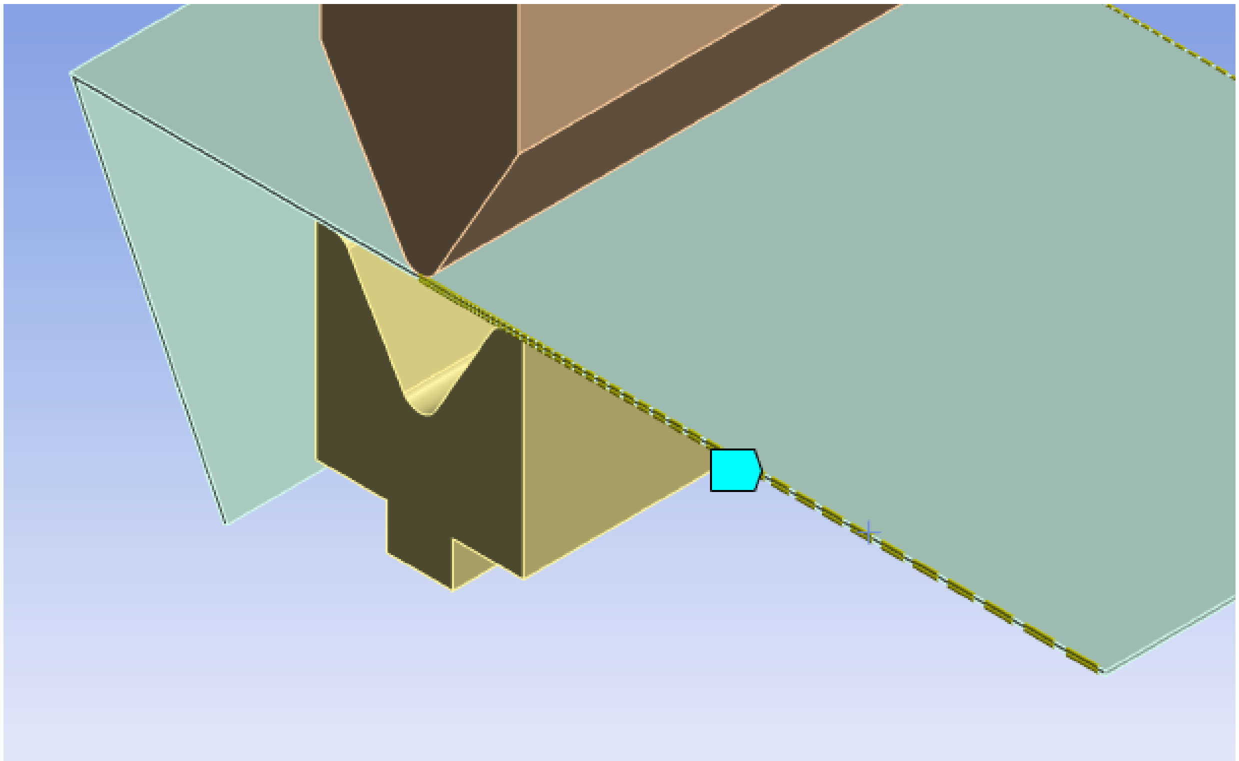


Figure 15f) Edge sizing of flat side of sheet (2nd bend)

Right click on the punch under Geometry and Hide Body. Select Edge Sizing Bending Axis. Select Edge above the graphics window. Select and apply the upper and lower split lines on the sheet, one on each side of the sheet, see Figure 7f).

Details of "Edge Sizing Bending Axis" - Sizing

Scope	
Scoping Method	Geometry Selection
Geometry	2 Edges
Definition	
Suppressed	No
Type	Element Size
Element Size	4.0 mm
Advanced	
Behavior	Soft
Bias Type	No Bias

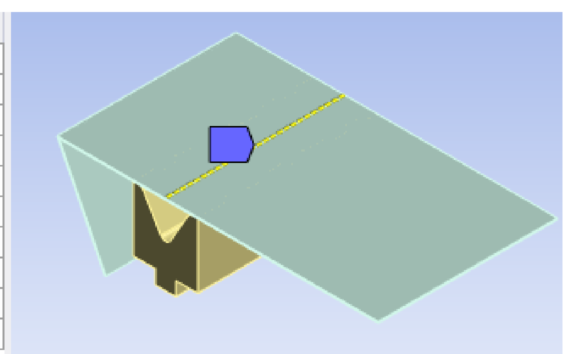


Figure 15g) Edge sizing of bending axis (2nd bend)

Right click on Mesh in Outline and select Generate Mesh. The mesh has 23,547 Nodes and 8,611 Elements. Right click on punch under Geometry and select Show Body.

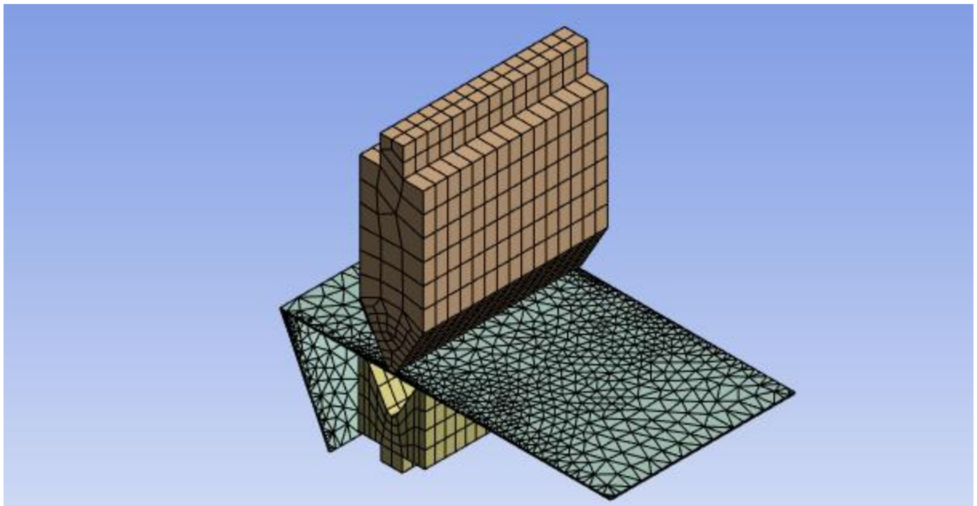


Figure 15h) Finished mesh for punch, die and sheet assembly (2nd bend)

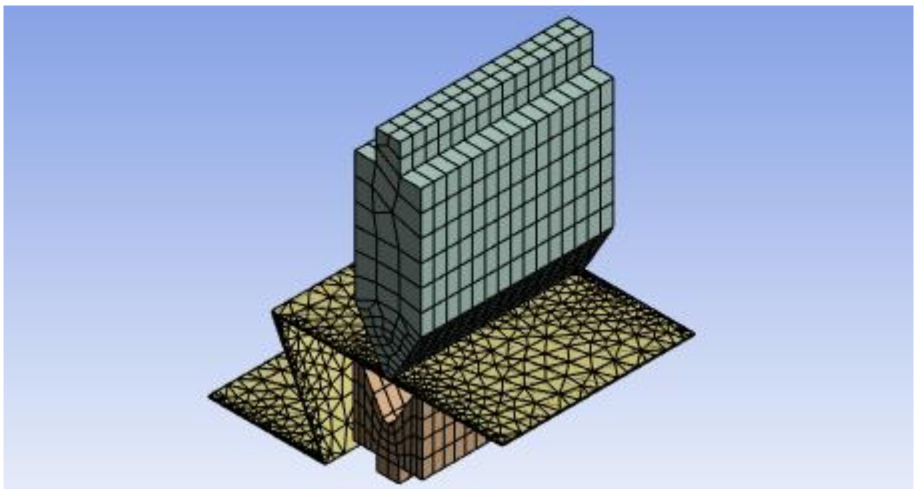


Figure 15i) Finished mesh for punch, die and sheet assembly (3rd bend)

Right click on punch under Geometry and select Hide Body. Select isometric view in the graphics window. Zoom in on the corner of the sheet that is closest to you and select the upper corner node of the mesh using  (available above graphics window) on the sheet, see Figure 7h)

Zoom in on the sheet edge at the split line and control-select the node at the intersection of the split line and the edge of the sheet, see Figure 7i).

Finally, zoom in on the bent corner on the same edge as the other two mesh nodes that have already been control-selected. Control-select the remaining upper corner node of the mesh, see Figure 15j). Zoom out on the sheet with isometric view in the graphics window. You will now have three control selected nodes on the sheet as shown in Figure 15j). Select Mesh Nodes Long Sheet Edge under Named Selections in outline. Apply the three selected nodes as geometry under details of Mesh Nodes Long Sheet Edge. Right click on punch under Geometry and select Show Body.

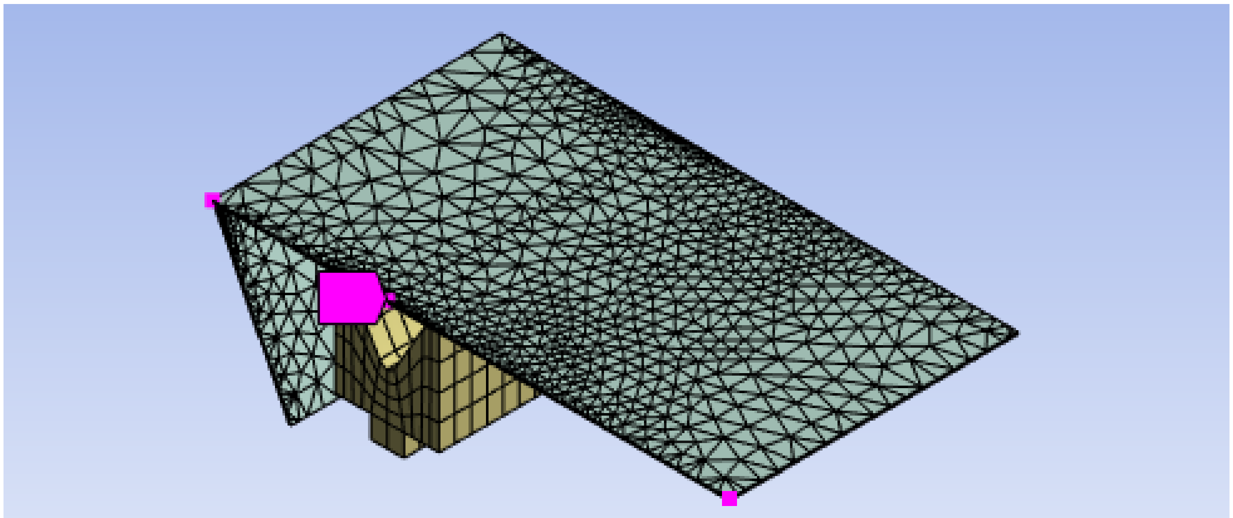


Figure 15j) The three control selected mesh nodes on sheet (2^{nd} bend).

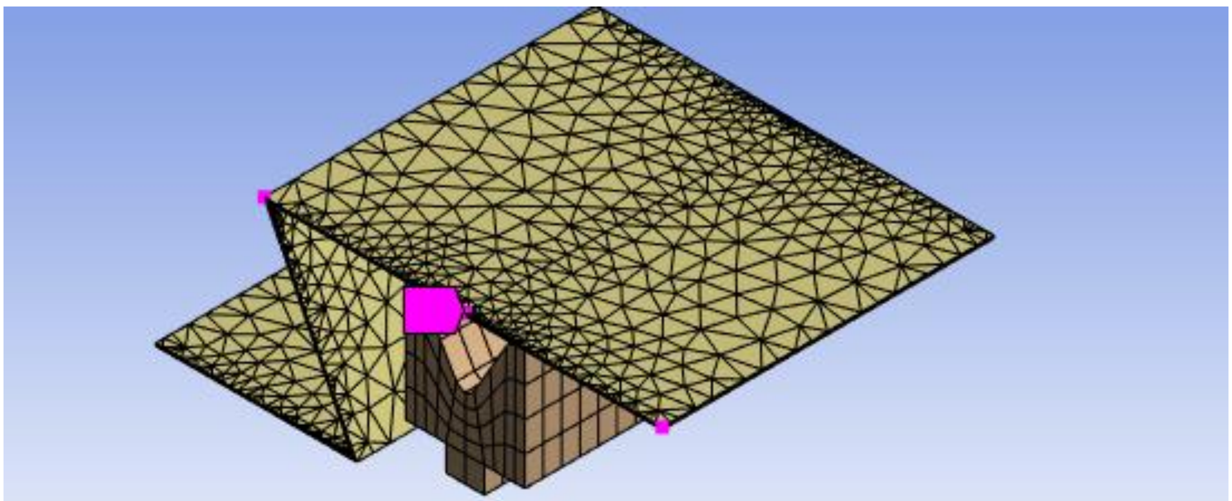


Figure 15k) The three control selected mesh nodes on sheet (3^{rd} bend).

16. Select Displacement Sheet Z Component under static structural. Select the two side faces of the Sheet (both faces that have a normal in the Z direction) and Apply these as Geometry.

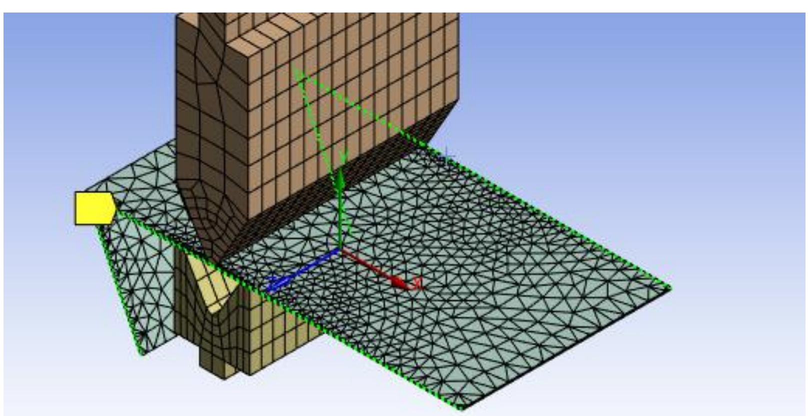


Figure 16a) Inserting Z component of displacement for sheet

Select Displacement Die under static structural. Select the bottom face of the die and apply as geometry.

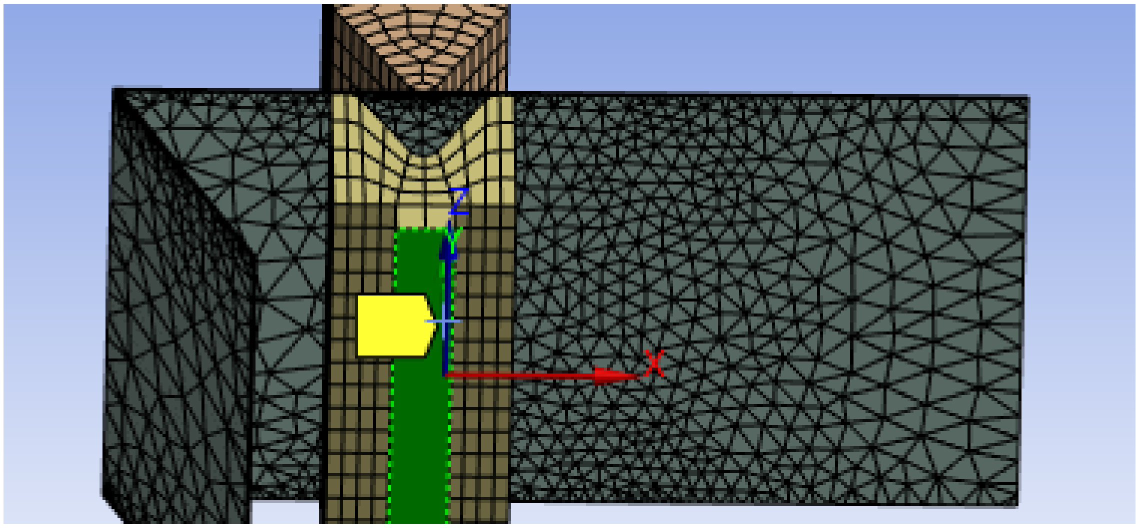


Figure 16b) Inserting die displacement component

Select Displacement under static structural. Select the top face of the punch and apply this face as geometry.

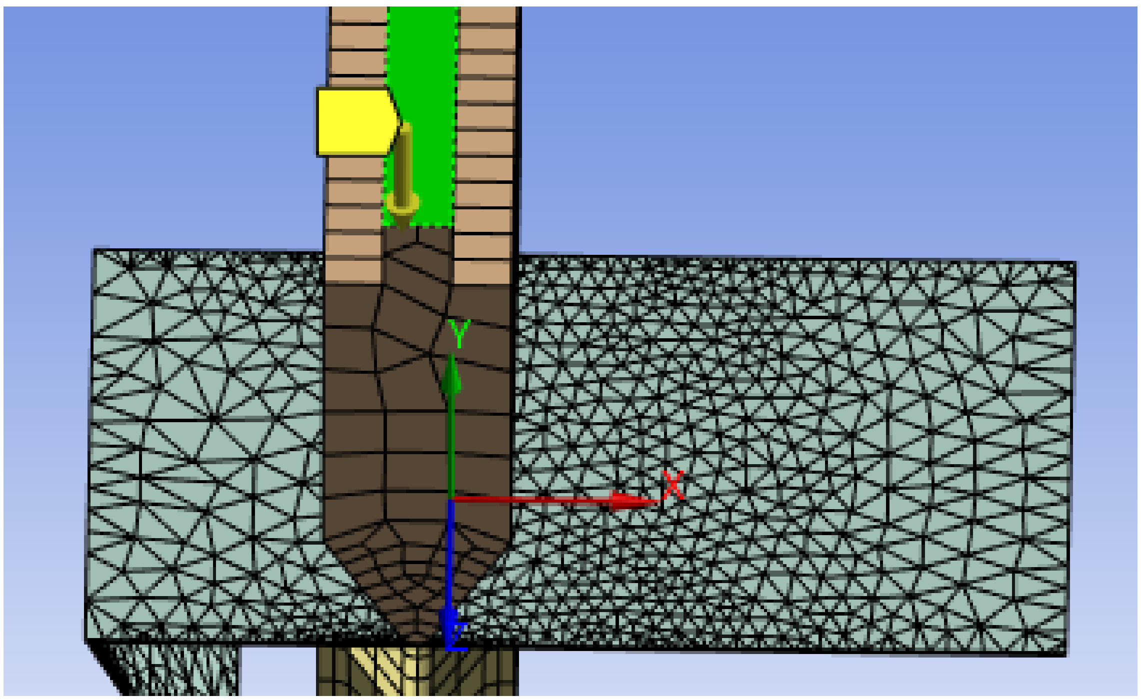


Figure 16c) Inserting punch displacement

Set the number of Cores to 4 under the Home tab in the menu, see Figure 9g). Save the project with the name Tacos Holder 2nd bend.wbpj or alternatively Tacos Holder 3rd bend.wbpj. Also, go to the Ansys Workbench window and save the project as File>>Archive... with the name Tacos Holder 2nd bend.wbpz (Tacos Holder 2nd bend.wbpz). Keep the current options checked in the Archive Options window and click on Archive. Go back the Ansys Mechanical window and select Solve from under the menu.

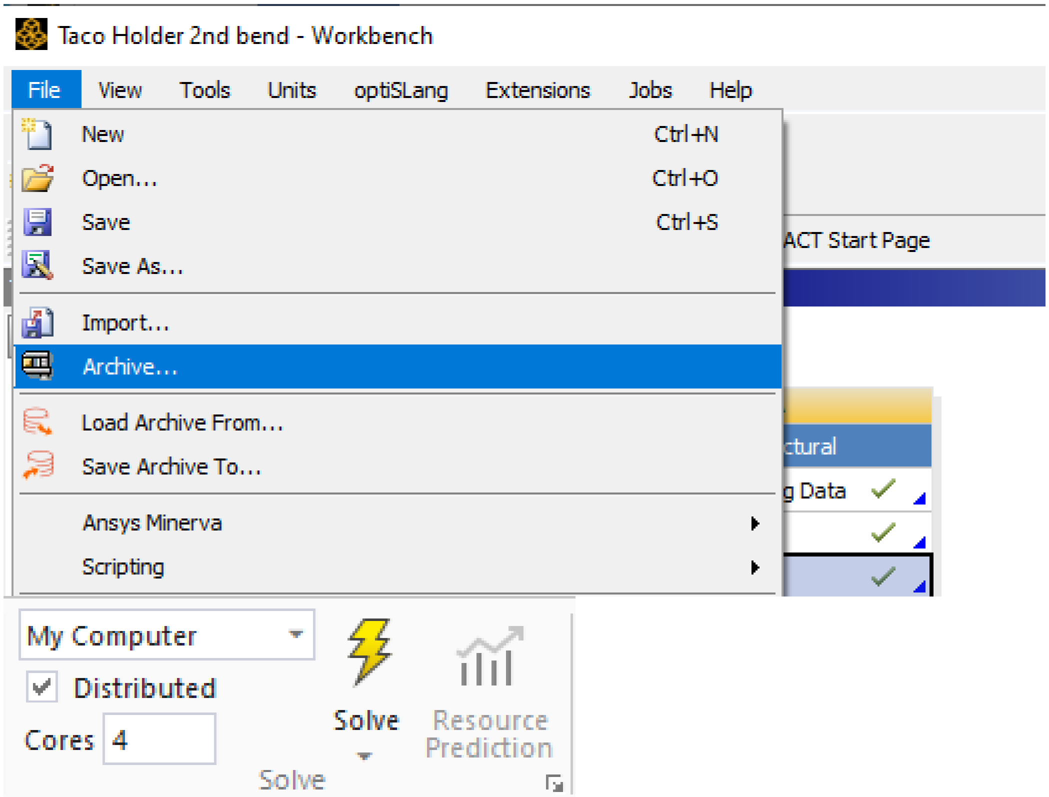


Figure 16d) Archive and details of solver

H. Post-Processing for 2nd and 3rd Bends

17. Double click on Directional Deformation Y Axis under Solution in the Outline. Select 100 Frames as Total number of frames in animation. Select 10 Sec as Play duration for animation. Export Video File and save the file with the name Tacos Holder V-Bending Directional Deformation Y Axis Video.mp4. Uncheck box for Average [mm] under Tabular Data. The minimum deformation in the Y direction is -20.667 mm at 50 s. Set Display Time to 50 s in Details of "Directional Deformation Y Axis". Right click on Directional Deformation Y Axis under Solution in Outline and select Retrieve This Result.

Continue setting Display Time 0, 10, 20, 30, 40, 50, 53.3, 56.7 and 60 s and Retrieve This Result for each Display Time. Take screenshots as shown in Figure 10b) and keep the height of the die the same in between each screenshot.

Right click on die and punch (one at a time) under Geometry in Outline and select Hide Body. Right click in the graphics window and select View>>Top. Select Equivalent Stress under Solution in the Outline. Set Display Time to 60 s under Definition in Details. Right click on Equivalent Stress and select Retrieve This Result, see Figure 10d).

Right click on die and punch (one at a time) under Geometry in Outline and select Show Body.

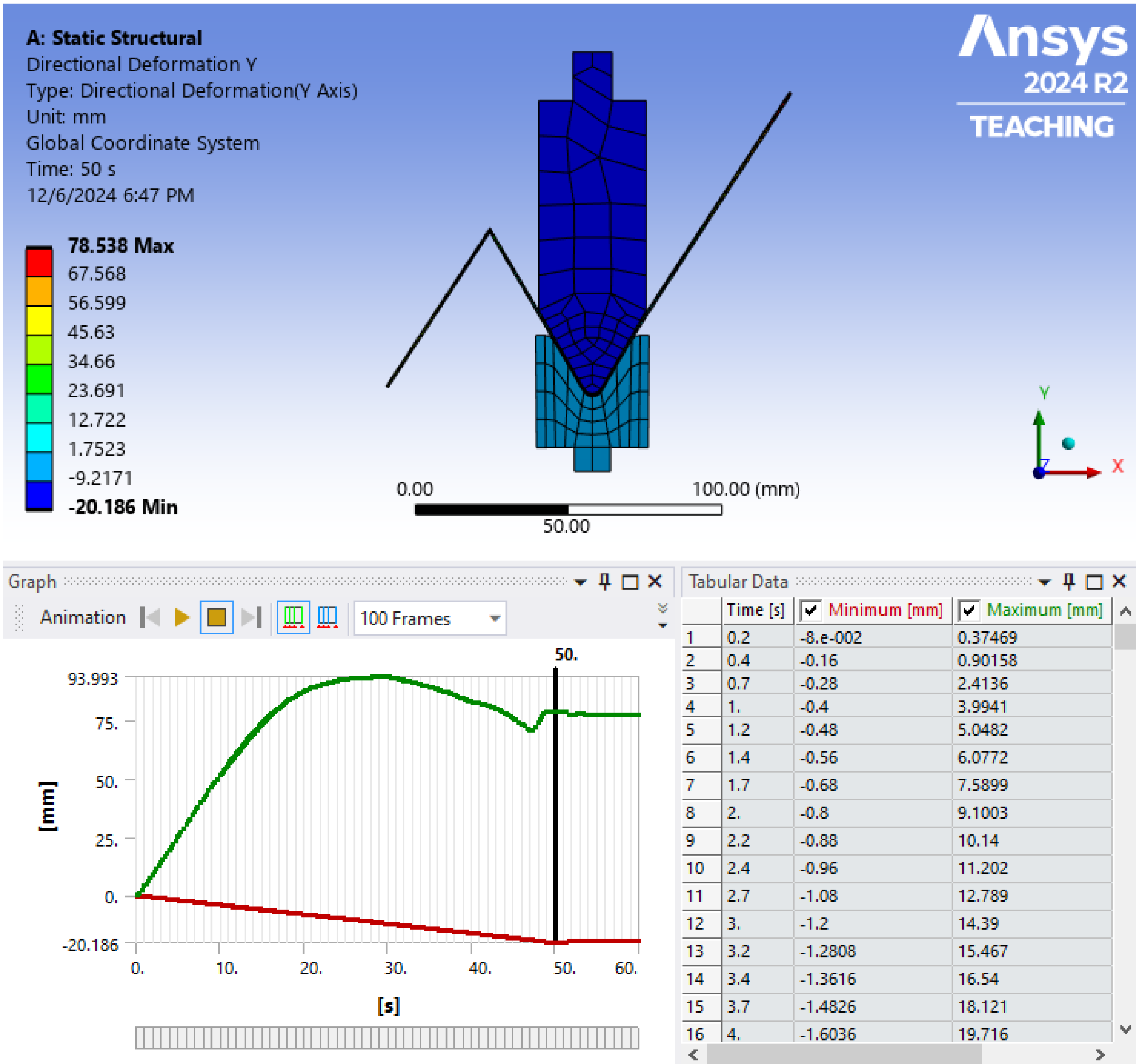


Figure 17a) Minimum and maximum Directional deformation Y Axis (2nd bend front view).

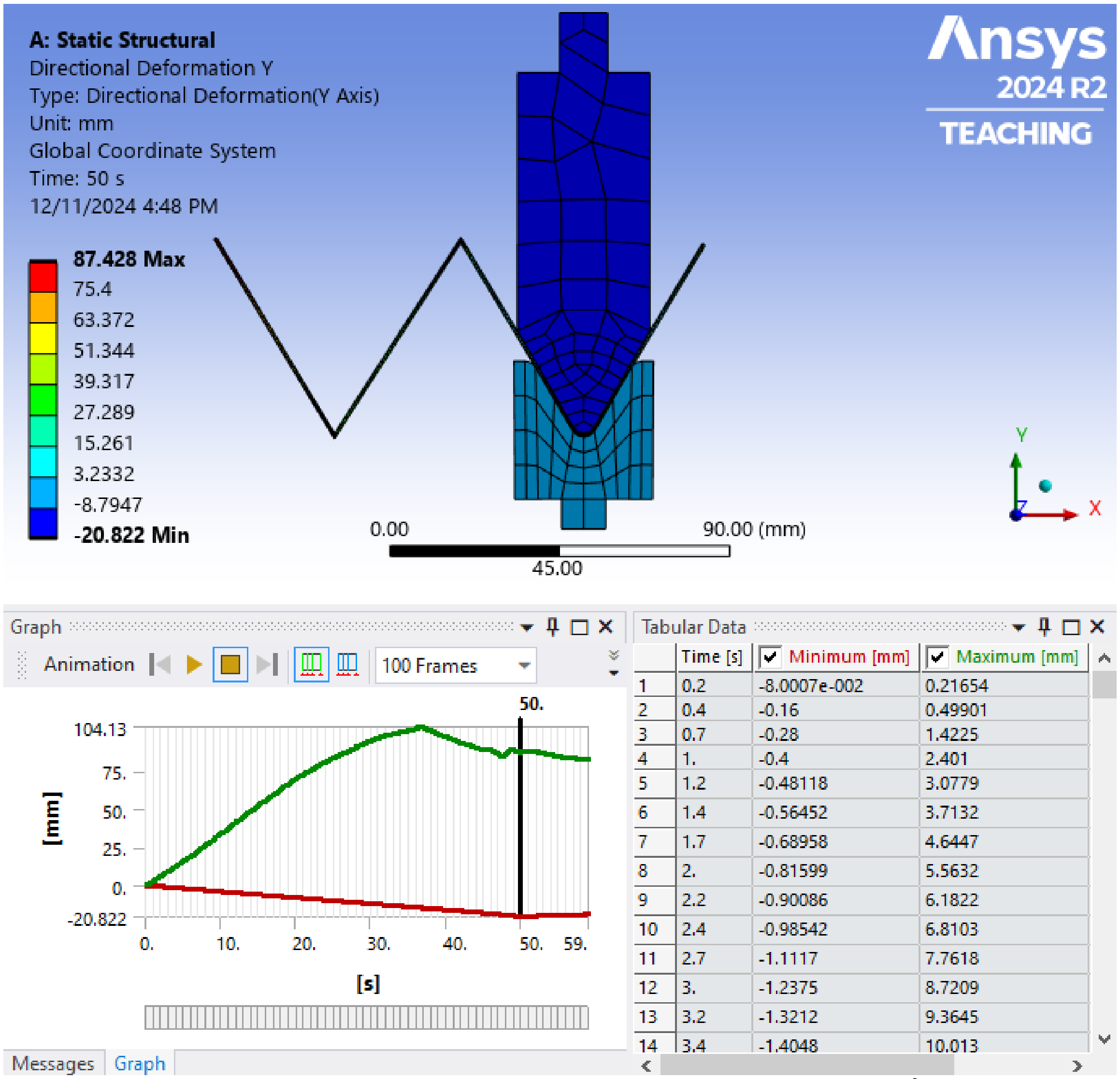


Figure 17b) Minimum and maximum Directional deformation Y Axis (3rd bend front view).

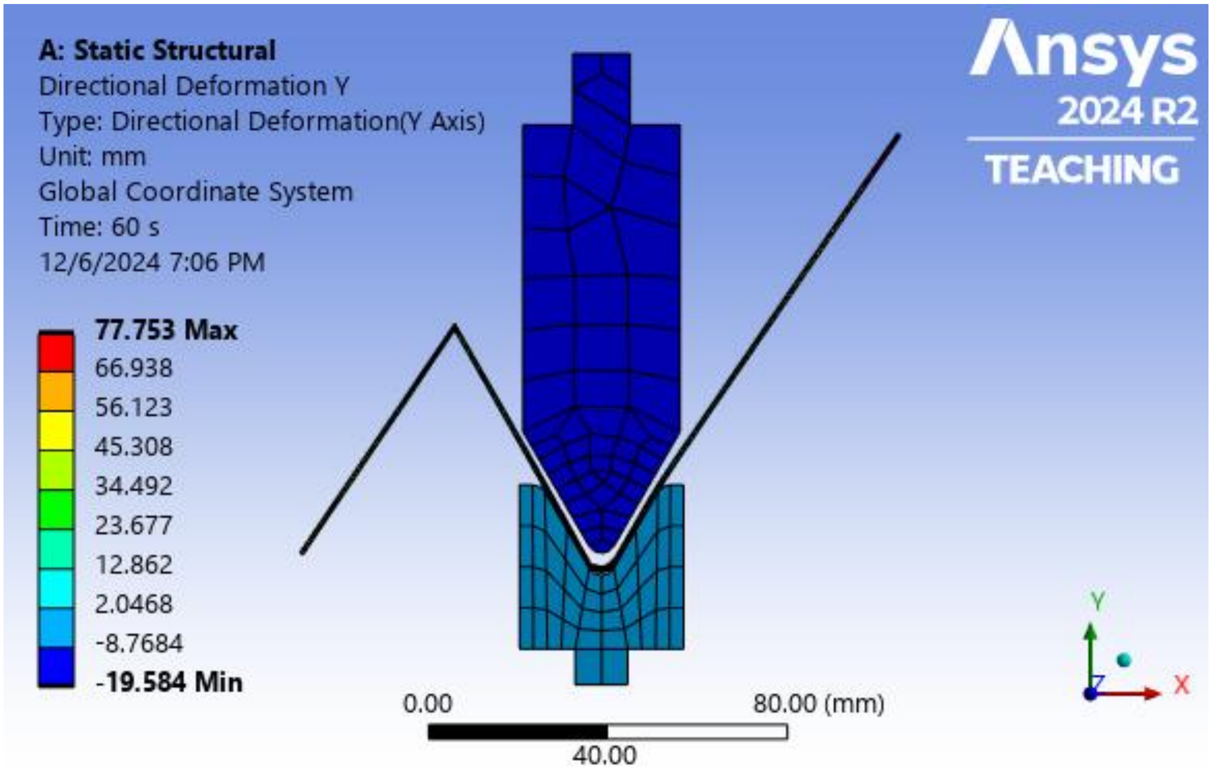


Figure 17c) Final Directional Deformation Y Axis at *t* = **60** s (2nd bend front view).

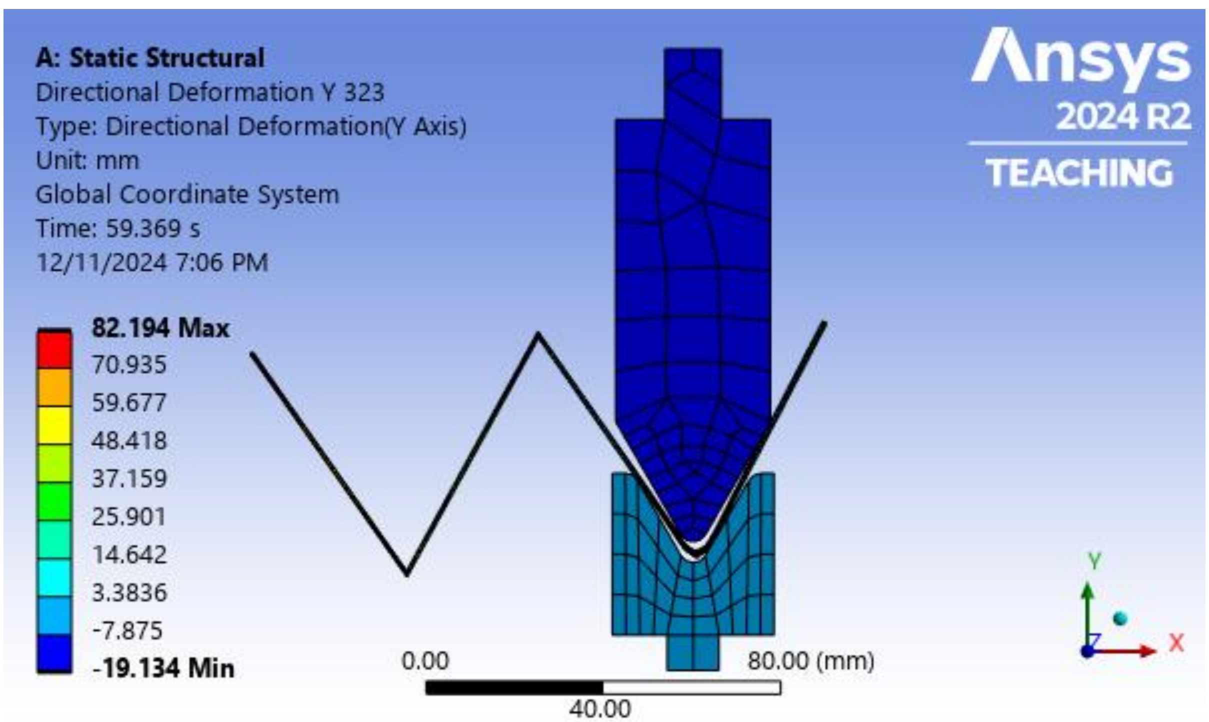


Figure 17d) Final Directional Deformation Y Axis at *t* = **60** s (3rd bend front view).

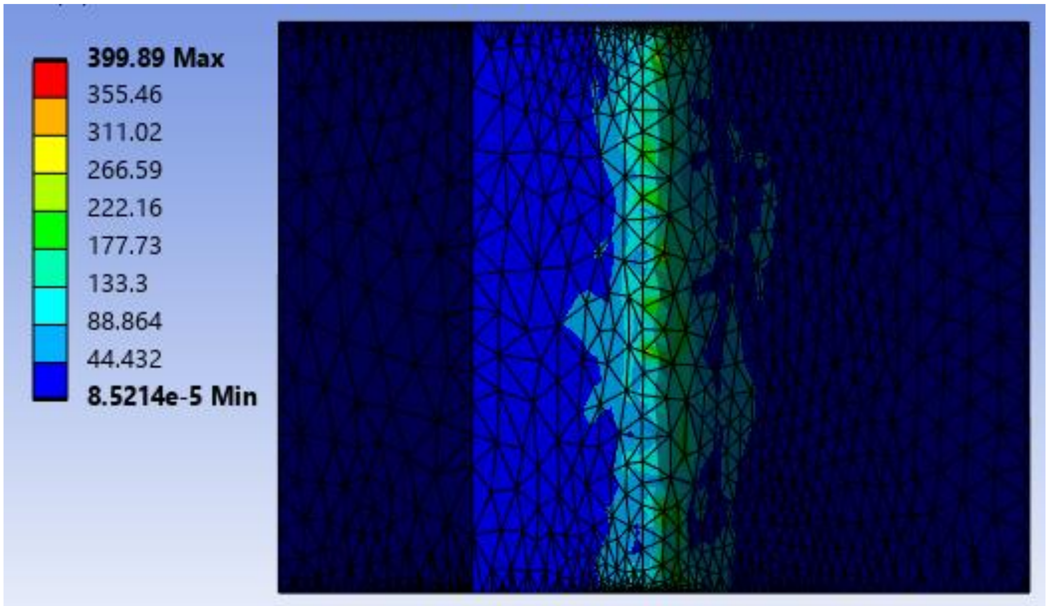


Figure 17e) Equivalent von Mises stress in metal sheet at t = **60** s (2nd bend top view).

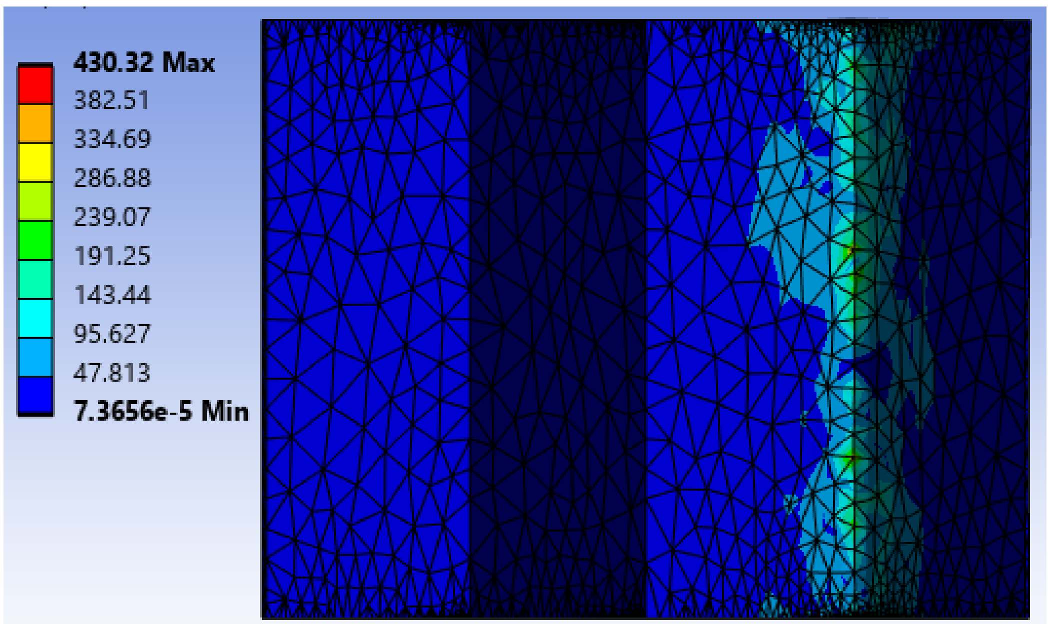
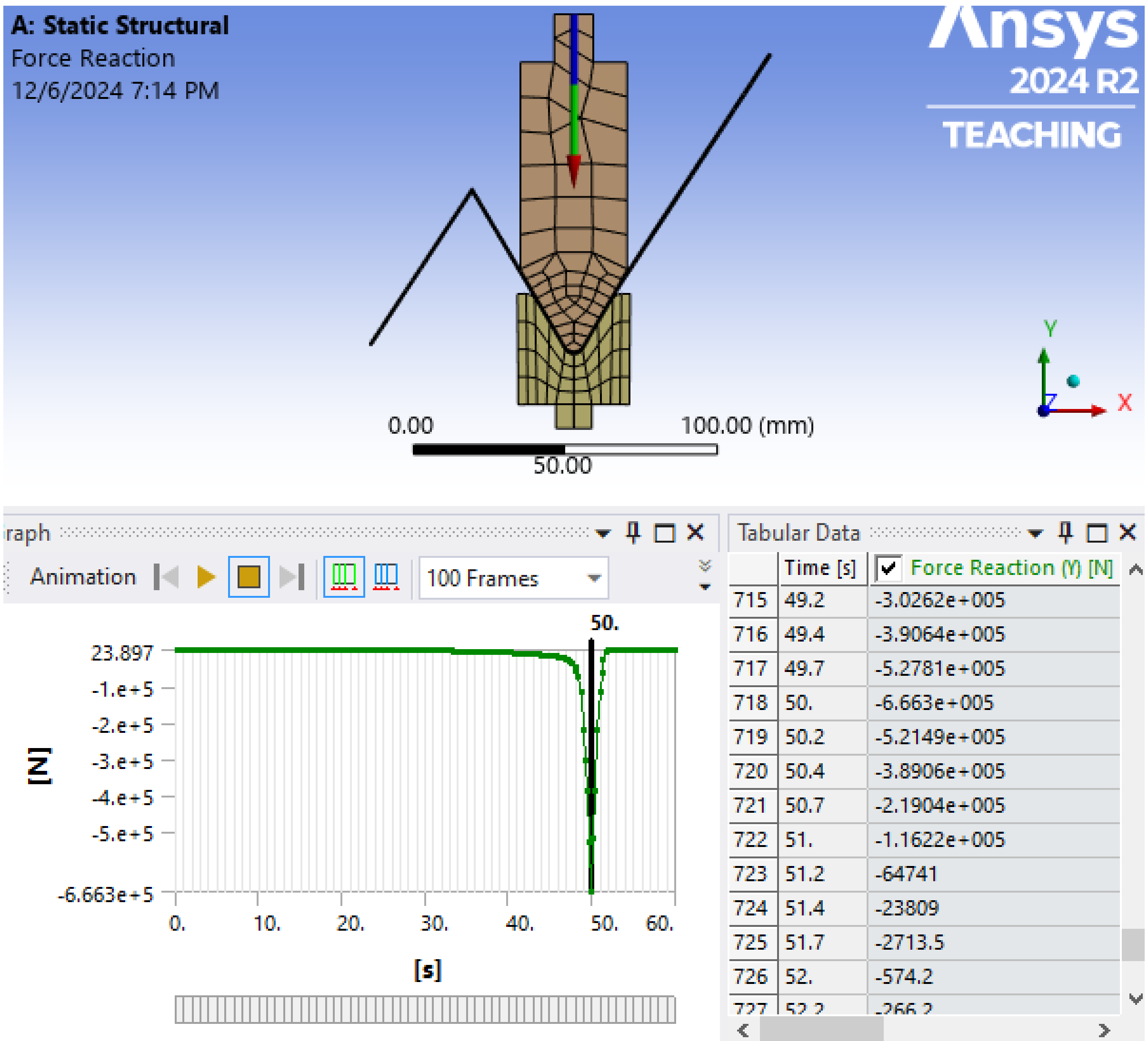


Figure 17f) Equivalent von Mises stress in metal sheet at t = **60** s (3rd bend top view).

Double click on Force Reaction under Solution in the Outline. Uncheck boxes for Force Reaction (X) [N], Force Reaction (Z) [N] and Force Reaction (Total) [N] under Tabular Data. Set Display Time to **50** s in Details of "Directional Deformation Y Axis". Right click on Force Reaction under Solution in Outline and select Retrieve This Result.

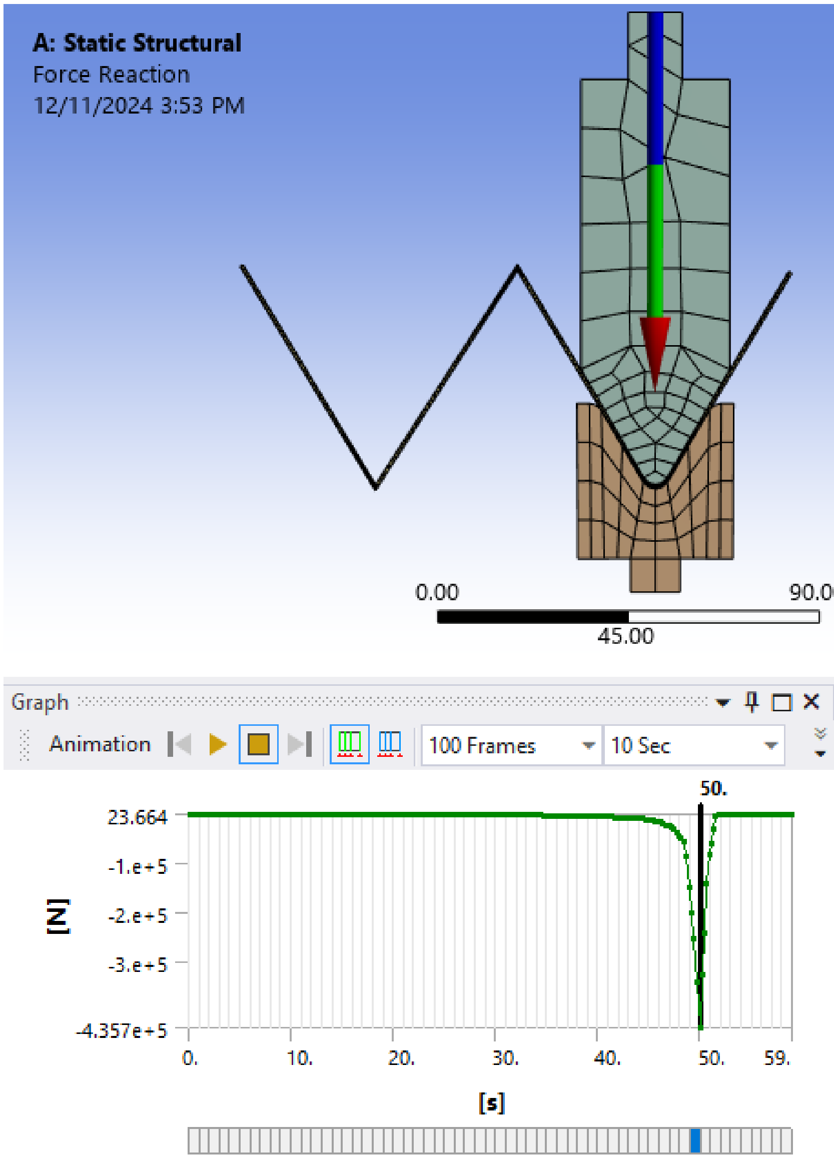
Select the Time [s] column under Tabular Data. Right click and select Copy Cell. Start an Excel sheet and paste the data in column A starting in cell A2. Include a heading labeled Time [s] in cell A1. In the same way, select the **Force Reaction (Y) [N]** column in Ansys Mechanical and copy over the data to column B starting in cell B2 in the Excel sheet and include a label in cell

Label column C in Excel as Bending Stroke (mm) in cell C1 and enter =**20***A2/**50** in cell C2. Select the lower right corner of cell C2 and drag this cell down column C all the way to row **718** corresponding to Time [s] equal **50**. Enter =**20-20***(A**719-50**)/**50** in cell C**719**. Select the lower right corner of cell C**719** and drag this cell down column C all the way to row **771** corresponding to Time [s] equal **60**. The value in cell C**771** will be **16**. Label column D in Excel as Bending Force [N] in cell D1 and enter =ABS(B2) in cell D2. Select the lower right corner of cell D2 and drag this cell down column D all the way to row **771** corresponding to Time [s] equal **60**. Label column E in Excel as Eq. 8.1 (N) in cell E1 and enter =1582 in cell E2. Select the lower right corner of cell E2 and drag this cell down column E all the way to row **771** corresponding to Time [s] equal **60**. **Change the numbers 718, 719, and 771 from the 2nd bend excel files to 200, 201, and 324 for the 3rd bend bending force Excel sheet.**



	Time [s]	Force Reaction (Y) [N]
715	49.2	-3.0262e+005
716	49.4	-3.9064e+005
717	49.7	-5.2781e+005
718	50.	-6.663e+005
719	50.2	-5.2149e+005
720	50.4	-3.8906e+005
721	50.7	-2.1904e+005
722	51.	-1.1622e+005
723	51.2	-64741
724	51.4	-23809
725	51.7	-2713.5
726	52.	-574.2
727	52.2	-266.2

Figure 17g) Maximum force reaction at *t* = **50** s (2nd bend front view).



	Time [s]	Force Reaction (Y) [N]
193	48.2	-49487
194	48.4	-57034
195	48.7	-84252
196	49.	-1.5021e+005
197	49.2	-2.0147e+005
198	49.4	-2.5444e+005
199	49.7	-3.4192e+005
200	50.	-4.357e+005
201	50.2	-3.2938e+005
202	50.4	-2.4051e+005
203	50.7	-1.4071e+005
204	51.	-82983
205	51.2	-58981

Figure 17h) Maximum force reaction at $t =$ **50** s (3rd bend front view).

	A	B	C	D	E
1	Time [s]	Force Reaction (Y) [N]	Bending Stroke (mm)	Bending Force [N]	Eq. 8.1 (N)
2	2.00E-01	-55.974	8.00E-02	55.974	1528
3	4.00E-01	-132.33	1.60E-01	132.33	1528
4	7.00E-01	-352.19	2.80E-01	352.19	1528
5	1.00E+00	-582.81	4.00E-01	582.81	1528
6	1.20E+00	-720.02	4.80E-01	720.02	1528
7	1.4	-821.61	5.60E-01	821.61	1528
8	1.7	-930.93	6.80E-01	930.93	1528
9	2	-1008.8	8.00E-01	1008.8	1528
10	2.2	-1055.6	8.80E-01	1055.6	1528
11	2.4	-1095.4	9.60E-01	1095.4	1528
12	2.7	-1151.2	1.08E+00	1151.2	1528
13	3	-1203.8	1.20E+00	1203.8	1528
14	3.2	-1236.7	1.28E+00	1236.7	1528
15	3.4	-1269.2	1.36E+00	1269.2	1528
16	3.7	-1318.5	1.48E+00	1318.5	1528
17	4	-1364.9	1.60E+00	1364.9	1528
18	4.2	-1393.7	1.68E+00	1393.7	1528

Figure 17i) Excel sheet with data for V-bending force (2nd bend).

	A	B	C	D	E
1	Time [s]	Force Reaction (Y) [N]	Bending Stroke (mm)	Bending Force [N]	Eq. 8.1 (N)
2	2.00E-01	-35.687	8.00E-02	35.687	1528
3	4.00E-01	-88.781	1.60E-01	88.781	1528
4	7.00E-01	-259.77	2.80E-01	259.77	1528
5	1.00E+00	-437.02	4.00E-01	437.02	1528
6	1.20E+00	-551.63	4.80E-01	551.63	1528
7	1.4	-629.89	5.60E-01	629.89	1528
8	1.7	-708.28	6.80E-01	708.28	1528
9	2	-759.83	8.00E-01	759.83	1528
10	2.2	-787.77	8.80E-01	787.77	1528
11	2.4	-812.85	9.60E-01	812.85	1528
12	2.7	-846.36	1.08E+00	846.36	1528
13	3	-876.9	1.20E+00	876.9	1528
14	3.2	-895.92	1.28E+00	895.92	1528
15	3.4	-914.17	1.36E+00	914.17	1528
16	3.7	-942.12	1.48E+00	942.12	1528
17	4	-970.1	1.60E+00	970.1	1528
18	4.2	-988.27	1.68E+00	988.27	1528

Figure 17j) Excel sheet with data for V-bending force (3rd bend).

Numbers with bold face below needs to be updated with your own values for homework assignment. Select columns C - E in the Excel sheet. Select Insert>>Charts>>Scatter from the Excel menu. Label the vertical axis as Bending Force (N) and the horizontal axis as Bending Stroke (mm). The maximum bending force (bottoming force) is 666,300 N (149,605 lb) for the 2nd bend and 435,700 N (978,278 lb) for the third bend corresponding to stroke **20** mm. Set the vertical scale to logarithmic with lower and upper bounds 10 N and 1,000, 000 N, respectively. Set the horizontal scale to linear with lower and upper bounds 0 mm and **20** mm. Save the Excel file with the name *Bending Force versus Bending Stroke for V-Bending*.

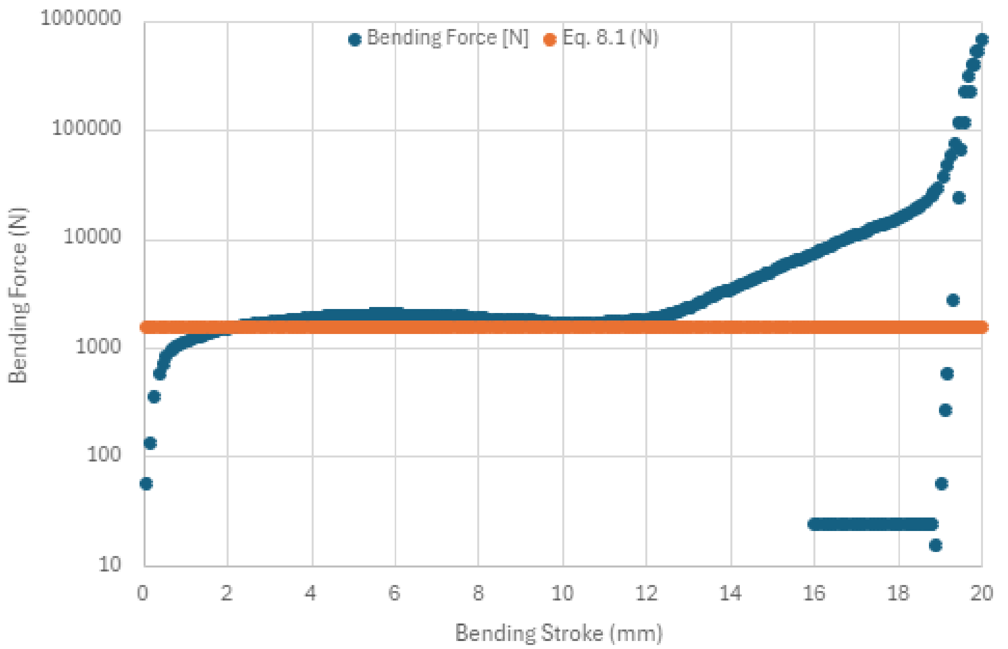


Figure 17k) Excel sheet with data for V-bending force (2nd bend).

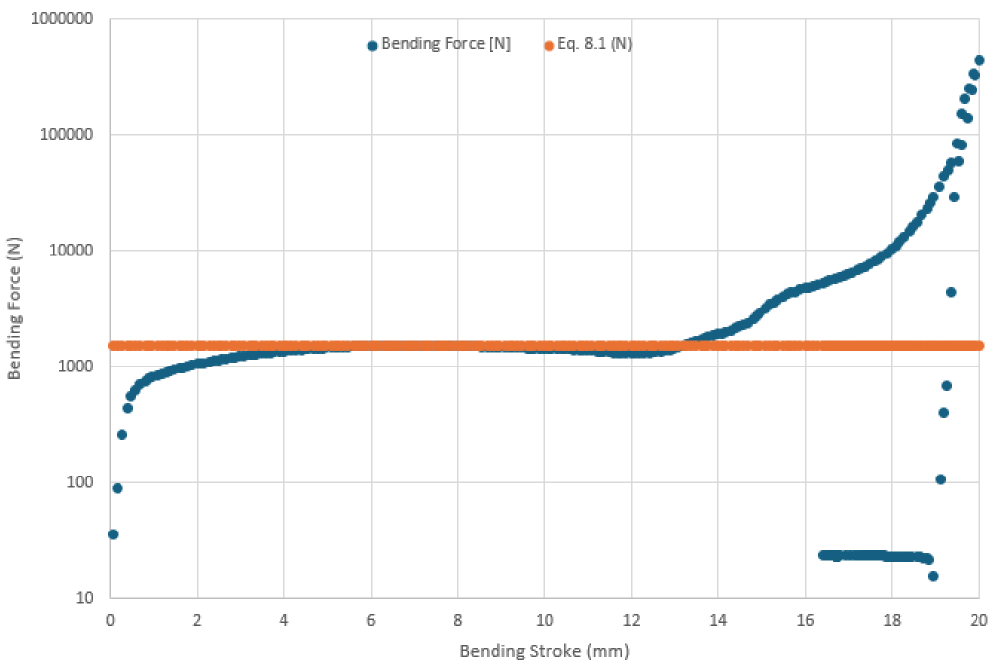


Figure 17l) Excel sheet with data for V-bending force (3rd bend).

Numbers with bold face below needs to be updated with your own values for homework assignment. The steps described on this page have already been completed in the Excel file *Deformed Sheet Coordinates.xlsx* that is available on d2l. This file can be used and updated with your data. Right click on x_t=**50**s under Solution in the Outline and select Export…>>Export Text File. Set Save as type: to Excel File (*.xls) and save the file with the name x_t=**50**s.xls. Repeat this step for y_t=**50**s, z_t=**50**s, x_t=**60**s, y_t=**60**s and z_t=**60**s.

Open the files x_t=**50**s.xls and y_t=**50**s.xls in Excel. Copy column B with the title LOC_DEFY (mm) from the file y_t=**50**s.xls and paste this data column including title to column C in file x_t=**50**s.xls. In the same way, copy column B with the title LOC_DEFZ (mm) from the file z_t=**50**s.xls and paste this data column including title to column D in file x_t=**50**s.xls.

Save the Excel file, Save as type: Excel Workbook (*.xlsx), with the name *Deformed Sheet Coordinates.xlsx*. Insert another row on the Excel sheet as the first row. Label cell A1 as t = **50** s, label cell B1 as x-coord, label cell C1 as y-coord. and label cell D1 as z-coord.

Select cells B3 – B5 on the Excel sheet. Select Sort & filter on the Editing tab under the Excel menu. Select Sort Smallest to Largest, Expand the selection in the Sort Warning window and select Sort in the same window.

Copy columns A and B with the titles Node Numbers and LOC_DEFX (mm) from the file x_t=**60**s.xls and paste these data columns including titles to cell A8 in file *Deformed Sheet Coordinates.xlsx*. In the same way, copy column B with the title LOC_DEFY (mm) from the file y_t=**60**s.xls and paste this data column including title to cell C8 in file *Deformed Sheet Coordinates.xlsx*. Finally, copy column B with the title LOC_DEFZ (mm) from the file z_t=**60**s.xls and paste this data column including title to cell D8 in file *Deformed Sheet Coordinates.xlsx*. Label cell A7 as t = **60** s, label cell B7 as x-coord, label cell C7 as y-coord. and label cell D7 as z-coord.

Select cells B9 – B11 on the Excel sheet. Select Sort & filter on the Editing tab under the Excel menu. Select Sort Smallest to Largest, Expand the selection in the Sort Warning window and select Sort in the same window. Enter Time [s] in cell A13, enter t = **50** s in cell A14 and enter t = **60** s in cell A15.

Enter γ & γ_f (deg.) in cell B13, enter =180*ATAN((C3-C4)/(B4-B3))/PI() in cell B14 and enter =180*ATAN((C9-C10)/(B10-B9))/PI() in cell B15. Enter β & β_f (deg.) in cell C13, enter =180*ATAN((C5-C4)/(B5-B4))/PI() in cell C14 and enter =180*ATAN((C11-C10)/(B11-B10))/PI() in cell C15. Enter α & α_f (deg.) in cell D13, enter =180-C14-B14 in cell D14 and enter =180-C15-B15 in cell D15. Enter SB (deg.) in cell E13 and enter =D15-D14 in cell E14. Enter SB, theory (deg.) in cell F13 and enter =F20 in cell F14. Enter % diff. in cell G13 and enter =100*ABS(E14-F14)/F14 in cell G14.

Enter the remaining theory section with headings and data in rows 17-20 in the Excel file as shown in Figure 8.10h). Enter **60** and **63.8948** in cells A19 and A20. Enter =25.4/8 in cells B19 and B20. Enter =3.175/0.9869 in cells C19 and C20. Enter 0.5 in cells D19 and D20. Enter =(C19+D19*0.7874)*A19/(B19+D19*0.7874) in cell E19 and =(C20+D20*0.7874)*A20/(B20+D20*0.7874) in cell E20. Enter =E19-A19 in cell F19 and enter =E20-A20 in cell F20.

Select cells B3 – C5 on the Excel sheet. Select Insert>>Charts>>Scatter with Straight Lines and Markers from the Excel menu. Include axis titles, label the horizontal axis as x (mm) and the vertical axis as y (mm). Include legend in the chart and insert cells B9 – C11 in the same graph.

	A	B	C	D	E	F	G
1	t = 50s	x-coord.	y-coord.	z-coord.			
2	Node Number	LOC_DEFX (mm)	LOC_DEFY (mm)	LOC_DEFZ (mm)			
3	10348	-38.862	52.872	56.403			
4	4154	-7.5141	-7.91E-02	56.403			
5	4181	58.761	97.098	56.403			
6							
7	t = 60s	x-coord.	y-coord.	z-coord.			
8	Node Number	LOC_DEFX (mm)	LOC_DEFY (mm)	LOC_DEFZ (mm)			
9	10348	-38.139	53.999	56.403			
10	4154	-7.7005	0.52897	56.403			
11	4181	60.521	96.351	56.403			
12							
13	Time [s]	γ & γ_f (deg.)	β & β_f (deg.)	α & α_f (deg.)	SB (deg.)	SB, theory (deg.)	% diff.
14	t = 50 s	59.3738	55.7059	64.9203	0.1803	0.75	76
15	t = 60 s	60.3487	54.5506	65.1006			
16							
17	Theory						
18	α (degrees)	R_i(mm)	R_f(mm)	K	α_f(degrees)	*SB* (degrees)	
19	60	3.175	3.2171	0.5	60.71	0.71	
20	63.8948	3.175	3.2171	0.5	64.65	0.75	

Figure 17m) Data in Excel file *Deformed Sheet Coordinates at t = 50s and 60s* (2nd bend).

	A	B	C	D	E	F	G
1	t = 50s	x-coord.	y-coord.	z-coord.			
2	Node Number	LOC_DEFX (mm)	LOC_DEFY (mm)	LOC_DEFZ (mm)			
3	8272	-37.867	50.822	56.403			
4	8182	-5.7773	-1.0042	56.403			
5	8989	25.967	49.078	56.403			
6							
7	t = 60s	x-coord.	y-coord.	z-coord.			
8	Node Number	LOC_DEFX (mm)	LOC_DEFY (mm)	LOC_DEFZ (mm)			
9	8272	-40.465	50.192	56.403			
10	8182	-4.9112	0.66645	56.403			
11	8989	23.81	52.506	56.403			
12							
13	Time [s]	γ & γ_f (deg.)	β & β_f (deg.)	α & α_f (deg.)	SB (deg.)	SB, theory (deg.)	% diff.
14	t = 50 s	58.2351	57.6317	64.1332	0.5291	0.75	30
15	t = 60 s	54.3259	61.0118	64.6623			
16							
17	Theory						
18	α (degrees)	R_i(mm)	R_f(mm)	K	α_f (degrees)	*SB* (degrees)	
19	60	3.175	3.2171	0.5	60.71	0.71	
20	63.8948	3.175	3.2171	0.5	64.65	0.75	

Figure 17n) Data in Excel file *Deformed Sheet Coordinates at t = 50s and 60s* (3rd bend).

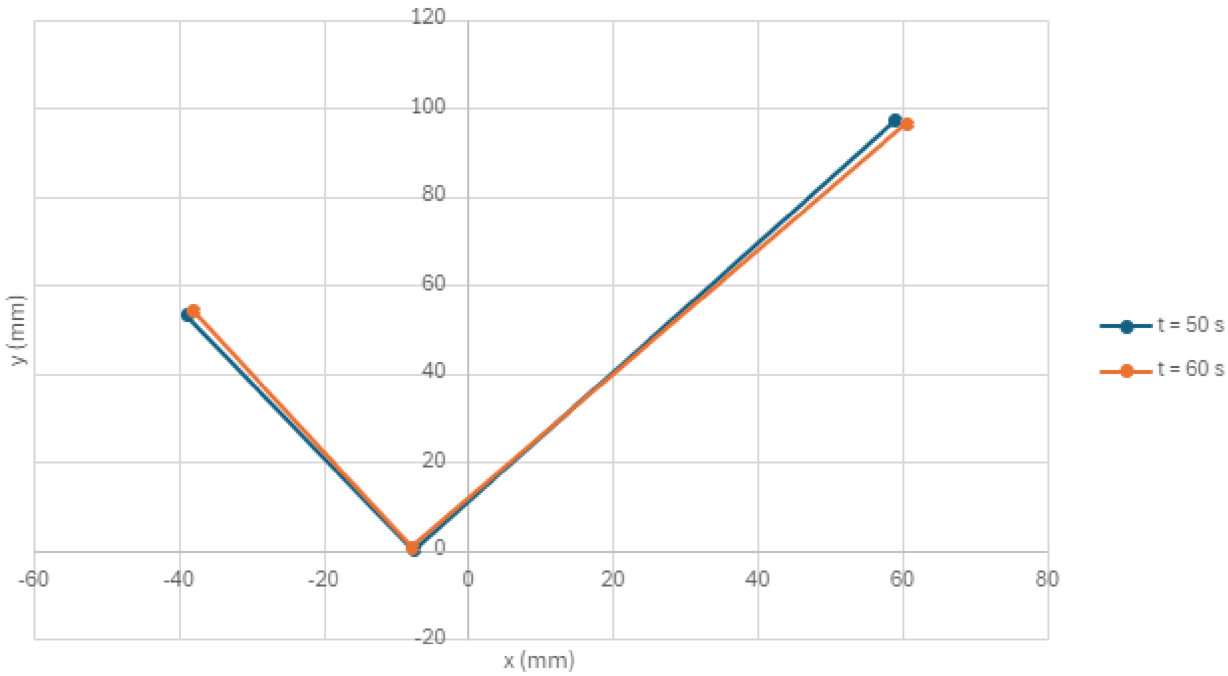


Figure 17o) Geometry of sheet at t = **50** s (bottoming) and t = **60** s after spring back (2nd bend).

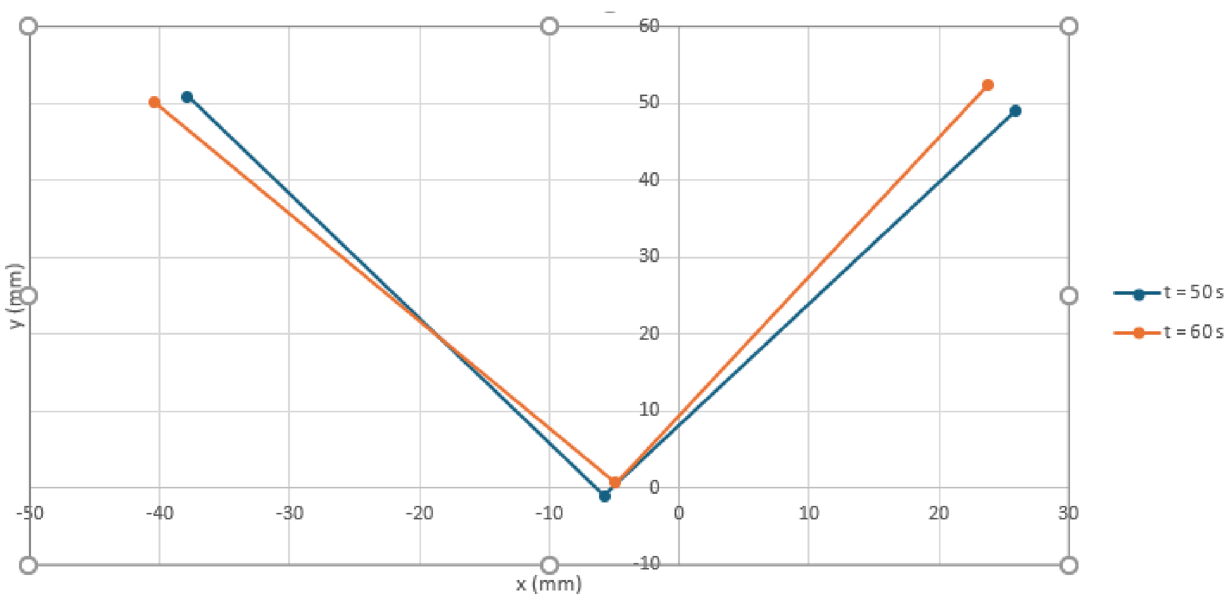


Figure 17p) Geometry of sheet at t = **50** s (bottoming) and t = **60** s after spring back (3rd bend).

I. Theory

18. Following Groover [4], we will start by defining important dimensions for the sheet and die. We define F as the bending force, h is the sheet thickness, D is the die opening dimension, TS is the ultimate tensile strength of the sheet material and w is the length of the sheet in the direction of the bending axis.

Table 1 Parameters with values used or determined in the theory section. **Numbers with bold face in the table needs to be updated with your own values for homework assignment.**

Bending force	F = 1,528 N
Constant determining location of neutral axis after bending	K = 0.5
Constant depending on bending process (V-bending)	K_{bf} = 1.33
Die opening dimension	d = 26.1 mm
Sheet thickness 22 GA	h = 0.7874 mm
Width of sheet in direction of bend axis	w = 101.6 mm
Length of sheet orthogonal to bend axis	L = 254 mm
Distance from sheet short side edge to first bending axis	l = 63.5 mm
Ultimate tensile strength for stainless steel sheet	UTS = 0.505 GPa
Yield strength	YS = 0.21 GPa
Young's modulus	E = 193 GPa
Desired inside bend radius	R_i = 3.175 mm
Bend radius after forming	R_f = 3.217 mm
Spring Back Factor	SBF = 0.9869
Theoretical Spring Back	$SB = \mathbf{0.71}°, \mathbf{0.75}°$
Included bend angle before spring back	$\alpha = \mathbf{60}°, \mathbf{63.8948}°$
Included bend angle before spring back from Ansys	$\alpha_{Ansys} = \mathbf{63.6885}°$
Included bend angle after spring back	α_f (degrees)

The bending force F required for the V-bending operation

$$F = \frac{K_{bf}\, wh^2 UTS}{d} = 1{,}528 \text{ N} = 352 \text{ lbf} \tag{1}$$

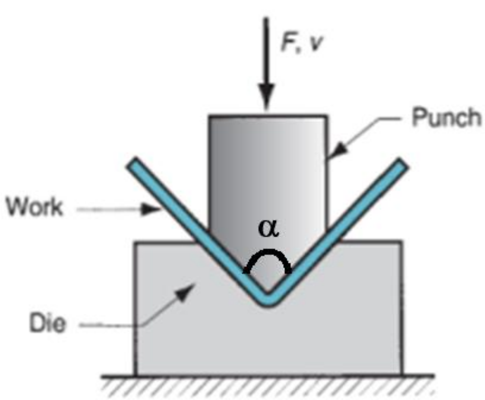


Figure 18a) Geometry for V-bending, see Groover[4].

We can calculate the spring back factor SBF using

$$V = \frac{R_i YS}{hE} = 0.0044 \tag{2}$$

$$SBF = (4V^2 - 3)V + 1 = 0.9869 \tag{3}$$

Bend radius after forming can now be determined

$$R_f = \frac{R_i}{SBF} = 3.217 \text{ mm} \tag{4}$$

The desired inside radius to thickness ratio can be determined as

$$r = \frac{R_i}{h} = 4.0323 \tag{5}$$

This ratio together with material used determines the *K*-factor that is related to the location of the neutral axis after bending. Values for *K* can be found in Table 2.

Table 2 *K*-factor for different materials, hardness and bending method

K-factor	*Material*	*Aluminum*	*Aluminum*	*Steel*
Bending	*Ratio*	*Soft*	*Medium*	*Hard*
Air Bending	*0 < r < 1*	0.33	0.38	0.4
Air Bending	*1 ≤ r < 3*	0.4	0.43	0.45
Air Bending	*r ≥ 3*	0.5	0.5	0.5
Bottoming	*0 < r < 1*	0.42	0.44	0.46
Bottoming	*1 ≤ r < 3*	0.46	0.47	0.48
Bottoming	*r > 3*	0.5	0.5	0.5

Numbers with bold face in the table needs to be updated with your own values for homework assignment. The final included bend angle after spring back for $\alpha = \mathbf{60}°$ and $\alpha = \mathbf{63.8948}°$ will be

$$\alpha_f = \frac{(R_f + Kh)}{(R_i + Kh)}\alpha = \mathbf{60.71}° \textit{ and } \mathbf{64.65}° \tag{6}$$

The spring back can now be determined as

$$SB = \alpha_f - \alpha = \mathbf{0.71}° \textit{ and } \mathbf{0.75}° \tag{7}$$

We can define the geometry of the V-bended sheet metal as shown in Figure 18b).

$$\tan\gamma = \frac{y1 - y2}{x2 - x1} \tag{8}$$

$$\tan\beta = \frac{y3 - y2}{x3 - x2} \tag{9}$$

$$\alpha = 180° - \beta - \gamma \tag{10}$$

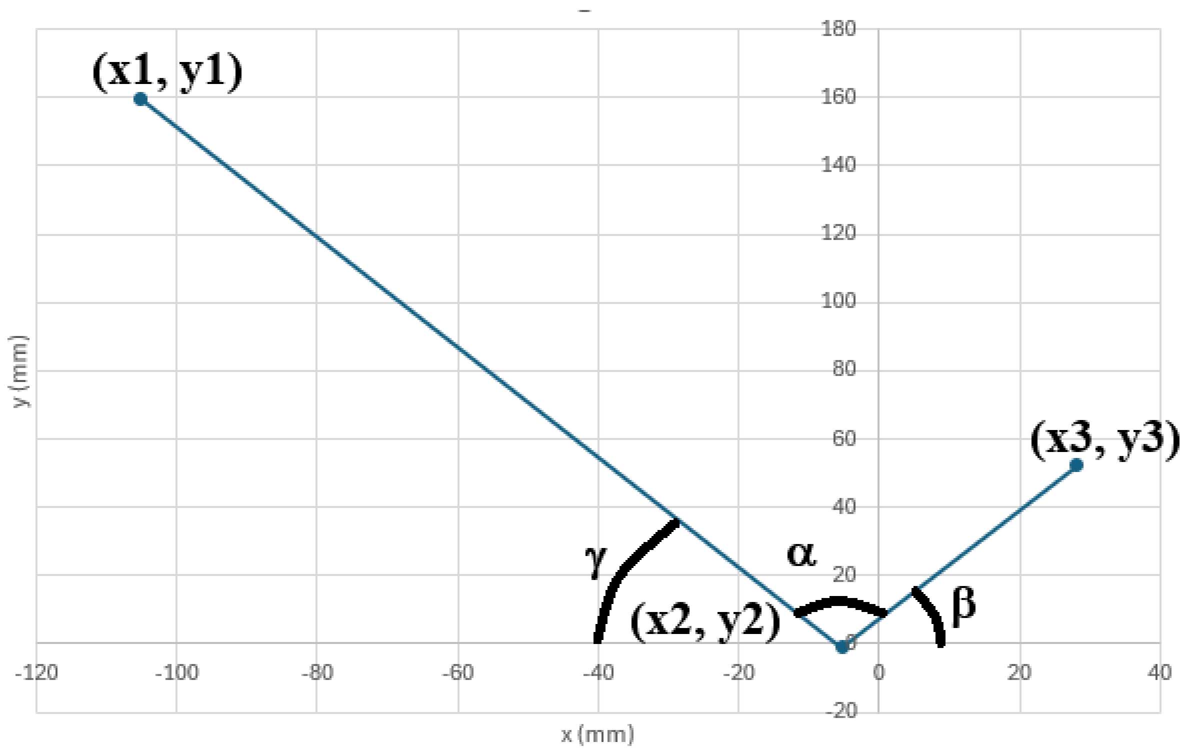


Figure 18b) Geometry for V-bended sheet metal

Numbers with bold face in the table needs to be updated with your own values for homework assignment.

We can determine the included angle $\alpha = \mathbf{63.8948}°$ of the bent sheet metal at bottoming, *t* = **50** s, from Ansys using Figures 10h), 10i) and 11b). This value **6** % higher than the intended value $\alpha = \mathbf{60}°$ based on the punch and die geometry for this V-bending operation. We can determine the included angle $\alpha = \mathbf{64.775}°$ of the bent sheet metal after spring back at *t* = **60** s from Ansys using Figures 10h), 10i) and 11b). The spring back is **0.86** degrees from Ansys which can be compared with **0.75** degrees spring back from theory, a difference of **14** %, see Figures 10h), 10i) and 11b) and equations (6) and (7).

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K. Exercices

8.1 Run the simulation as listed in the table below for your values.

V-Bending	Start, Min, End Y-comp. displacement punch (mm) Figure 8.9a)	ΔY (mm) Figure 8.9a)	*No of Steps* **Figure 8.8**	*Current Step No* **Figure 8.8**	Step End Time (s) **Figure 8.8**
Chapter 8	0, -20, -16	-0.4, 0.4	60	60	60
Student A	0, -19.6, -15.6	-0.4, 0.4	59	59	59
Student B	0, -19.2, -15.2	-0.4, 0.4	58	58	58
Student C	0, -18,.8, -14.8	-0.4, 0.4	57	57	57
Student D	0, -18,.4, -14.4	-0.4, 0.4	56	56	56
Student E	0, -18, -14	-0.4, 0.4	55	55	55
Student F	0, -17.6, -13.6	-0.4, 0.4	54	54	54
Student G	0, -17.2, -13.2	-0.4, 0.4	53	53	53
Student H	0, -16.8, -12.8	-0.4, 0.4	52	52	52
Student I	0, -16.4, -12.4	-0.4, 0.4	51	51	51
Student J	0, -16, -12	-0.4, 0.4	50	50	50
Student K	0, -15.6, -11.6	-0.4, 0.4	49	49	49
Student L	0, -15.2, -11.2	-0.4, 0.4	48	48	48
Student M	0, -14.8, -10.8	-0.4, 0.4	47	47	47
Student N	0, -14.4, -10.4	-0.4, 0.4	46	46	46
Student O	0, -14, -10	-0.4, 0.4	45	45	45

8.2 Run the simulation as listed in the table below for your values.

V-Bending	Start, Min, End Y-comp. displacement punch (mm) Figure 8.9a)	ΔY (mm) Figure 8.9a)	*No of Steps* **Figure 8.8**	*Current Step No* **Figure 8.8**	Step End Time (s) **Figure 8.8**
Chapter 8	0, -20, -16	-0.4, 0.4	60	60	60
Student A	0, -19, -15.2	-0.38, 0.38	57	57	57
Student B	0, -18, -14.4	-0.36, 0.36	54	54	54
Student C	0, -17, -13.6	-0.34, 0.34	51	51	51
Student D	0, -16, -12,8	-0.32, 0.32	48	48	48
Student E	0, -15, -12	-0.3, 0.3	45	45	45
Student F	0, -14, -11.2	-0.28, 0.28	42	42	42
Student G	0, -13, -10.4	-0.26, 0.26	39	39	39
Student H	0, -12, -9.6	-0.24, 0.24	36	36	36
Student I	0, -11, -8.8	-0.22, 0.22	33	33	33
Student J	0, -10, -8	-0.2, 0.2	30	30	30
Student K	0, -9, -7.2	-0.18, 0.18	27	27	27
Student L	0, -8, -6.4	-0.16, 0.16	24	24	24
Student M	0, -7, -5.6	-0.14, 0.14	21	21	21
Student N	0, -6, -4.8	-0.12, 0.12	18	18	18
Student O	0, -5, -4	-0.1, 0.1	15	15	15