Challenger Shuttle Disaster Study:
51L SRB Field Joint Static Analysis

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MEGN 324 – Intro to FEA

Fall 2020 – Section B

Executive Summary (I)

Problem Statement and Background

This report follows the investigative static analysis for the field joint assembly from the 51L solid rocket booster used for the launch of the Challenger Space Shuttle on January 28, 1986. This analysis aims to study the relevant stress, displacement, and safety factors around the region of the field joint under statically loaded conditions.

Analysis

Testing using FEA methods in a computer simulated static loading environment were carried out using Solidworks Simulation. A pressure of 1000 psi was applied to the negative x-directional face of the entire assembly, and faces leading into the region above the first O-ring slot. Fixities were applied to all cut faces to simulate full model composition, with the exception of axial stress applied to the top face of the tang to allow for accurate deformation. Hand calculations using MoM principles and results derived from NASA's investigative report were used to verify model accuracy for deformation and stress.

Conclusion

The results from the analysis showed that significant deformation did occur in the gap opening between the tang and clevis above the O-ring slot, a displacement of 0.0266 inches (Figure 1). The factor of safety in the joint also showed regions < 1, pointing towards unexpected failure occurrence as well. These results concluded that the joint design was indeed faulty and had major implications that lead to the catastrophic events that occurred on January 28, 1986 with the Challenger Space Shuttle Disaster.

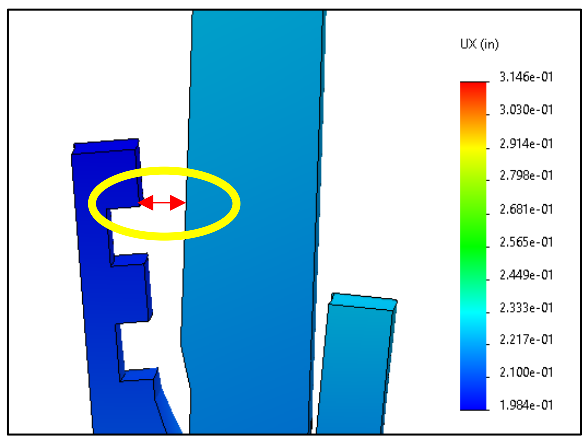


Figure 1: Deformation in the tang/clevis above O-ring Slots

Background (II)

This report aims to investigate the static in flight analysis of a 51L solid rocket booster (SRB) designed by Morton Thiokol for the Challenger Shuttle launch on January 28, 1986. The focal point of this analysis lies in the design of the tang and clevis connection used for the field joints on the SRB. To make computational modeling more efficient, the assembly will only include a smaller section of the SRB joint to include one pin, a ten foot vertical section of the tang, a ten foot vertical section of the clevis, and a section of the pin retainer band. Appropriate fixtures will be applied at the boundaries of these parts to retain the integrity of the design.

Questions that will be answered regarding this design include an explanation of why the failure occurred on the shuttle launch, what errors from the original model lead to the failures, and how well the reconfigured part that was created by Morton Thiokol after the disaster should hold up to further flights. The software suite used for the simulation will be Solidworks Simulation paired with the CAD files provided for the assembly.

System Configuration (III)

The finalized assembly combines the four previously mentioned parts in a 1/177th configuration of the SRB as seen in Figure 2 and 3. Full dimensions for each of the individual parts and part sections can be found in Appendix A1 – A6. A regular rectangular coordinate system was used to orient the parts inside the study.

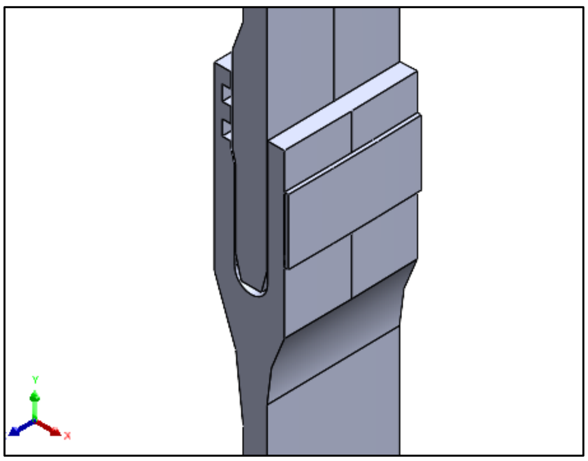


Figure 2: Close up of joint SRB assembly

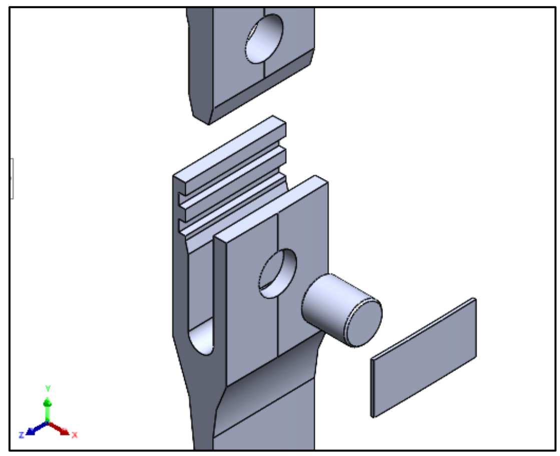


Figure 3: Exploded close up view of the SRB joint assembly

System Properties (IV)

The joint components will be modeled using D6AC steel material, a derivative type of 4340 steel that was custom made in Solidworks Simulation for this part. The specific properties can be seen in Table 1 below. These specifications were provided for the study based on the original material properties of the joint on the 51L SRB.

Table 1: Material Properties for D6AC joint on 51L solid rocket booster

Elastic Modulus	Poisson's Ratio	Shear Modulus	Mass Density	Yield Strength
30,179 ksi	0.32	11,603 ksi	$0.2846 \frac{lb}{in^3}$	190 ksi

System Conditions (V)

Loads and fixtures were applied to the part under the notion that the SRB experienced symmetrical and evenly distributed pressure. An internal pressure of 1000 psi was applied to all internal negative x-directional faces of the assembly, including faces leading into the first O-ring position, to simulate mean effective operating pressure (MEOP) of the SRB provided by Morton Thiokol's testimony [2]. Roller/Slider fixtures were applied to the entire z-face planes on both sides of the joint assembly to simulate attachment to a fully modeled geometry of the SRB. A Roller/Slider fixture was also added to the bottom y-directional face of the clevis to emulate full theoretical assembly being portrayed. A negative x-directional view of the main joint connecting section of the assembly can be seen in Figure 4.

For the tang, an axial stress for a thin walled pressure vessel using $\frac{pr}{2t}$ was applied to the top y-directional face at the top end of the tang to properly fix the assembly while allowing for deformation to occur, thus not violating St. Venant's principle. A global contact of no penetration was set for the model to accurately allow for shifting and deforming of parts without inaccurate simulation interactions. However, a bonded contact set was added to the positive x-direction face of the clevis and the negative x-direction face of the pin retainer band. The applied loads and fixtures can be seen in more detail in Appendix A7 – A10.

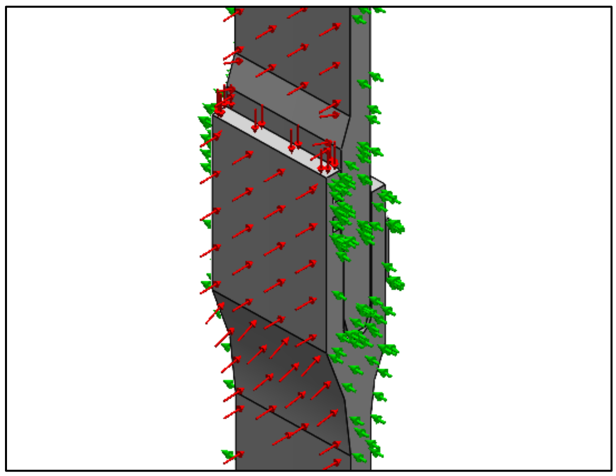


Figure 4: Applied loads and fixtures on the SRB joint assembly

System Discretization (VI)

The mesh used for this study was curvature based to aid with refining the slight curve that all of the parts exhibit due to the cylindrical shape of the full SRB design. The mesh convergence study was based on the max von Mises stress values since the D6AC steel is a ductile material. The other key thing that was sought after was approaching stable displacement values around the joint in the x-direction. These displacement values are the focus of the simulation study to see how big of a gap was created to allow for fuel to leak through the tang and clevis assembly.

A global element size of 1 inch was arrived at from the convergence study, where both the stress and displacement values saw no further changes between iterations greater than five percent. Sensors used to display maximum stresses were used for the von Mises plot and separate sensors were used in the x-displacement plot in the region above the gap for first O-ring slot. Figure 5 shows the convergence plot, notice the 1/h value of 1 is the value taken for the global element size in the final mesh. Figure 6 shows the final mesh applied to the assembly for the study.

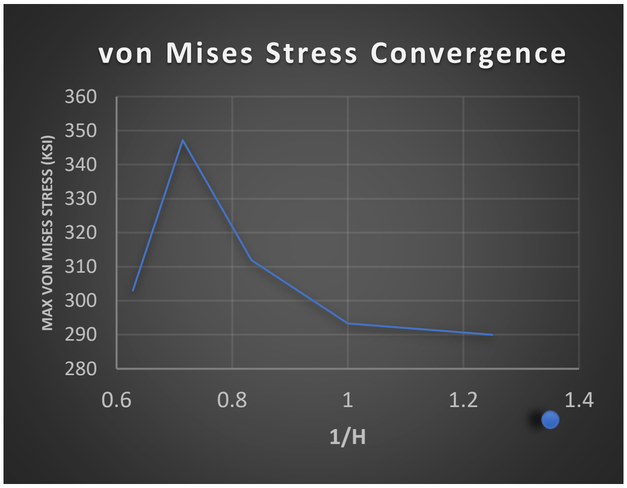


Figure 5: Mesh convergence chart for SRB joint assembly

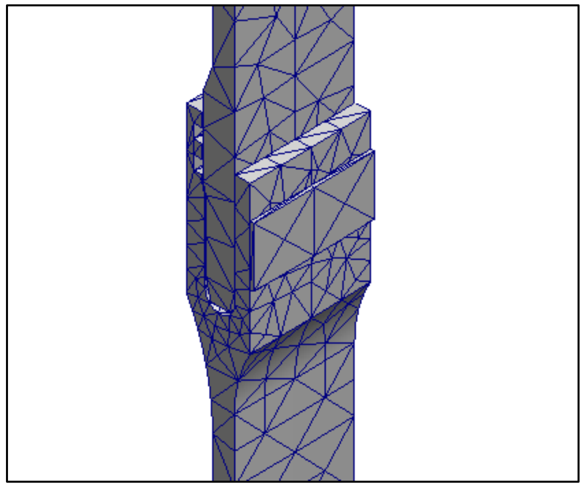


Figure 6: Final mesh applied to assembly

Validation and Analytic Verification (VII)

Verification of the solutions were performed by comparison to hand calculation using mechanics of materials techniques for stress and displacement. After calculating the axial stress that was applied to the top end of the tang, the hoop stress was also calculated by hand as seen in Table 2 below. A value matching the hoop stress was probed in the z-direction in Solidworks simulation and can be seen in Appendix A12.

The displacement of the radius of the cylindrical section of the SRB was also calculated by hand as can be seen in Table 2. The assembly model was probed away from the joint in Solidworks simulation as seen in Appendix A13 in order to get accurate values that aren't tainted by the joint feature, which verifies that these calculations match the solution arrived at in the model. Full calculations of the stresses and displacement can be seen in the Mathcad spreadsheet in Appendix A11.

Table 2: Analytic verification results from hand calculations

Axial Stress (ksi)	Hoop Stress (ksi)	X-Directional Radial Displacement (in)
76.159	152.317	0.309

A displacement value of ~0.03 inches was probed from the difference in the gap opening above the O-ring and was verified in the newspaper report by D. Hanink on the 51L SRB investigation. The analysis reported values of 30/1000ths to 40/1000ths of an inch gap opening found in later simulations of the gap after the investigation of the incident occurred [1]. The tests run by Morton Thiokol and NASA during the investigation used more rigorous fixture and failure criteria to provide a more accurate assessment of the conditions on the rocket from the day of the disaster, thus backing the newly discovered gap opening solutions.

Results (VIII)

A finite element analysis was run on the final design with proper boundary conditions as mentioned previously. The result findings showed a displacement of the tang and clevis near the upper O-ring of 0.2251 inches and 0.1985 inches respectively. The difference between these two displacements equates to a gap opening of 0.0266 inches. A plot of the displacements around the gap opening can be seen in Figure 7 along with a deformed screenshot of the assembly in Figure 8 to demonstrate the severity of the gap opening.

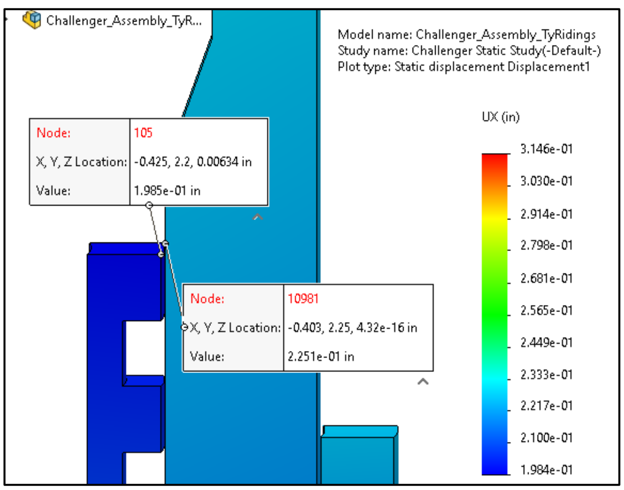


Figure 7: Displacement values in the x-direction around the joint O-ring feature

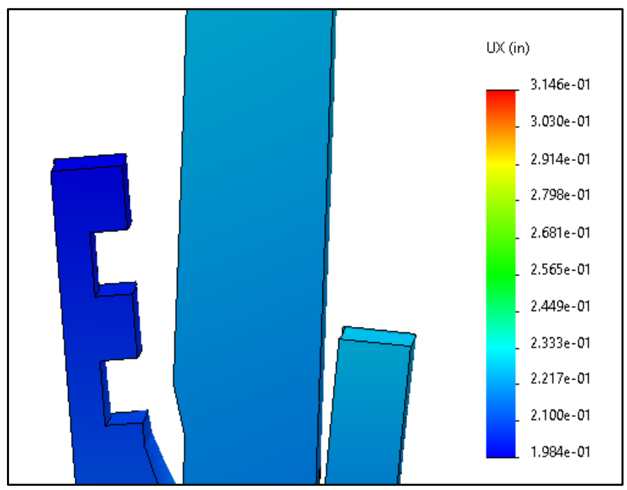


Figure 8: Deformed shape showing the gap near the O-rings

Along with the displacement, a factor of safety (FOS) plot based on von Mises failure criterion was produced in the simulation to show the minimum FOS in the joint assembly. As seen in Figure 9, there is significant representation of safety factors < 1 which demonstrate that stresses in those regions exceed yield strength, likely contributing to failure and further displacement caused by the applied loads.

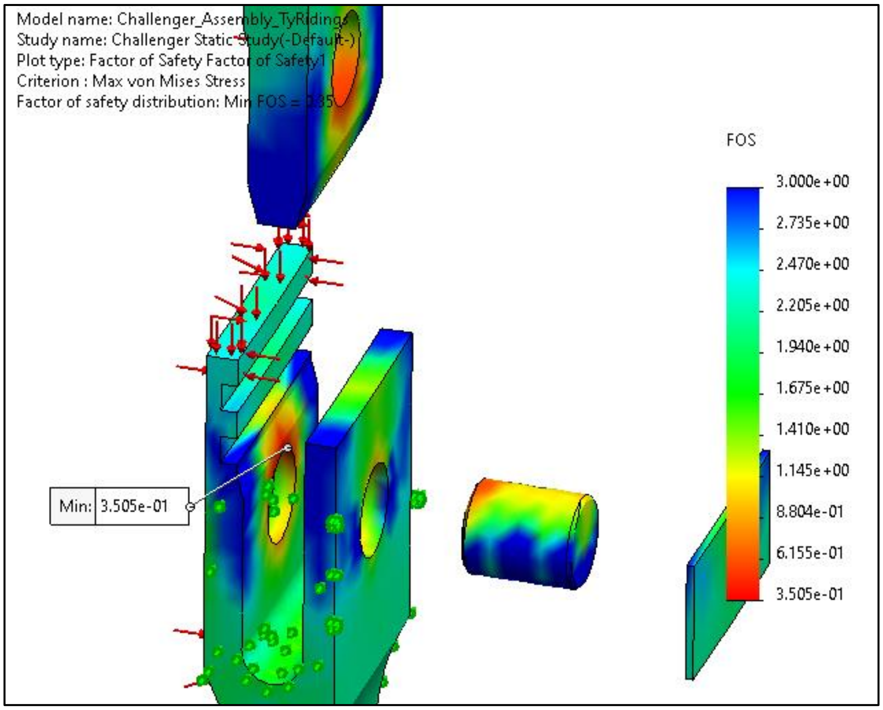


Figure 9: FOS plot with minimum factor of 0.3505 in the clevis

Discussion (IX)

Based on calculations and the results found in the static analysis showing a gap displacement of 0.0266 inches along with exceedingly high stress regions in the joint, the design for the tang and clevis connection was indeed faulty. The main drawback with the design lies in an unnecessary amount of reliance on the O-rings as a fail safe to protect the SRB from leaking excessive propellant. Even with both O-Rings in place, the risk is too high of failure when the material of the O-Ring was not acceptable for the temperature conditions they were subjected to on the day of the launch, paired with just how much displacement was actually occurring and not predicted in Morton Thiokol's prior analysis. Better mechanical attachments to mitigate the displacement in the gap opening would help reduce the risks associated with bypass of propellant and reduce reliance on the O-rings as a failure prevention mechanism.

There were a combination of errors that lead to not adequately modeling and explicitly predicting the behavior of the SRB joint for the day the Challenger launched. One main inaccuracy in Morton Thiokol's original model was fixing the pin holes with a stiffness that approximates the pin rather than modeling with an actual pin in pin hole position. Another contributing factor was not accurately applying axis-symmetrical loading for the pin stiffness to match the symmetry of the model that's based around the circumference of an axis running through the vertical center of the SRB. Most critically however, was not having enough data to back the O-ring resiliency for the launch pad temperatures. Most simulations and actual shuttle launches had never run lower than 53 degrees Fahrenheit at ignition prior to the January 28th launch of Challenger [2, p. 76-103]. Ignoring what implications this factor had on the ability of the O-rings to form properly to the gap, of which had loosely been approximated in the joint prior, lead to an excessive and extended amount of propellent bypass that eventually did combust and lead to the unfortunate demise of the crew. Making the decision to recommend the launch in spite of the insufficient amount of evidence for these launch conditions through previous testing was a serious and fatal mistake that should be avoided in common engineering practices.

The redesign of the field joint did provide solutions to many of the faults in the original design. The "capture feature" added behind the double O-ring wall of the clevis (Appendix A14) not only added and extra O-ring to seal any bypass, but also reinforced the clevis wall with more material and mechanical advantage. Rigorous testing was performed on the redesign by Morton Thiokol. Some of the simulations included compound failures in different components at or around the joint in order to fully expose the O-rings to measures in which their response was critical. The findings of these tests showed average results with significantly lower fluctuations in the gap opening and successful failure prevention on behalf of the joint seals, making them more reliable for future space missions [1].

Conclusion (X)

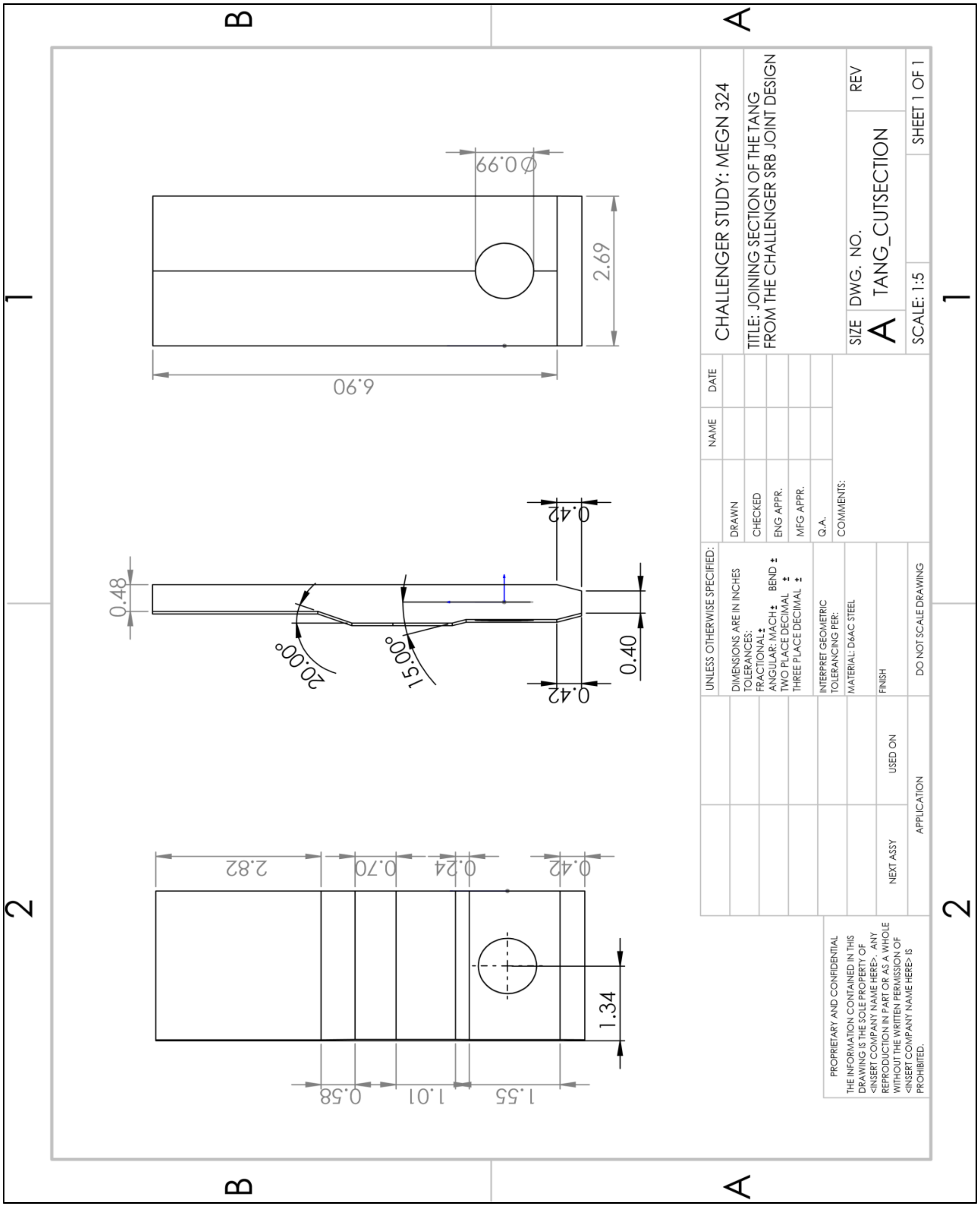
The static simulation performed on the 51L solid rocket booster used on the Challenger space shuttle for this analysis proved to be reliable. The boundary conditions and stresses applied to the assembly produced simulation results that matched analytic calculations, along with results produced by NASA and Morton Thiokol after the Roger's Commission Report investigation. Further simulation could better approximate dynamic loads and flight conditions of the rocket as it ascended into the atmosphere. The Roger's Commission report did make mention of shear winds that could have progressed the extent of displacement in the seals, along with many other factors that may not be fully accounted for. However, since the report did show that bypass was prevalent as seen from photos in the very first stage of ignition [2, p. 22 – 25], modeling this as a static study was sufficient for cases of high pressure and static assembly.

REFERENCES:

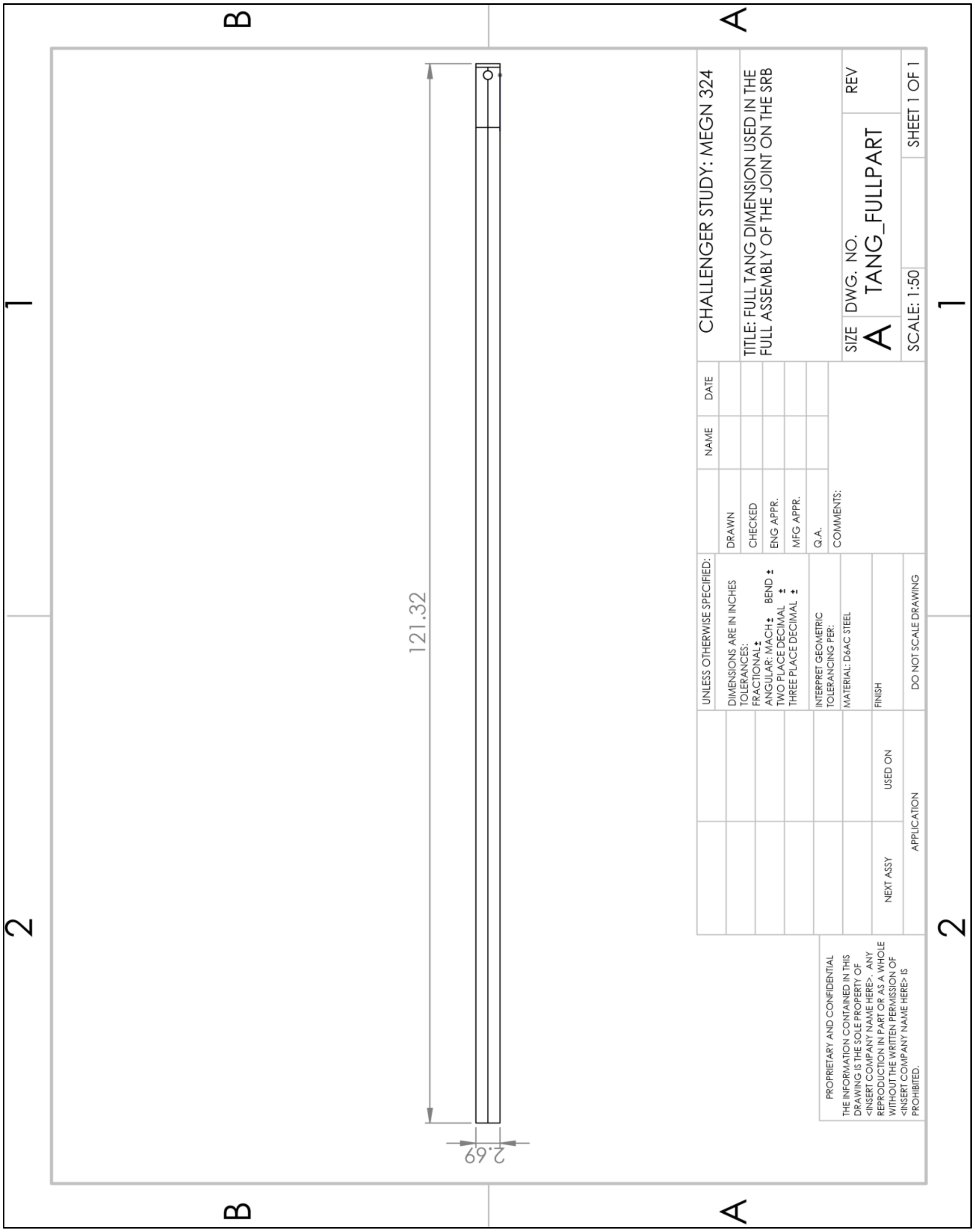
[1] Hanink, D. K. (n.d.). Some Aspects of Redesigning Solid-Rocket Boosters for the Space Shuttle.

[2] Rogers, W. P. (1986). *Report to the President by the Presidential Commission on the Space Shuttle Challenger Accident* (pp. 1-261, Rep.). Washington, D.C.: NASA.

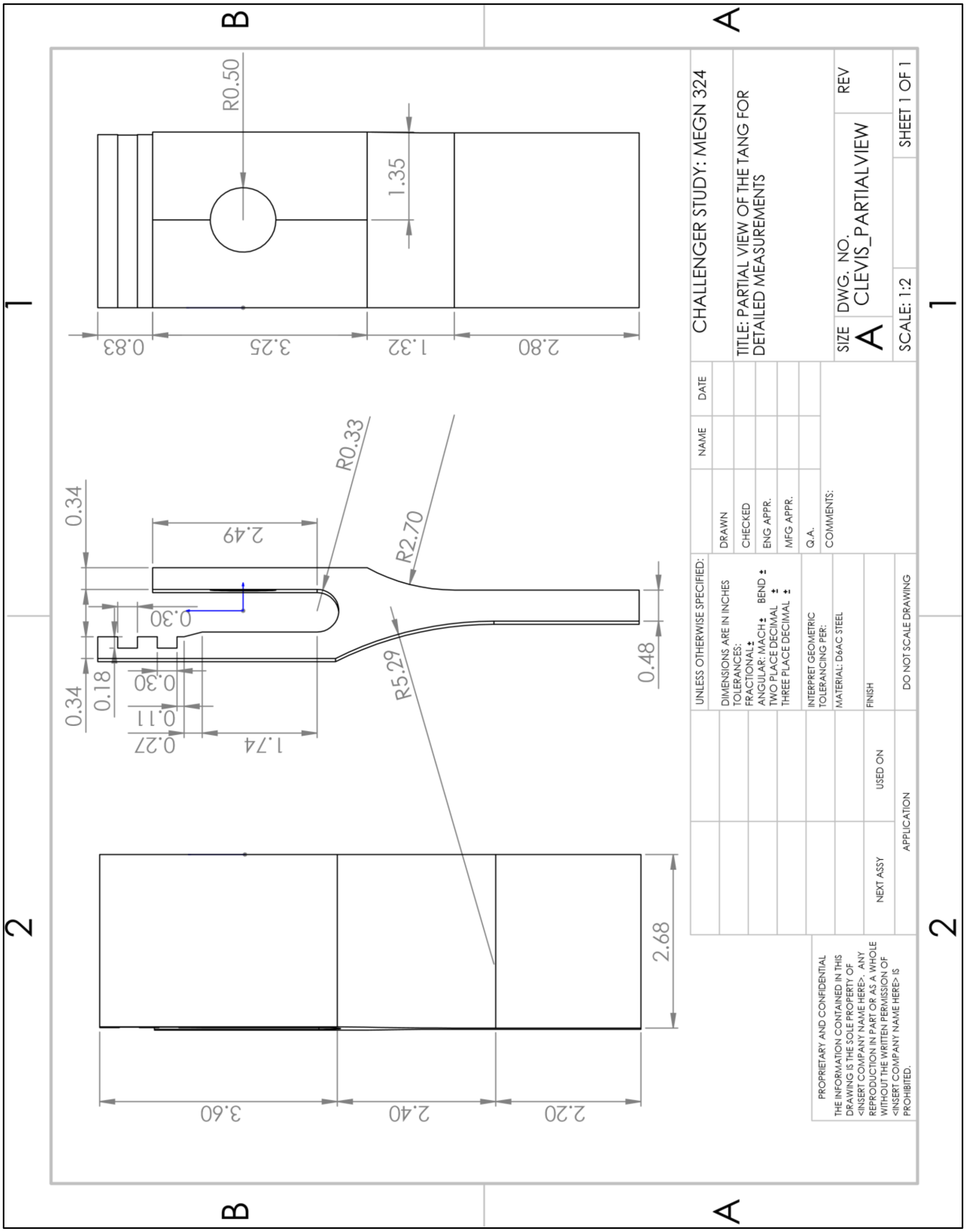
APPENDIX:



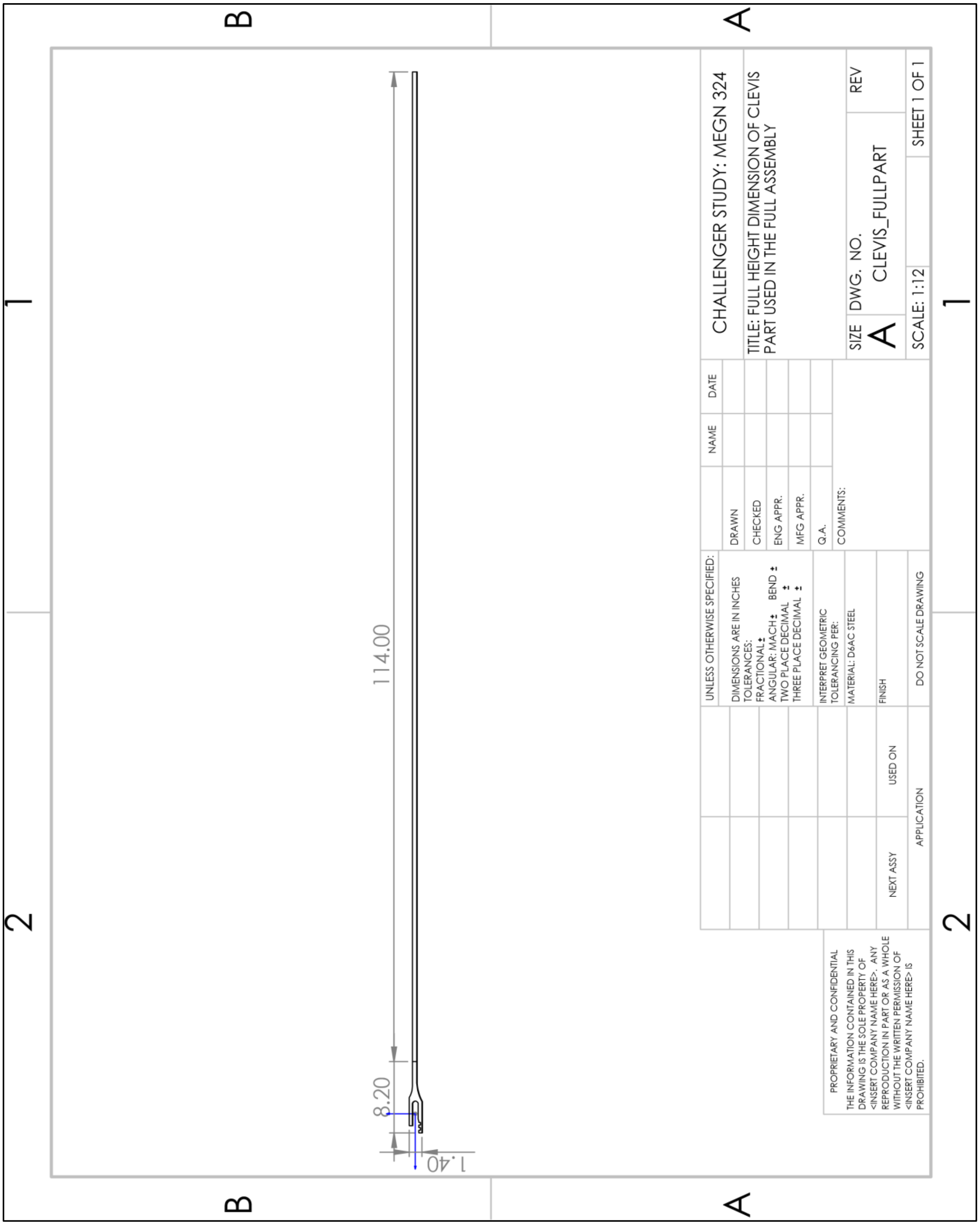
A1: Drawing of main joining section of the tang part



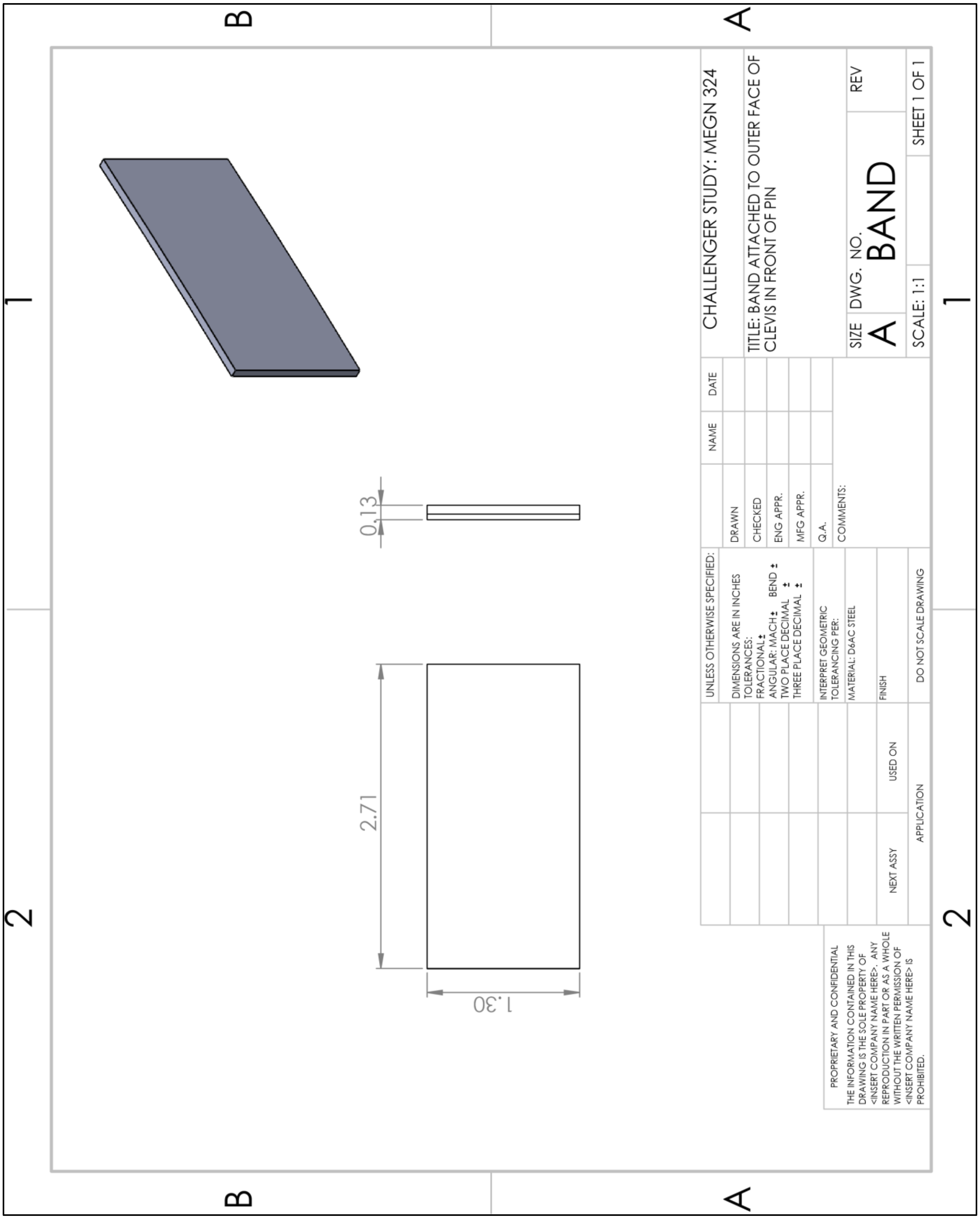
A2: Drawing with dimensions of the full tang part



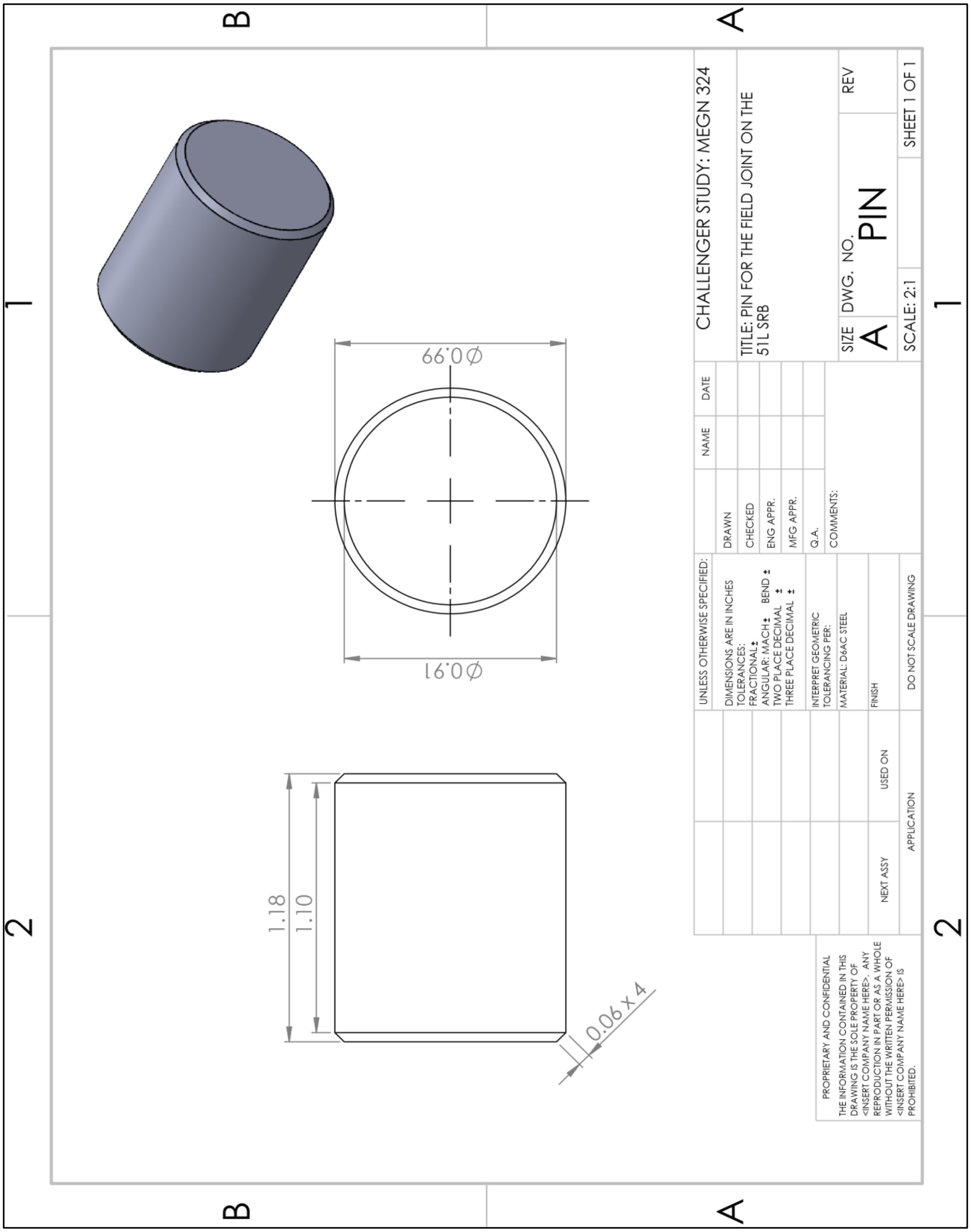
A3: Drawing with dimension of main joining section for the clevis part



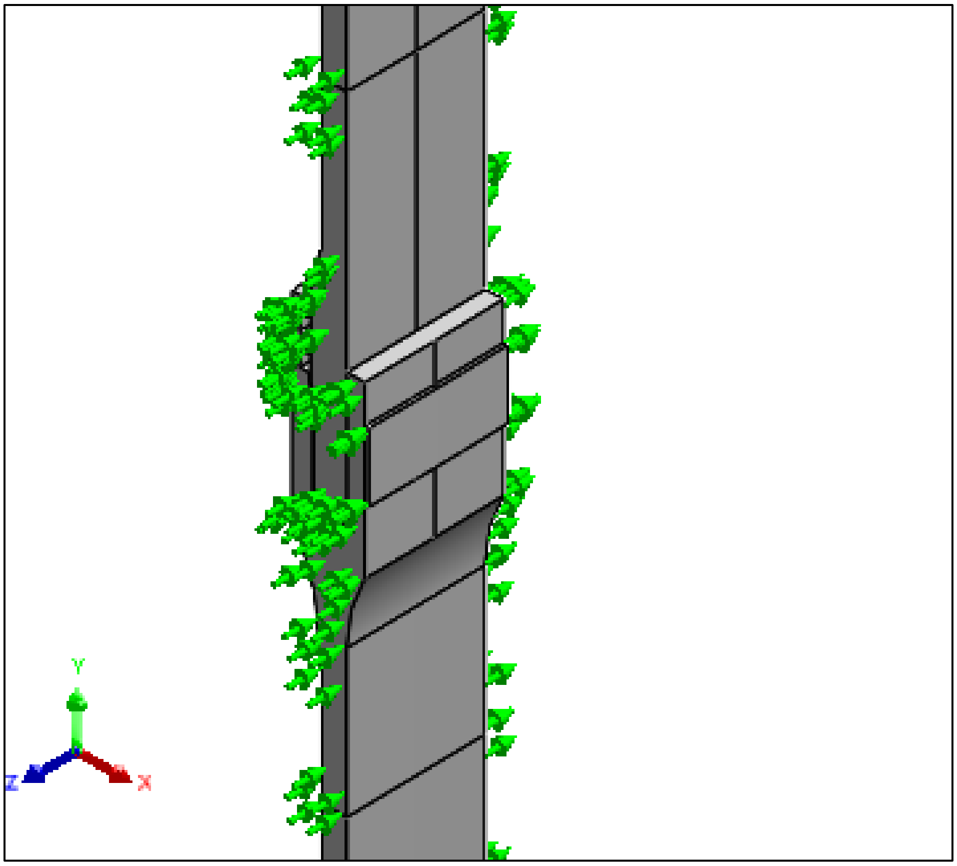
A4: Drawing with dimensions for the full clevis part



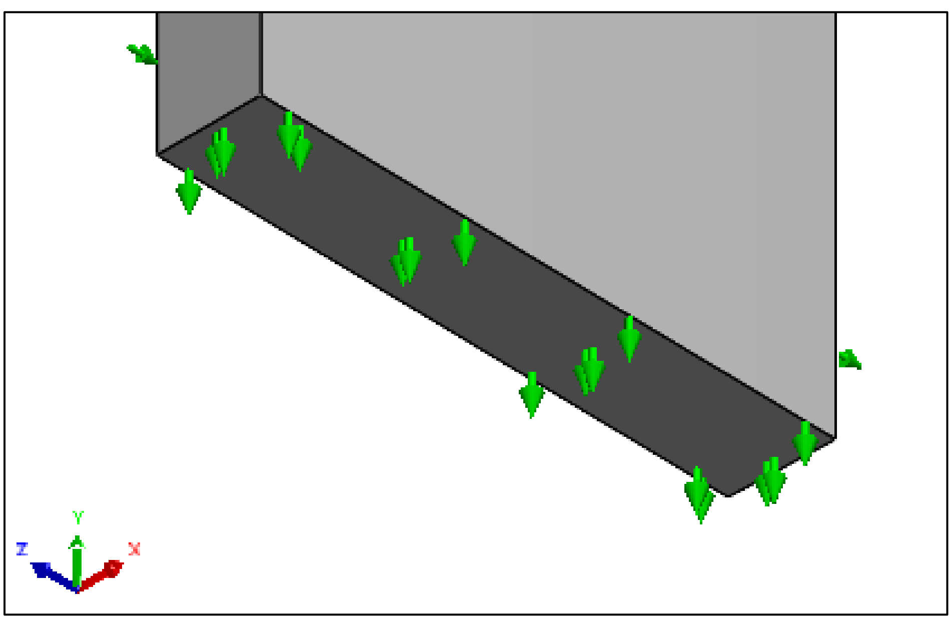
A5: Drawing for the pin retaining band with dimensions



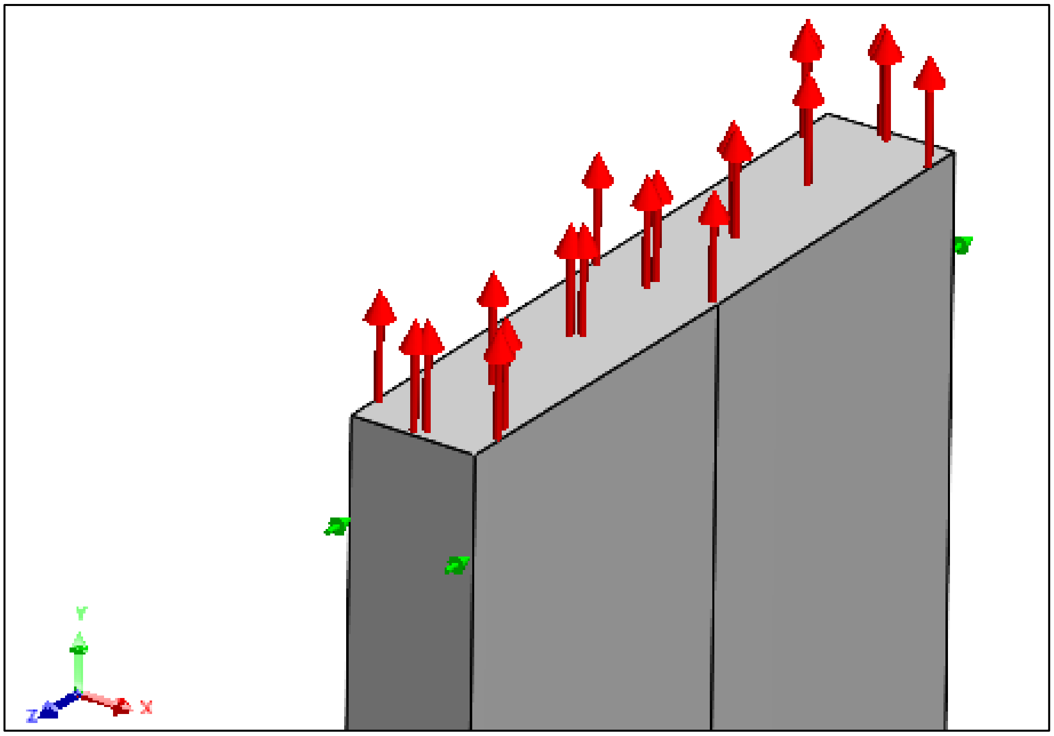
A6: Drawing with dimensions for the joint pin



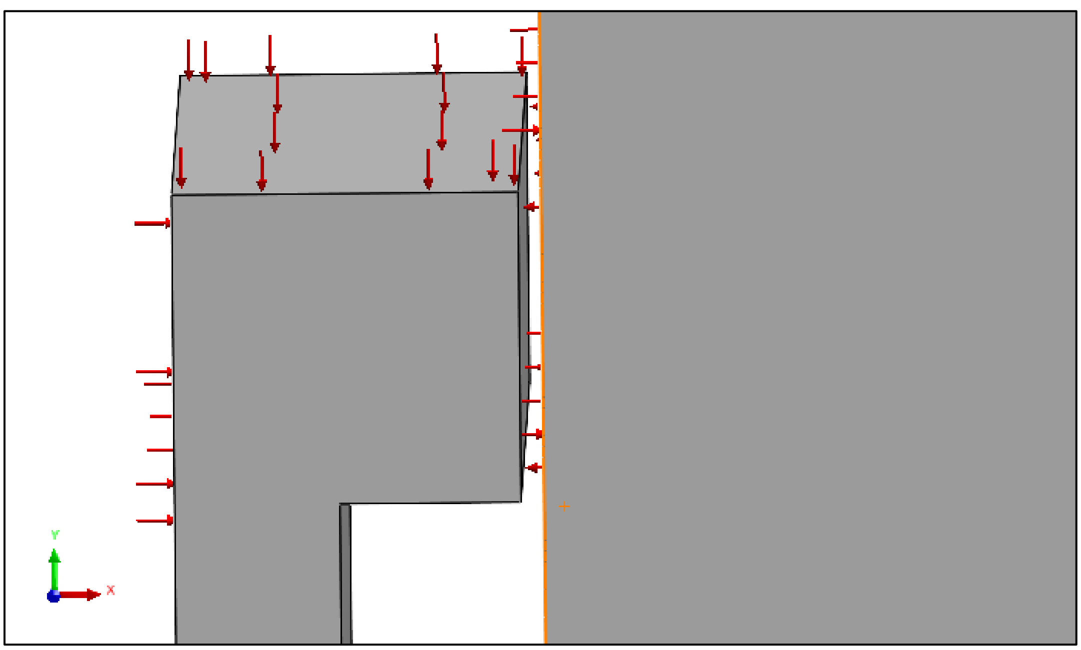
A7: Roller/Slider fixture applied to both z-direction faces of the entire assembly



A8: Roller/Slider fixture on bottom y-direction face of clevis part in assembly



A9: 76.16 psi axial stress applied to top y-directional face of tang part in tension



A10: Close-up view of 1000 psi pressure applied to inner faces between tang and clevis above first O-ring slot.

Challenger Study Mathcad Sheet
Ty Ridings, Section B

Given Values

$r_o := 72.96\ in$	Radius from Center axis to wall
$t := 0.479\ in$	Thickness of SRB wall
$p := 1000\ psi$	Pressure inside SRB
$E := 30179\ ksi$	Young's Modulus (D6AC Steel)
$v := 0.32$	Poisson Ratio (D6AC Steel)
$\sigma_{yield} := 190\ ksi$	Yield Strength (D6AC Steel)

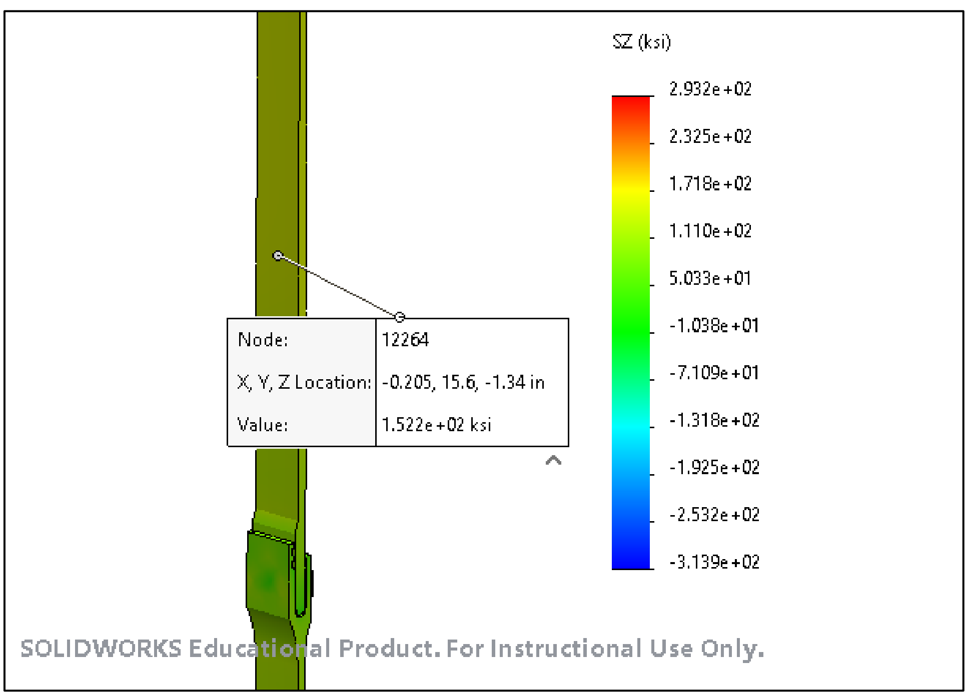
Section 1 - Calcuating Thin Walled Pressure Vessel Stresses

$$\sigma_{axial} := \frac{p \cdot r_o}{2\ t} = 76.159\ ksi \qquad \sigma_{hoop} := \sigma_{axial} \cdot 2 = 152.317\ ksi$$

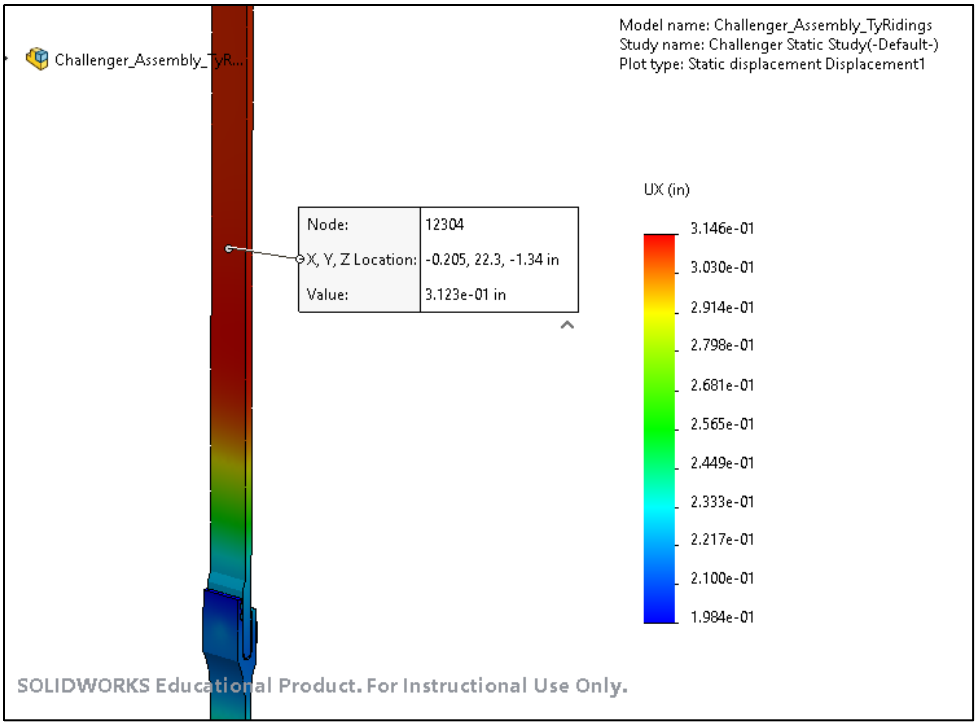
Section 2 - Calculating x-directional displacement in Radius

$$\delta_r := \frac{\sigma_{axial} \cdot r_o}{E} \cdot (2 - v) = 0.309\ in$$

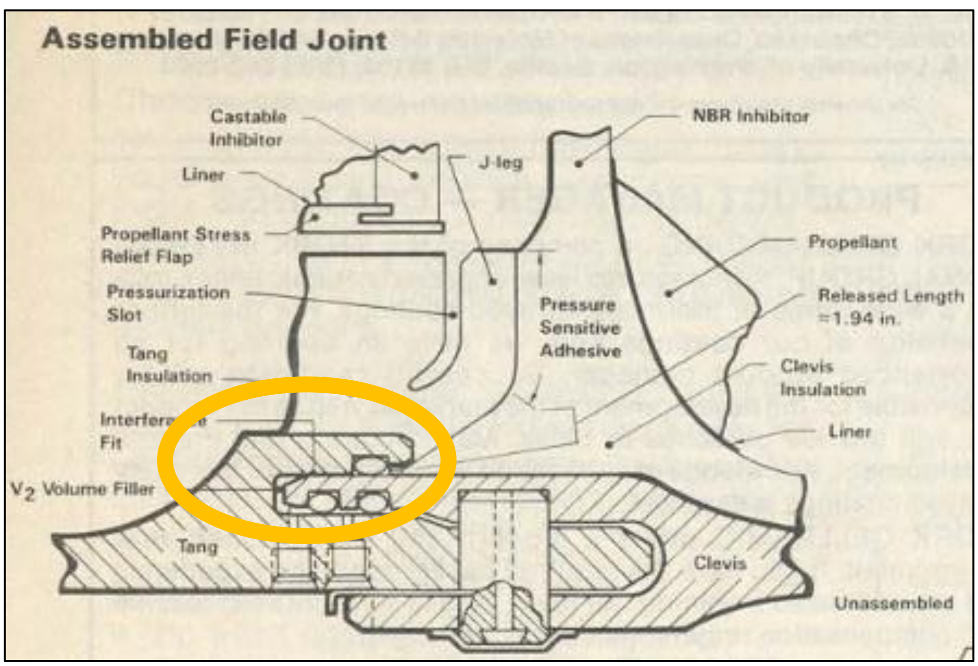
A11: Mathcad MoM Calculations



A12: z-directional stress calculated as the hoop stress (152.2 ksi)



A13: Radial displacement in the x-direction above the joint (0.3123 inches)



A14: Redesign of the assembled field joint with "catch feature" highlighted with yellow oval [1]