Boeing 707 Tie Rod

Supreme Aerospace

S. Saul, S. Shea, P. Ian, A. Luka

3/27/2023

Section 53

0.0 Table of Contents

0.1 List of Tables

0.2 List of Figures

1.0 Executive Summary

A new engine has been installed into the Boeing 707 that invalidates the existing part responsible for securing the engine to the aircraft. A part of the engine connection is too heavy and is insufficient in strength for this new engine and could break in an emergency. We propose a new tie rod made of titanium to replace the older, heavier, tie rod that was made of steel. Because our new engine is stronger than before, we must also change the parts that the tie rod attaches to on the engine and aircraft body. We have included recommendations for these additional attachment changes as well as our part and material proposal and justifications.

2.0 References

[1] ChatGPT, Personal Communication, March 25, 2023

[2] McMaster-Carr. (2023). *Titanium Bar Stock*. McMaster. Retrieved March 27, 2023, from https://www.mcmaster.com/titanium-bar-stock/

[3] Rice, R. C., Jackson, J. L., Bakuckas, J., & Thompson, S. (2003, January). Metallic Materials Properties Development and Standardization (MMPDS). Columbus. Retrieved March 2023.

[4] FAA. "DOT/FAA/AR MMPDS 01 - [PDF Document]." *Vdocuments.site*, Everyspec.com, Jan. 2003, https://vdocuments.site/dotfaaar-mmpds-01.html.

3.0 Design Process

In this section we will discuss the forces our assembly has to withstand. We will describe the design. This description will include: the forces our assembly must overcome, the materials chosen, the overall shape of our design and the number of components in our assembly. Next, we will justify our design by detailing the forces that our assembly is able to overcome, which will include an explanation of our material choice.

3.1 Design Description

The new assembly of a tie rod, pins, and clamps are designed to withstand a load from a Fan Blade-Out. Using the engine's weight of 4,600 lbs. and a potential load of 200 G's, we have determined that the tie rod must withstand a force of 300,000 lbs.

Part Name	Quantity	Material
Base Plate	1	Steel (AISI 4340)
Clevis Mount	1	Steel (AISI 4340)
Base Plate Pin	1	Titanium (Ti-6Al-4V)
Clevis Mount Pin	1	Titanium (Ti-6Al-4V)
Base Plate Clamp	1	Titanium (Ti-6Al-4V)
Clevis Mount Clamp	1	Titanium (Ti-6Al-4V)
Tie Rod	1	Titanium (Ti-6Al-4V)

Table 1 shows the part name, the quantity of the part, and the selected material for the part.

Below is a picture of our base plate clamp. The base plate clamp was designed to join the main tie rod to the base plate. We used a light weight, robust design that is easy to manufacture. The base plate clamp would be welded to the base plate, with a custom base plate pin to keep it in place.

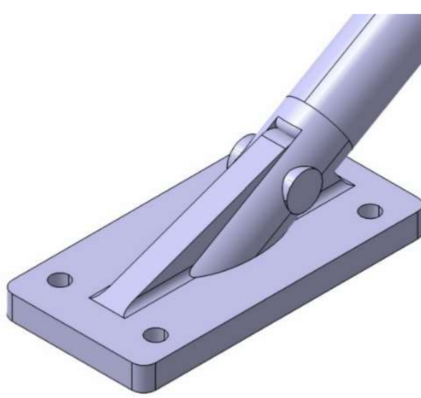

Figure 1 shows the base plate clamp interfacing with the base plate.

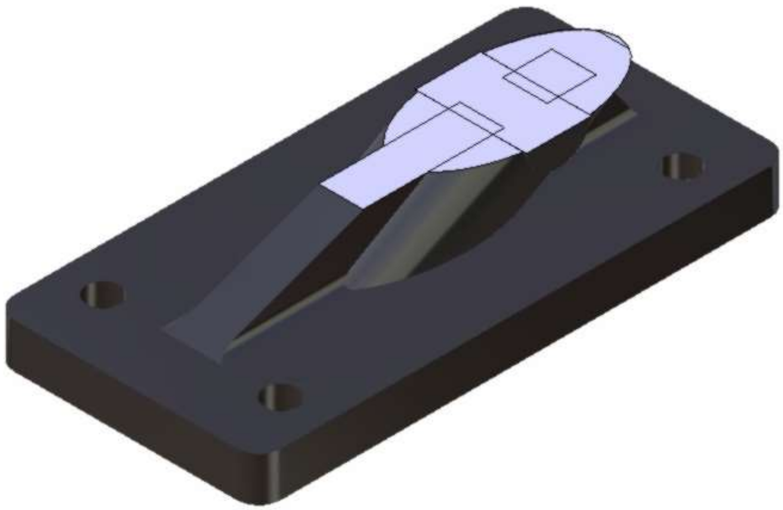

Figure 2 shows a section view of the base plate clamp interfacing with the base plate.

The base plate clamp has an interior geometry designed to contour the ridge atop the base plate. This is to ensure that the tie rod moves as little as possible, while maintaining a high enough margin of safety. Ideally, the base plate clamp and the tie rod would be one part along with the clevis mount. But, if manufacturing does not allow this, the base plate clamp would be welded to the tie rod.

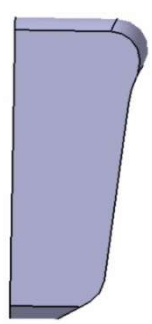

Figure 3 shows the contour of the surface connecting the base plate and the base plate clamp.

Below is a picture of the clamp for the clevis mount. The clevis mount clamp is formed to maximize surface area contact. The fillets on the edge in contact with the clevis mount itself are there because the clevis mount has a corresponding fillet. The reason the bracket is so wide is it fills the space in between the brackets, leaving little wiggle room that could increase the stress on the mount, clamp, and pin.

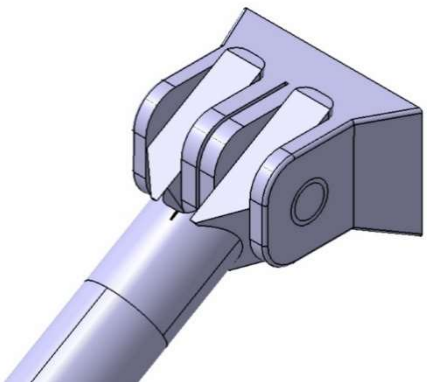

Figure 4 shows the clevis mount clamp interfacing with the clevis mount.

Figure 5 shows a section view of the clevis mount clamp interfacing with the clevis mount.

3.2.0 Design Justification

The primary design decisions to be justified are as follows:

1. Geometry and Diameter of Tie Rod
2. Geometry of Base Plate Clamp
3. Geometry of Clevis Mount Clamp
4. Diameters of Base Plate and Clevis Mount Pins

Titanium alloy MIL-T-9047[3] (Grade 5 Ti-6Al-4V) was selected on basis of personal conversation with ChatGPT when prompted[1] for the highest cost to weight ratio material that also has favorable thermal and axial force characteristics. This alloy was also selected on its historical merit in aerospace applications for tie rod and other implementations. We then, of course, confirmed this with our calculations below before selecting this material for our project.

3.2.1 Geometry and Diameter of Tie Rod

The length of our tie rod for the purposes of force calculations is 32.064 inches, as measured by CATIA, with a uniform circular cross section as measured by CATIA. The tie rod then has a diameter of 2.500 inches for a total volume of 162.927 inches cubed.

The stresses applied to the tie rod are completely axial resulting in calculations of buckling compression and tensile pressure forces to be performed. Under the 300,000 pound-force load, buckling compression (Euler's Critical Load) is calculated as follows, where E is the Modulus of Elasticity, K is a constant 1 because we assume no reaction forces on the ends (pinned), L is our length, and I is the moment of inertia:

$$P_{cr} = \frac{\pi^2 EI}{(KL)^2}, \; I = 0.25\pi r^4$$

Using a Python defined function (included in appendix) and the elasticity modulus for our material of 16.9 GPa[3], our calculated P_{cr} is equal to 311085.58 pounds of force, or 311.086 kips. Calculating our MOS therefore is as follows, where P_{bu} is the 300,000 load:

$$\text{MOS} = \frac{P_{cr}}{P_{bu}} - 1$$

As before, using the created Python script, our MOS is calculated as +3.695%. Lowering our tie rod diameter by any substantial amount from here results in part failure, such as a diameter of 2.475 inches which when calculated has a MOS of -0.391%.

The solid circular cross-sectional geometry of our tie rod is then justified by a greater ease of manufacturability and a greater ultimate strength due to the rod being solid. The cylindrical shape is selected for similar reasons as bar stock is often cylindrical, contributing to more market prevalence and thus less cost, as well as a circular cross section maximizing bounded cross-sectional area while minimizing exposed surface area contributing to longevity of the part.

3.2.2 Geometry of Base Plate Clamp

The clamp for the base plate is designed in such a way that the tie rod should never move. There is a cavity inside of the clamp that envelopes the rib of the base plate, preventing any movement. If welded, that part will be rigid. This being welded on also dramatically reduces the force bearing on the pin, increasing our margin of safety.

The edges of the base plate clamp have edge fillets because they ease manufacturing.

3.2.3 Geometry and Clevis Mount Clamp

The clamp for the clevis mount is constructed to increase surface area contact with the clevis mount, making welding much easier. Since the tie rod isn't supposed to move, the clevis mount clamp has edge fillets and fills the gaps in between the brackets of the clevis mount.

3.2.4 Diameters of Base Plate and Clevis Mount Pins

Justification for the pin hole diameter and partnering pin diameter stems from the sheer stress pressure exerted on the horizontal connection pins at both mounting plates.

The diameter of the base plate pin is 1.500 inches, and the length is 2.500 inches. Sheer stress on the base plate pin is calculated with "V" equal to the experienced force load and "A" equal to the cross-sectional area the force is exerted over:

$$\tau = \frac{V}{A},$$

On the base plate bracket and mount interface, the load is distributed evenly over two connection points, thus "V" is set to 150,000 pounds-force and from CATIA the cross-sectional area of the base plate pin is 1.767 inches squared. This is calculated in the created script as a sheer stress of 84882.708 psi. The associated MOS is then found using the thermal knockdown coefficient "T" (equal to 0.76 at 570°F for our alloy[3]), and an ultimate sheer force value $F_{su} = 124000$ psi[3] as:

$$MOS = \frac{T * F_{su}}{A}$$

Resulting in an output MOS value of +16.87%.

A diameter less than this value at a standard drill bit size results in a negative MOS and thus part failure.

The clevis mount pin is similar in calculation with the primary exception of the load being uniformly distributed over three contact points with the tie rod resulting in an acceptable standard diameter of 1.25 inches, a calculated sheer stress of 81487.400 psi, and an MOS of +21.74% with the same thermal knockdown. This was the nearest standard bit diameter that passed MOS.

3.2.5 Table of Critical Values

Part	Sheer MOS	Tensile MOS	Buckling MOS
Base Plate Pin	0.1687		
Clevis Mount Pin	0.2174		
Tie Rod		0.5544	0.0370

Table 2 shows the MOS for all relevant loads and stresses for every part.

3.3 Design Details

Our design involves a main tie rod connected to the base plate and tie rod using two clamps. We have a base plate clamp and a clevis mount clamp. We also have two pins, one for each clamp, to hold the tie rod in place. The rod part of the tie rod will be welded onto each of the clamps. The clamps will have pins inserted into them and then be welded to the mount and base plate.

Material Properties

One of the main considerations with our design is the overall weight of our part. Specifically, we reduced it as much as possible.

Part	Density (lbs/in^3)	Volume (in^3)	Weight (lbs)
Base Plate Pin	0.160	4.418	0.707
Clevis Mount Pin	0.160	5.522	0.884
Tie Rod	0.160	124.549	19.9
Clevis Mount Clamp	0.160	27.648	4.42
Base Plate Clamp	0.160	10.73	1.72
TOTAL WEIGHT	27.7 lbs.		

Table 3 shows the weight calculations for every part.

Compared to our original weight of 86.4 lbs., we reduced our assembly to 27.7 lbs. This assembly is a mere 32% of the original weight.

4.0 Conclusions

We were able to reach a safe Margin of Safety on all parts of the assembly. We were also able to reduce this part from its original weight of 86.4 lbs to 27.7 lbs. This is a weight reduction of 68% while staying safe during a potential Fan Blade-Out situation.

Regarding our price, an estimate from McMaster is about $2000. We found that our selected material costs around $56 per pound. This, combined with labor costs, comes out to be around $100 per pound (While this part is not excessively complicated to manufacture, it is not trivial by any means, being that the tie rod is made of titanium). So, for 27.7 pounds, we get an estimate ranging from $2000-$2700. It is important to consider that cost was not a constraint for the project.

Something to consider is the potential galvanic reaction that occurs between Ti-6Al-4V titanium and AISI 4340 steel due to the high temperatures of operations. In the event of a galvanic reaction, there are certain coatings we can implement to reduce these effects. Such a coating is not necessary for this project; however, it is still something to consider for operation.

The design for the base plate must be fixed. With the larger hole in the base plate, the MOS is in the negative, due to the much smaller cross-sectional area caused by a widened hole. We recommend either making the base plate's rib taller or wider. The base plate has a Cross-Sectional Area (CA) of 1.617 in^2. The CA must be increased to a minimum of 3.175 in^2 to have a positive MOS. The Clevis Mount already has a CA of 4.337 in^2 and therefore does not need to be edited outside of widening the holes.

5.0 Appendix

Titanium TK

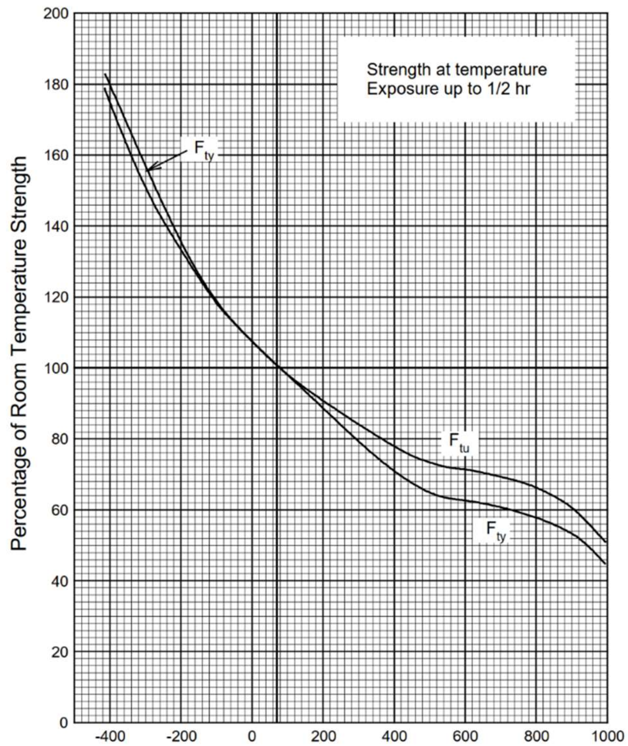

Figure 6 shows the critical values for our selected titanium alloy.

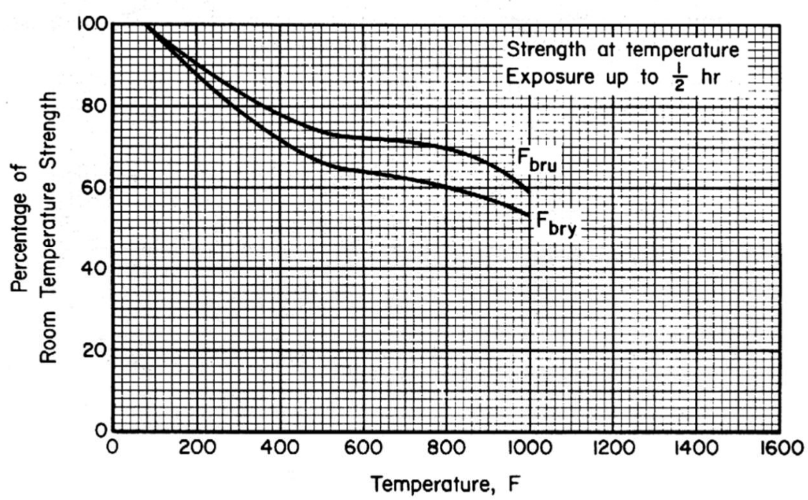

Figure 7 shows the thermal properties of our selected titanium alloy

Figure 8 shows a section view of our entire assembly

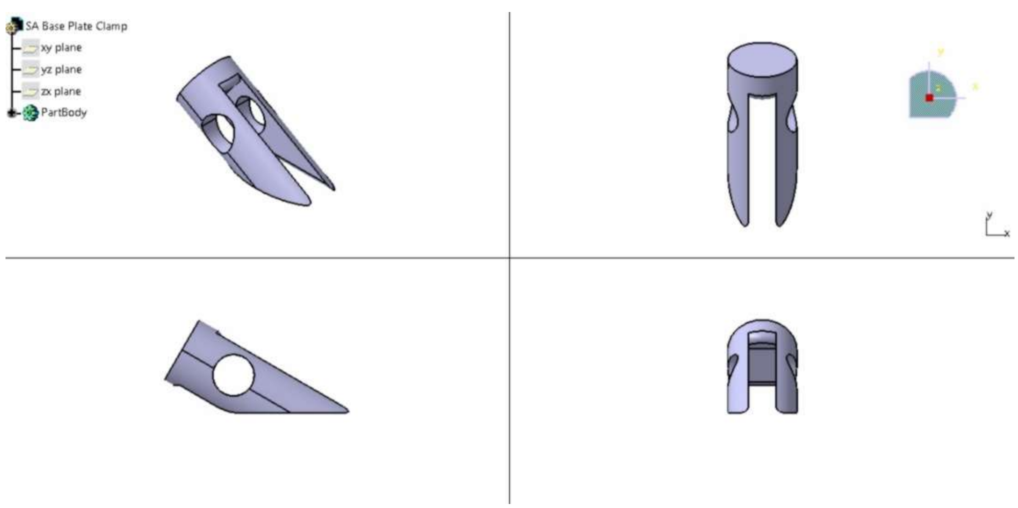

Figure 9 shows the base plate mount in 4 views

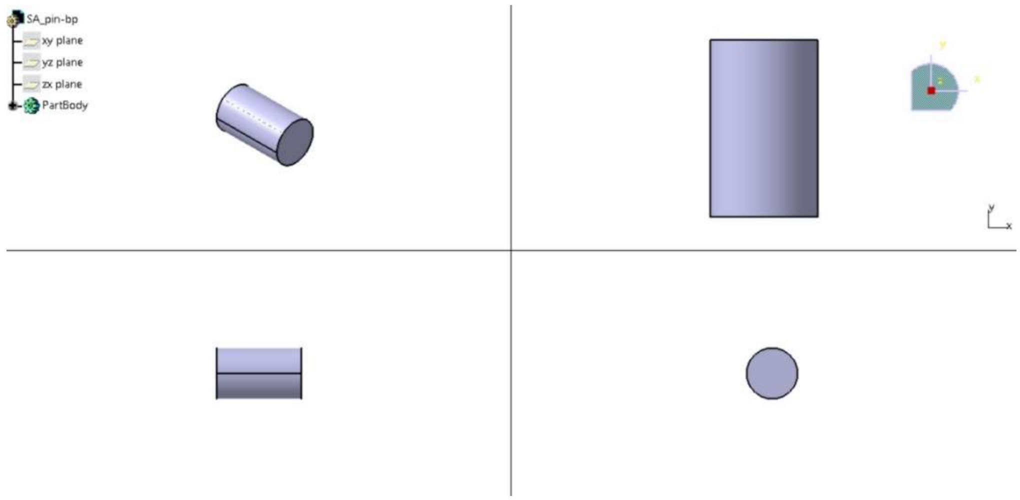

Figure 10 shows the base plate pin in 4 views

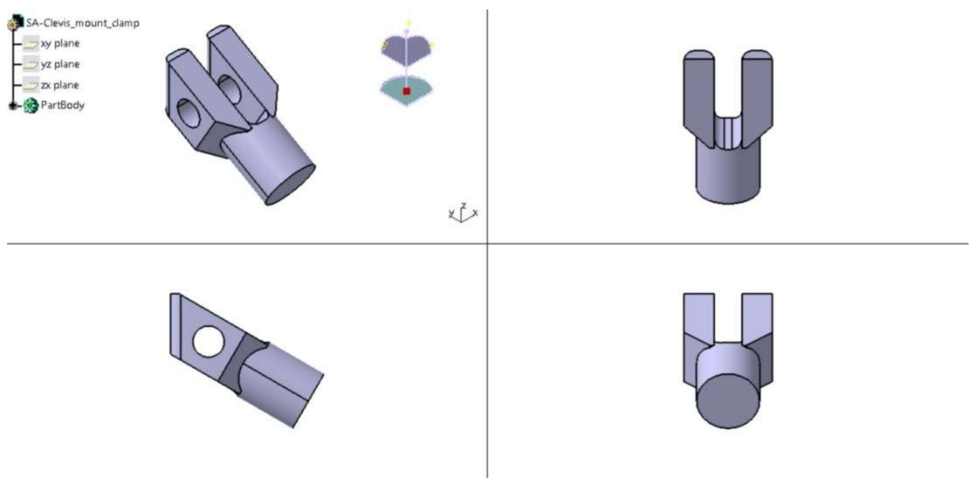

Figure 11 shows the clevis mount in 4 views

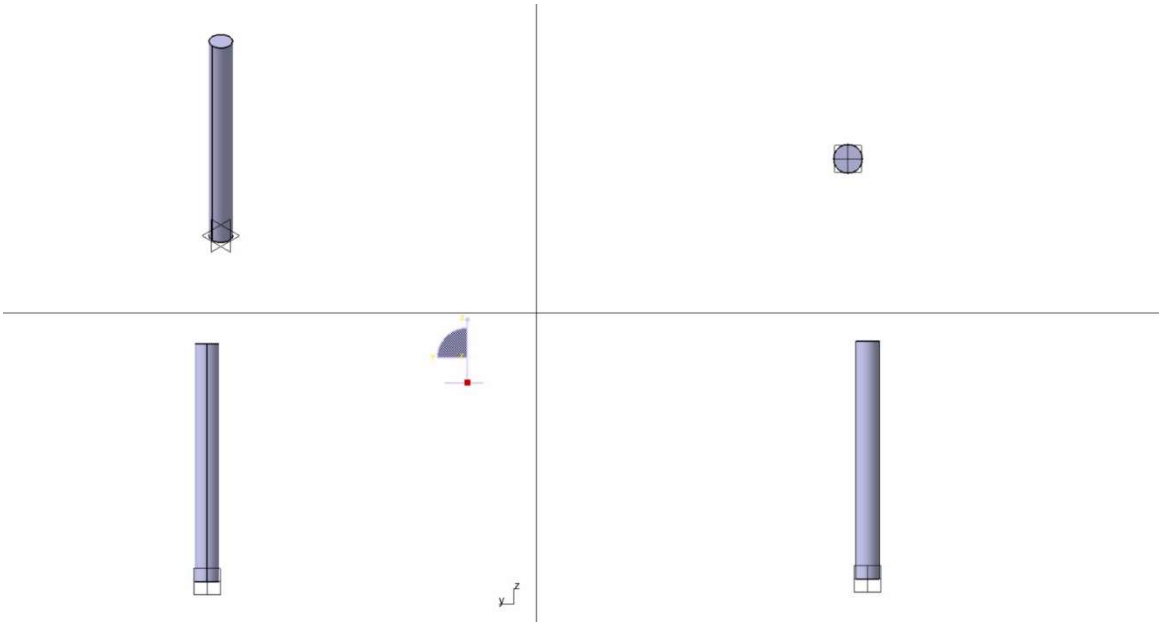

Figure 12 shows the tie rod in 4 views

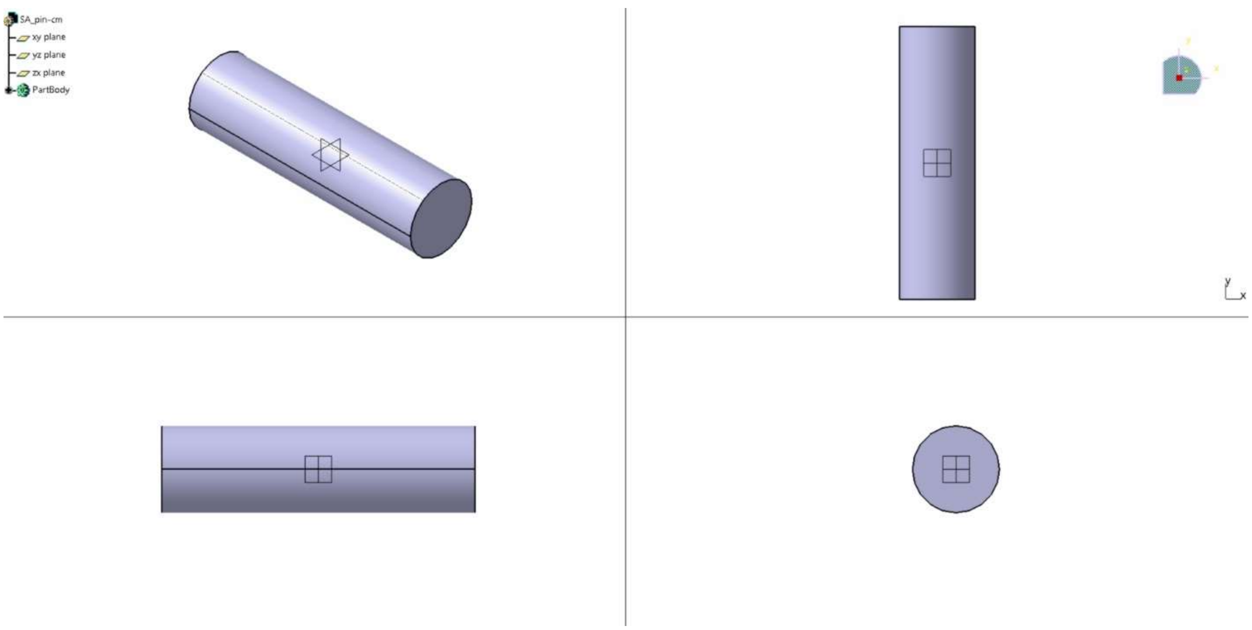

Figure 13 shows the clevis mount pin in four views

Python Script

```python
# Update these fields for the material in question:

# Material Vector: [0] Material [1] Ftu [2] Fsu [3] Tktu [4] Tksu [5] Elasticity Modulus [6] Density

alloy1 = ["Ti-6Al-4V", 125000, 124000, 0.76, 0.80, 16900000, 0.16]
alloy2 = ["AISI 4340", 260000, 235000, 0.91, 0.95, 29000000]
alloy3 = ["Stainless Steel 17-4PH", 0, 0, 0, 0, 28500000]
materialProperties = alloy1

# Physical Vector: [0] Tie Rod Diameter [1] Pin Diameter [2] Tie Rod Length [3] Plate Normal Cross Sectional Area [4] Volume

physicalProperties = [2.50, 1.25, 32.064, 3.2, 162.927+5.522+4.418]

# Input Forces

inputSheerForceLbs = 150000 #lbs
inputForceLbs = 300000 #lbs obviously

pindiameter = physicalProperties[1] #inches
TRdiameter = physicalProperties[0]
pinCA = 0.25*3.14159*(pindiameter)**2 #inches squared
TRCA = 0.25*3.14159*(TRdiameter)**2 #inches squared
length = physicalProperties[2] #inches
plateNormCA = physicalProperties[3] # inches squared

Ftu = materialProperties[1] # Material Allowable tensile stress [psi]
Fsu = materialProperties[2] # Material Allowable sheer force [psi]
tktu = materialProperties[3] # Thermal Knockdown Coefficient Tensile Ultimate
tksu = materialProperties[4] # Thermal Knockdown Coefficient Sheer Ultimate

modElasticity = materialProperties[5]

weight = materialProperties[6] * physicalProperties[4]

print("\nCalculations for " + materialProperties[0] + ":\n")

def sheerStr():
    sheerStr = (inputSheerForceLbs/pinCA)
    MOS = ((Fsu*tksu)/sheerStr)-1
    print("Sheer Stress: "+str(sheerStr)+" psi\n\tMOS: "+ str(MOS*100)+"%")

def bucklingCompStr():
    bucklingCompStr = (((3.14159**2)*modElasticity*(0.25*3.14159*((physicalProperties[0]/2)**4)))/(length**2))
    MOS = (bucklingCompStr/(300000))-1
    print("Buckling Compression: "+str(bucklingCompStr)+" lbf\n\tMOS: "+ str(MOS*100)+"%")

def tensileStr():
    tensileStr = (inputForceLbs/TRCA)
    MOS = ((Ftu*tktu)/tensileStr)-1
    print("Tensile Strength: "+str(tensileStr)+" psi\n\tMOS: "+str(MOS*100)+"%")

# Plate Calculations

def plateNorm():
    tensileStr = (inputForceLbs/plateNormCA)
    MOS = ((Ftu* tktu)/tensileStr)-1
    print("Plate Normal: "+str(tensileStr)+" psi\n\tMOS: "+str(MOS*100)+"%\n")

# Calculations:

print("Mass: "+ str(weight) + " lbs.\n")
sheerStr()
bucklingCompStr()
tensileStr()
plateNorm()
```