Understanding Factors of Safety and Failure: Simulations in Fusion 360

Sean Thomas

Principal Mechanical Engineer

AUTODESK® UNIVERSITY

About the speaker

Sean Thomas

- Mechanical Design Engineer by education and practice (though I’m technically in management now)
- Over 10 years of experience in the world of simulations using several different FEA packages
- Passionate about the benefits of simulations and what they allow us to do in the design world
- Experience with Aerospace/Defense, Oil and Gas and Telecomm

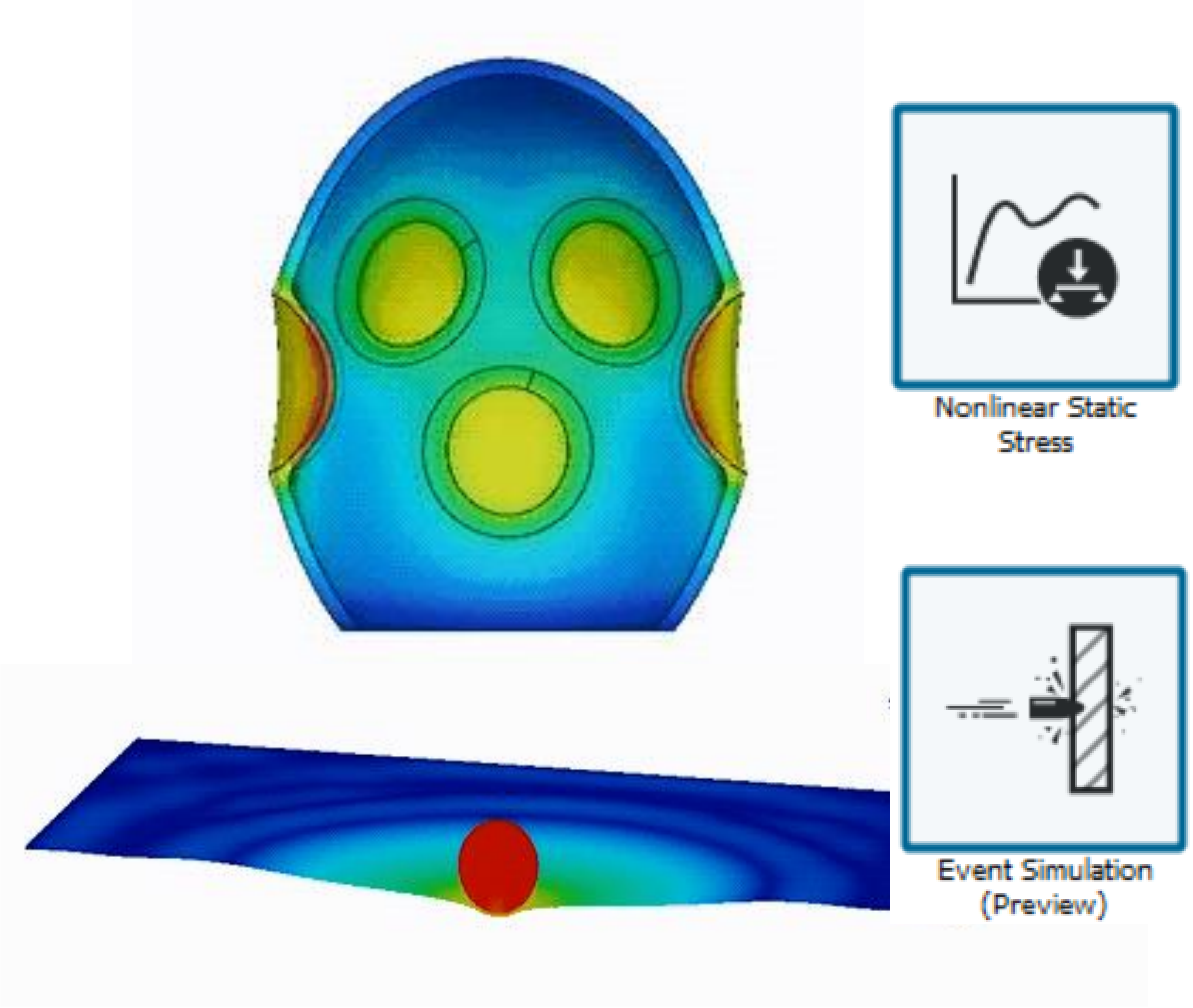
Class Overview

Key Learning Objectives

- Learn about non-linear simulations and when they are necessary
- Learn about Factor of Safety as it applies to Simulation Results
- Understand what Simulation results mean “in the real world”
  - Is red bad?!
- Understand how to interpret results well enough to predict failure – Catastrophic (single event) or Fatigue

Types of Non-Linear Simulations in Fusion 360

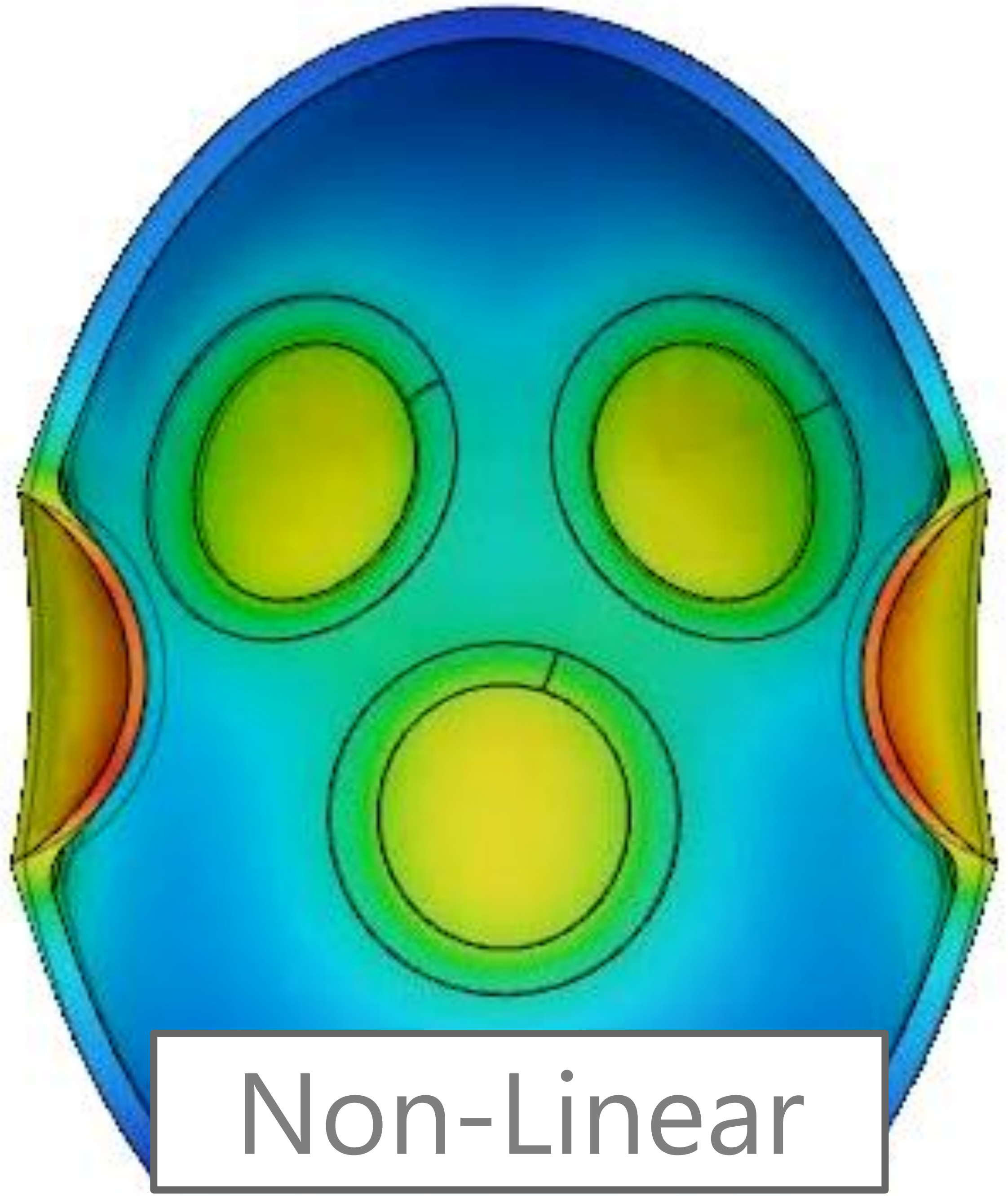
- Non-Linear static stress
  - Necessary for Large Displacement as well as Non-Linearities in materials and Boundary Conditions
- Event Simulations
  - Very short duration dynamic events such as impact analyses and drop test
  - Includes material, contact and geometric non-linearities



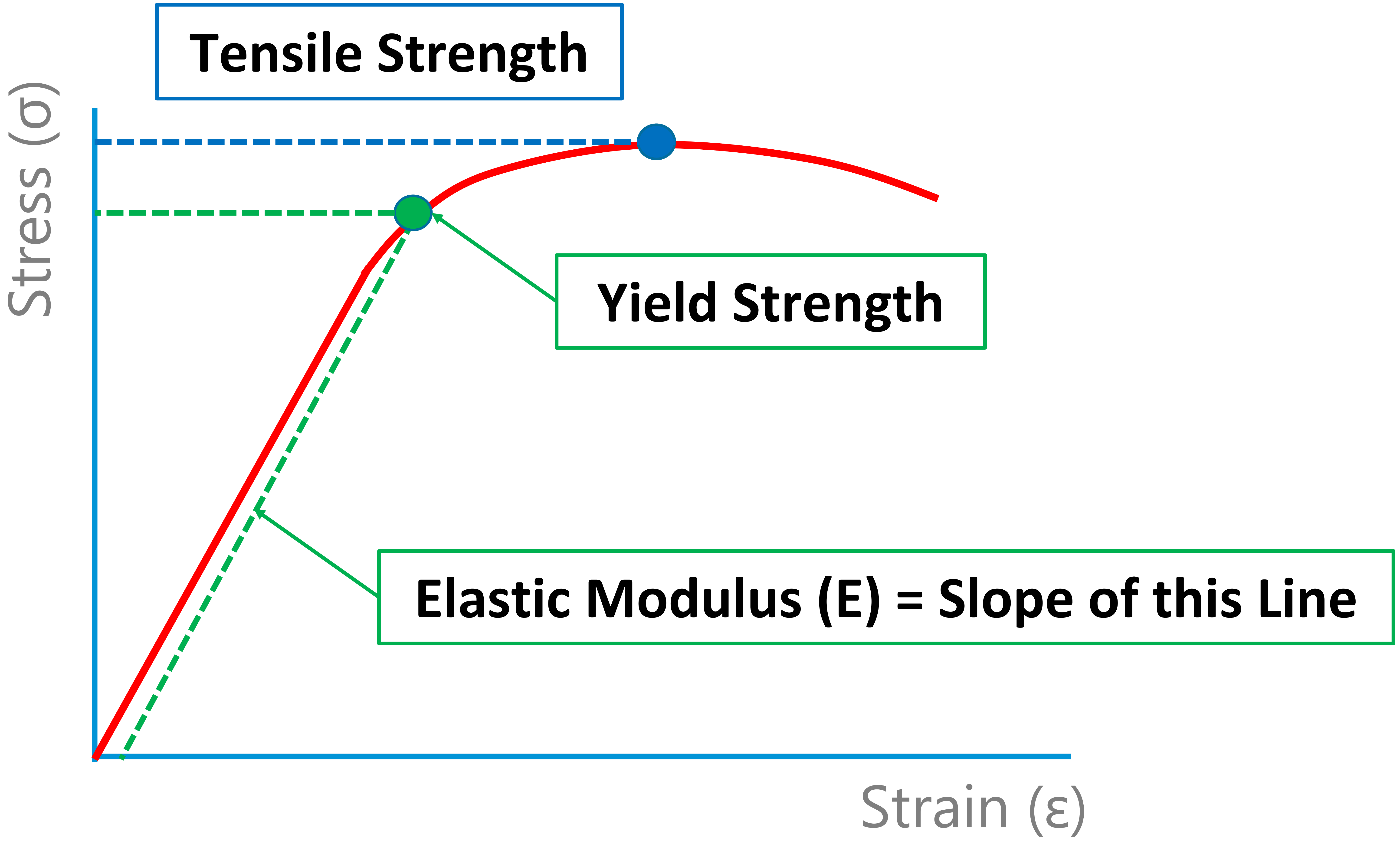
What is a Non-Linear Large Displacement?

The 2 simulations below are set up with identical loads and constraints, but one is linear and one is non-linear.

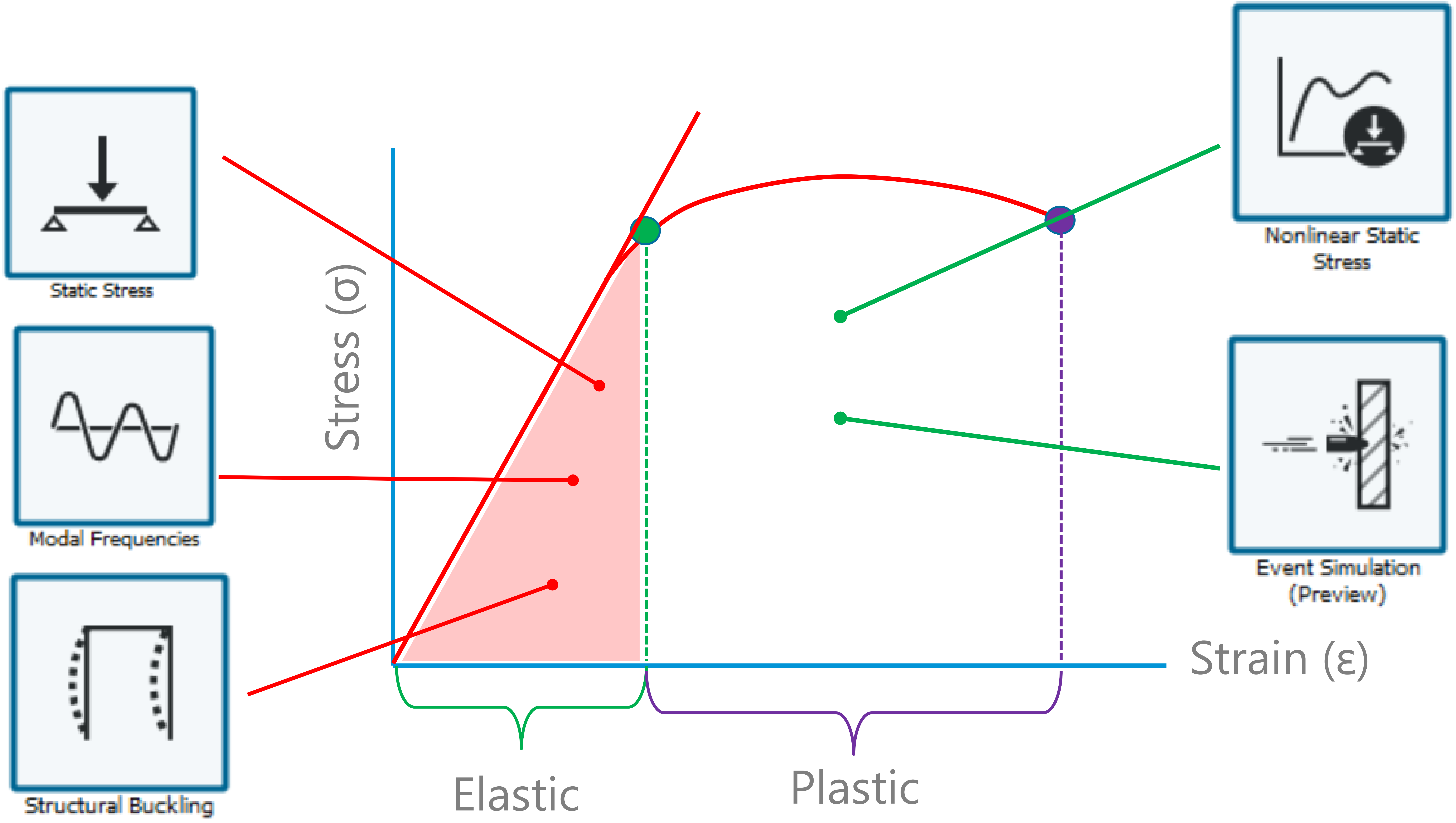
Notice how the non-linear moves as you would expect an inflating object to:



What is a Non-Linear Material Model?



What is a Non-Linear Simulation (material non-linearity)



When to use a Non-Linear Simulation

- Anytime you have large displacements
- When stresses exceed yield strength/strain or enter a region of material non-linearity
- It will never hurt the quality of results to start with a non-linear simulation (it just takes longer)
- For very short duration (non static) studies, an Event Simulation should be used

Factor of Safety Overview

Factor of Safety Definition

Factor of Safety is a ratio that compares the allowable load or stress of a design with the actual applied load or stress. From an FEA standpoint this is typically defined by the equation below:

$$Factor\ of\ Safety = \frac{Maximum\ Stress}{Design\ Stress}$$

Where:

- Maximum Stress can equal yield stress, ultimate stress, shear stress or even a fatigue based stress limit that is the maximum value your design should allow without any margin applied
- Design Stress is the actual stress in your design when subject to the load case it is designed for. For the purpose of this class, it is the stress result given to us by our simulation.

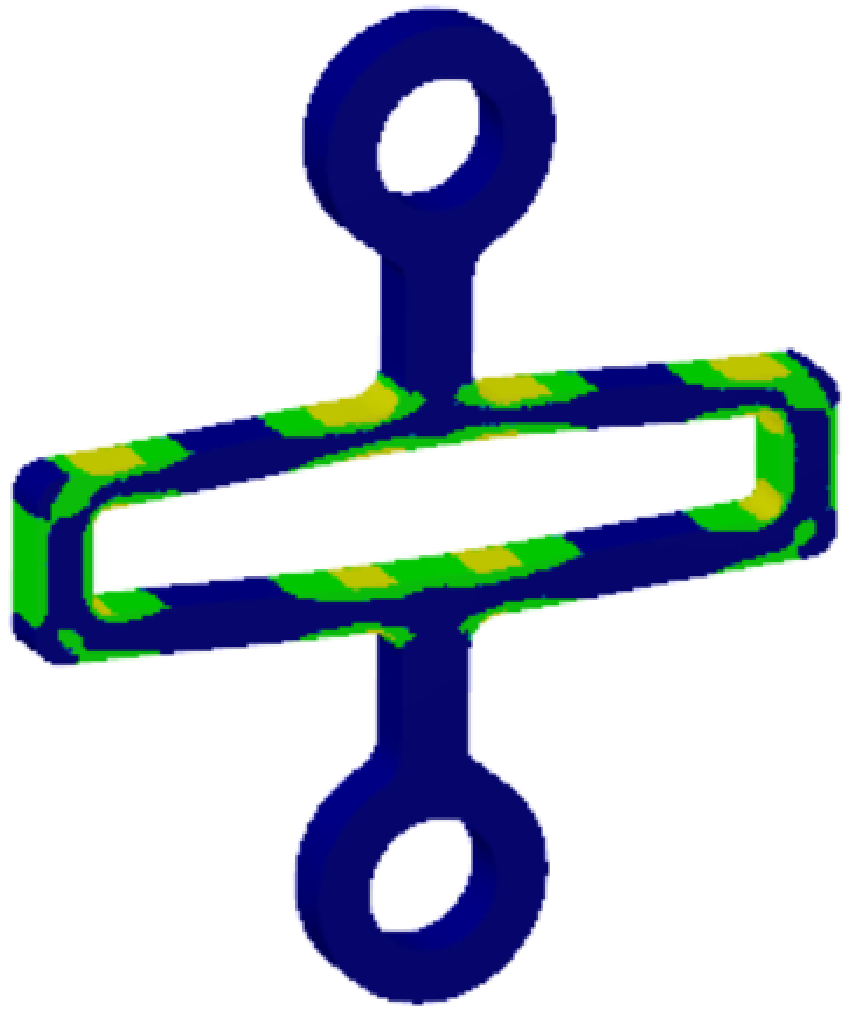
Factor of Safety Considerations

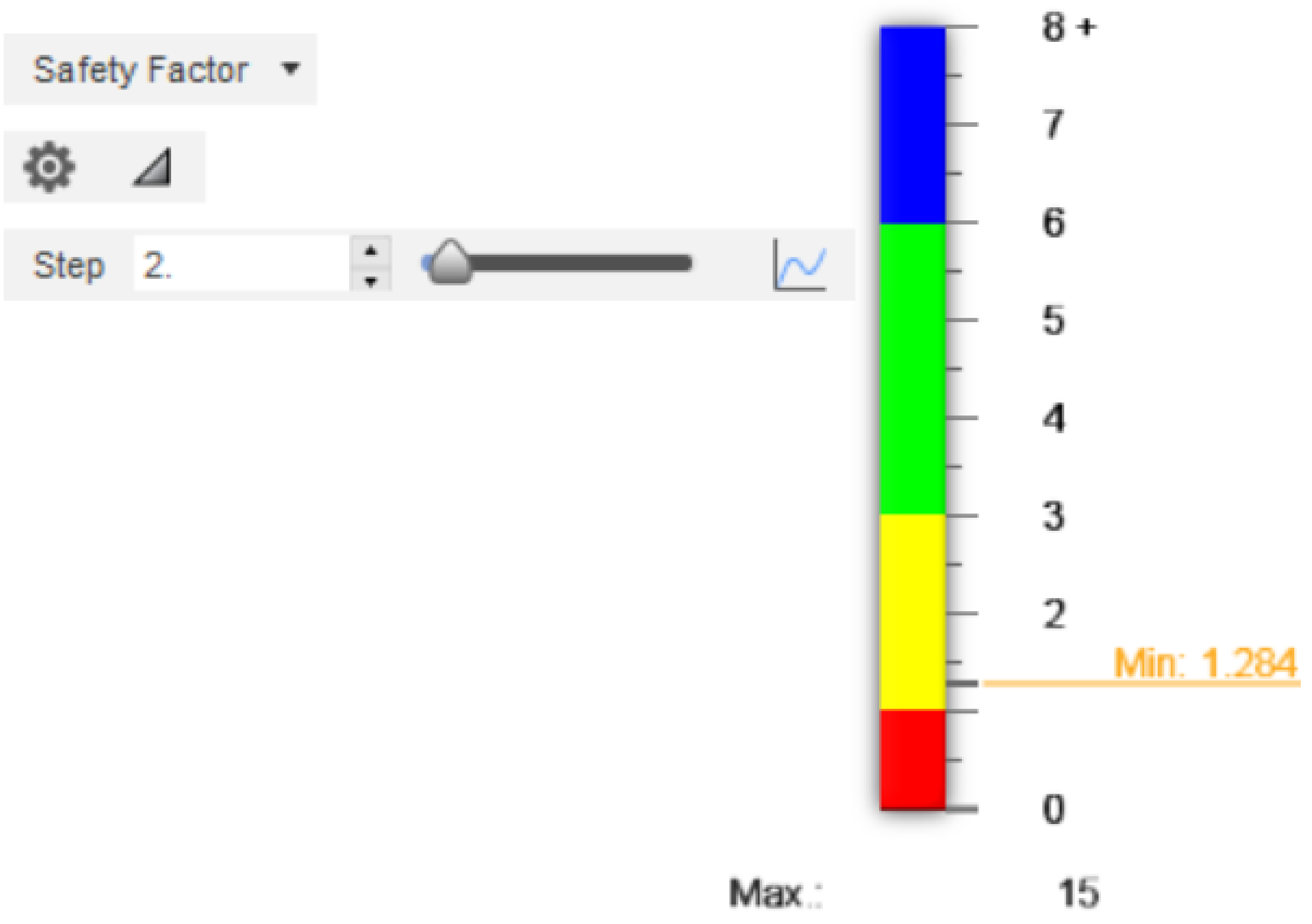
- Typical Safety Factors can vary based on the industry, and in some cases are defined by standards. There is a broad range of factors based on the application with some of the more common values being:
  - Aerospace: 1.5-2.0
  - Pressure Vessels: 3.5-6.0
  - Lifting Equipment: 4.0 – 10.0

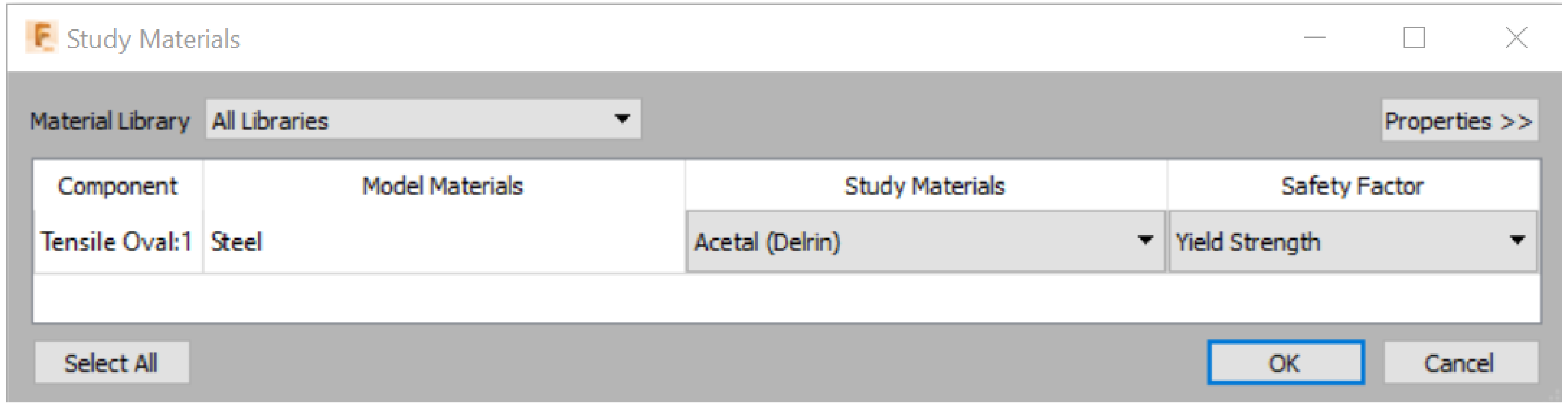
- The Maximum Stress value should be determined by the application
  - Static Load cases typically use yield or ultimate strengths
  - Cyclic load cases may use endurance limit or other fatigue based values

Factor of Safety Plots in Fusion 360

Fusion 360 can produce Factor of Safety plots in your Simulation results based on Yield Strength or Ultimate Strength:







Factor of Safety Warnings

- When using factor of safety plots, make sure to review both stress AND STRAIN data
- Your factor of safety calculation should suit the load case and industry norms – Don’t just use the plots without understanding this
- Some standards require additional factors in conjunction with your FoS

Interpreting and Applying Results in the Real World – Non Linear Static

Overview

In this section we will go over the results of different Non-Linear Static simulations, calculate the FoS and compare it with Real World results. We will specifically review:

- Defining whether we need to base our decisions on yield strength or fatigue strength (or both)
- Understanding how to treat stress concentrations
- Approximating Catastrophic Failure

RC Car Motor Mount Example Problem **Video**

This video demonstrates a possible shock load on the Motor Mount of this RC Car

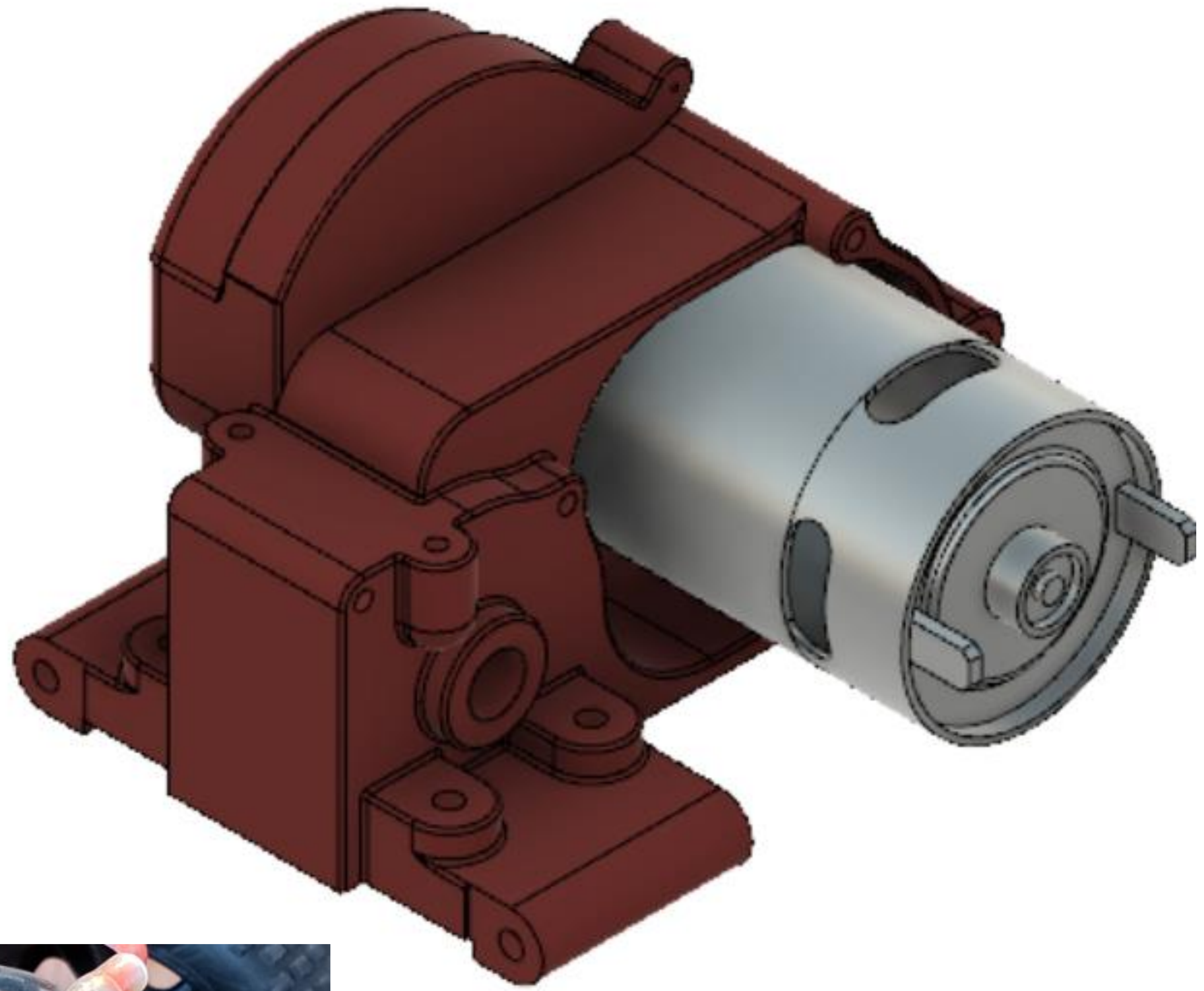
RC Motor Mount Example Overview

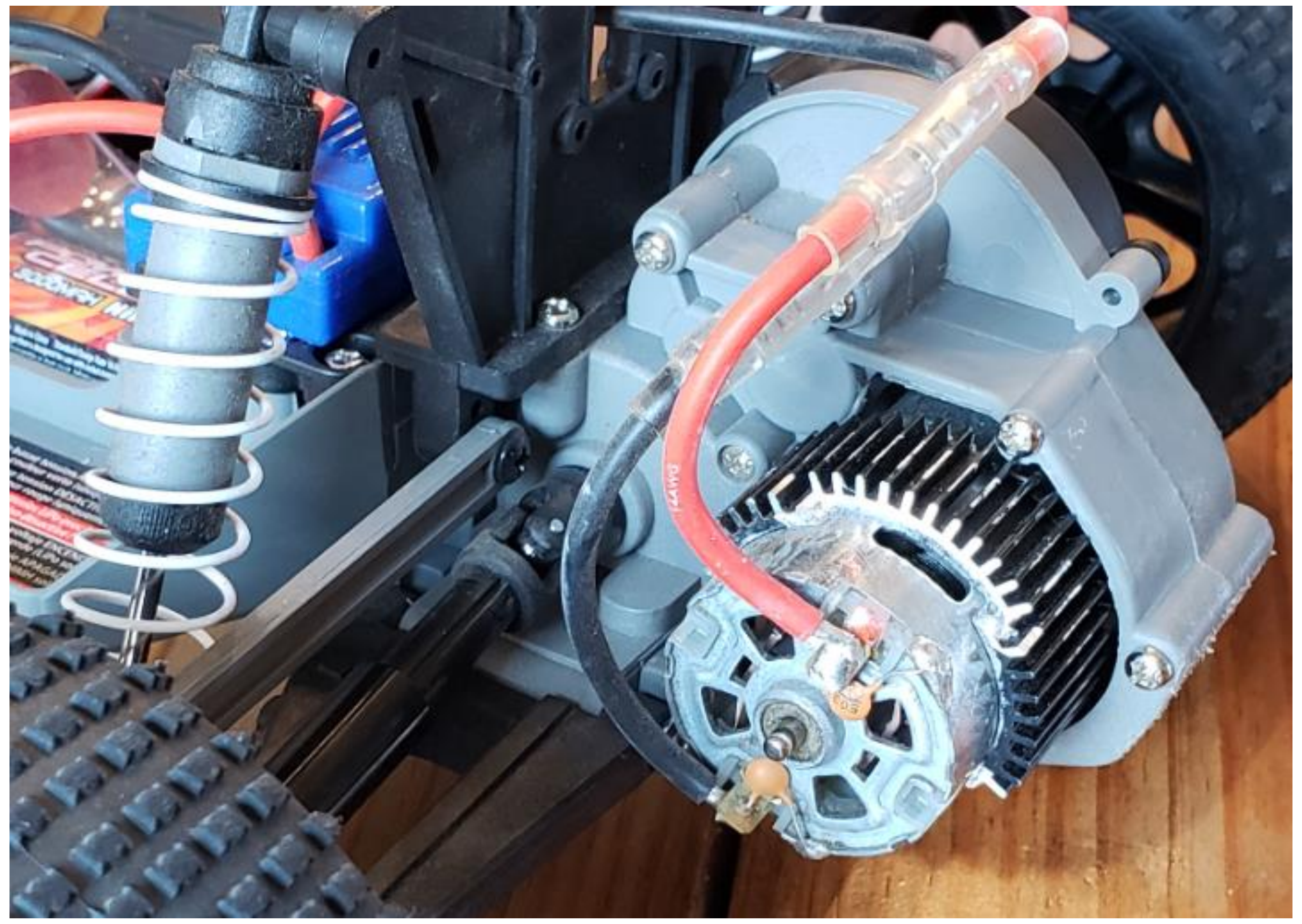
Component: Motor Gearbox Mount – RC Car

Load Cases:

- **Operating Shock:** 16g for 25ms, Half Sine
  - -1,000,000 Events
- **Severe Operating Shock:** 27g for 25ms, Half Sine
  - -10,000 Events
- **Max Survival Shock:** 35g for 25ms, Half Sine
  - -Less than 10 Events

-**Beyond Yield Demonstration**: 60g





RC Motor Mount Example Problem – Acetal Fatigue Life

- Motor Mount Material: Acetal
  - Max Stresses (fatigue):
    - 1,000,000 cycles: 32 MPa (4,641.2 psi)
    - 10,000 cycles: 46 MPa (6,671.7 psi)
  - Max Stress (single event):
    - Yield Strength: 9,500 psi
    - Elongation to Failure: 25%

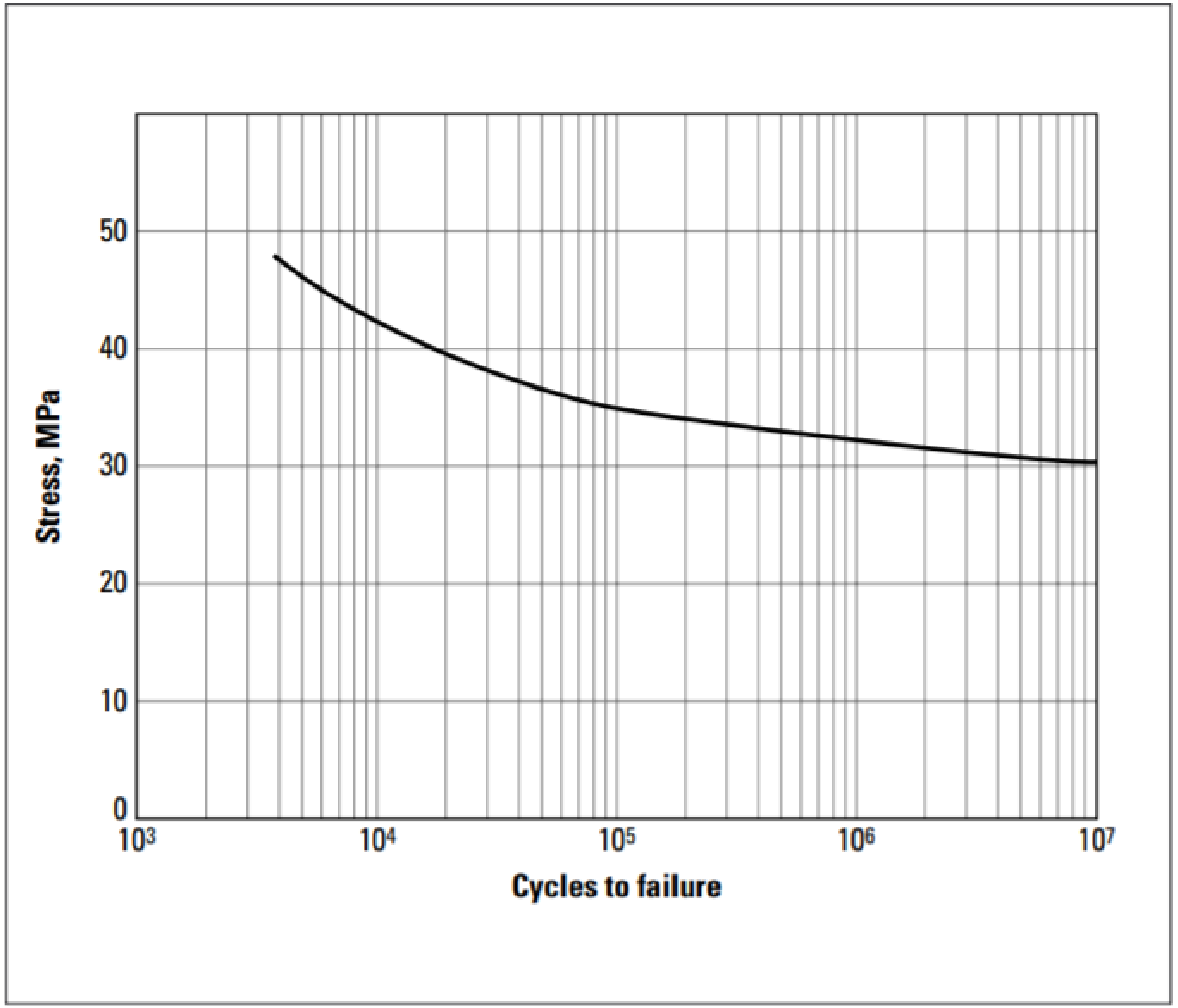


Figure 6.14 **Flexural fatigue of DELRIN® 100 (ASTM D671) at 23°C; 50% RH**

RC Motor Mount Example Problem – Simulation Setup

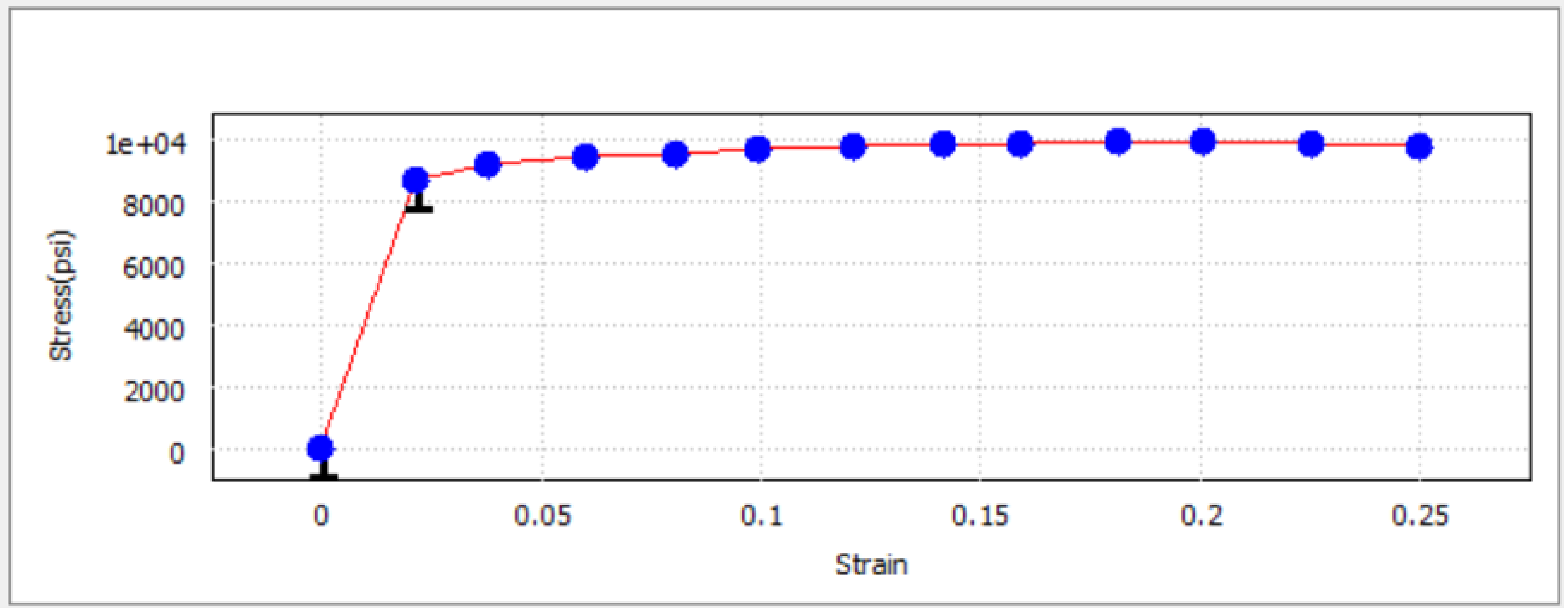
This simulation will be a non-linear static structural simulation setup as follows:

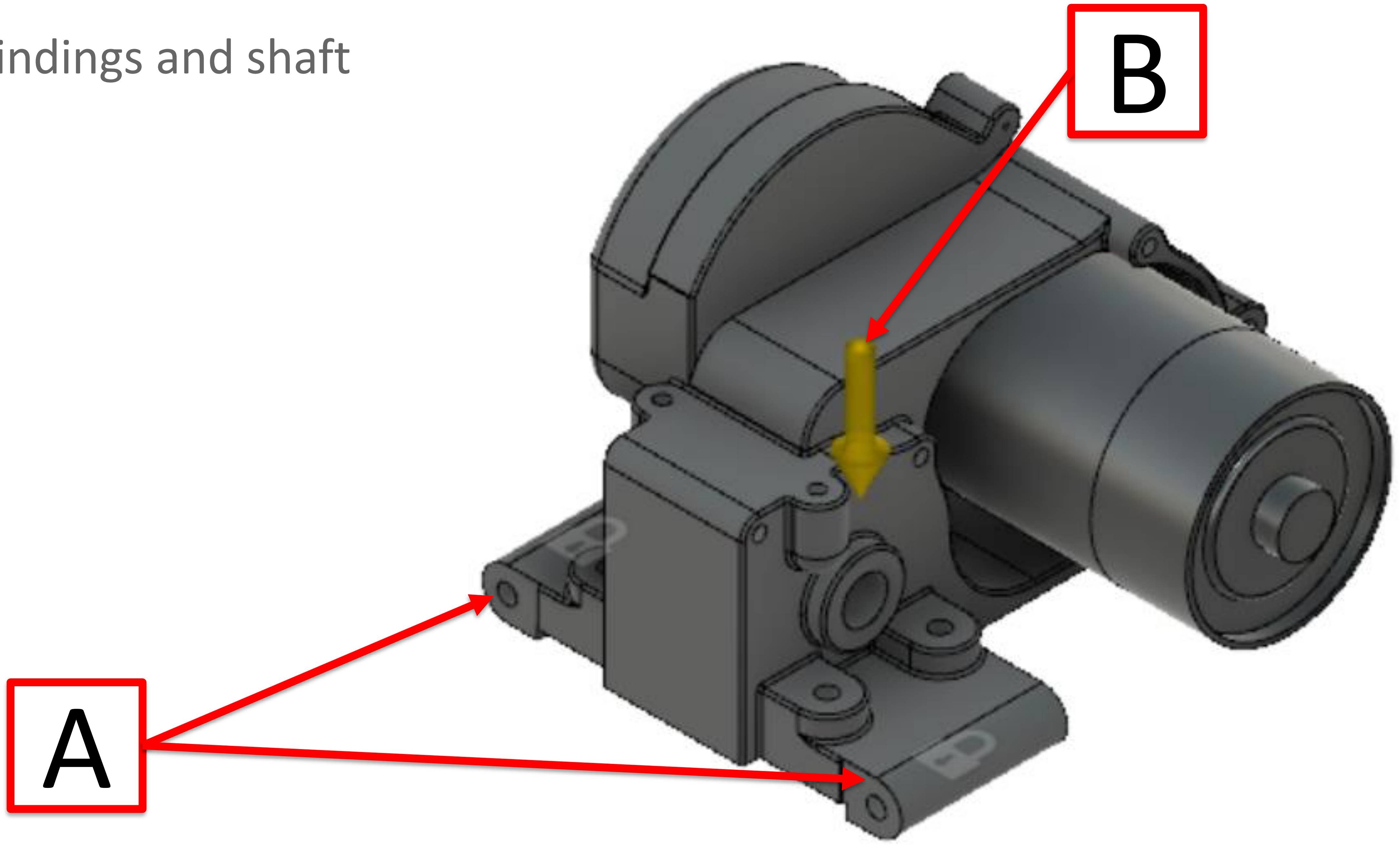
A. Fixed Constraint where the rear suspension linkage mounts

B. Linear Global Acceleration applied for the given shock value

C. Motor Housing – Steel with a Point Mass to represent windings and shaft

D. Motor Mount – Non-Linear acetal

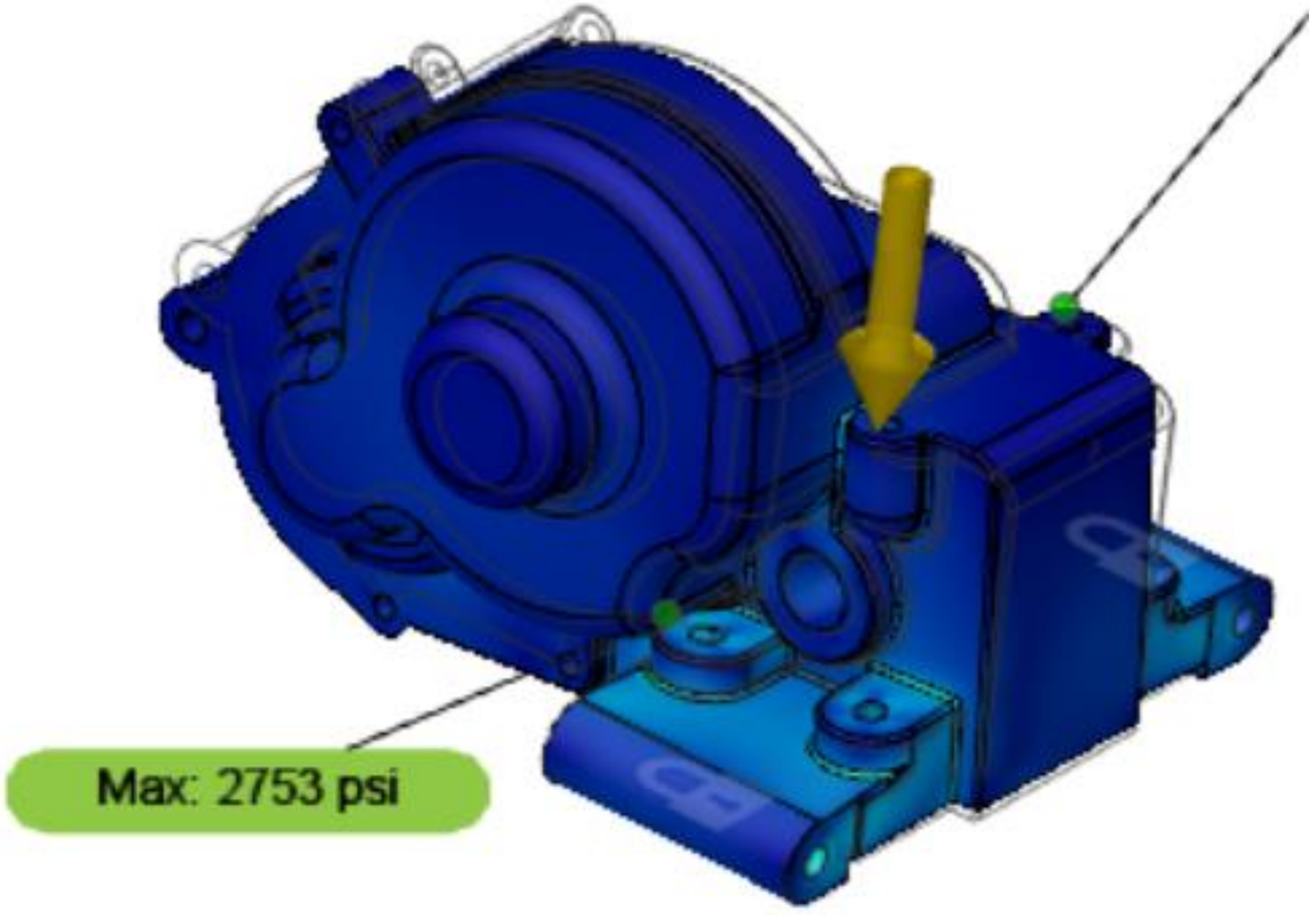




RC Motor Mount Example – Results, 16g

- Max Allowable Stress (1,000,000 cycles): 4,641 psi
- Max Simulation Stress: 2,753 psi
- Factor of Safety:

$$Factor\ of\ Safety = \frac{4{,}641\ psi}{2{,}753\ psi} = \mathbf{1.69}$$



RC Motor Mount Example – Remaining Factors of Safety

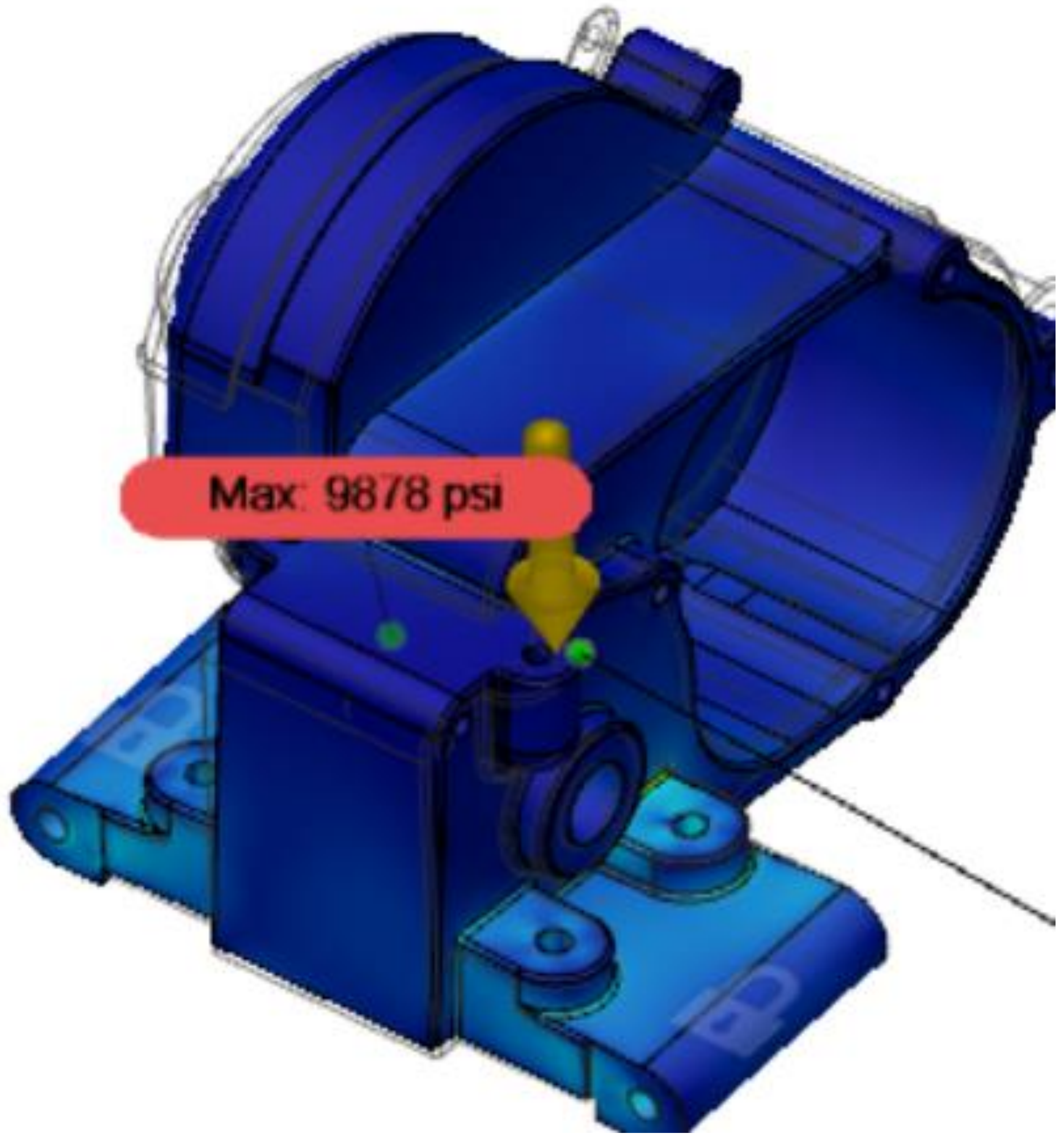
The remaining factors of safety are calculated the same way with each taking their respective maximum stresses as shown below:

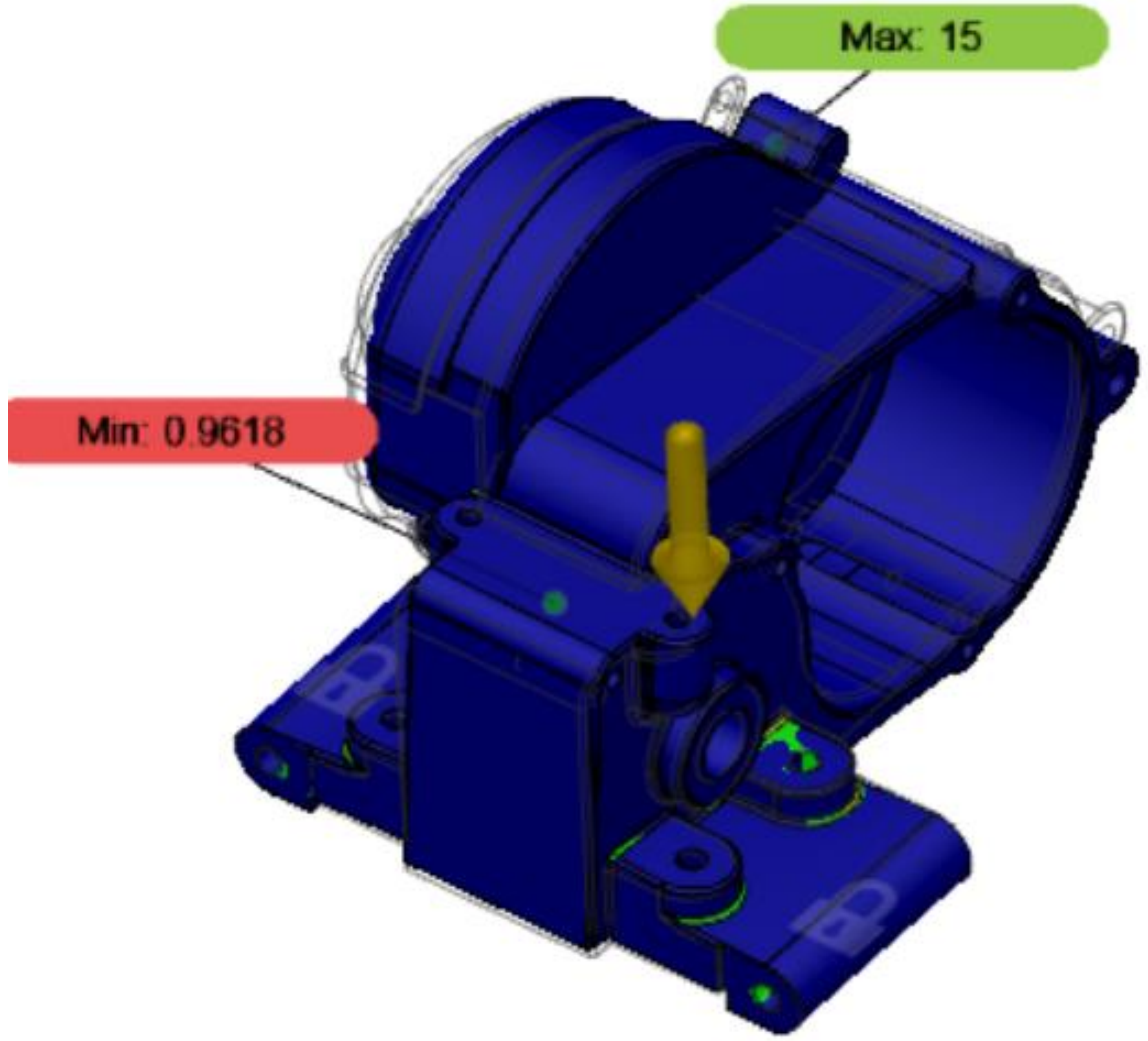
$$Factor\ of\ Safety, Severe\ Operating\ Shock = \frac{6{,}671\ psi}{4{,}534\ psi} = \mathbf{1.47}$$

$$Factor\ of\ Safety, Max\ Survival\ Shock = \frac{9{,}500\ psi}{5{,}829\ psi} = \mathbf{1.63}$$

RC Motor Mount Example – Beyond Yield Strength

Our final test load case was a 60g event, which is done purely as an example of demonstrating how we can look at results beyond yield strength of a material. The results below detail that we have a factor of safety below 1 – so what will happen?



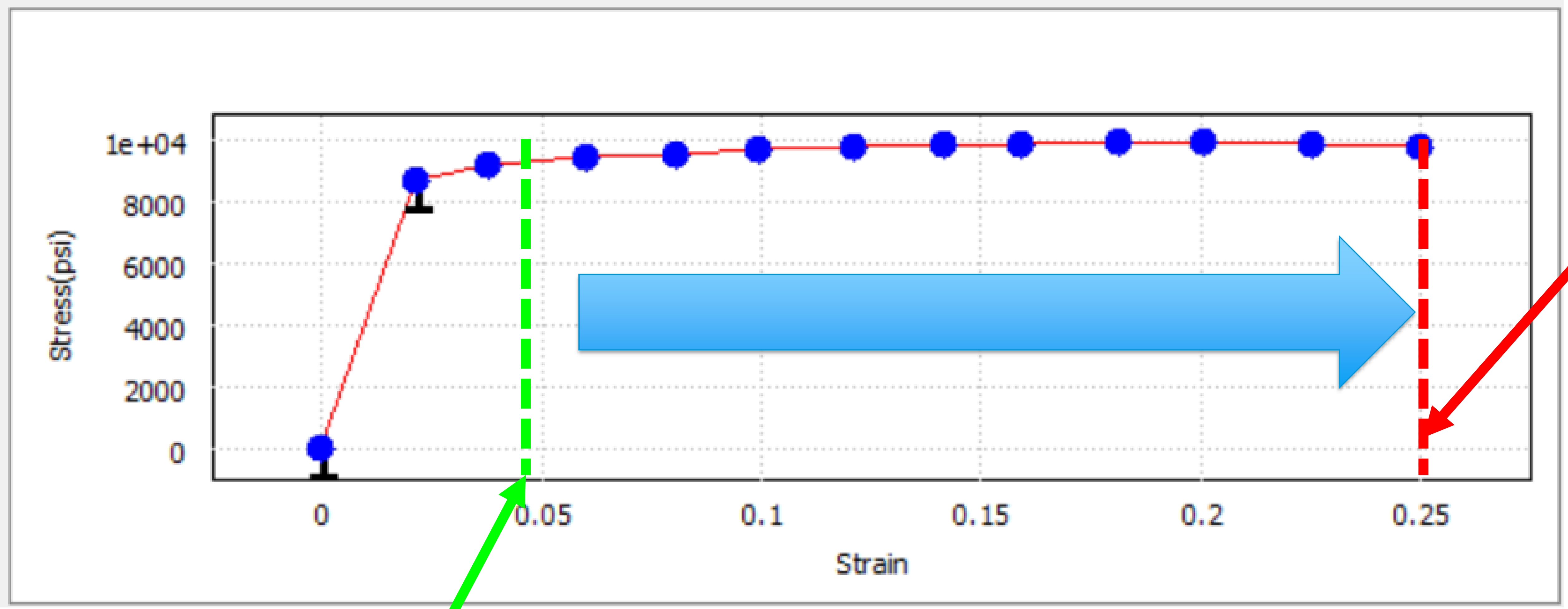


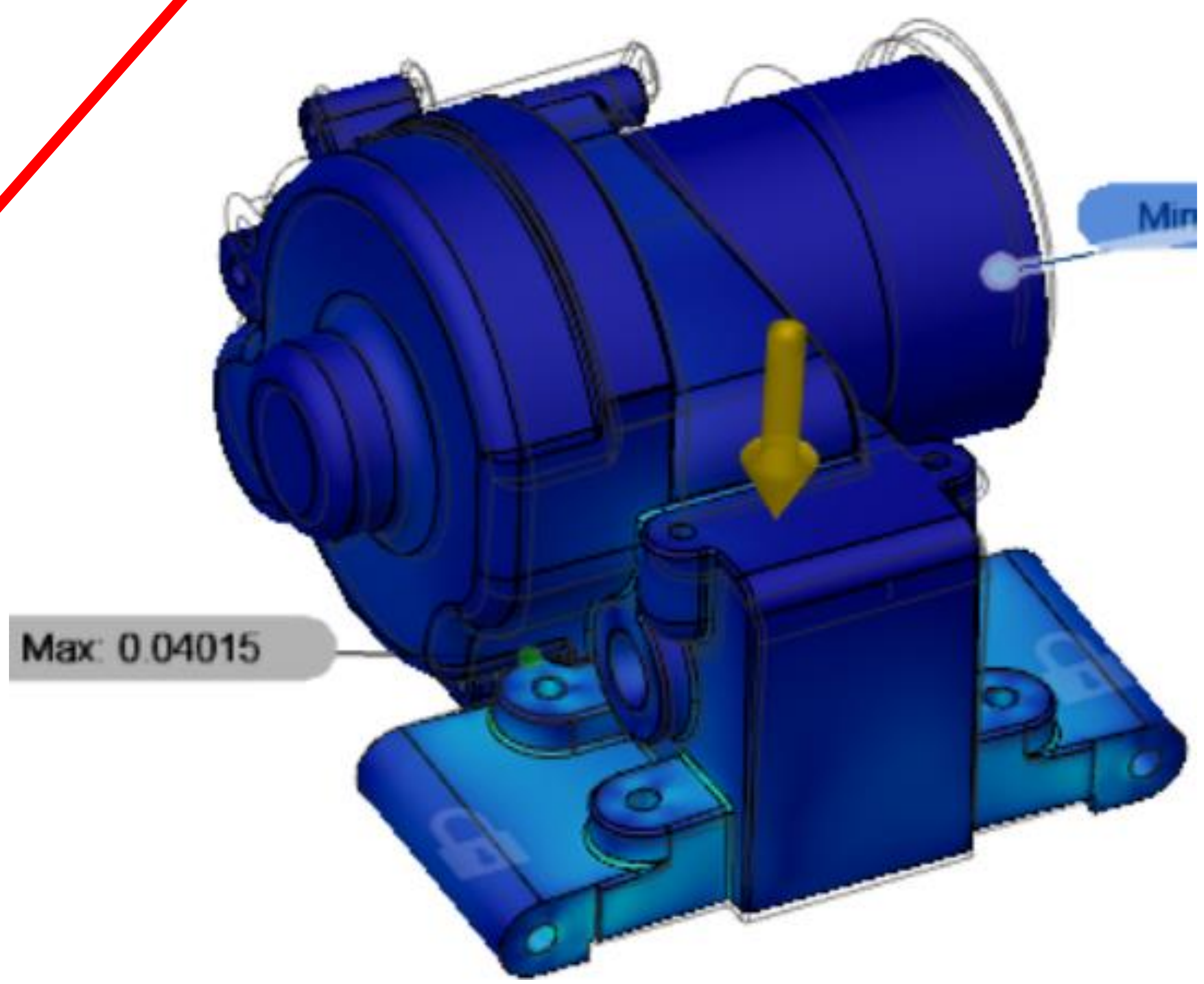
Strain must be reviewed when the yield strength of a material has been exceeded to draw meaningful conclusions.

RC Motor Mount Example – Strain, 60g

If we look at the strain with respect to the stress-strain curve and max elongation, we see a better picture:

Elongation to Failure



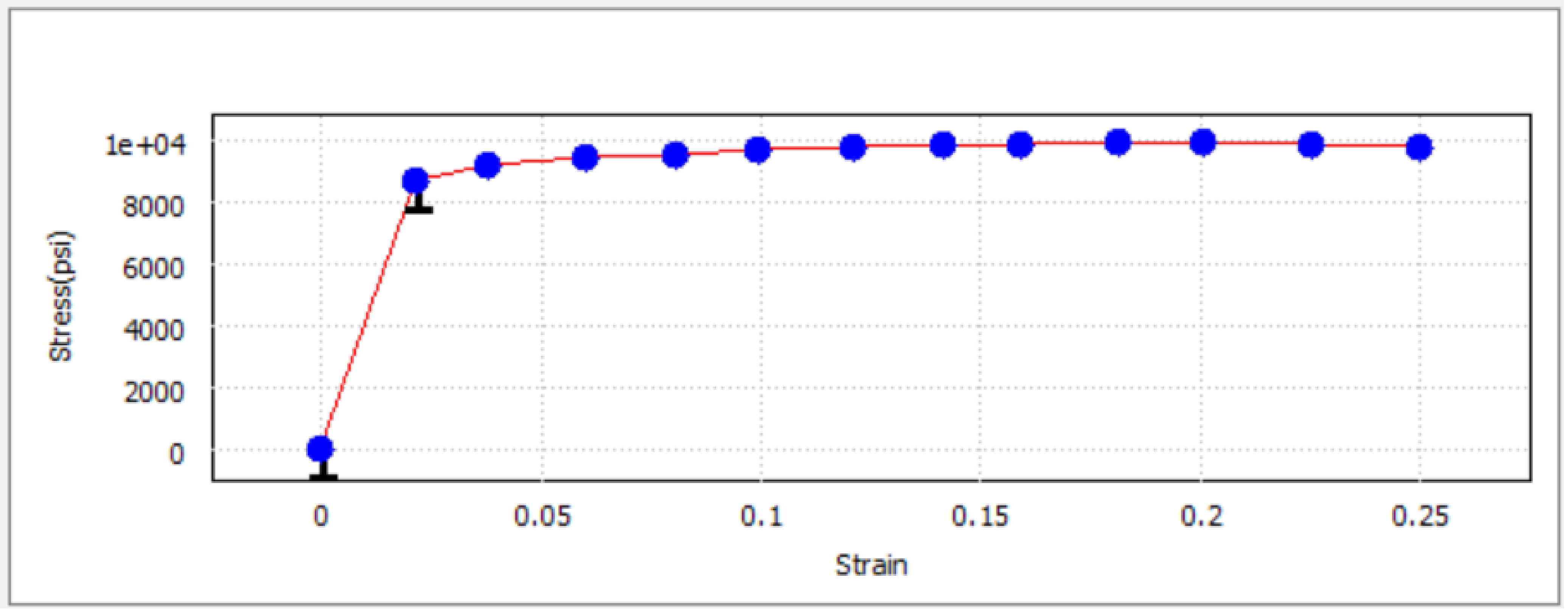


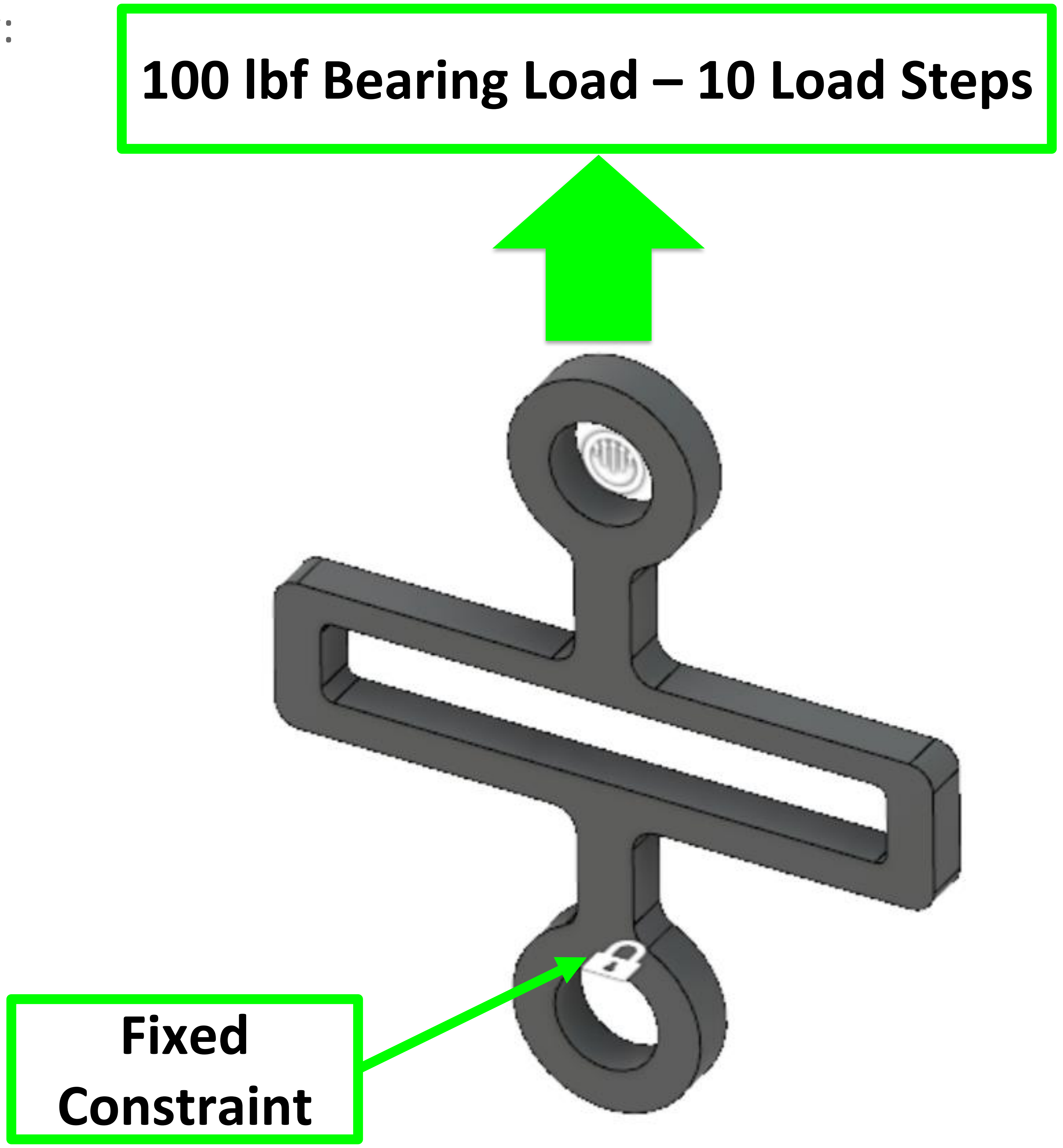
Localized yielding will occur, but we still have a long way to go for major damage. Cracks may form with low cycles.

Acetal Lifting Ring – Real World Correlation, Setup

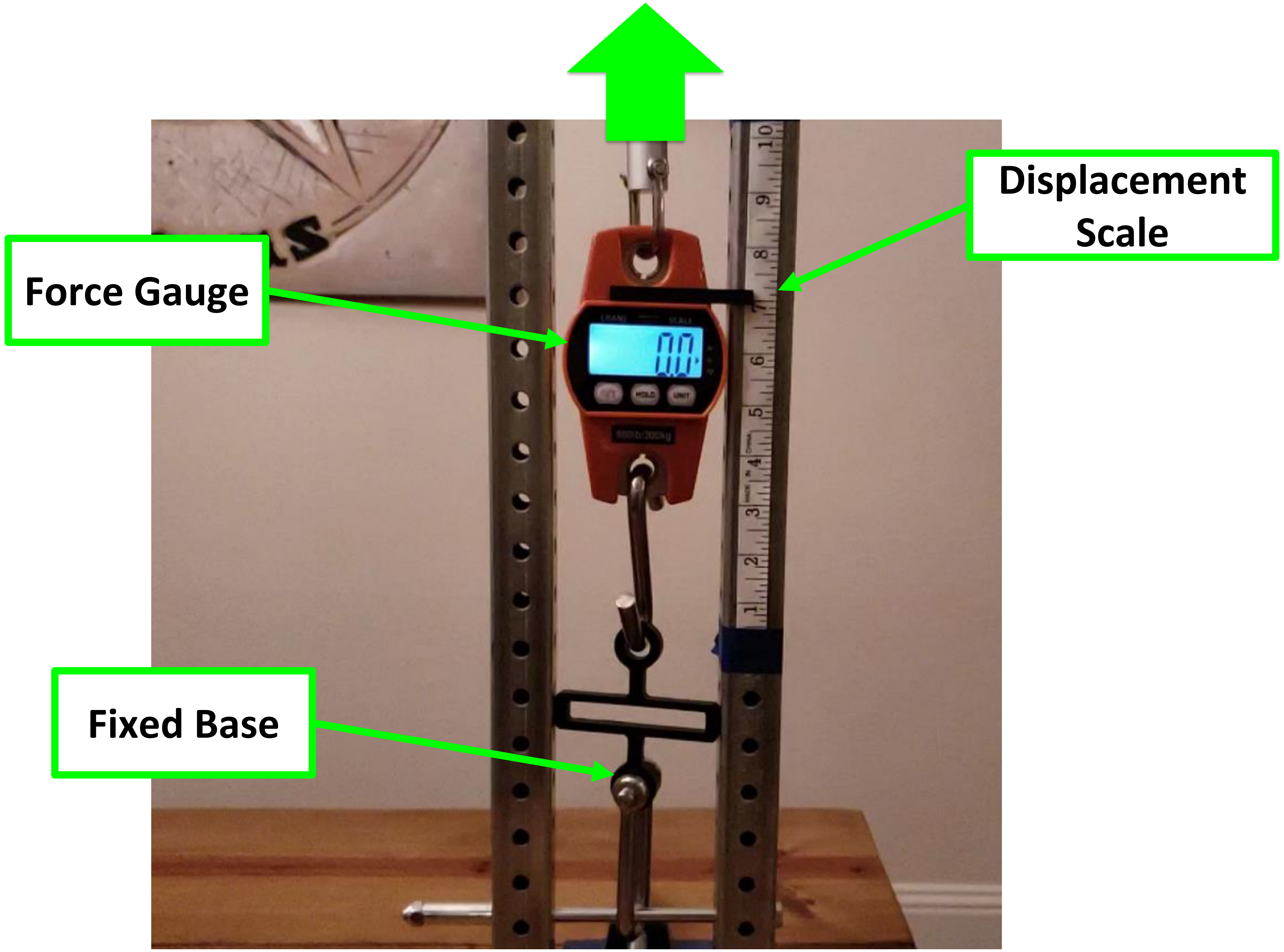
This example looks at an acetal lifting ring in direct tension as shown below:

Material – Acetal (same as prior example)



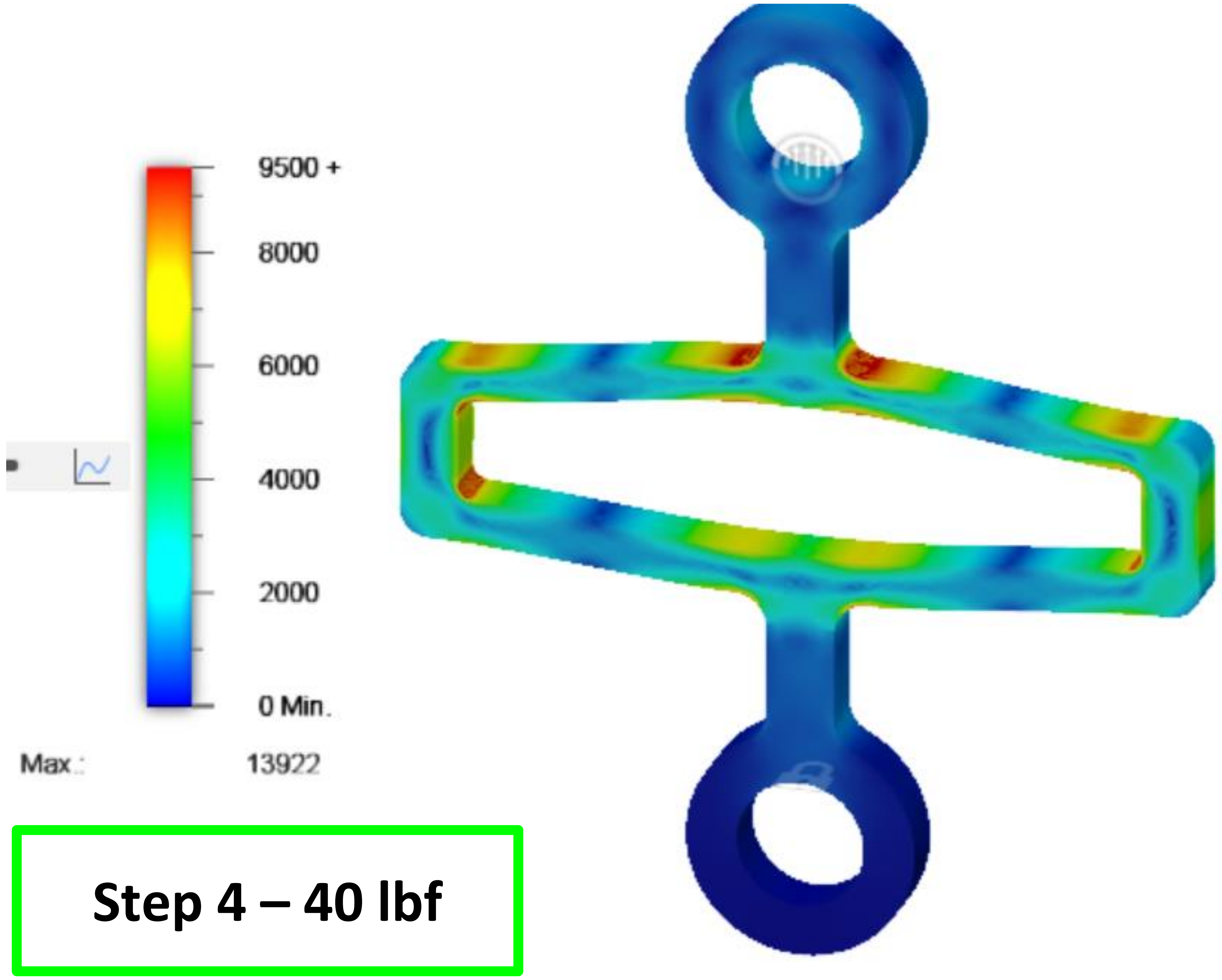


Acetal Lifting Ring - Real World Correlation, Test Setup

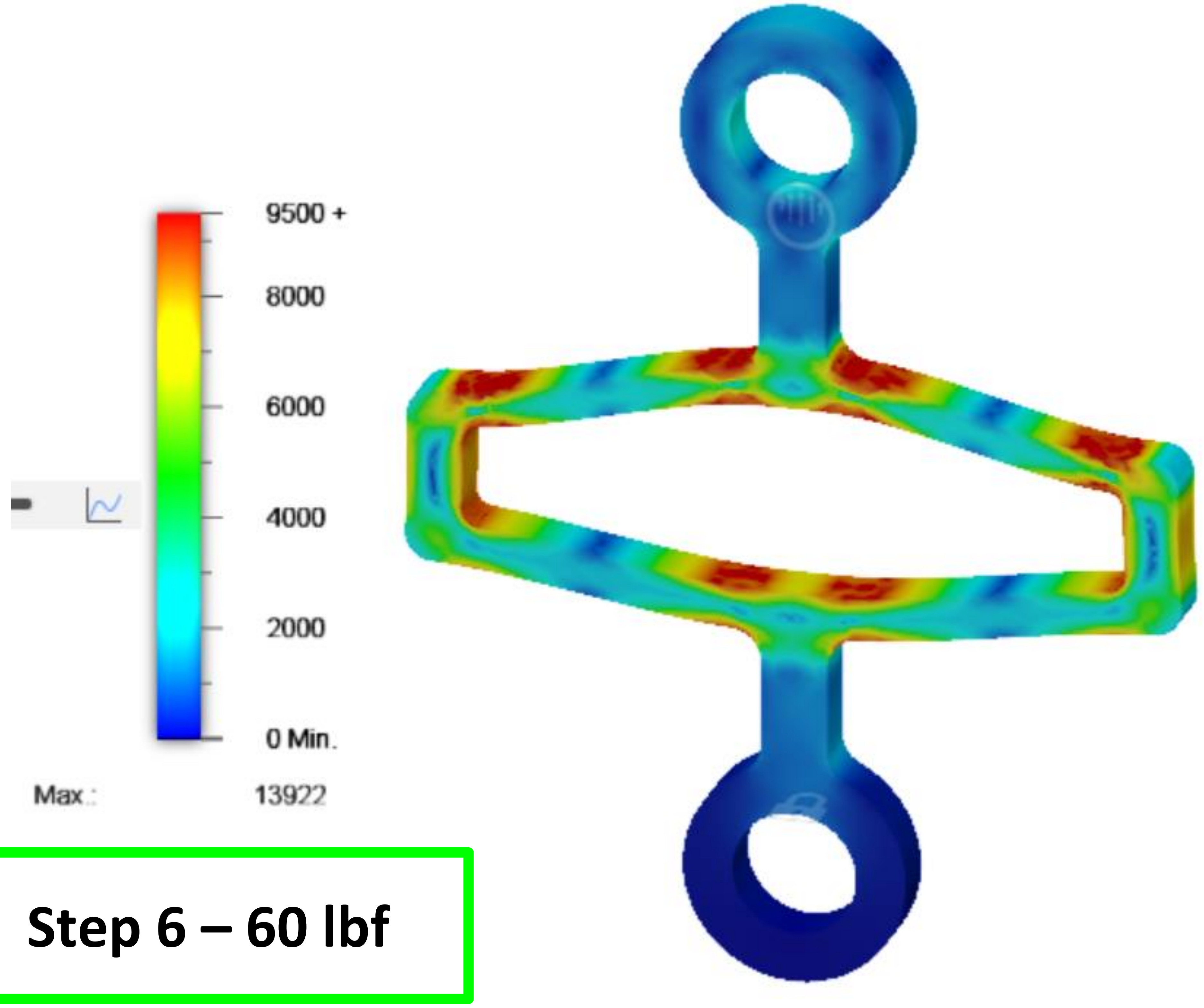


Acetal Lifting Ring - Real World Correlation, Stress Results

Yielding begins between load steps 3 and 4 which is equal to 30 and 40 lbs respectively. By load step 6 (60 lbf) we see substantial yielding. So will we fail at 60 lbf?



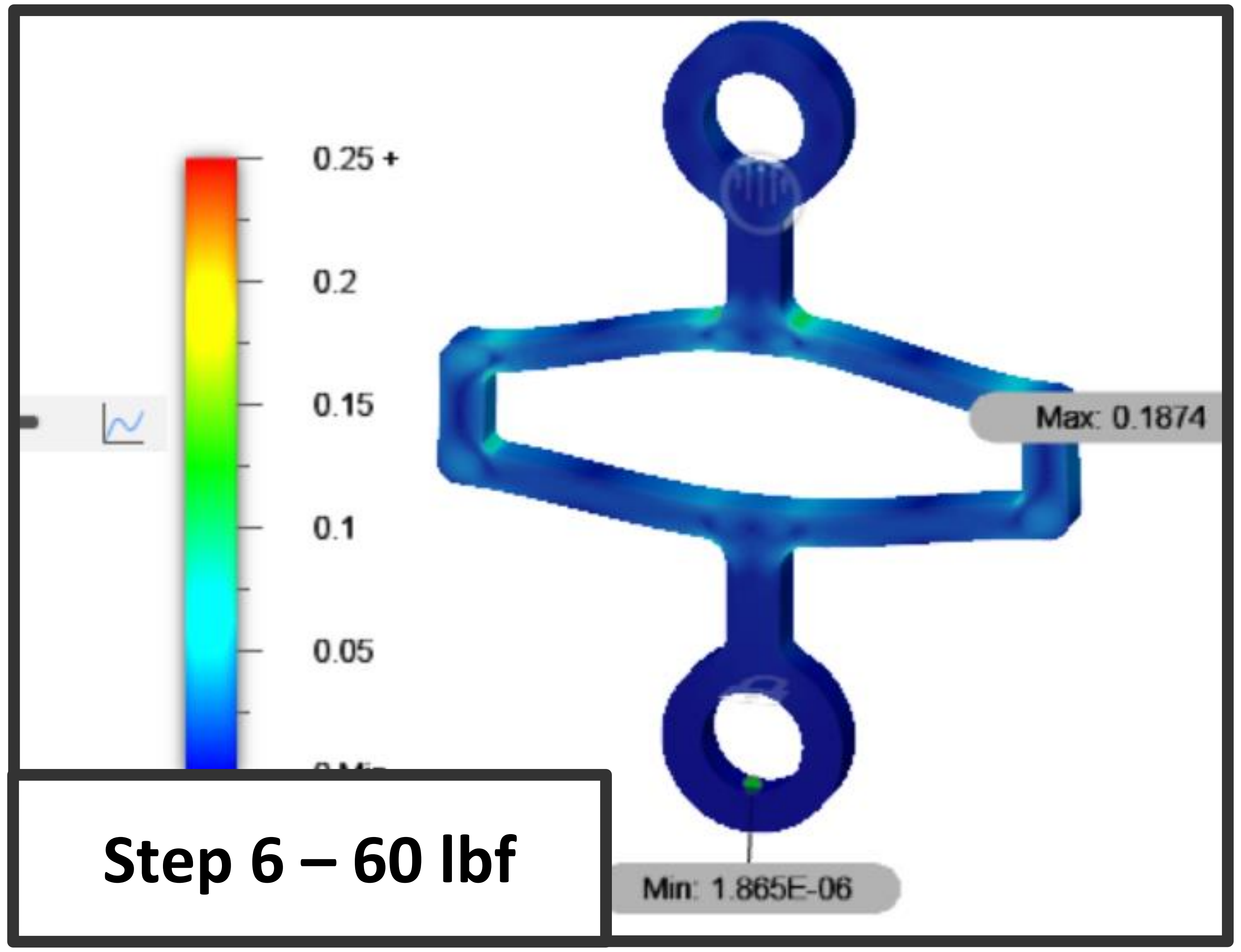
Step 4 – 40 lbf



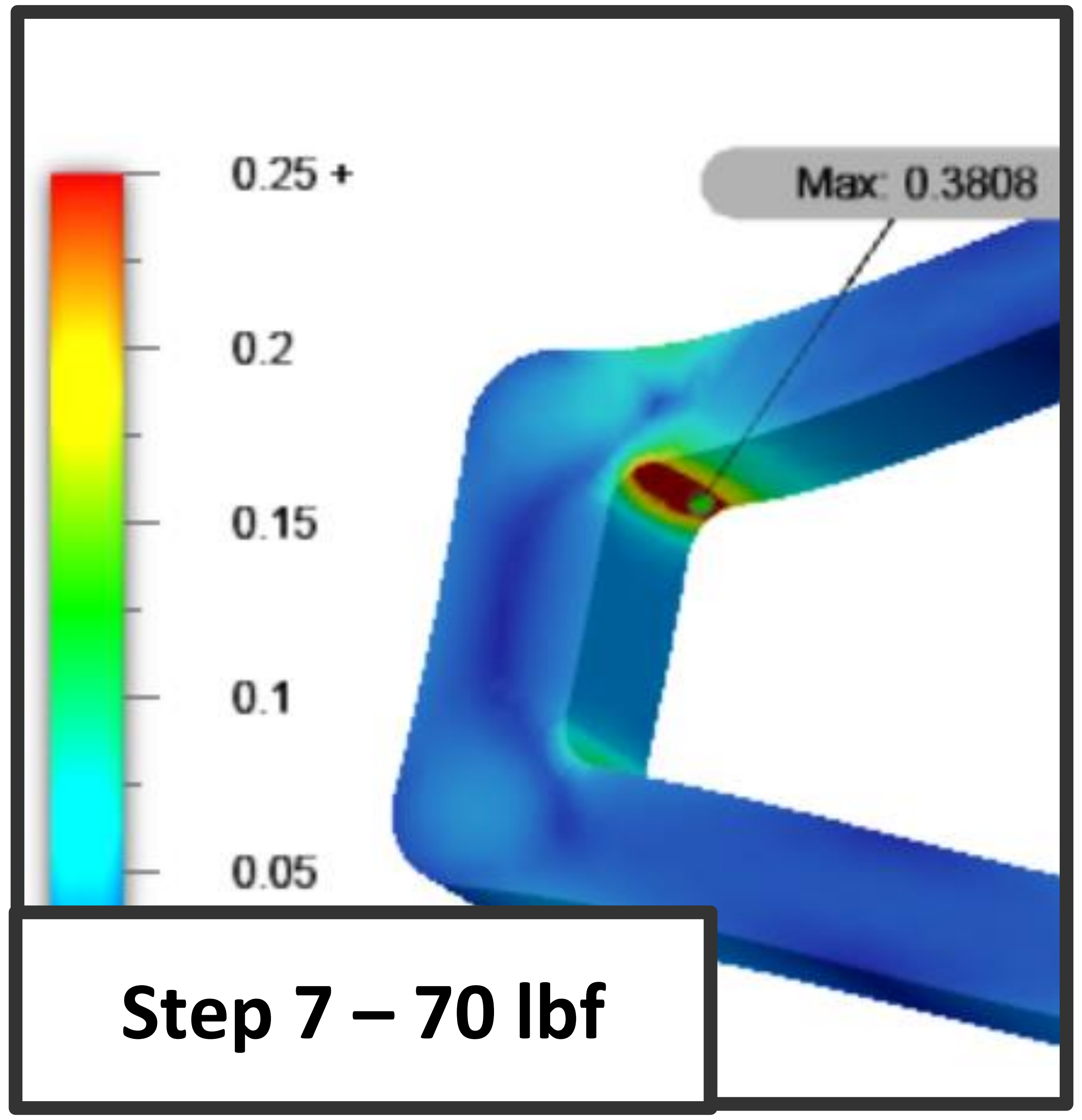
Step 6 – 60 lbf

Acetal Lifting Ring - Real World Correlation, Strain Results

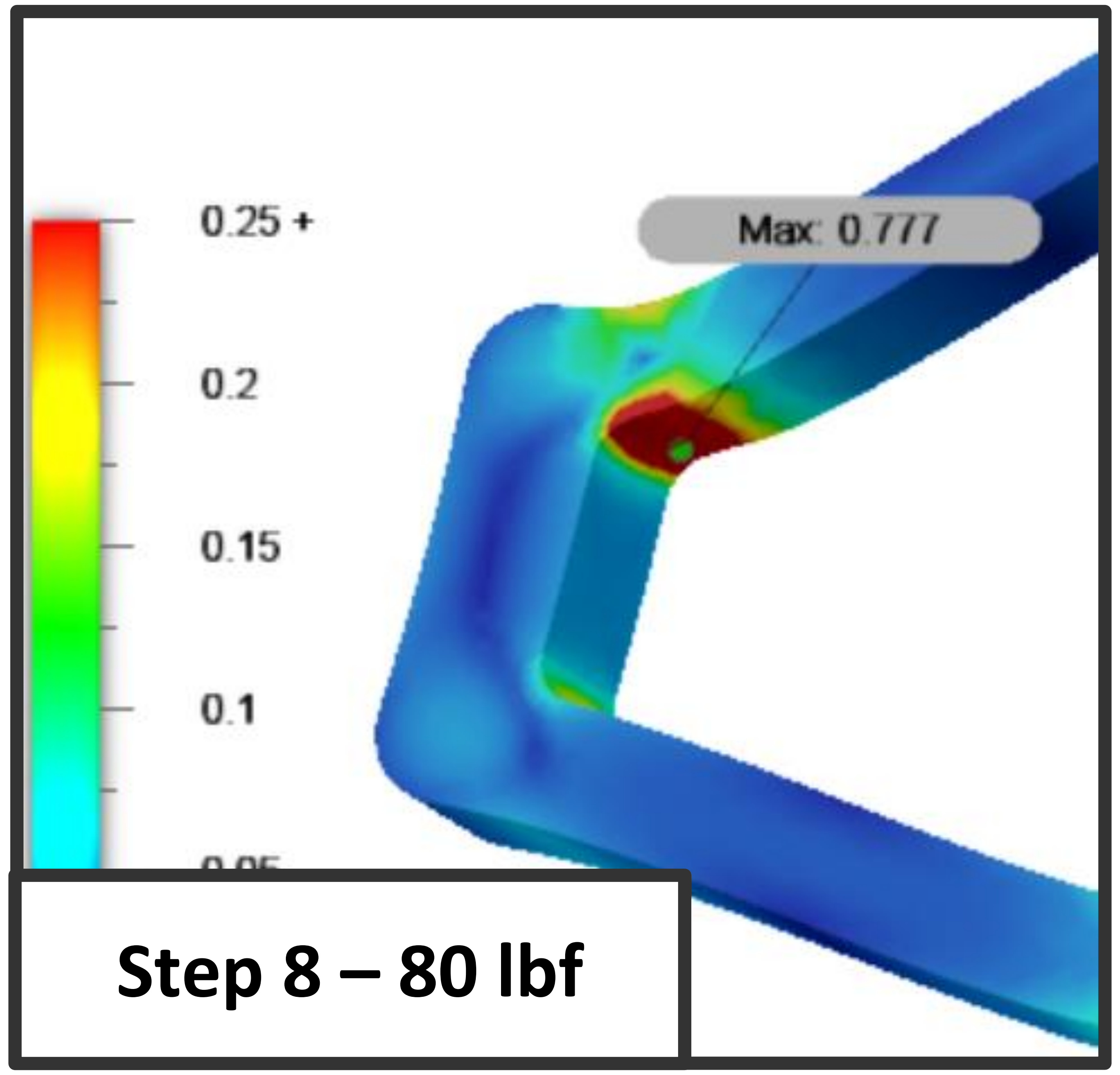
We need strain results to answer the question of whether we will see a crack form immediately (creep is being ignored in this case):



Step 6 – 60 lbf



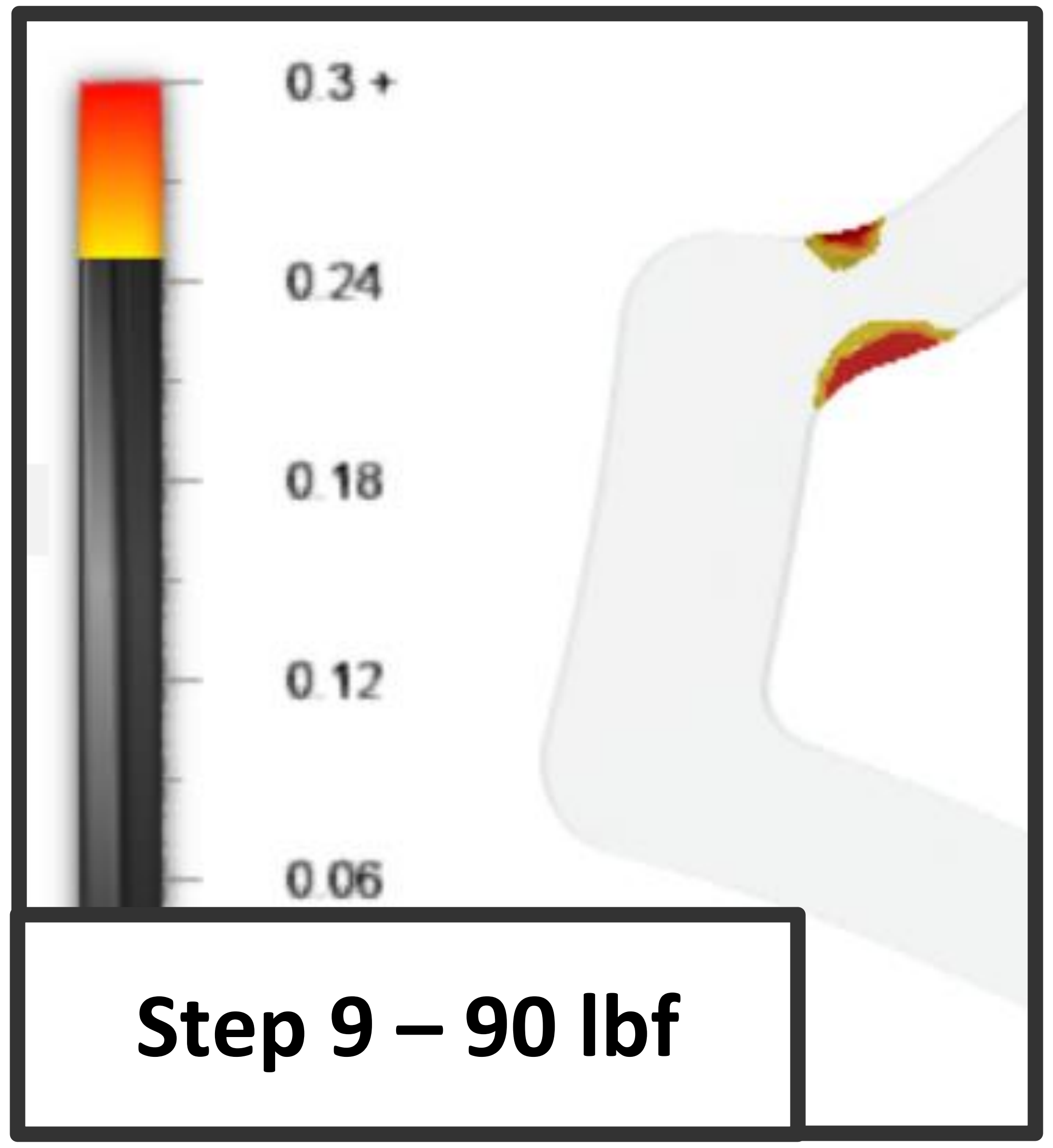
Step 7 – 70 lbf



Step 8 – 80 lbf

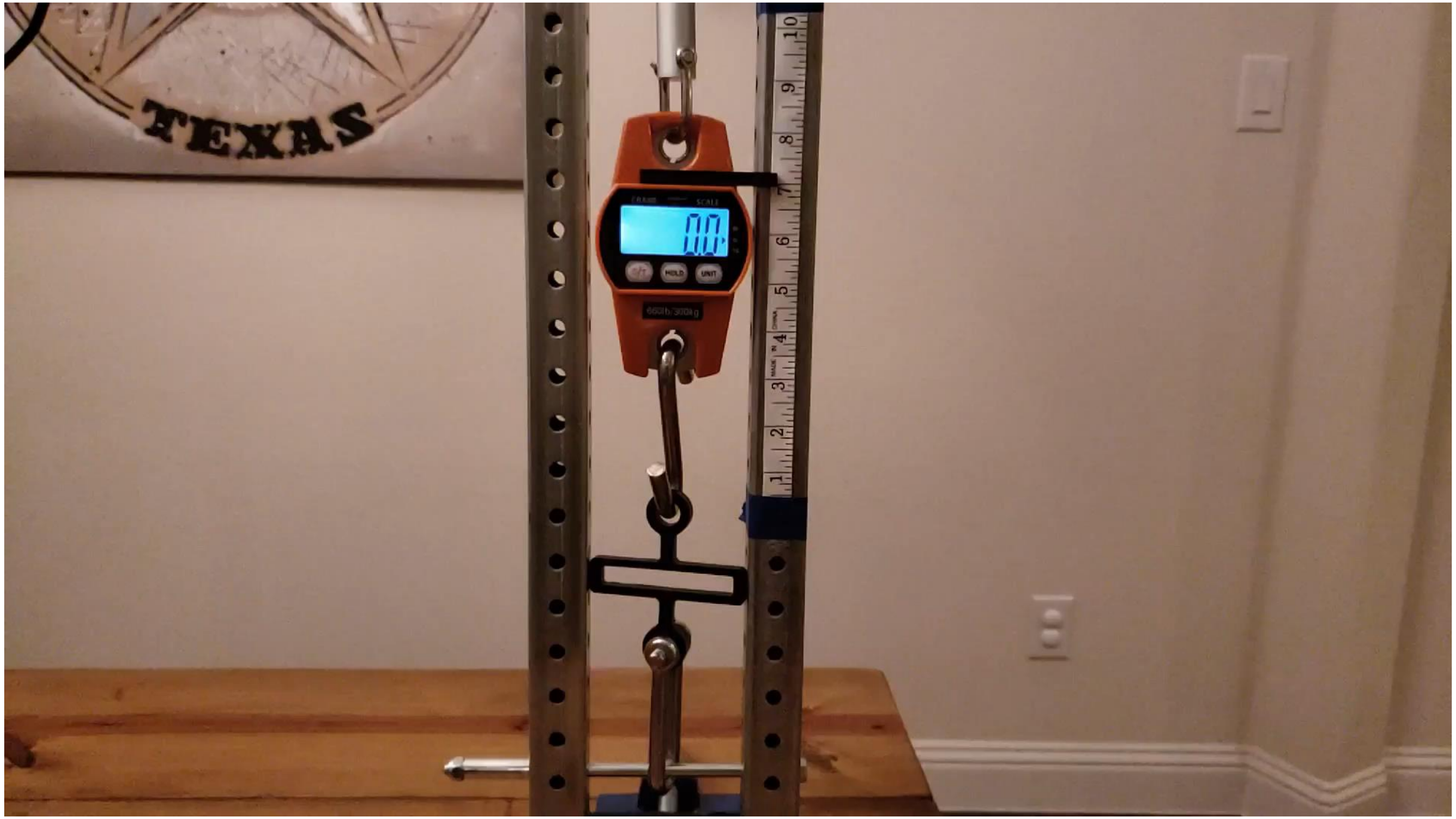
Acetal Lifting Ring - Real World Correlation, Strain Results

It helps to hide elements below our strain to failure to get a better picture of how deep the simulation tells us these strain levels penetrate.



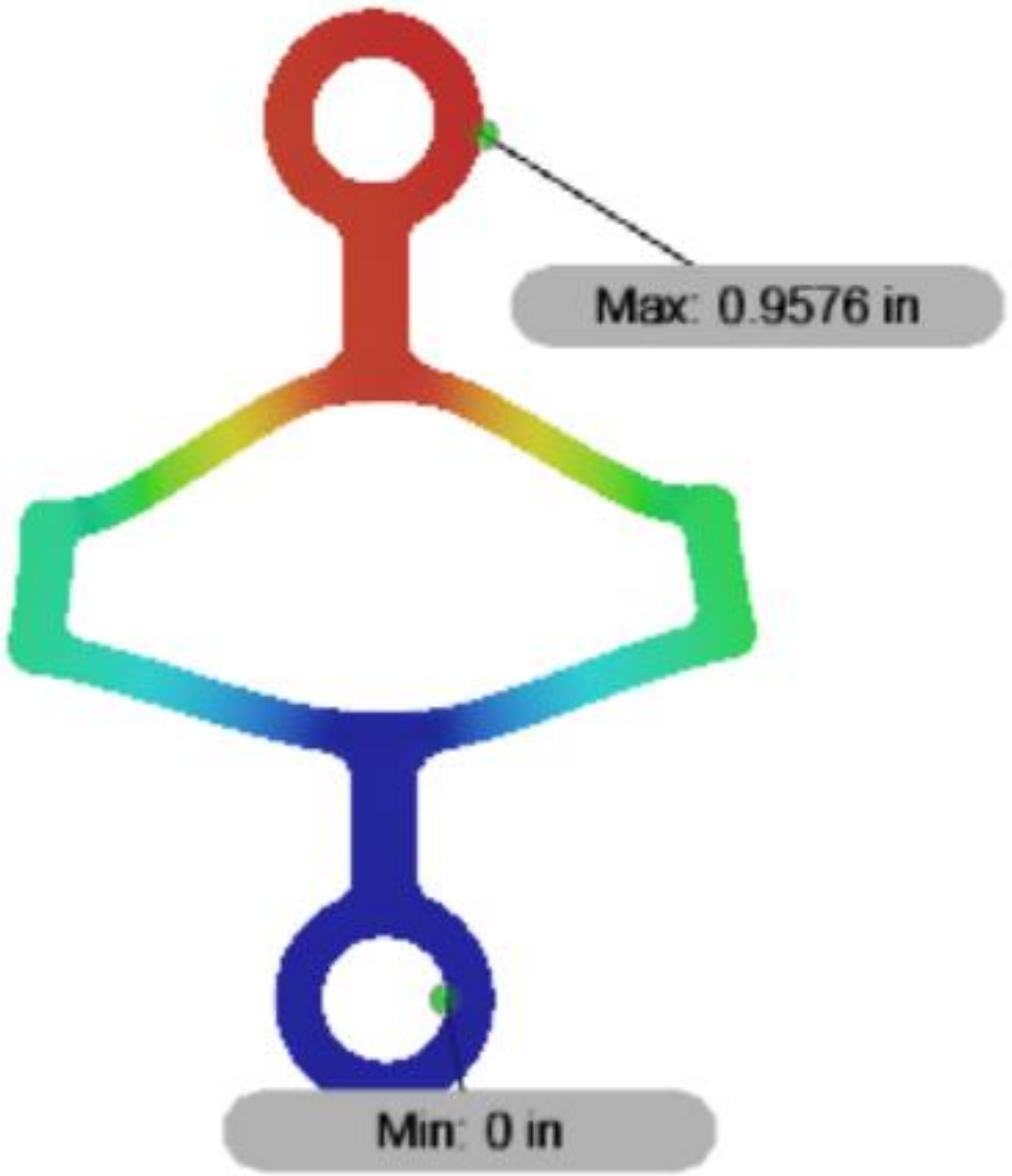
Failure could occur as early as 70 lbf, but certainly before 90 lbf

Acetal Lifting Ring - Real World Correlation, Failure **Video**



Acetal Lifting Ring - Real World Correlation, Displacement

If we review displacement, we see that the simulation did a good job of tracking this as well. The images below are at 80 lbf:

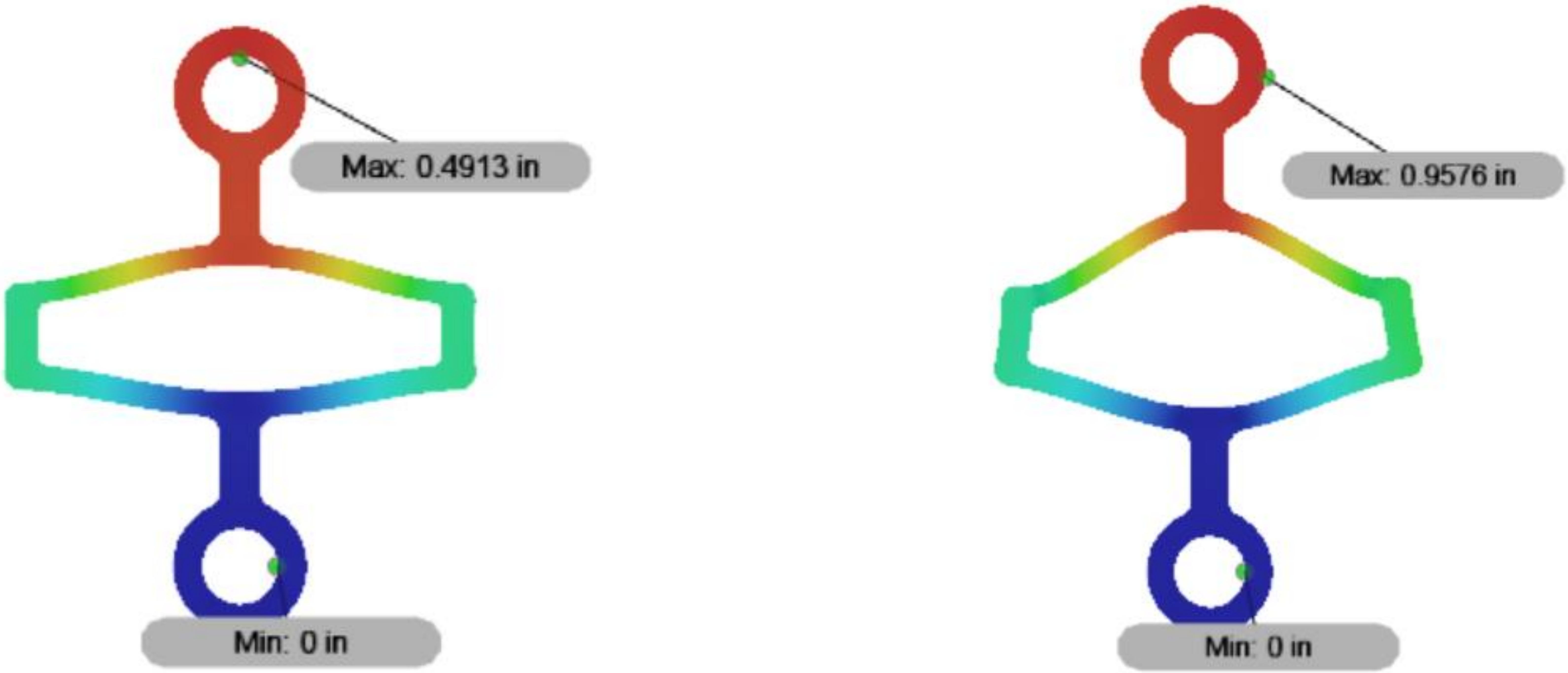


Approx. End Point (~1" of displacement)

Approx. Start Point

Acetal Lifting Ring - Real World Correlation, Displacement (Linear vs Non-Linear)

If we look at the side by side displacement between a linear simulation (left) and non-linear simulation (right), we can see that the linear simulation was pretty far from the correct displacement value at 80 lbf. This is due to large displacements and material exceeding yield strength.



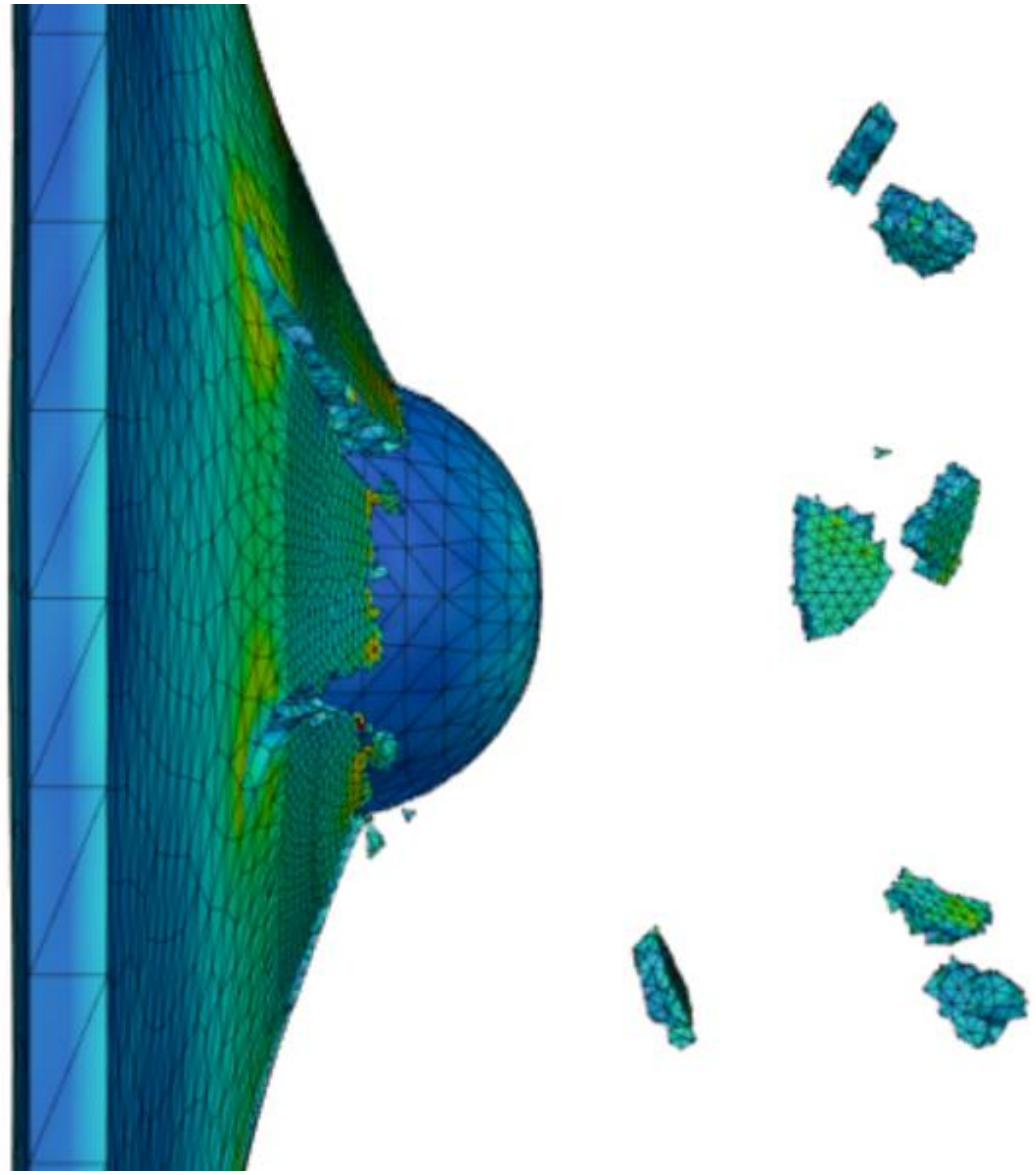
Predicting Catastrophic Failure and Large Scale Yielding – Event Simulations

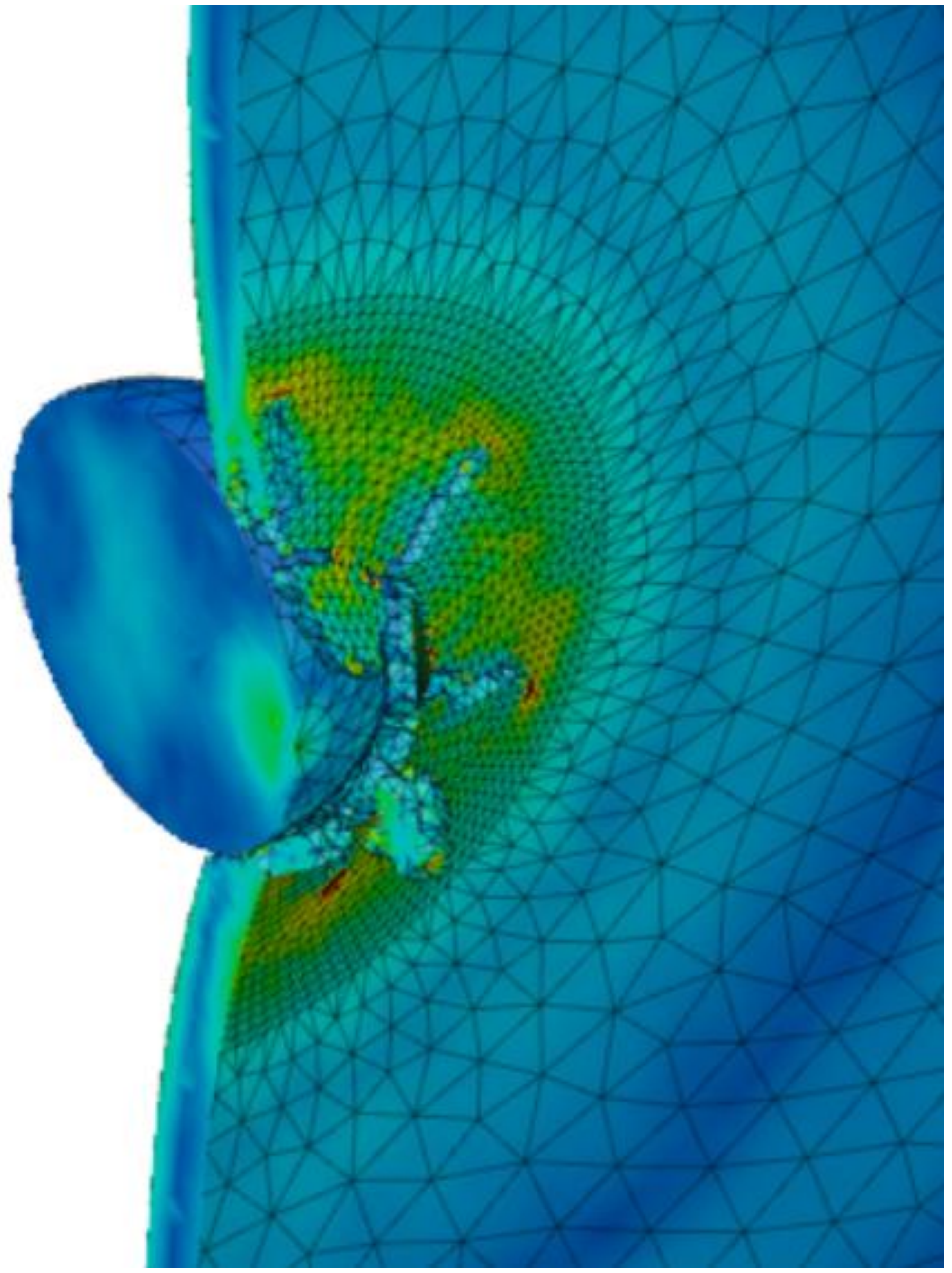
Overview

This section is dedicated to event simulations where we will cover simulation results and compare them to some real world tests. We will specifically review:

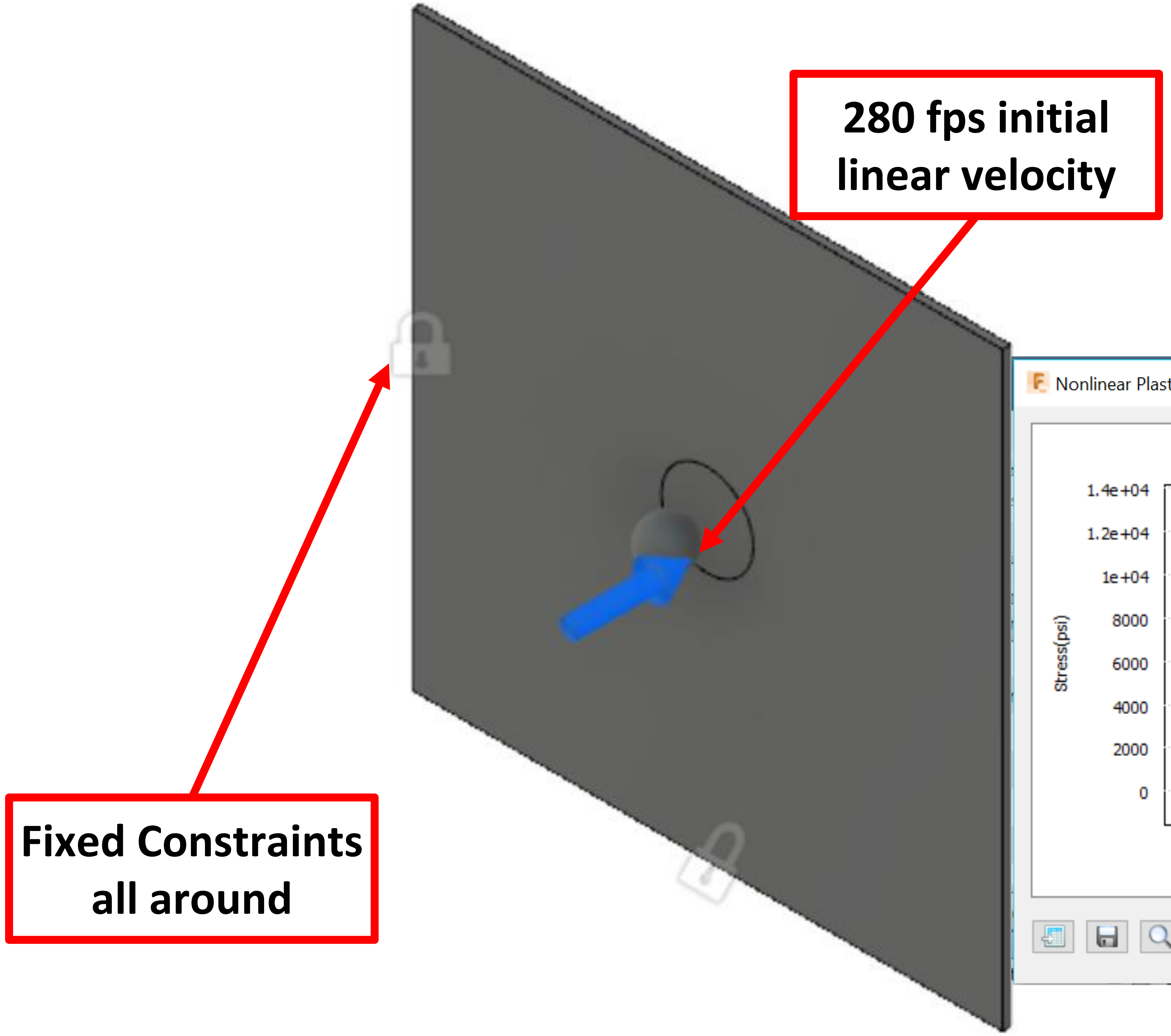
- Understanding event simulation results
- Methods of predicting catastrophic failure through element deletion
- Determining if yielding has occurred (this can be a grey area in some cases)
- Challenges with Factor of Safety Calculations

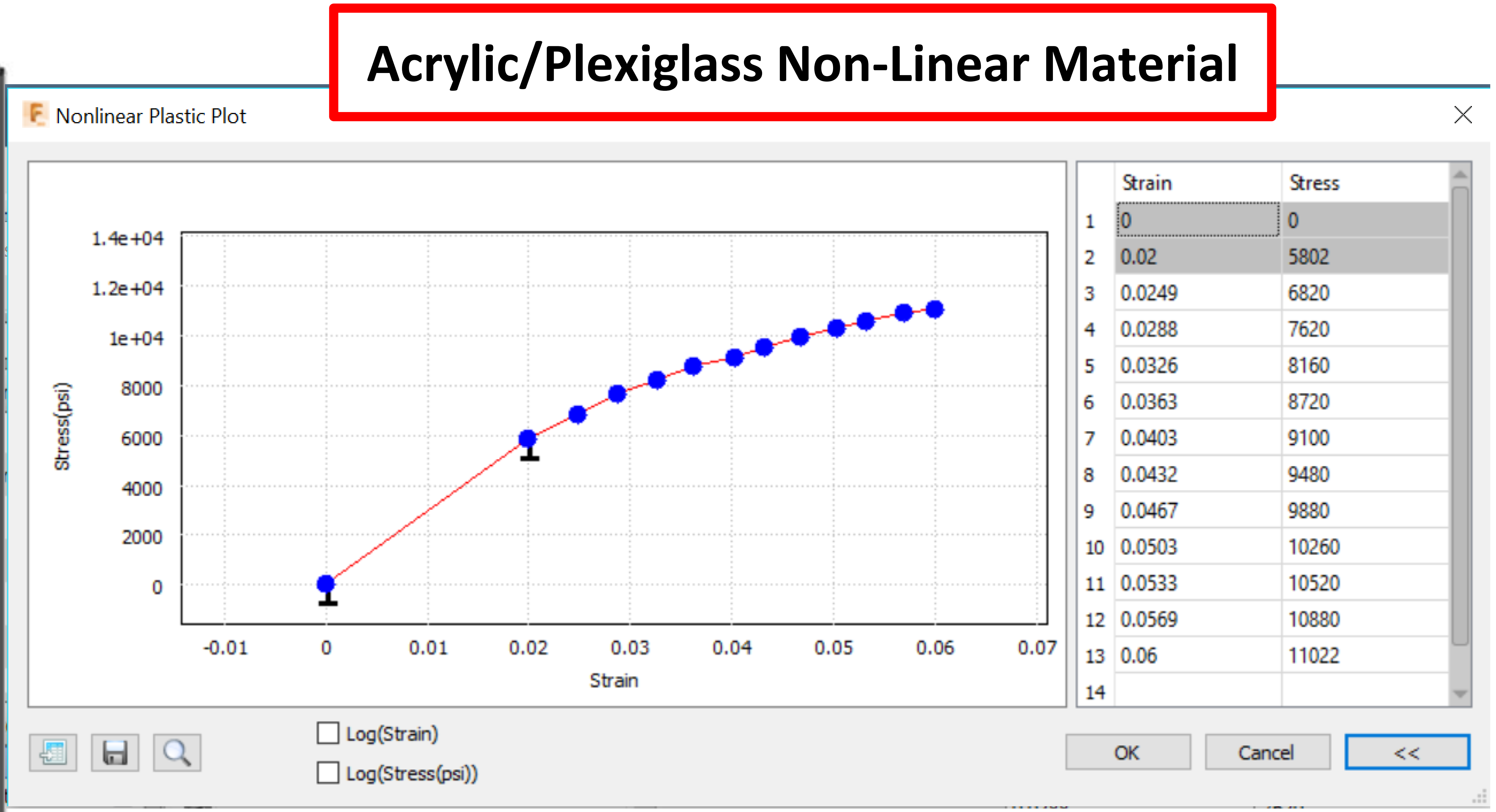
Plastic Paintball Impact Simulation - Acrylic





Plastic Paintball Example – Acrylic, Simulation Overview

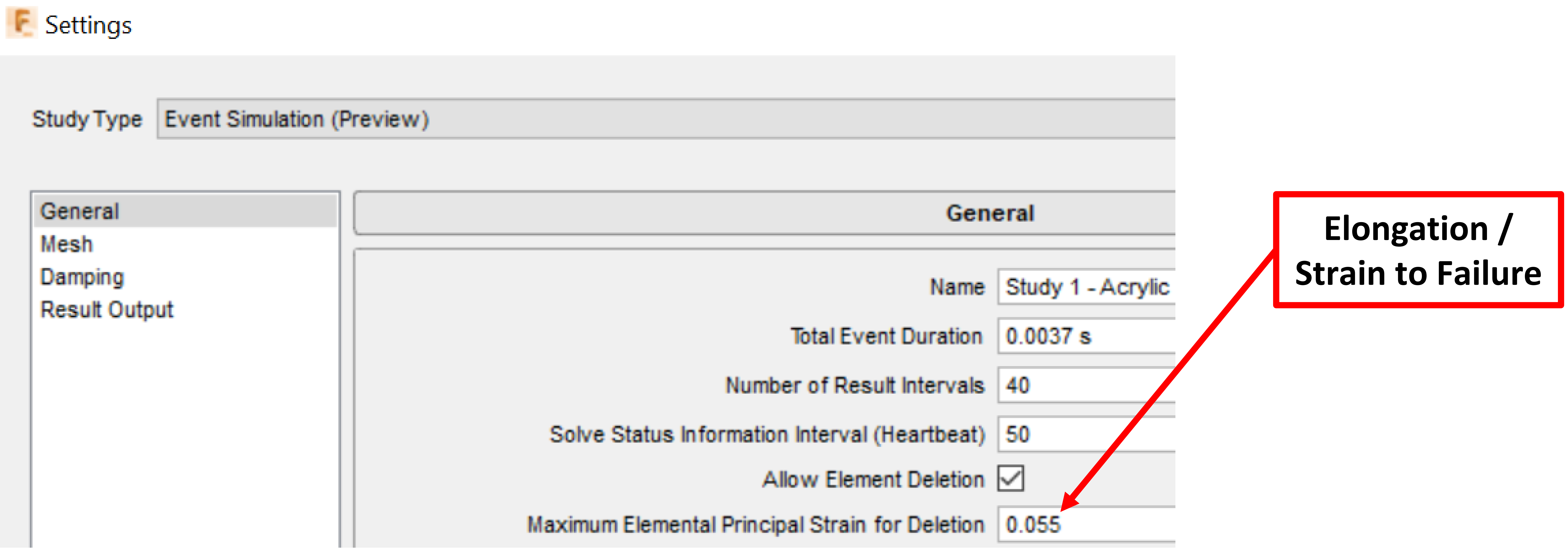




	Strain	Stress
1	0	0
2	0.02	5802
3	0.0249	6820
4	0.0288	7620
5	0.0326	8160
6	0.0363	8720
7	0.0403	9100
8	0.0432	9480
9	0.0467	9880
10	0.0503	10260
11	0.0533	10520
12	0.0569	10880
13	0.06	11022
14		

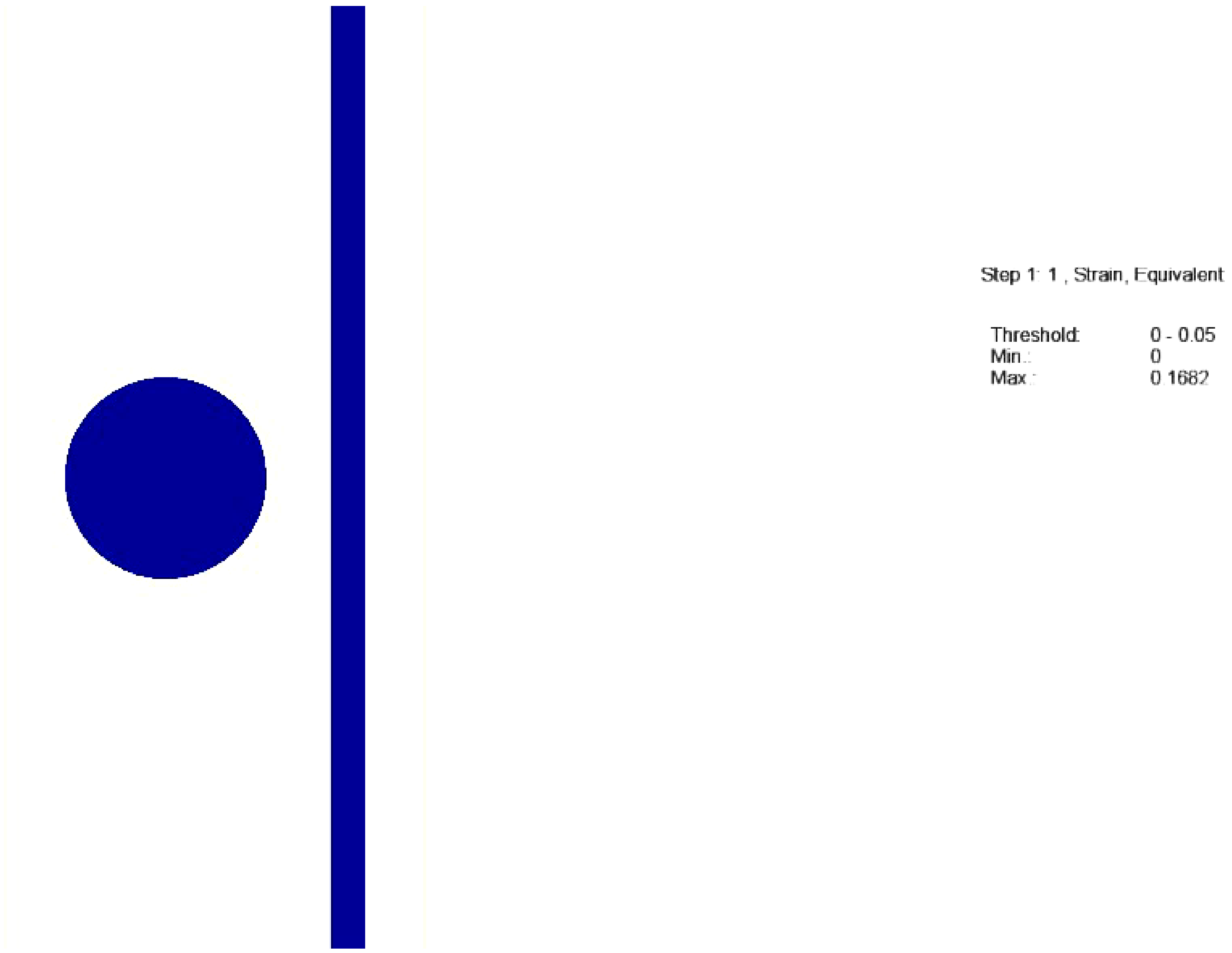
Plastic Paintball Example – Acrylic, Element Deletion

Element deletion can be useful to predict when a part will being to fail based on known stress-strain responses. In this case, I have set my element deletion to the elongation to failure of acrylic (plexiglass).

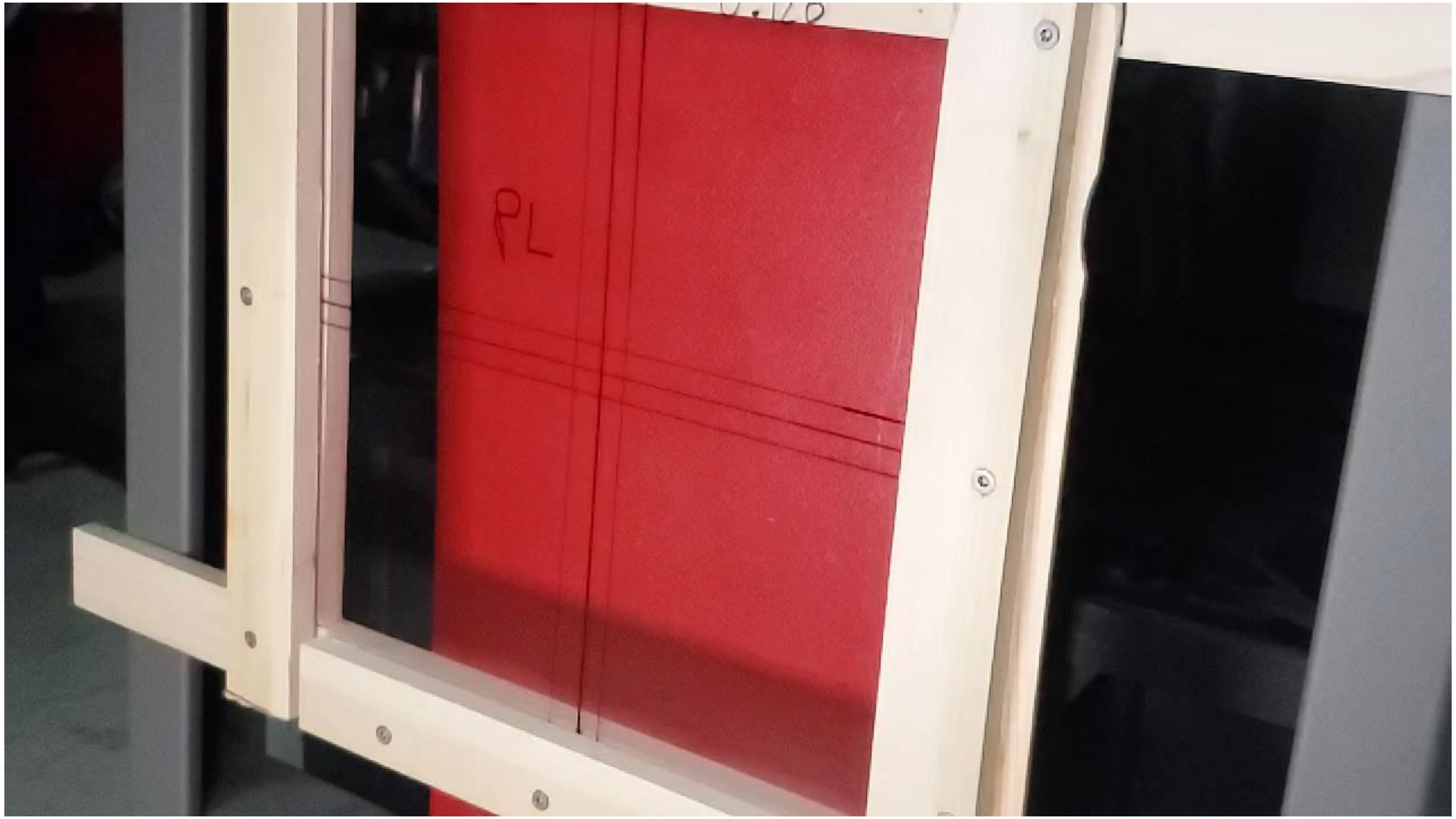


Plastic Paintball Example – Acrylic, Results **Video**

The simulation indicates that the hard plastic paintball should have no trouble penetrating the 0.120” thick acrylic sheet as we can see below:



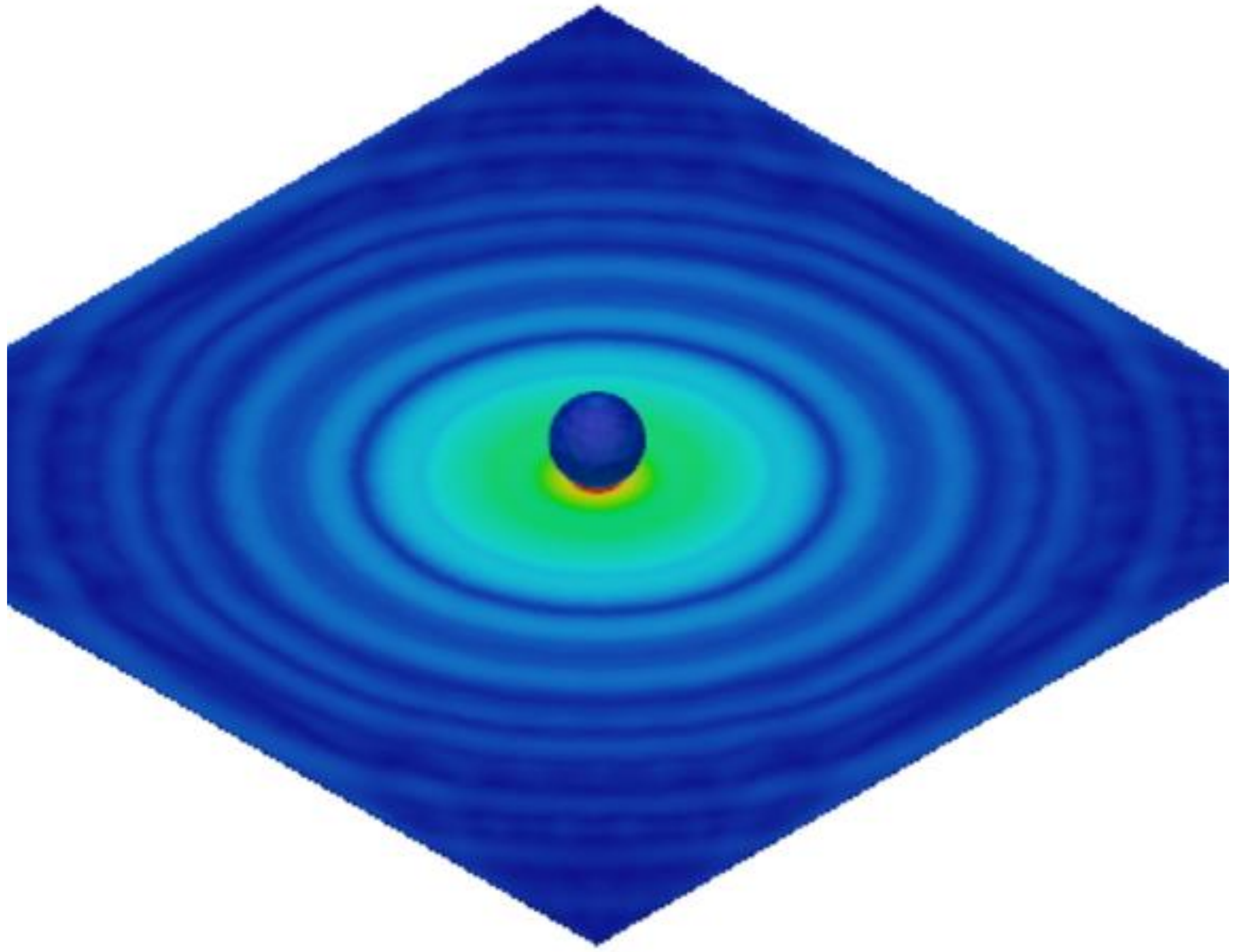
Plastic Paintball Impact Example – Real World Test **Video**



Plastic Paintball Example – Aluminum, Setup

This example is very similar to our prior acrylic simulation, but will look for permanent deformation (yielding) under 2 load cases:

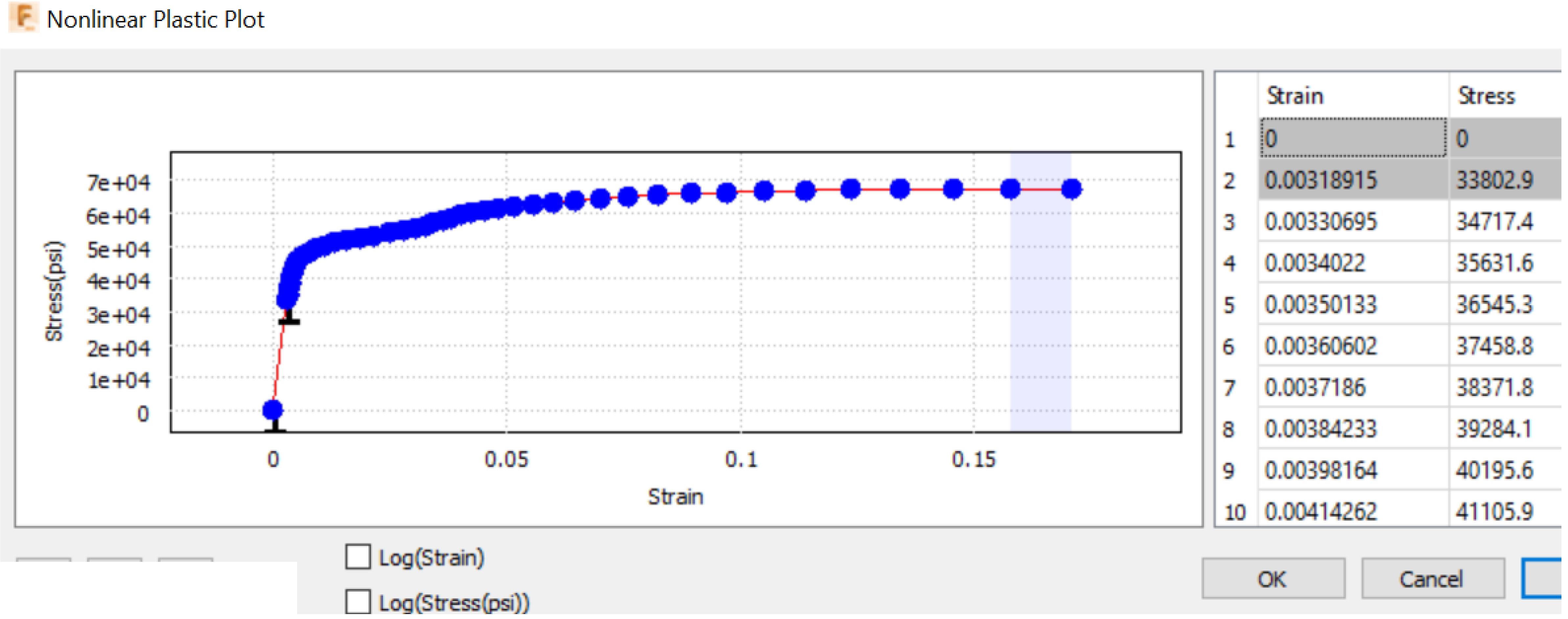
- Load Case 1 - 74 feet per second (hail velocity)
- Load Case 2 - 280 feet per second (paintball gun velocity)

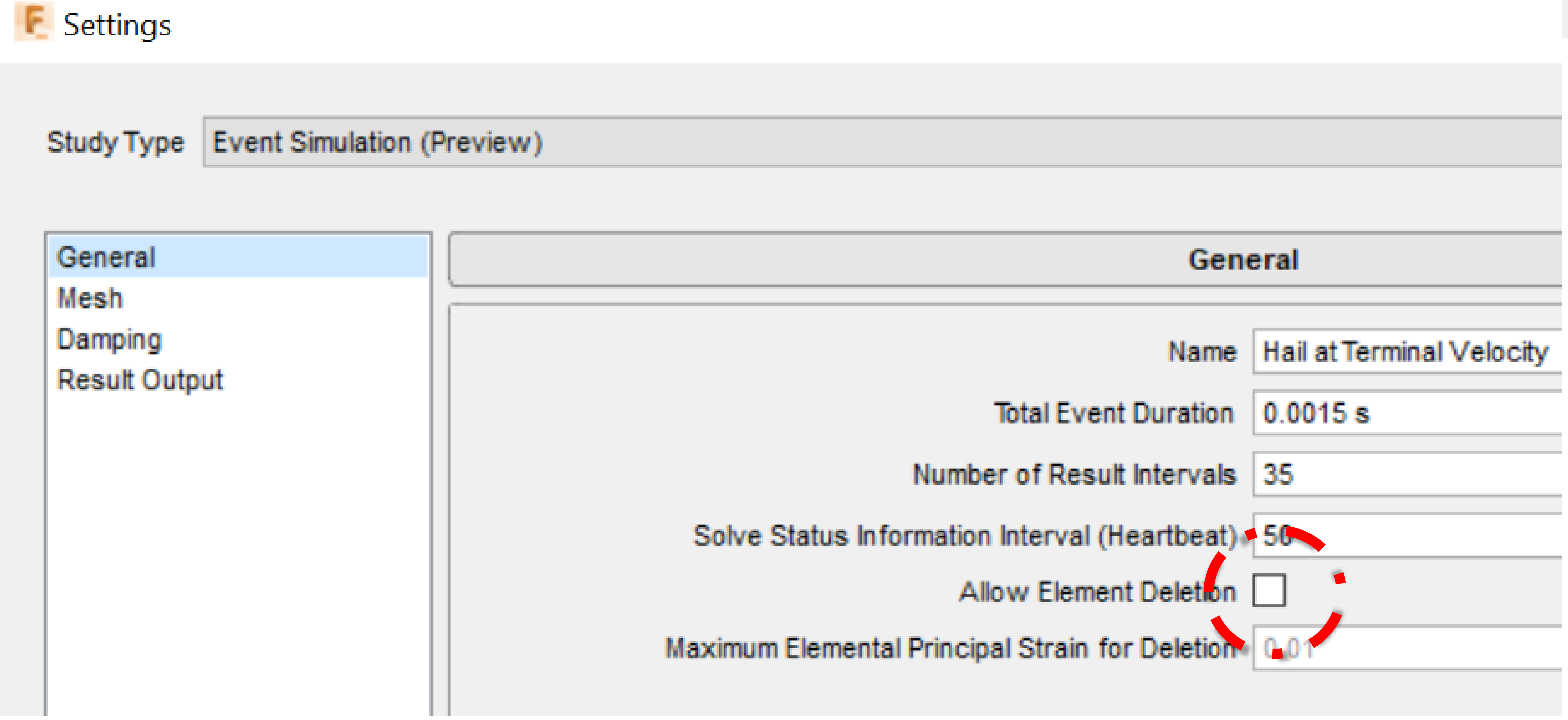


Plastic Paintball Example – Aluminum, Setup

Additional Setup Parameters:

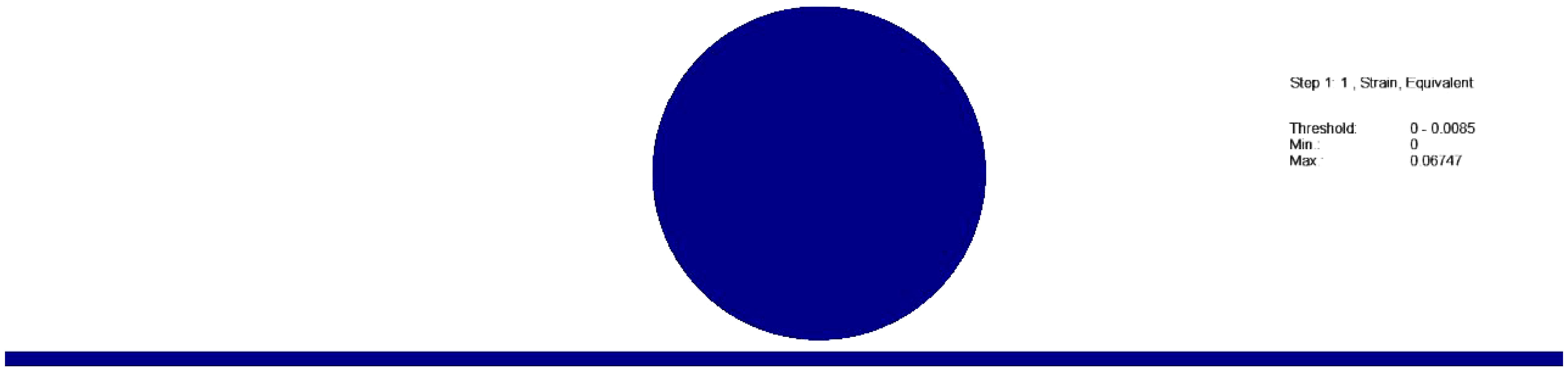
- Material:
  - Fusion 360 High Strength Aluminum Alloy (non-linear)
- Element Deletion:
  - Off – I do not expect material ultimate failure





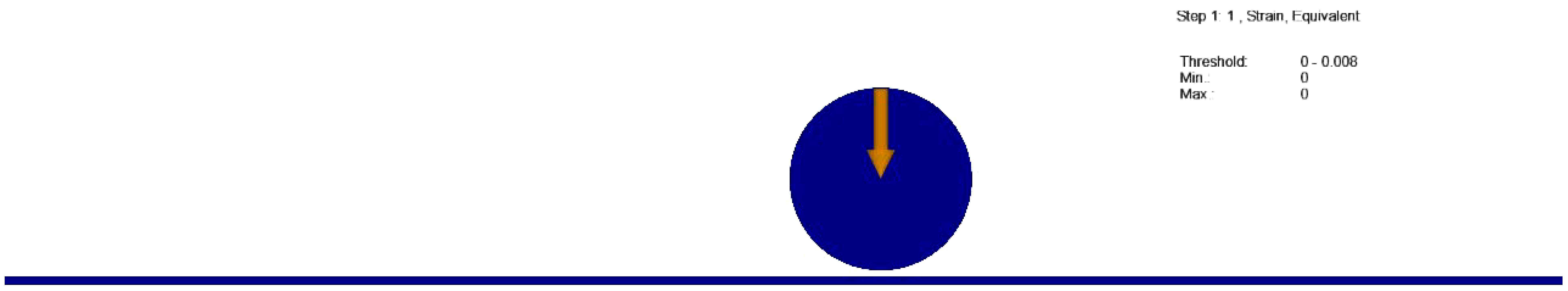
Plastic Paintball Example – Aluminum, 74 fps Results **Video**

If we watch the results video, we see how difficult it may be to predict failure…and the final conclusion really depends on your definition of failure.



Plastic Paintball Example – Aluminum, 280 fps Results **Video**

When we review the results of the 280 fps simulation, we see a very clear depiction of yielding. This case would not require any judgement calls if we were concerned about a permanent dent in the sheet metal.



Plastic Paintball Example – Aluminum, 280 fps Test **Video**

This simulation result was once again validated by real world testing:

Event Simulations and Challenges with Safety Factors

Safety factor is normally not as straight forward with event simulations because it’s not a simple load to consider. Some examples are:

- If you double velocity, you actually quadruple kinetic energy if all other variables are held constant. This means you can’t look at safety factor plots as linear for impact simulations
- Shock events can excite certain modes depending on the load profile, so a resonant response may occur depending on the system. Scaling in this case would not be appropriate.
- Inertial effects and damping values can be impacted by velocity, so again the safety factor may not scale linearly.

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