January 30, 2020

Subject: Load Study with Misalignment Considerations for a 5-Pier Kiln

Problem Statement

The primary purpose of this study is to determine the stresses induced in the shell of the kiln under misalignment. The study will also serve as verification or otherwise of the Optimus Solutions' in-house Load Study Analysis Tool.

Work Scope

- Load Study
    - Determine Loads on Piers
    - Determine Stresses in the shell based on the beam method
- Misalignment Consideration with Finite Element Analysis
    - Calculate Shell Stresses (without misalignment)
    - Calculate Shell stresses (Based on misalignment measurements)
- Compare the shell stresses from the FEA and the Load Study

Beam Stress Analysis

Method
A beam stress analysis is a common method used in statics that determine stresses across a long beam with supports. This is relevant in the rotary equipment industry in the sense that the shell is the long beam and the contact points between the tires are the supports, as seen in Figure 1. The red arrows show point loads, and the green lines show different distributed loads.

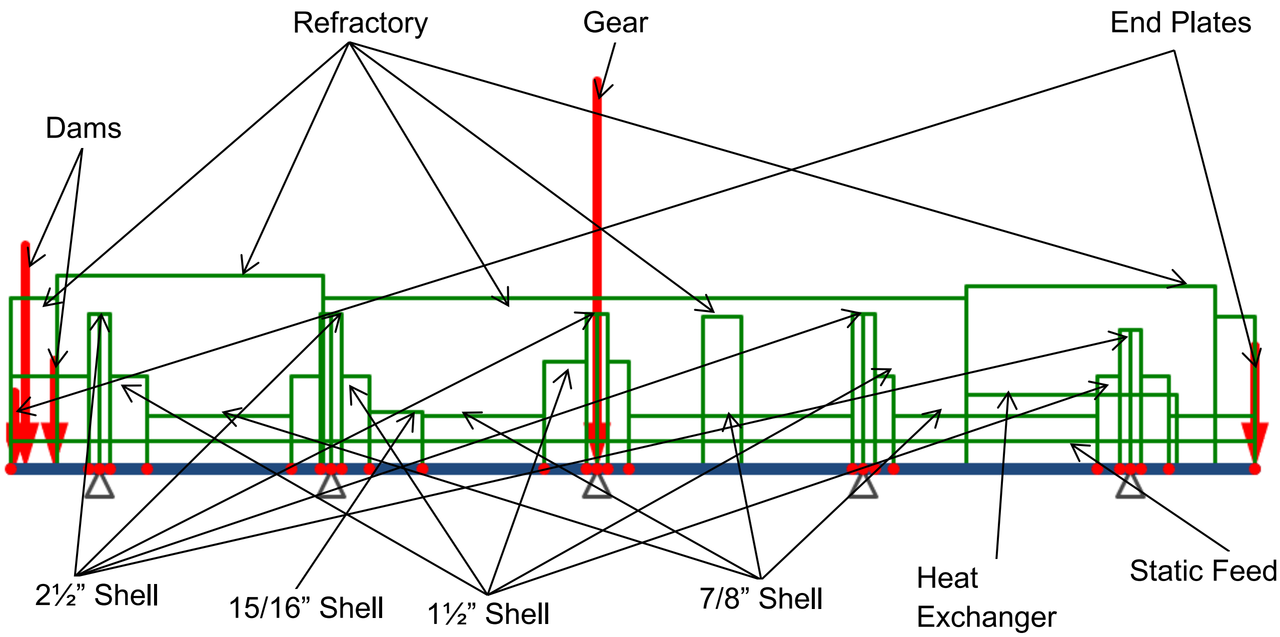


Figure 1 - Beam stress diagram setup with multiple loads

Load Types:
The loads for this study consist of:

- Shell Section – 615,454 lbs, distributed load
- Discharge End Plate – 5,000 lbs, point load
- Feed End Plate – 8,000 lbs, point load
- Dams – 21,480 lbs, point loads
- Refractory – 1,546,922 lbs, distributed load
- Gear – 25,000 lbs, point, load
- Heat Exchanger – 106,766 lbs, distributed load

Mechanical Summary

The kiln was examined mechanically by comparing the values obtained with common load limits used in industry. The limits are as follows:

- Hertz Pressure < 60,000 psi
- Tire Bending Stresses < 10,000 psi
- Tire Ovality < 0.20%

Tire/Roller Contact/Hertz Stress

Contact stress or Hertz pressure is the contact pressure between two mating parts. In the case of a kiln, the two mating points are between the tire and roller. An image of this phenomenon is shown in Figure 2. An additional consideration that **Optimus Solutions** utilizes is the use of a dynamic load. This considers the rotation of the unit and additional vibratory loads that is more representative of real forces. Therefore, our analysis will be more conservative on the calculations.

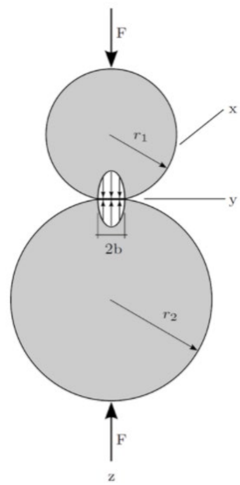


Figure 2. Hertz pressure between two cylinders.

The Hertz pressure or contact stress between the tire and rollers for the tires are shown in the graph below (**Figure 3**). The results show that the Hertz pressure for all the tires are above the recommended industry limits. The values for Tires 1 to Tire 5 are as follows: **60,137 psi, 62,345 psi, 66,717 psi, 63,028 psi** and **65,838 psi** respectively.

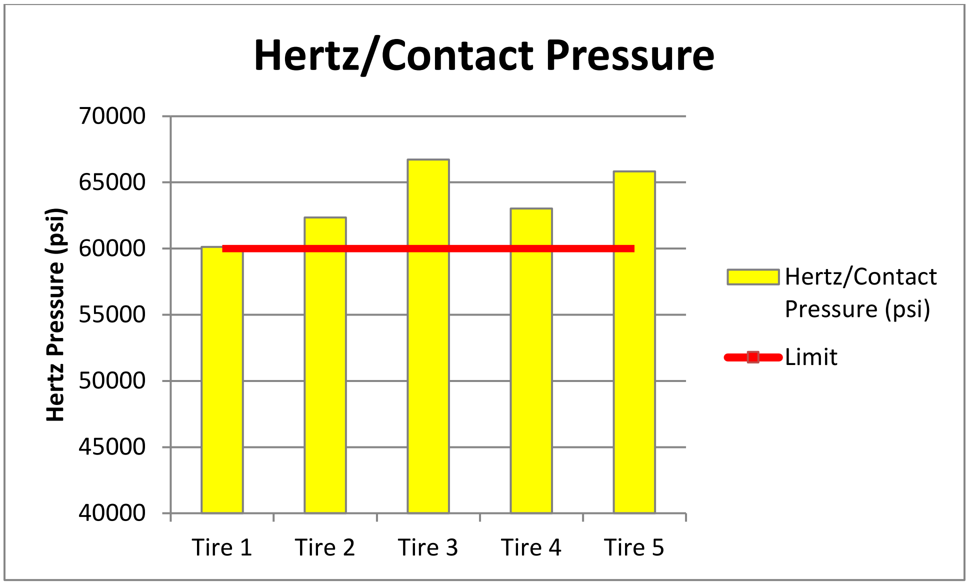


Figure 3 - Hertz Pressures between the tires and rollers

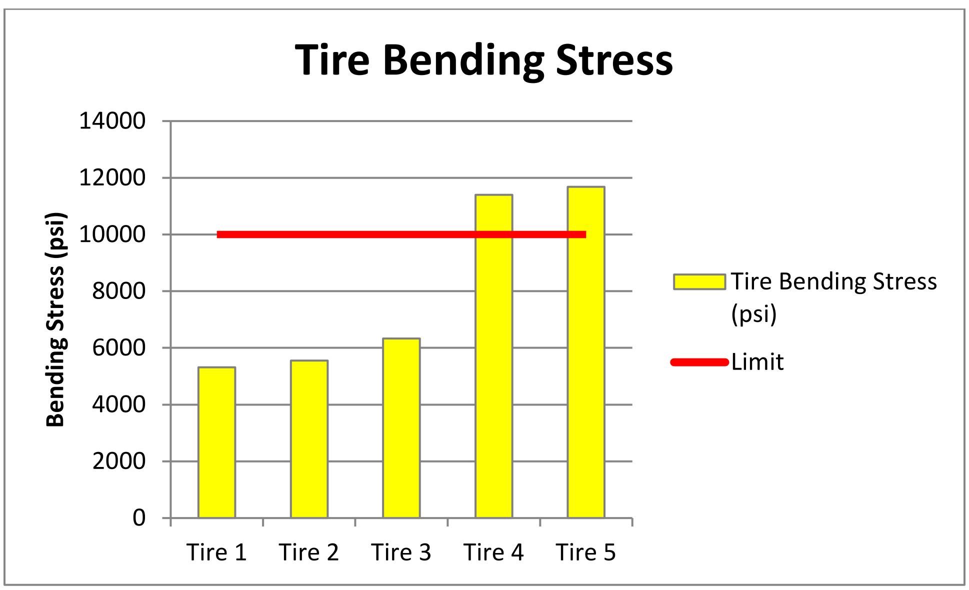


Figure 4. Bending stresses associated with the tires

The calculated values of the Bending stresses are shown in **Figure 4.** Tires 1, 2, and 3 have values below the recommended value of 10,000 psi. Tires 4 and Tire 5 have values above the recommended values. Tire 4 has a bending stress of 11,402 psi and Tire 5 has a bending stress of 11,676 psi.

The ovalities calculated for the tires follow the same pattern as the bending stresses. **Figure 5** shows the graph for the calculated ovalities. From the figure, both tires 4 and Tire 5 have ovalities above the recommended values. Both tires have an ovality of 0.36%.

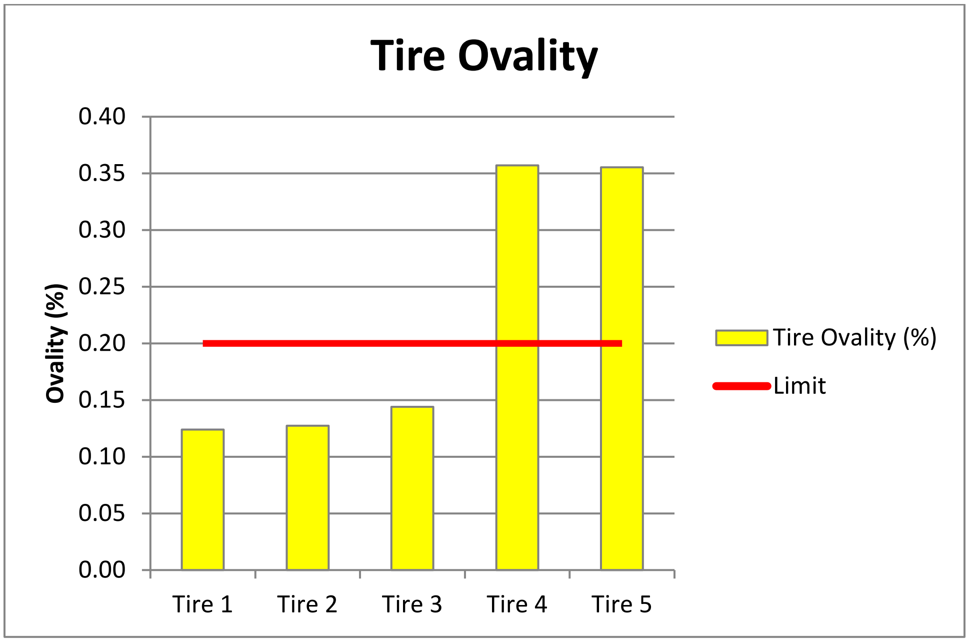
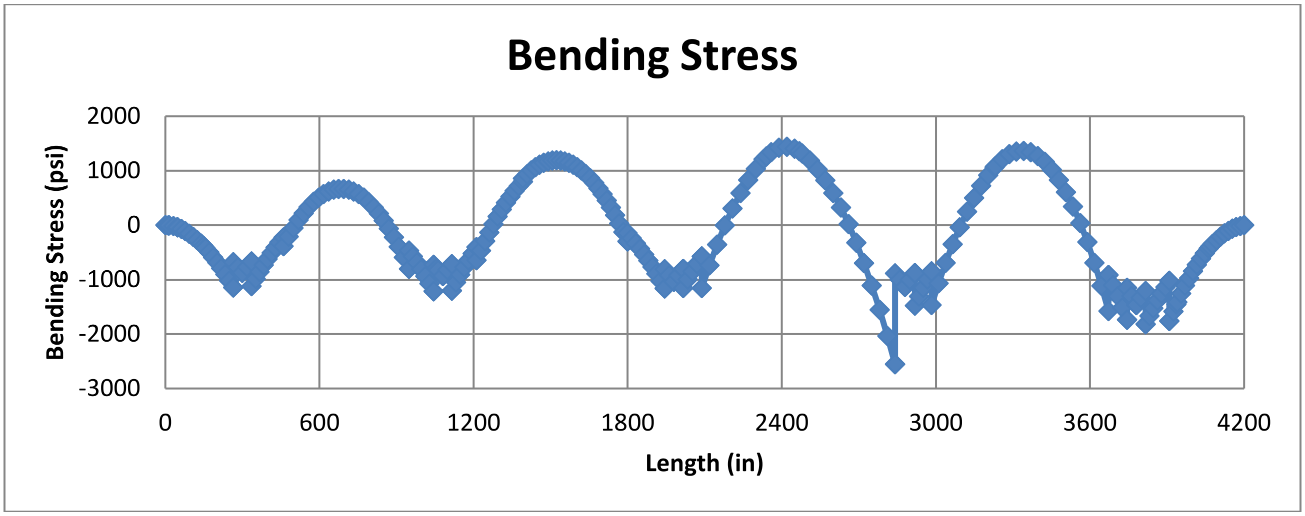


Figure 5. Tire Ovalities (Note: this is different from shell ovality)

Summary
The load study highlighted possible issues with all the tires. High ovalities and bending stresses have a strong relationship with tire width and thickness. The presence of the high ovality implies that the tire is not providing adequate girdling support for the shell. Such a condition predisposes the shell to high bending stresses, which in turn could lead to axial cracks. Increasing the width and/or the thickness of the tire could reduce the ovality, bending stress and improve the girdling support for the shell.

Bending Stresses



Bending Stress (Optimus)

From the results the maximum bending stress occurs at the Pier 4. Reading from the chart, the stress is **2,841 psi**. The maximum bending stress from a similar study performed by an external contractor also occurs at Pier 4 with a value of **2,435 psi** (% difference of 14%)**.** The closeness of the results gives credence to the validity of both studies.

Finite Element Model

The finite element model created for the kiln is shown below (meshed). The model consisted of 190,272 elements and 331,104 nodes, with a maximum element size of 8 inches.
The shell structure was modeled using quadratic shell elements. Tires, tire pads and the gear were modeled using quadratic solid elements.

FE model showing meshing

Material Properties of the model components

Material	Young's Modulus	Poisson Ratio	Min. Yield Strength (Ys)
A36	29000	0.3	36,000
ASTM 4140	20300	0.3	120,000 (240 BHN)

Technical Data for the Kiln

Type	Kiln
Shell I.D. (in)	138
Shell Length (in)	4,200

Boundary Conditions
Two scenarios were run: Kiln with misalignment and without misalignment. For both scenarios the kiln was constrained in the radial direction at the contact between the trunnions and their respective tires.

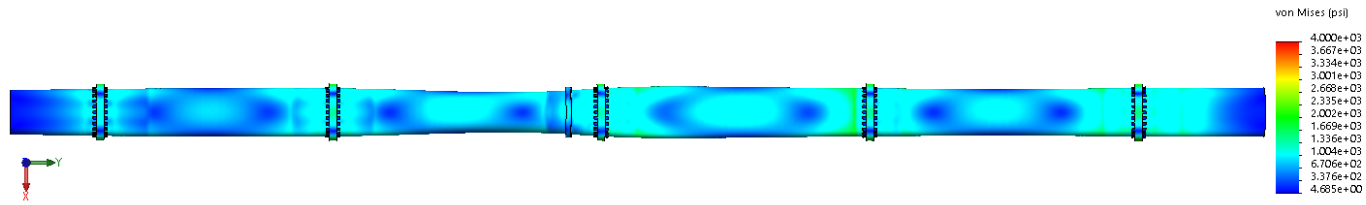
The first scenario considered the kiln without misalignments; all the rollers for this scenario were fixed such that the centerlines of the tires are in a straight line.

The second scenario considered the kiln under misalignments. Misalignment values from an earlier Kiln Axis Survey were used as prescribed deflections. The rollers on piers 1 and 5 were fixed for this scenario.

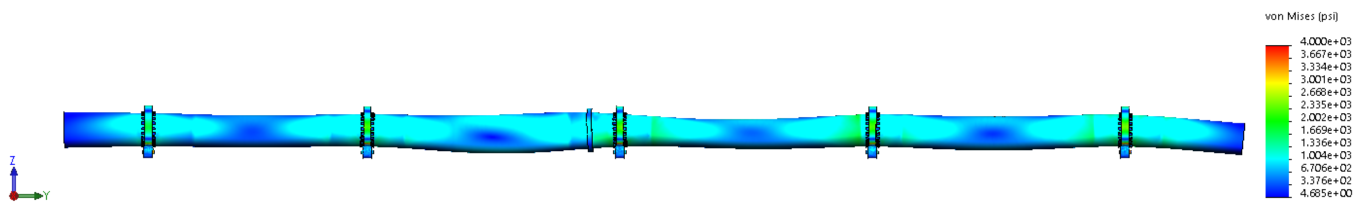
Results

The results for this summary considered only the stresses on shell of the kiln.

Scenario 1
Kiln without Misalignment

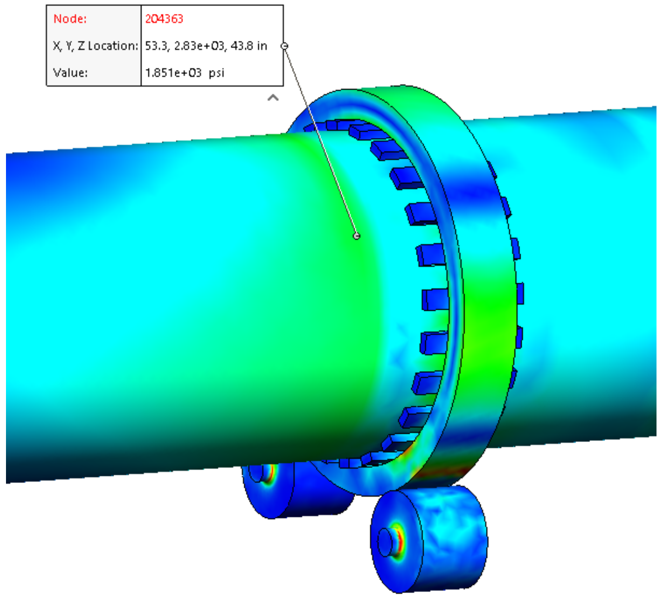


Top View – Von Mises Stress



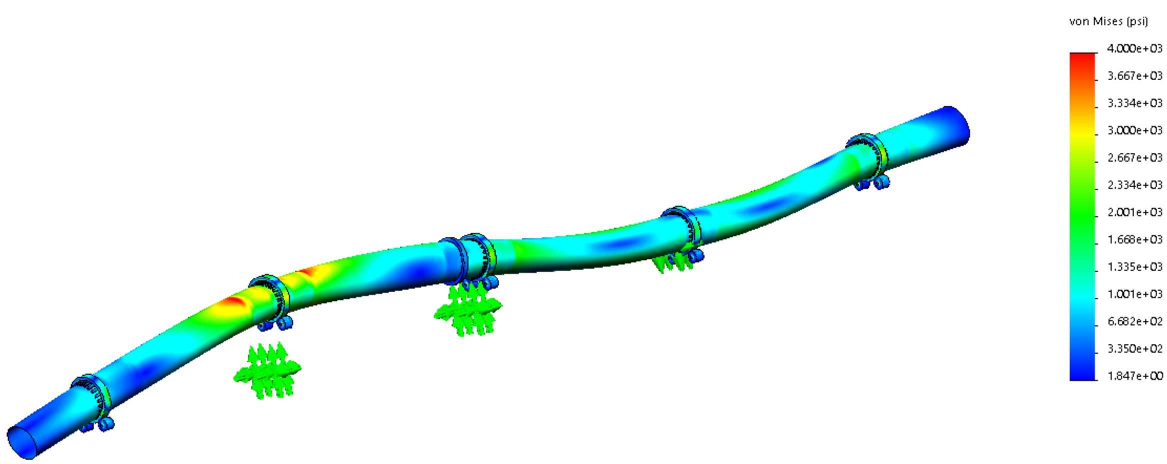
Side View – Von Mises Stress

The maximum von mises stress occurs at pier 4. From the calculations, the maximum von mises stress on the shell is 1,851 psi.

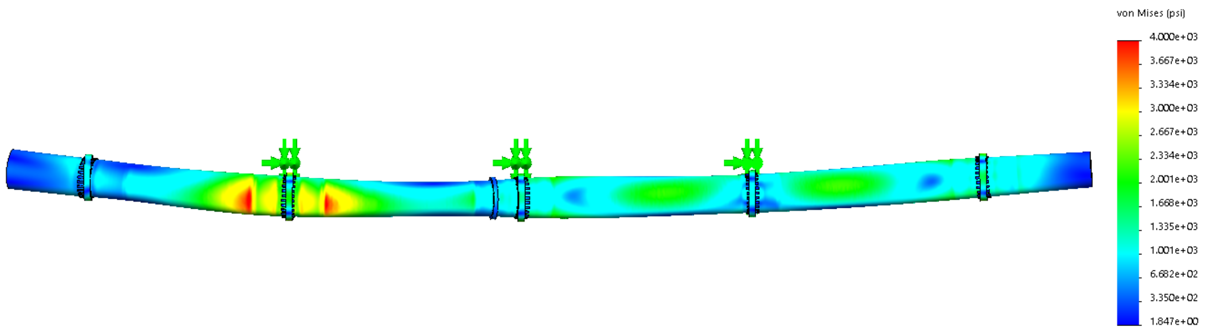


Maximum Shell Stress at Pier 4.

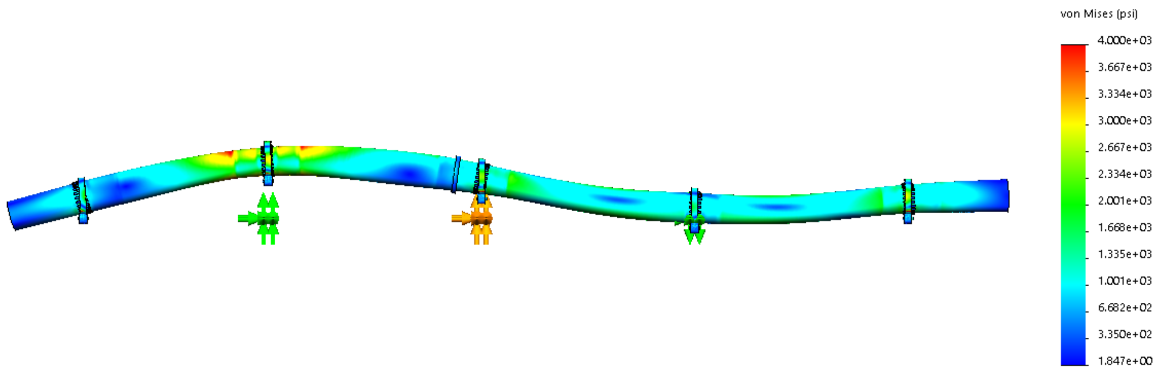
Scenario 2
Kiln with Misalignment



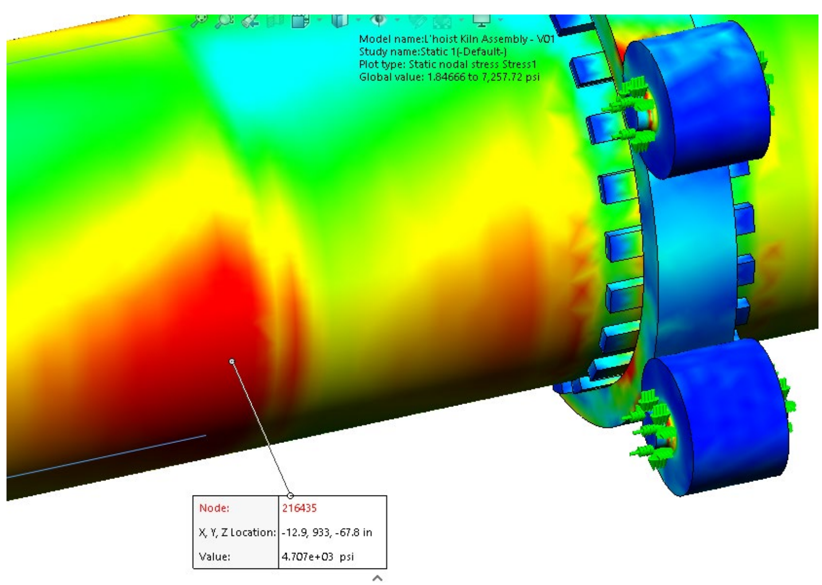
Isometric View showing Misalignment (exaggerated)



Top View – Von Mises Stress



Side View – Von Mises Stress



Maximum Shell Stress at Pier 2.

The maximum von mises stress occur at Pier 2. The magnitude from the calculation is **4,707 psi.**