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Application of Computer Aided Engineering Processes

Structural Design & Fluid Analysis (ACHA6010)

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2003848

December 2022

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1 Introduction

Computer aided engineering (CAE) is a fast-emerging field that has taken the use of computer aided design to a higher level, using CAE allows greater engineering studies to take place on the models allowing companies to expose their products to the elements that it will face once it has been manufactured. This report will firstly validate the analytical algorithms within Ansys by analytically solving a cantilever beam and a bimetallic strip, one has a uniform pressure being applied and the other will have a thermal condition applied, these models are then replicated in Ansys, and the results are analysed to validate Ansys. This validation will then allow a model of a crankshaft with 4 pistons to be simulated and the report will analyse how the piston reacts under the realistic load boundaries it will encounter when running in a vehicle studying the structural loadings and the fatigue life of the product. The report then aims to improve the initial material of the piston which is 6061-T6 Aluminium with targets to reduce the weight, reduce the temperature of the piston and then reduce the total deformation by 20% this has been achieved by running tests with different alternative materials to see which material can reach the criteria of the targets.

2 Literature Review

Computer aided engineering also known as CAE is the procedure of the entire engineering process from design to testing which uses sophisticated analytical algorithms to give the most accurate results as stated by (SIMSCALE, 2022). Using such software programmes like Ansys which is the CAE software being used in this report allows companies to save time when designing their products and therefore for some companies will save them money, using a CAE software will also reduce errors in final products as it allows companies to run multiple tests and find the best design for its purpose. (Academy, 2022)

The model of the crankshaft has been modelled from a 1.6 ford sigma engine as provided from the University of Wales Trinity Saint David (Noble, 2022) the engines pistons are made out of 6061-T6 Aluminium which is one of the most popular aluminium alloy categories in the world (MatMatch`, 2022) and therefore this report will discuss whether although it's the most common is it the best for this purpose.

3 Validation

To measure the accuracy of the output results and the credibility of Ansys, analytical calculations are required to validate the results. To do this, 2 simplified test cases will be analytically solved based on fundamental principles and then recreated within Solid works and Ansys to compare the results. For this report the simplified test cases will be a Cantilever Beam with uniform pressure and a Bimetallic strip with a thermal loading.

3.1 Cantilever Beam

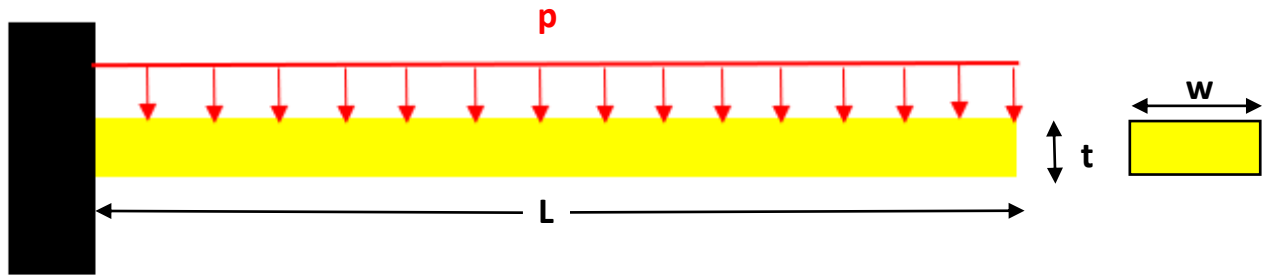


Figure 3-1 - Cantilever Beam Validation

As can be seen above is a diagram of a cantilever beam fully fixed on the left-hand side, and is subjected to a uniform pressure p . The material is set to have the following properties (Young, et al., 2011).

Table 3-1 Cantilever Beam Material properties

Modulus Of Elasticity (E)	210000Mpa
Poisson's Ratio (ν)	0
Shear Modulus (G)	105000Mpa
Length (L)	1m
Width (W)	0.050m
Thickness (t)	0.005m
Pressure (P)	2750Pa

Using These properties allows for the maximum deflection to be calculated, this can be done using the following equation:

$$U_{zmax} = \frac{3pL^4}{2Ew^2t}$$

Which is solved as shown below:

$$U_{zmax} = \frac{3 \times 2750 \times 1^4}{2 \times 2.1e^{10} \times 0.05^2 \times 0.005}$$

$$U_{zmax} = 157.143mm$$

Therefore, this calculation has stated that under a uniform pressure of 2750Pa this material will have a maximum deflection of 157.143mm. The material properties and calculations can be validated from (Young, et al., 2011). Now the analytical analysis for the cantilever beam has been done, this material can be developed

within Solid works and simulated in Ansys which be seen in figure 3-4. For this model a static structural study will be used as shown in figure 3-2 below this is because this study is not dependent on time or temperature.

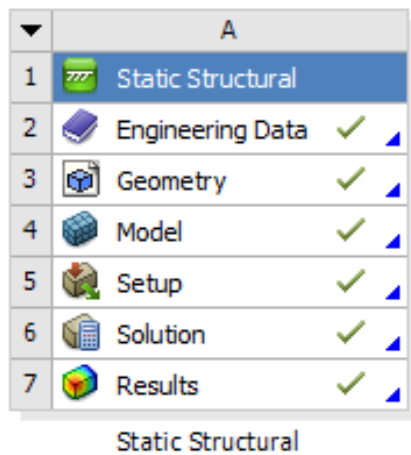


Figure 3-2 - Cantilever Static Structural Ansys

When using Ansys the Solid works model is imported into the static structural study. Once that is done the study can begin. Figure 3-3 shows the outline of this test. As can be seen the study is demonstrating a fixed support with an applied pressure and solving a solution for the total deformation, green ticks implying that the study is ready to be solved.

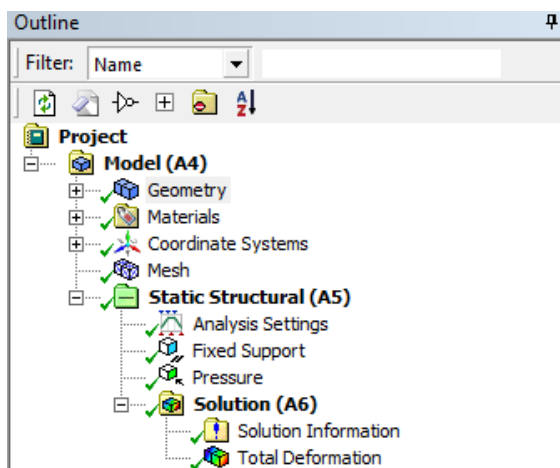


Figure 3-3 - Cantilever Beam Ansys Outline.

The initial test run has used a mesh sizing of 2.5mm and has given the total deformation of 157.15mm this results in 0.004% percentage error when compared to the analytical method. Which is satisfactory enough however one factor that could be affecting this result is the mesh therefore to see whether the mesh has caused effect on the result mesh sizes of 3mm to 1mm in increments of 0.5mm have been tested and have provided the following results:

Table 3-2 - Cantilever Beam Percentage Error

Mesh Size	Total Deformation	Percentage error
1mm	157.15mm	0.004%
1.5mm	157.15mm	0.004%
2mm	157.15mm	0.004%
2.5mm	157.15mm	0.004%
3mm	157.15mm	0.004%

Looking at table 3-2 changing the mesh size for this model had no effect on the result and therefore when a pressure is applied the mesh size does not have any effect on the result. The results from the 1mm mesh can be seen below however due to the small mesh size it is hard to work out the coloured results and all other mesh size results can be seen in appendix 9.2.

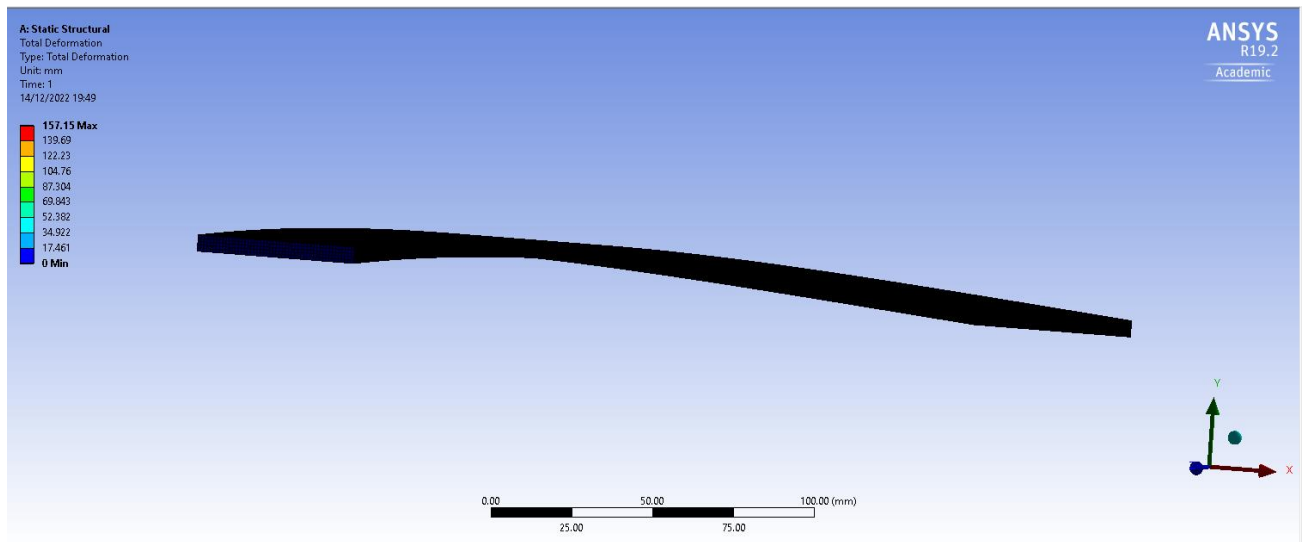


Figure 3-4 - Ansys Results from Cantilever Beam

3.2 Bimetallic Strip

The next validation case is the Bimetallic strip, this metal strip is composed of the top layer being made from Invar and the bottom half being copper. The bimetallic strip is fixed at the left-hand side and is then exposed to a thermal loading across it and this case will be studying the total deformation when a temperature is applied. The strip has the following properties (Young, et al., 2011) and the diagram can be seen in figure 3-5.

Table 3-3 Bimetallic Strip Properties

Properties	Invar	Copper
Modulus of Elasticity (E)	137000Mpa	130000Mpa
Poisson's Ratio (V)	0.28	0.354
Coefficient of Thermal Expansion (α)	1.2E-06 W/m-k	2.00E-05 W/m-K
Cross Section Width (W)	5mm	
Thickness (t)	1mm	
Length (L)	100mm	
Thermal Loading (Tc)	100°C	



Figure 3-5 – Bimetallic Strip Diagram

Like done previously the bimetallic strip firstly needs to be solved analytically to find the total deformation. This can be done using the following equation which have been acquired from (Young, et al., 2011):

$$U_{Zmax} = \frac{6(\alpha_i - \alpha_c)(t_i + t_c)Tc}{t_s^2 \times K_1} \times \frac{L^2}{2}$$

However, to solve this the dimensionless coefficient K_1 needs to be solved this is done with the following equation:

$$K_1 = 4 + 6\frac{t_c}{t_i} + 4\left(\frac{t_c}{t_i}\right)^2 + \frac{E_c}{E_i}\left(\frac{t_c}{t_i}\right)^3 + \frac{E_i t_i}{E_c t_c}$$

$$K_1 = 4 + 6\frac{1 \times 10^{-3}}{1 \times 10^{-3}} + 4\left(\frac{1 \times 10^{-3}}{1 \times 10^{-3}}\right)^2 + \frac{1.3 \times 10^{11}}{1.37 \times 10^{11}}\left(\frac{1 \times 10^{-3}}{1 \times 10^{-3}}\right)^3 + \frac{1.3 \times 10^{11} \times 1 \times 10^{-3}}{1.37 \times 10^{11} \times 1 \times 10^{-3}}$$

$$K_1 = 16$$

Now K_1 has been solved the total deformation can be solved as shown below.

$$U_{Zmax} = \frac{6(1.2 \times 10^{-6} - 2 \times 10^{-5})(1 \times 10^{-3} + 1 \times 10^{-3}) \times 100}{(1 \times 10^{-3})^2 \times 16} \times \frac{(100 \times 10^{-3})^2}{2}$$

$$U_{Zmax} = -7.05mm$$

These equations have resulted in the total deformation when 100°C of thermal loading has been applied to be -7.05mm. Now the analytical methods have been solved the model can be developed within Solid works and imported to Ansys. For this model a static structural study will be used. The reason for using this and not the steady state thermal is because there is only one temperature being tested on the model. This results in the test being a thermo-mechanical study, because the

two materials have different coefficients of thermal expansion and therefore for the same given temperature one will attempt to expand more than the other creating mechanical deformation within the system. The model within Ansys can be seen in figure 3-6 and shows the results from a 0.5mm mesh.

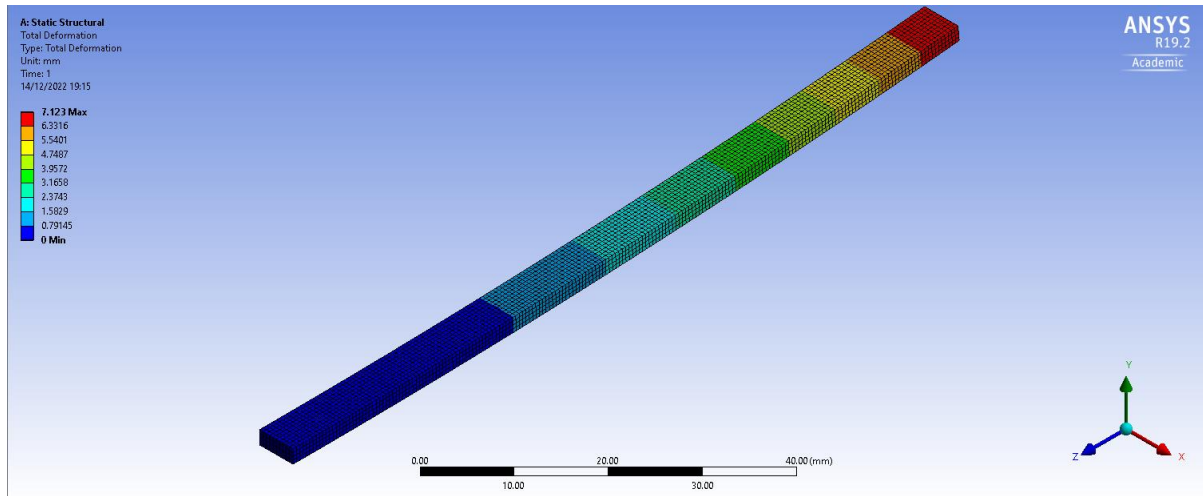


Figure 3-6 - Bimetallic Strip 0.5mm mesh Total Deformation

And when looking at the outline in figure 3-7 a thermal condition has been applied. Now because the atmospheric temperature within Ansys is set to 22°C the thermal condition needs to be set at 122°C to allow a 100°C thermal loading to be applied to the bimetallic strip, the initial mesh condition for this test is 0.75mm.

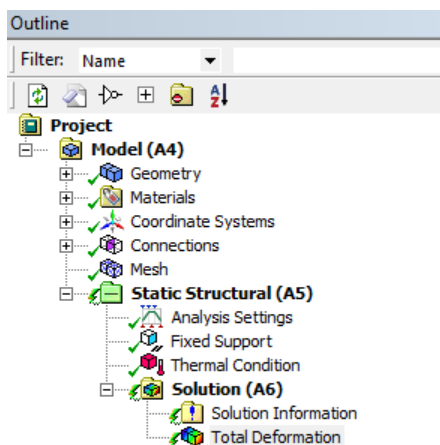


Figure 3-7 - Bimetallic Strip Outline

This model can now be solved, and the results can be seen in table 3-4 below with all Ansys images of results in appendix 9.3.

Table 3-4 - Bimetallic Beam Changing Mesh Sizes

Mesh Sizing	Total Deformation	Percentage Error
0.25mm	7.1213mm	1.0153%
0.5mm	7.123mm	1.0431%
0.75mm	7.1236mm	1.0472%
1mm	7.1233mm	1.0431%
1.25mm	7.1233mm	1.0104%
1.5mm	7.1228mm	1.0103%
1.75mm	7.123mm	1.0104%
2mm	7.1224mm	1.0103%

As can be seen from the results varying the mesh has resulted in a varying set of results with percentage error ranging from 1.0431% down to 1.0103% error as a concluding result the best mesh size for the bimetallic strip is 1.5mm or greater and this is because if the mesh is too small then when Ansys does the calculations if it makes any rounding within each of the mesh's then the overall rounding error is going to be increased causing a less accurate result as proven above.

4 CAD Modelling and Assembly

The next section of this report is to analyse an assembly with multiple parts capable of running a kinematic study. The kinematics study will demonstrate realistic loading conditions that the system may be exposed to. These will then be inputted into a static structural study to allow analysis of what happens when a kinematic solution is applied. A thermal loading will also be applied to represent temperatures the model is expected to be exposed to. Shown below is the Solid works and Ansys model of a 4-cylinder crankshaft and pistons.

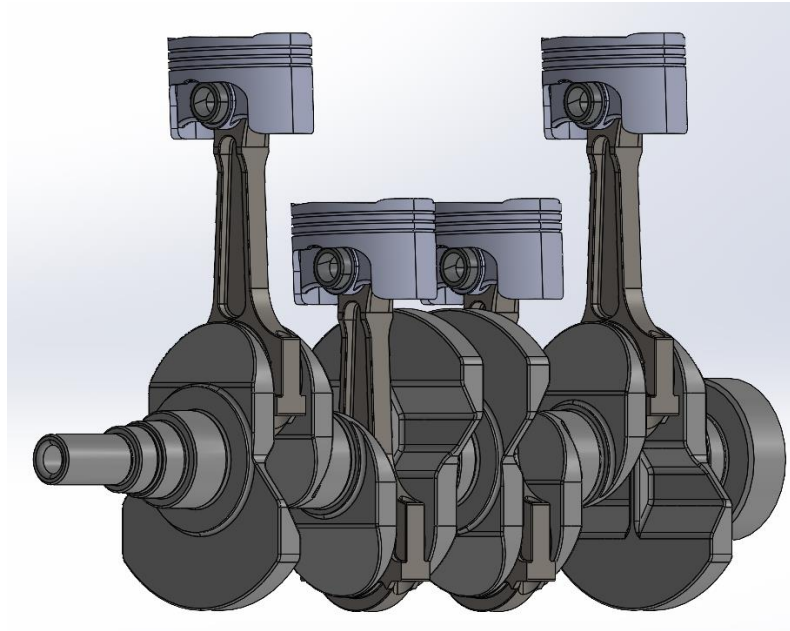


Figure 4-1 - Solid works Model of the Full Crankshaft

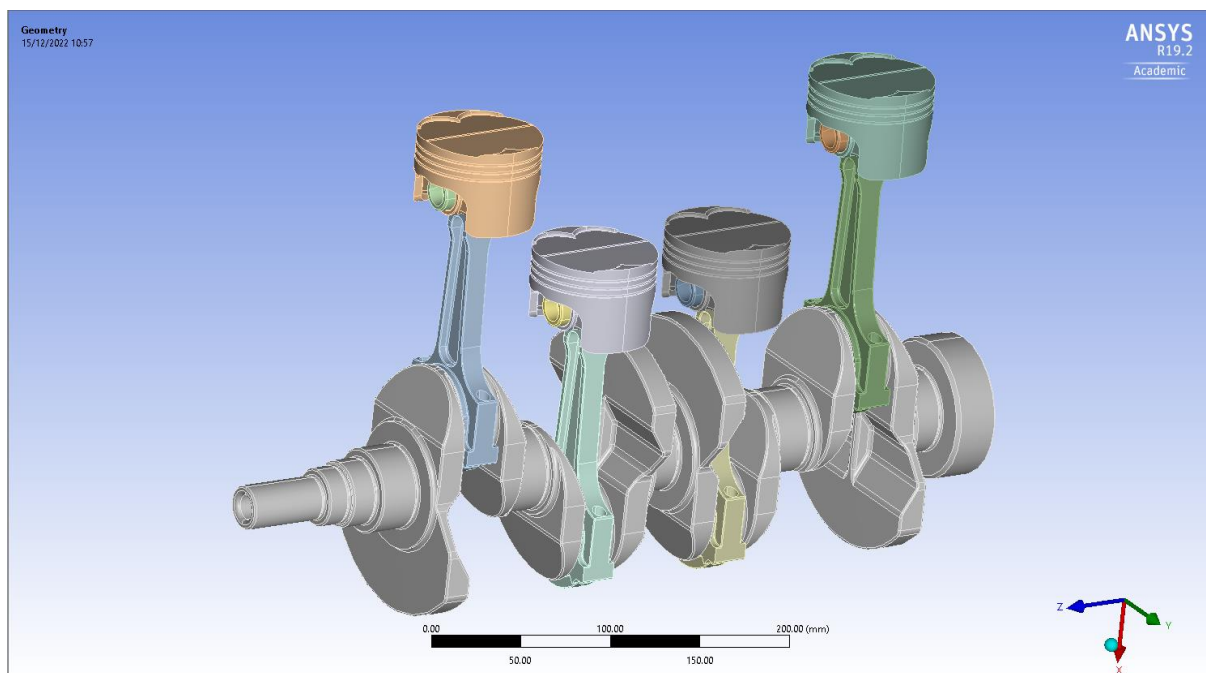


Figure 4-2 - Ansys Model for the Full Crankshaft

5 Ansys Analysis

5.1 Project Schematic

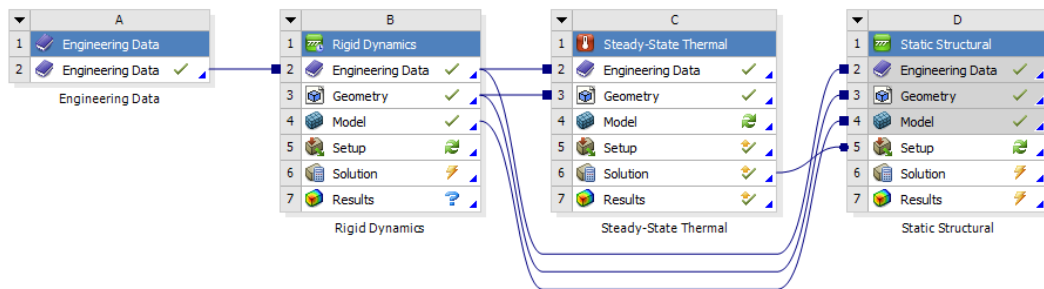


Figure 5-1 - Project Schematic

When looking at Figure 5-1 above it is clear there are four separate sections within the schematic, Engineering data is where the profile for the material has been built using the materials properties. The next section is the rigid dynamics section. This section initially calculates the motion loads that occur between the gudgeon pin and the piston the angular velocity for this section was set to 4000rpm, the maximum motion load is then exported from this section and inputted into the static structural section and the piston material is changed to flexible. Before that is solved the steady state thermal section needs to be completed. Within this section thermal study boundary conditions are made this is where convection parameters that include heat transfer coefficient and the temperature at which different parts of the piston are exposed to this data can be seen in figure 9-1 within Appendix 9.1 and have been acquired from the University of Wales Trinity Saint David. From here the steady state can be solved to give an overall piston temperature and this solution can be inputted into the setup of the static structural as seen in the above figure. Within the static structural multiple mesh sizes are created on different faces the Crown, Crown side and skirt of the piston have a 1mm mesh and the piston rings and the underside have a 0.5mm. Structural study boundaries will also be set here this will consist of applying a pressure to the crown of the piston which is set to be 10.53Mpa and to turn weak springs on to allow the piston to be supported but to still remain flexible this does not have any effect on the results. Total deformation and equivalent stress can now be added to the solution and can now be solved to give results. This can be seen within the full outline below:

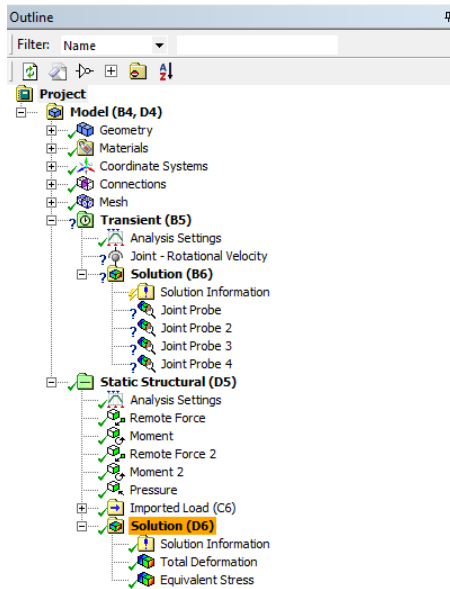


Figure 5-2 - Full Outline of kinematic Study

5.2 Material

The pistons within the model will initially be modelled as 6061-T6 Aluminium and have the following properties (Noble, 2022):

Table 5-1 - 6061-T6 Youngs Modulus

Temperature (°C)	Youngs Modulus (Gpa)
22	67
100	70
150	68
200	64
250	56
300	48
350	41
400	32
450	21
500	12

Table 5-2 - 6061-T6 Properties

Properties	Value
Poisson's Ratio	0.33
Coefficient of Thermal Expansion @ 22°C (1/°C)	2.36E-5
Thermal Conductivity (W/m-K)	167
Density (g/cm ³)	2.7

6 Ansys Results

6.1 Initial Material Design

When the material properties for 6061-T6 aluminium have been inputted it has been found that the piston achieved 327.48°C max temperature, a maximum equivalence stress of 2968.3Mpa and maximum deformation of 0.39142mm and a peak motion load of 2380.5N. These results can be demonstrated below:

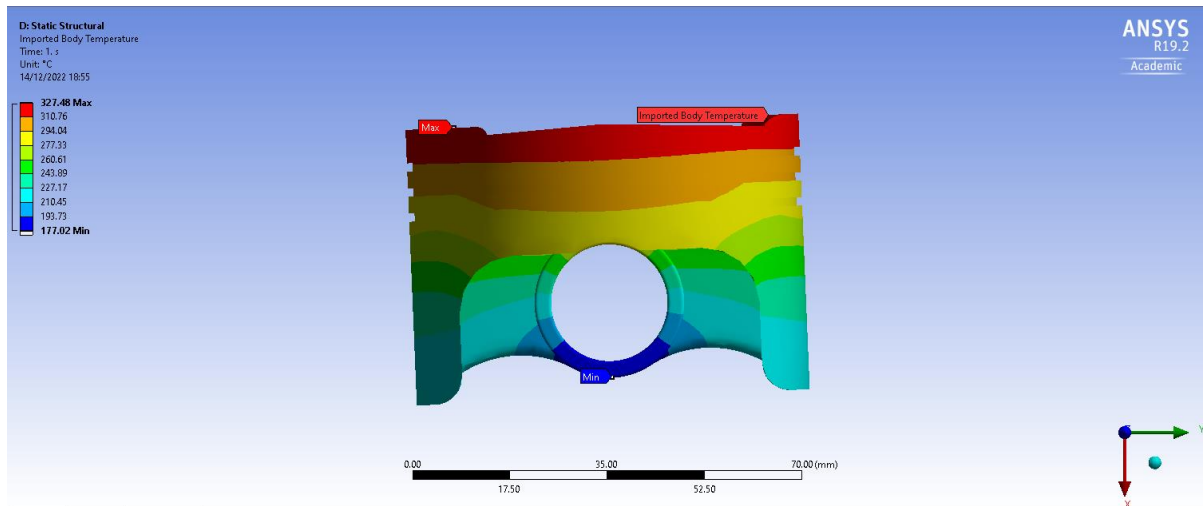


Figure 6-1 - 6061 Temperature Side Profile

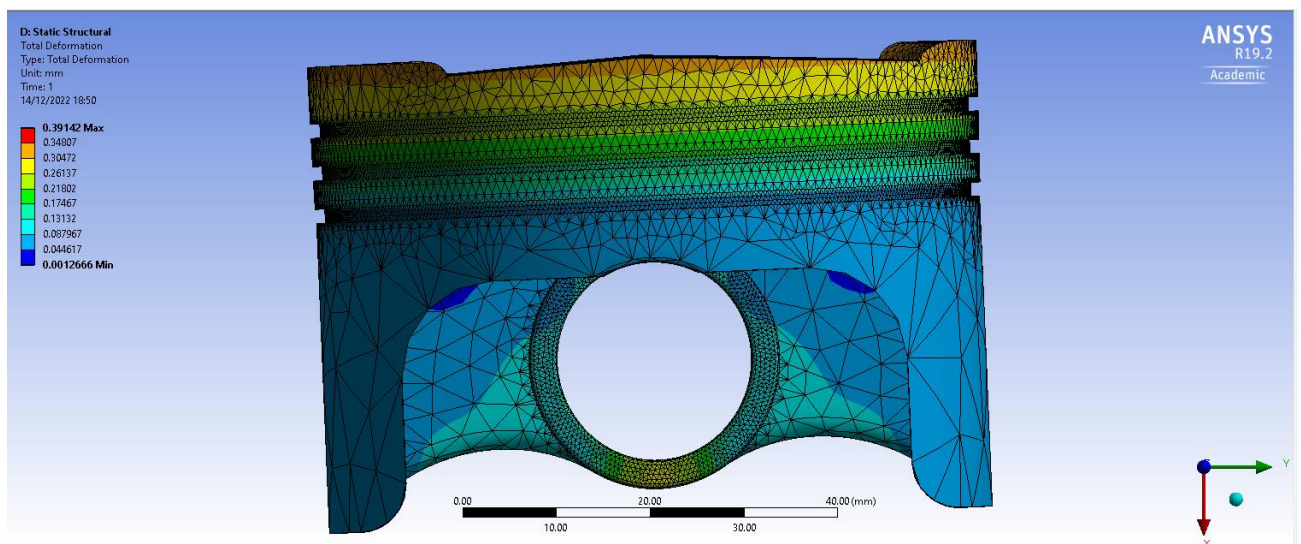


Figure 6-2 - 6061 Total Deformation Side Profile

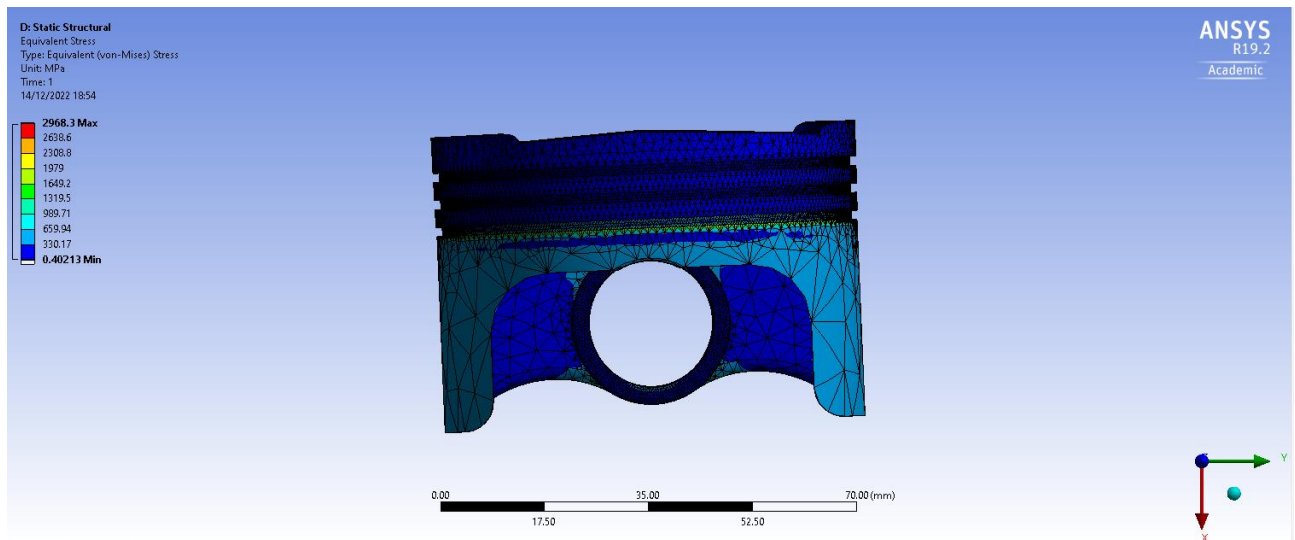


Figure 6-3 - 6061 Equivalent Stress Side Profile

Other angles of these figures can be found in Appendix 9.4. However, when taking a closer looking at the total deformation result in figure 6-2 the main deformation is found on the crown of the piston which would be expected down to the fact that is where the pressure is applied however a high amount of deformation can be seen on the ring for where the gudgeon pin is which isn't as expected, this is caused from the motion loads of the simulation. This could result in higher fatigue within the piston resulting in failures down the line and is a vital area to improve on.

7 Improving The Performance of The Component

Although the piston has performed well and there is minimal deformation caused within simulation improvements can still be made to improve the overall performance. For a satisfactory result several targets have been set these consist of reducing the weight of the piston, reducing the temperature the piston achieves and then finally reducing the overall deformation by 20%. To achieve a result various material will be tried and tested until an optimum result is achieved. 3 alternative results have been chosen these are cast iron, 4032 Aluminium and 2168 Aluminium each having varying material properties and are expected to have fluctuating results. The key aspects of the properties of the chosen materials that will allow the targets to be met are the density, thermal conductivity, and young's modulus.

7.1 Cast Iron

Ductile cast iron has been chosen as an alternative test material as it has the capabilities of withstanding thermal cycling and is often used within vehicle gears and suspension (MatMatch`, 2022). Another main advantage of cast iron is it has high compressive strength and this therefore should reduce the total deformation of the piston.

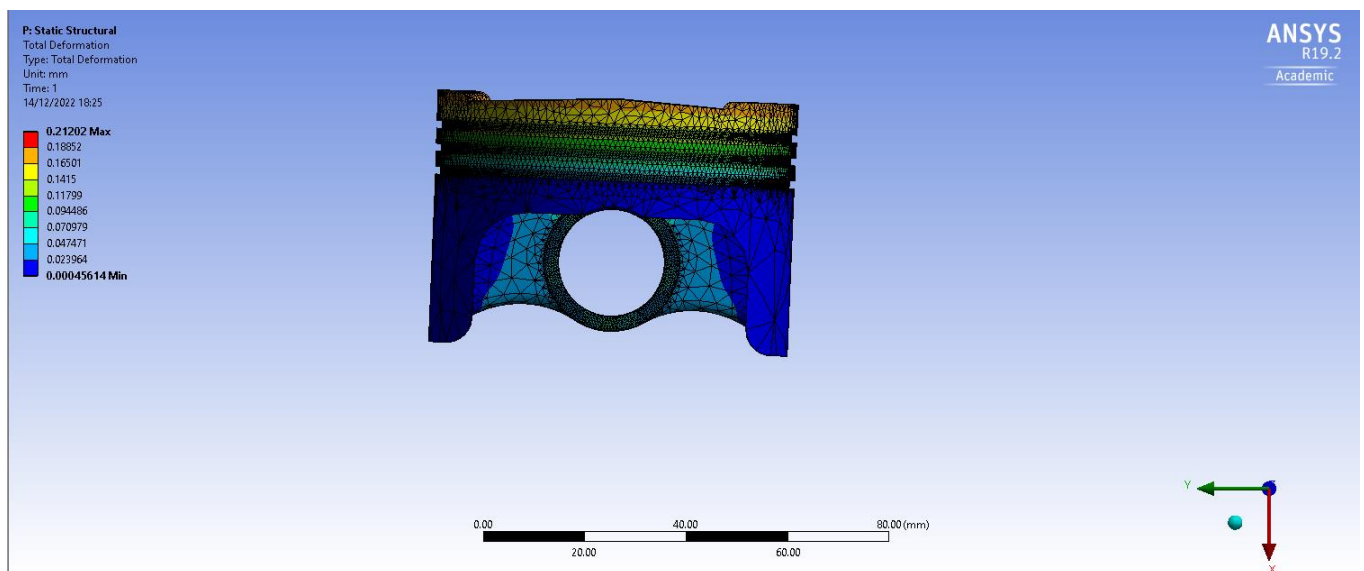


Figure 7-1 - Cast Iron Total Deformation Side Profile

As can be seen in figure 7-1 the total deformation has significantly improved, the max deformation has improved by 45.8% which is massively above target and has made significant improvements around the ring for the gudgeon pin. However, when running the rigid dynamics, the peak motion load achieved 6203.4N and therefore has occurred in greater temperatures across the piston as demonstrated in figure 7-2 below as well as having a greater density of 7.05g/cm^3 resulting in a

heavier piston and therefore has not met the targets for this report. All other angles for these tests can be found in appendix 9.6 along with the equivalent stress results.

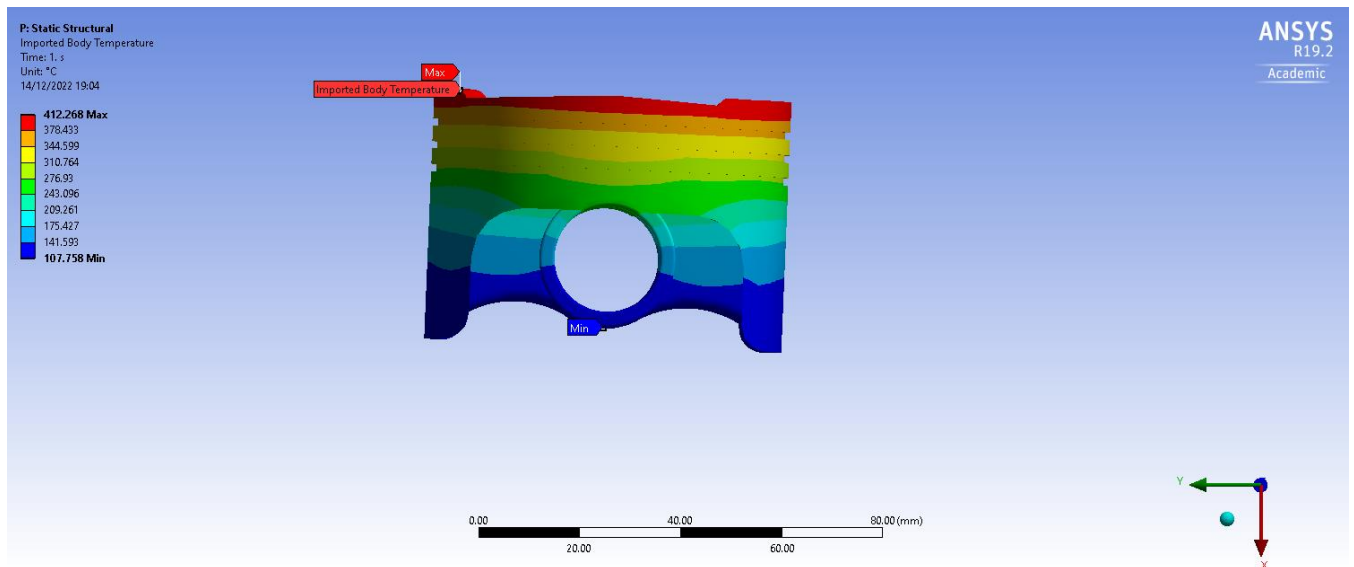


Figure 7-2 - Cast Iron Temperatures Side Profile

7.2 2618 Aluminium

The second material that has been trialled is 2618 Aluminium which is a strong aluminium alloy containing 2% copper and 1.5% magnesium (Smithmetal, 2022). All the material properties for 2618 aluminium can be found in Appendix 9.7 (Azom, 2022). 2618A pistons are also known to be excellent with high temperature strength and therefore is a suitable material for this test and will aim to reduce the total deformation. The total deformation results can be seen below.

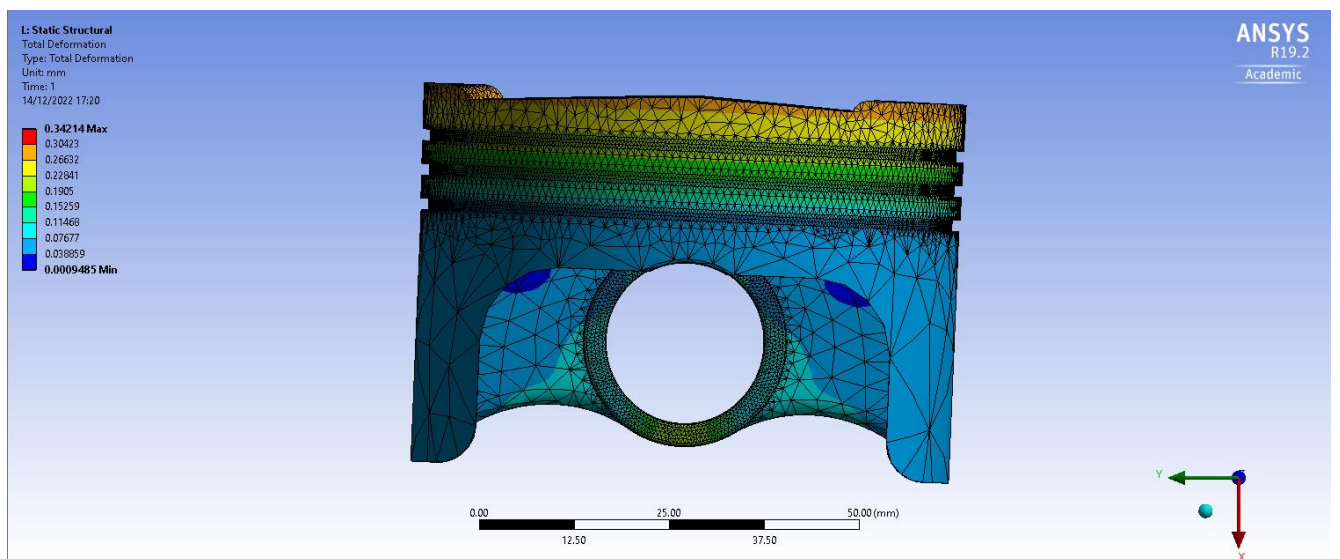


Figure 7-3 - 2618 Total Deformation Side Profile

Likewise with the cast iron the 2618 Aluminium has reduced the total deformation by 12.5% but this has not quite reached the target of 20%. However, when taking a looking at the temperature the piston achieved in figure 7-5 the overall temperatures have decreased with the max temperature decreasing by 3.7% therefore meeting one the required targets.

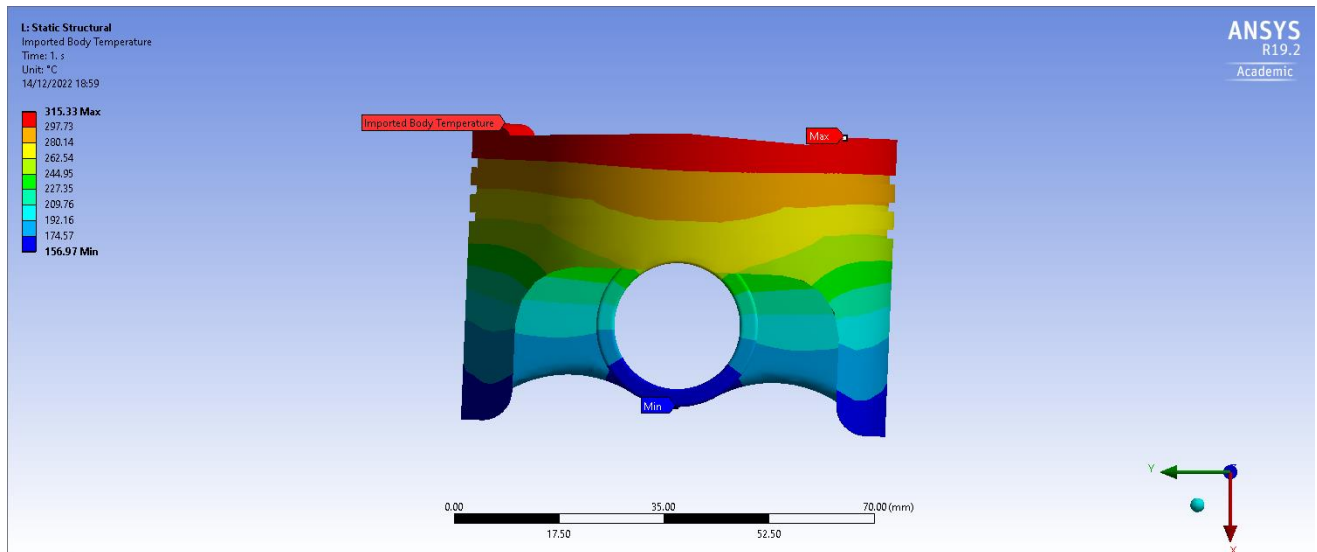


Figure 7-4 - 2618 Temperature Side Profile

7.3 4032 Aluminium

The final material that is being tested is 4032 aluminium the main reason this material has been chosen is down to the fact that the density is smaller than any of the other materials with a value of 2.6g/cm^3 (Makeitfrom, 2022) which has met one of the targets before any testing has been done. When this material was tested a motion load of 2433.2N was achieved and this is greater than the original material implying more force is being created at the same rpm which is another advantage of this material. When the material was tested the following results were given.

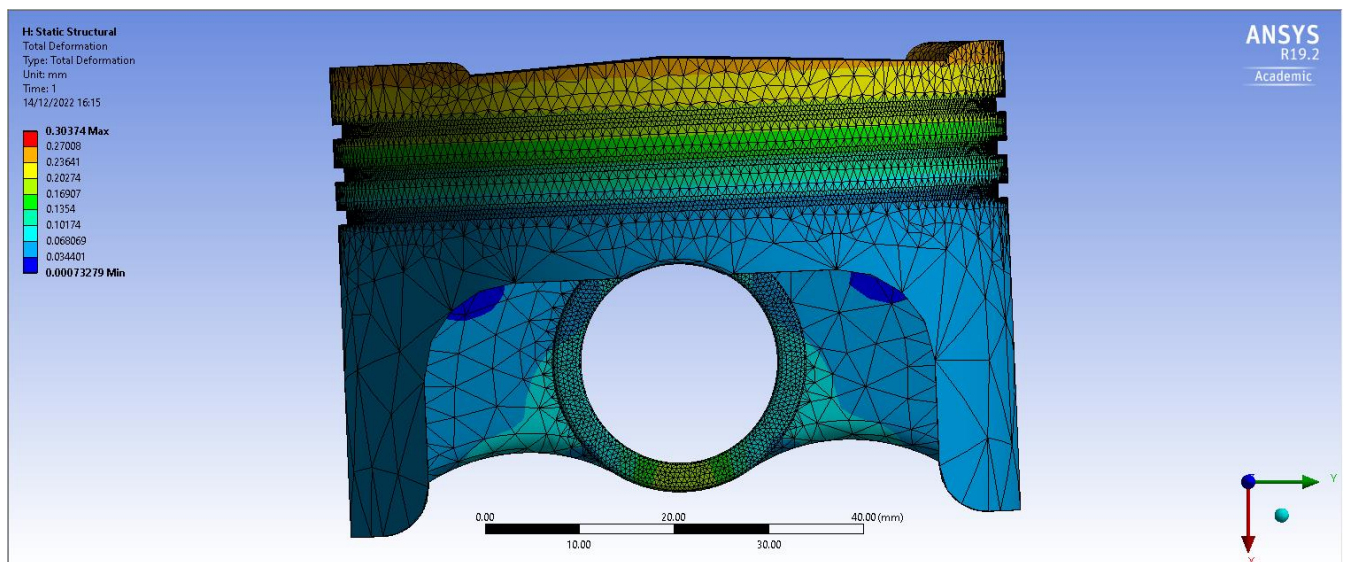


Figure 7-5 - 4032 Total Deformation Side Profile

Figure 7-6 identifies the total deformation within the piston and as seen the deformation has reduced on the crown as well as around the ring for the gudgeon pin and for the max total deformation an improvement of 22.4% has been made which is greater than the deformation target set. The final target was to reduce the overall piston temperature and as can be seen within figure 7-7 below this has also been achieved with a max value of 317.758°C which is nearly 10°C cooler. As a result, 4032 has met all targets and using this material will improve the performance of the piston. Appendix 9.5 shows other angles of the results across the piston and it replicates the same results. The results for the equivalent stresses can also be found in appendix 9.5

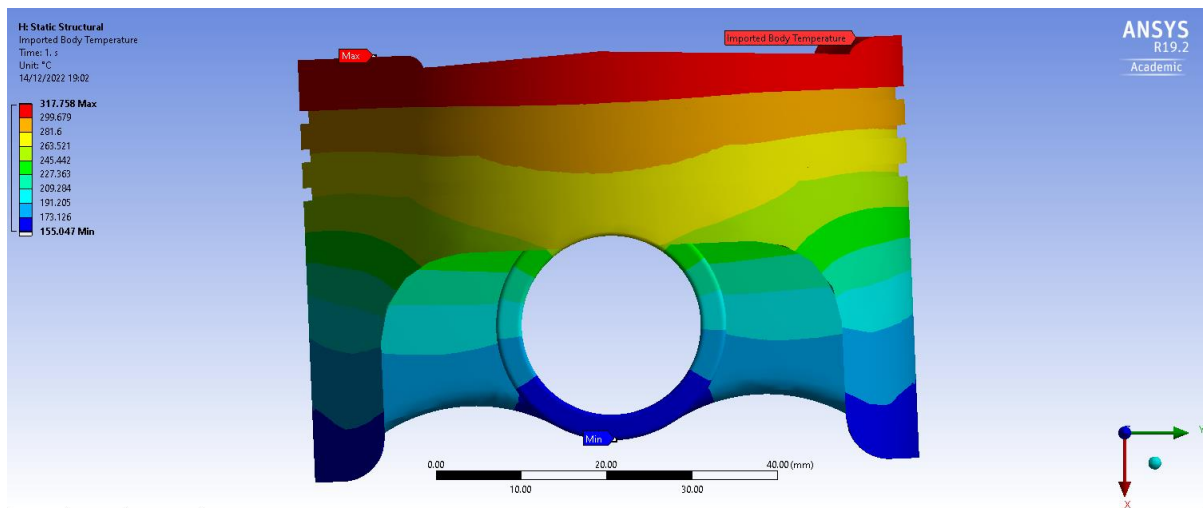


Figure 7-6 - 4032 Temperatures Side Profile

8 Conclusion

From running the validation tests within Ansys it was found that when mesh sizes were changed for the cantilever beam with pressure applied the mesh had no change on the overall result and concluded that the Ansys provided a percentage error of 0.004%, however when a thermal condition was applied to the bimetallic strip, when mesh sizes were changed so did the percentage errors it was found that reducing the mesh size resulted in greater errors and resulted in an optimum mesh size of 1.5mm. When it came to testing the piston, the initial material performed well however there were places for improvement, there was a high total deformation especially around the ring for the gudgeon pin which can result in greater fatigue therefore the material was changed. Although the cast iron piston performed the best in the total deformation category especially reducing the rings deformation due to the other targets it was not successful in becoming the improved material however after running 3 different materials 4032 Aluminium came out on top meeting all targets and coming out with beating the target for the total deformation with an overall improvement of 22% this therefore improves the fatigue life of the piston. To improve on this report tests could have been run to demonstrate the performance of the piston at different rpm's to see whether that had any varying results.

9 Appendix

9.1 Test Boundaries

Thermal Study Boundary Conditions										
	Heat Transfer Coefficient					Temperature (Celcius)				
	1	2	3	4	Average	1	2	3	4	Average
Crown	600	350	500	540	497.5		928.5			928.5
Crown Side	500	540	350	400	447.5	250	650	500	300	425
Top Groove	300	650	200	600	437.5	180	150	180	250	190
Middle Groove	300	650	200	600	437.5	180	150	180	250	190
Oil Groove	260	520	175	400	338.75	165	150	170	170	163.75
Underside	1500	750	250	200	675	95	90	90	90	91.25
Skirt	1000	400	150	300	462.5	110	110	120	90	107.5

Structural Study Boundary Conditions			
	Pressure	Inertia	Side
Max P	10537060	11371.29	7440.469
Max I	304222.2	18089.83	-1.10E-12
Max S	8907806	6954.198	8707.43

Figure 9-1 - Test Boundaries

(Noble, 2022)

9.2 Cantilever Beam Ansys Results

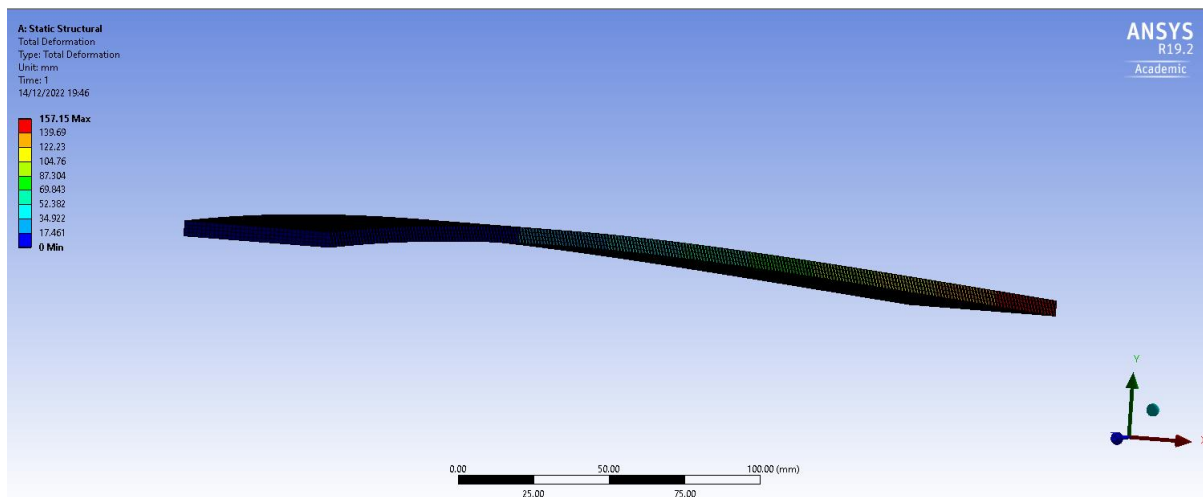


Figure 9-2 - Cantilever Beam 1.5mm mesh

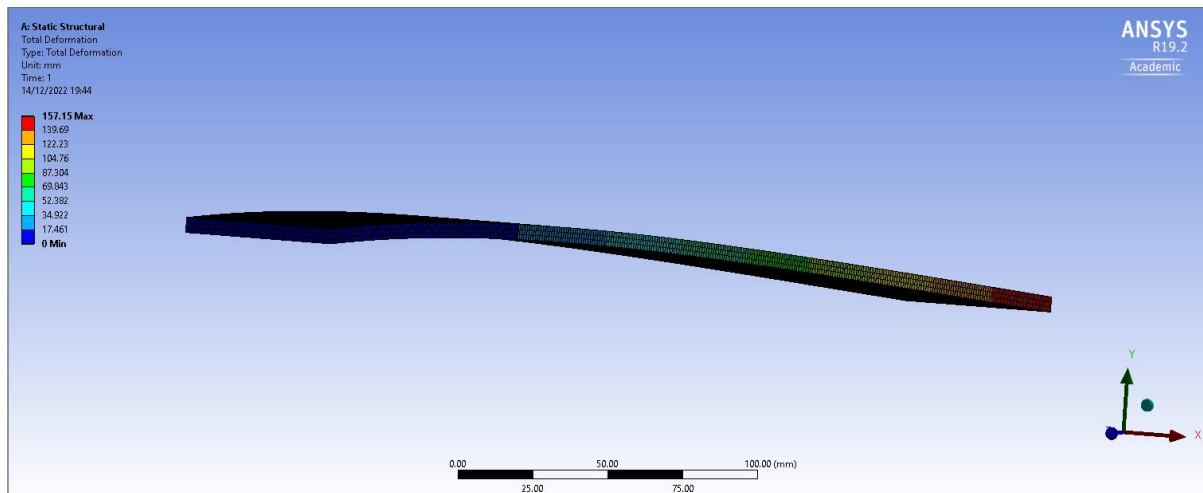


Figure 9-3 Cantilever Beam 2mm mesh

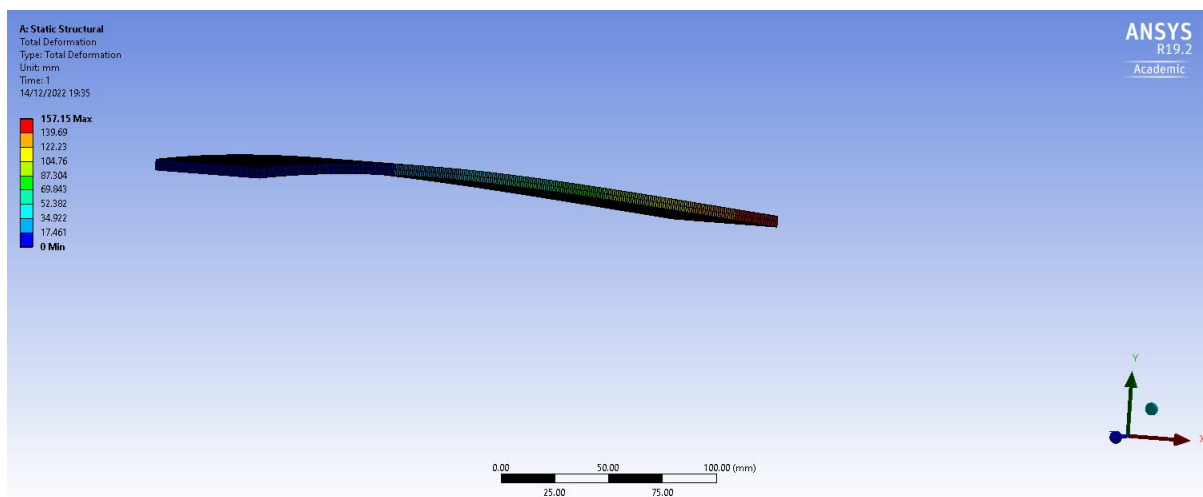


Figure 9-4 - Cantilever Beam 2.5mm mesh

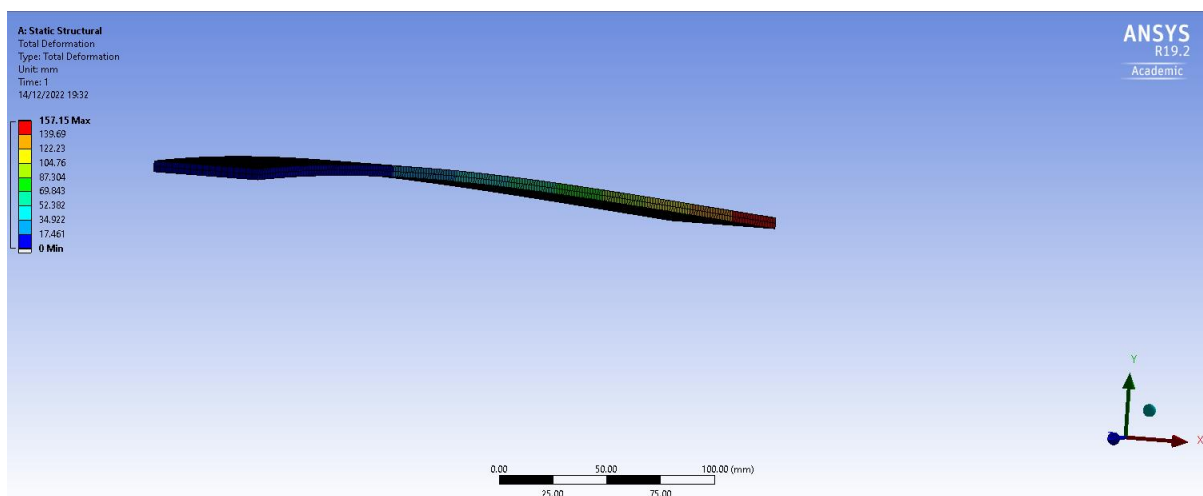


Figure 9-5 - Cantilever Beam 3mm mesh

9.3 Bimetallic Strip Ansys Results

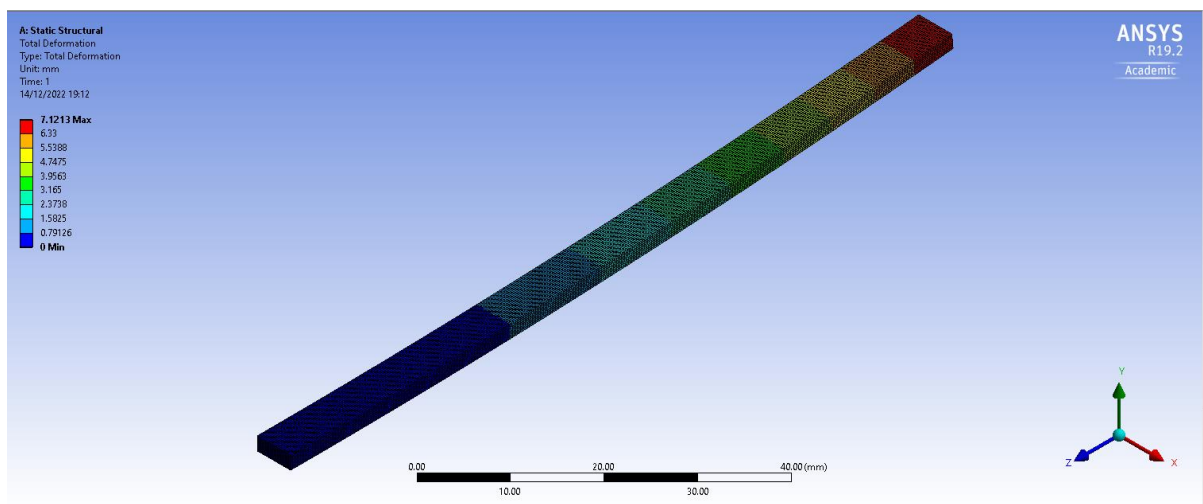


Figure 9-6 - Bimetallic Strip 0.25mm mesh

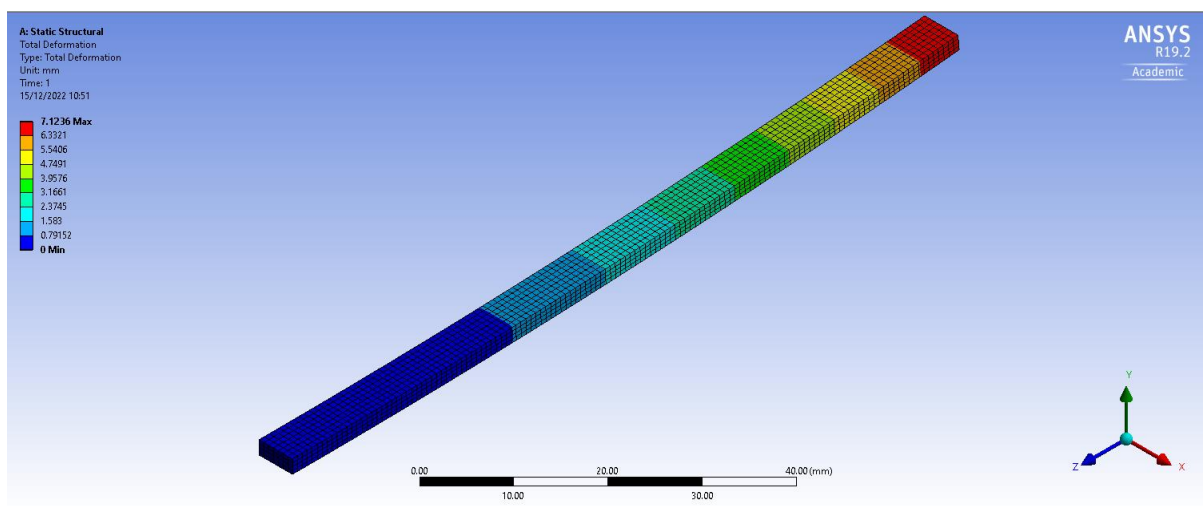


Figure 9-7 - Bimetallic Strip 0.75mm mesh

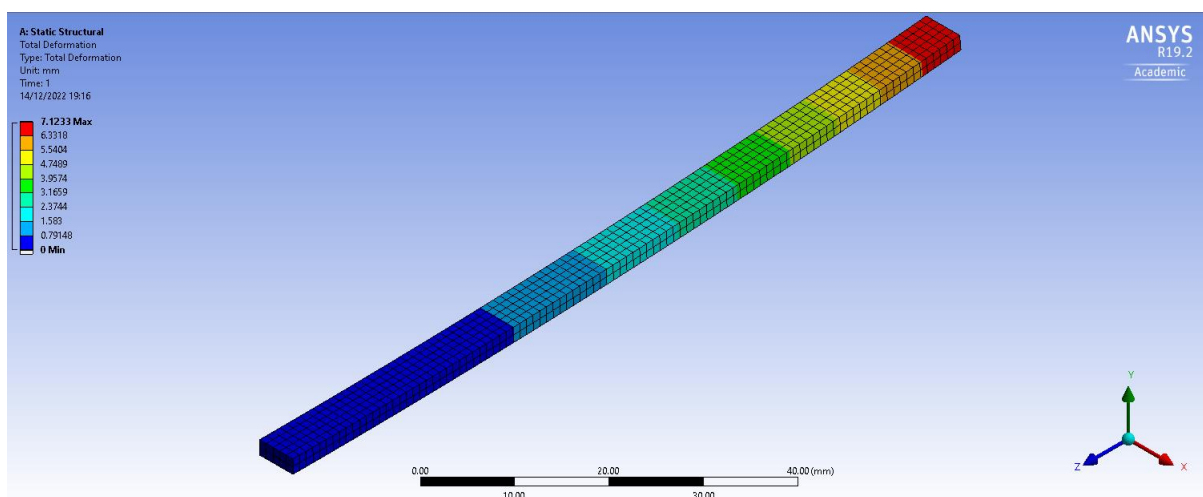


Figure 9-8 - Bimetallic Strip 1mm mesh

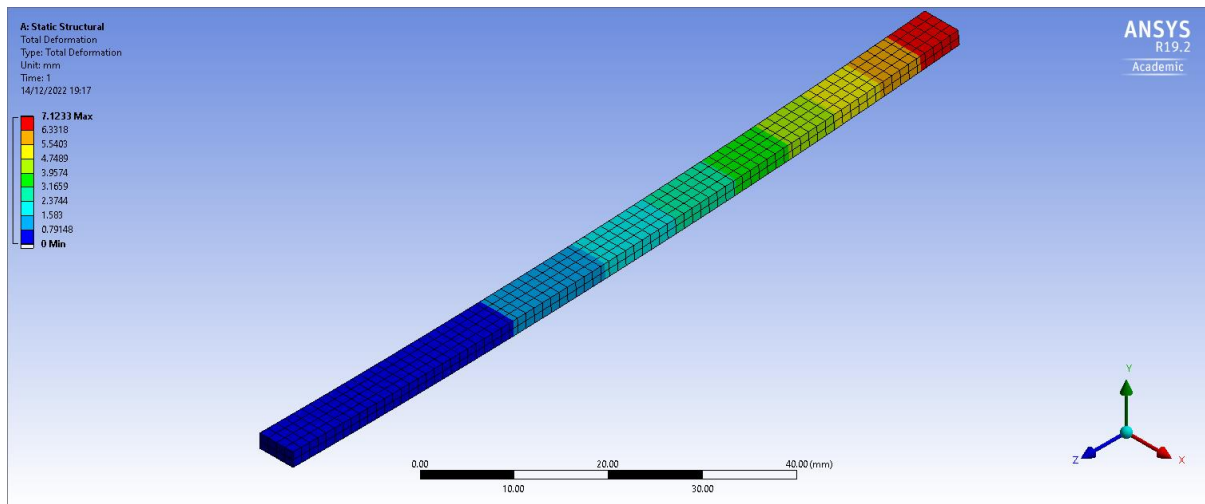


Figure 9-9 - Bimetallic Strip 1.25mm mesh

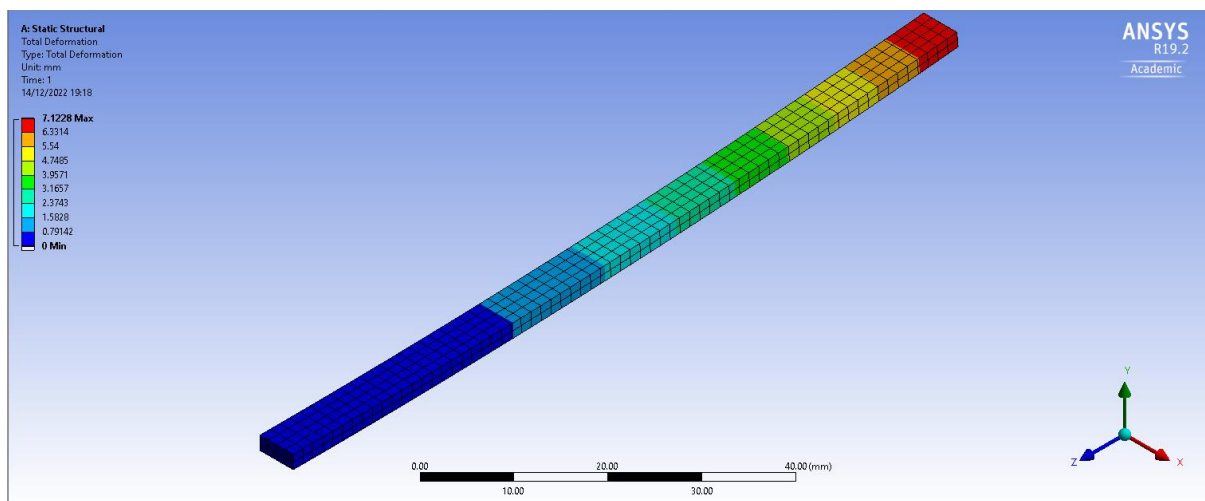


Figure 9-10 - Bimetallic Strip 1.5mm mesh

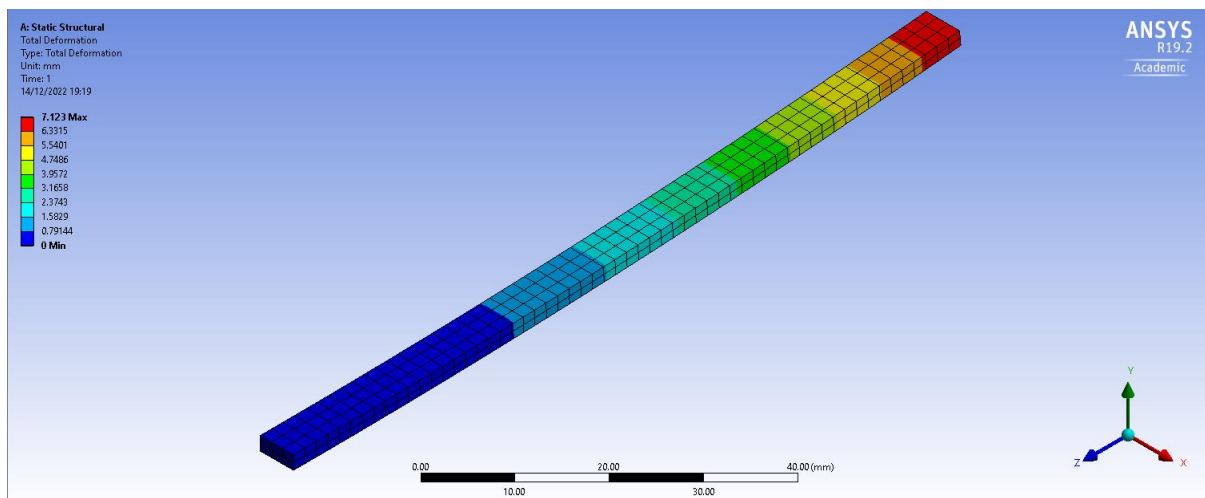


Figure 9-11 - Bimetallic Strip 1.75mm mesh

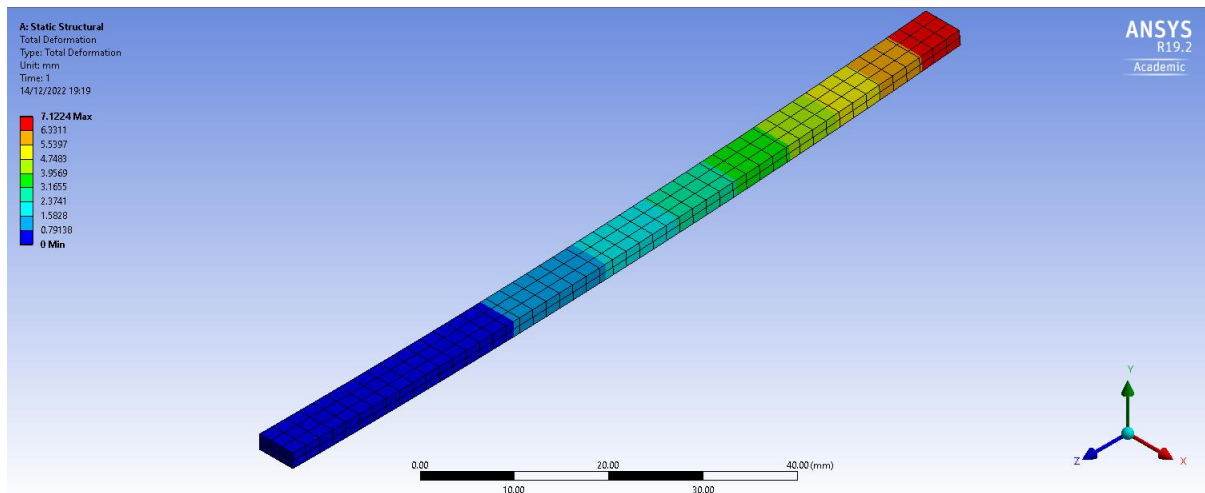


Figure 9-12 - Bimetallic Strip 2mm mesh

9.4 Initial Material Ansys Results

9.4.1 Total Deformation

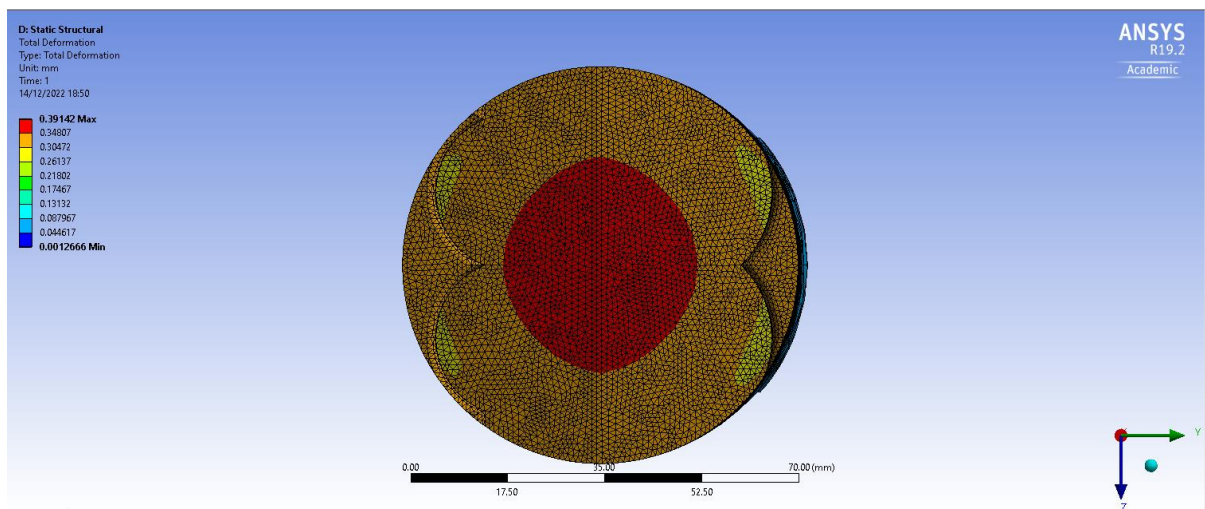


Figure 9-13 - 6061 Total Deformation Top profile

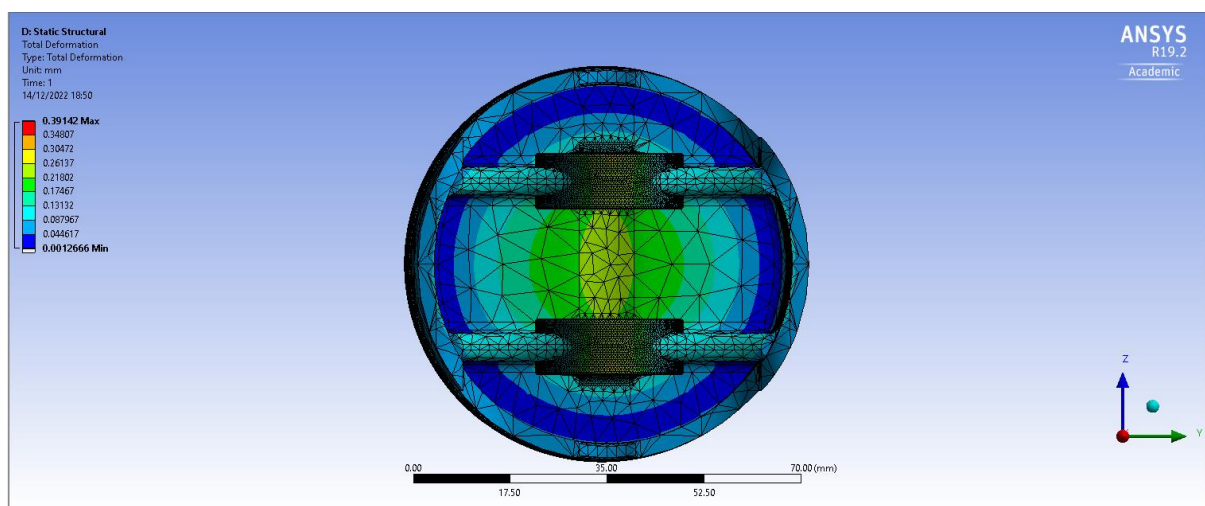


Figure 9-14 - 6061 Total Deformation Underside Profile

9.4.2 Equivalent Stress

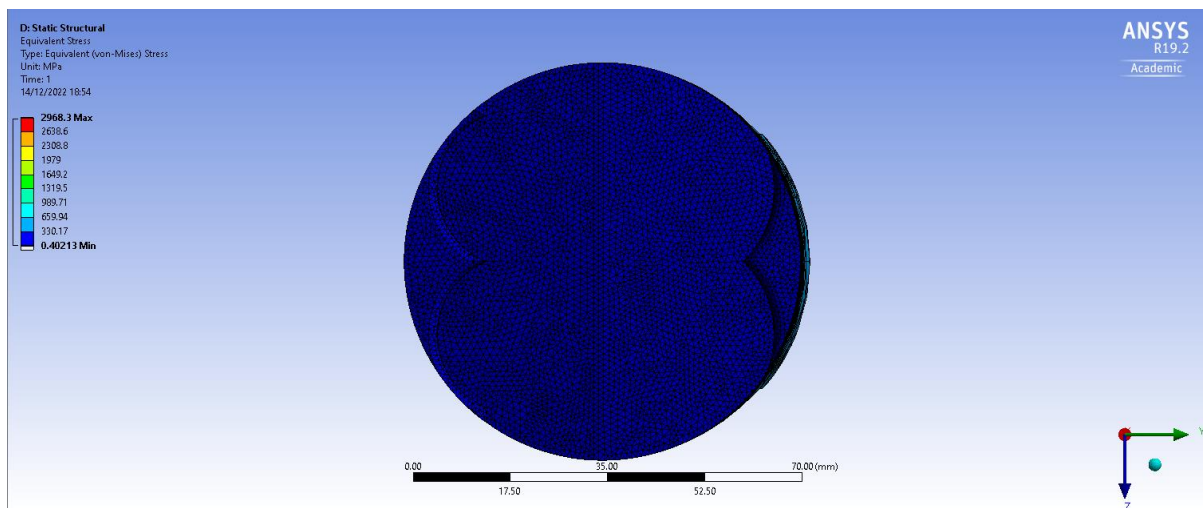


Figure 9-15 - 6061 Equivalent Stress Top Profile

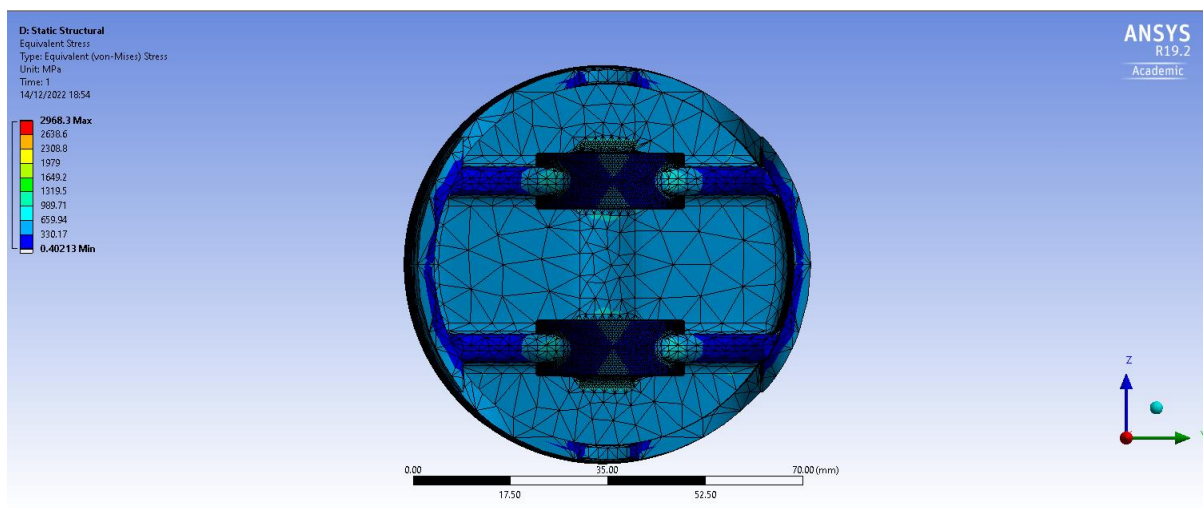


Figure 9-16 - 6061 Equivalent Stress Underneath profile

9.5 4032 Aluminium Ansys Results

9.5.1 Material Properties

Table 9-1 - 4032 Material Properties

Property	Value
Density	2.6 g/cm ³
Poisson's Ratio	0.33
Young's modulus	73Gpa
Thermal Conductivity	140W/m-K
Thermal Coefficient of expansion	1.9E-05 °C ⁻¹

(Makeitfrom, 2022)

9.5.2 Total Deformation

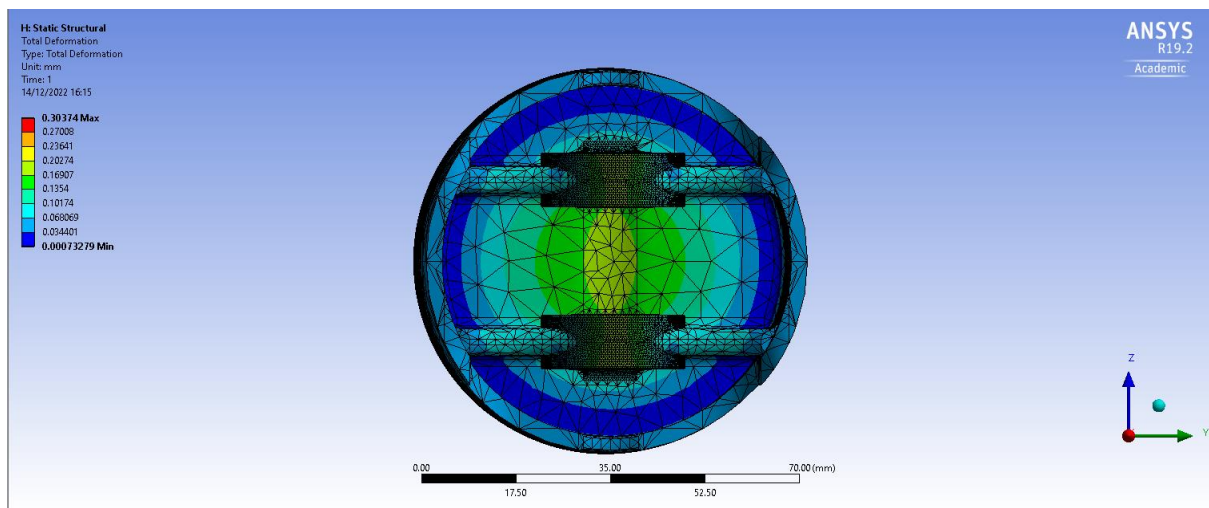


Figure 9-17 - 4032 Total Deformation Underneath profile

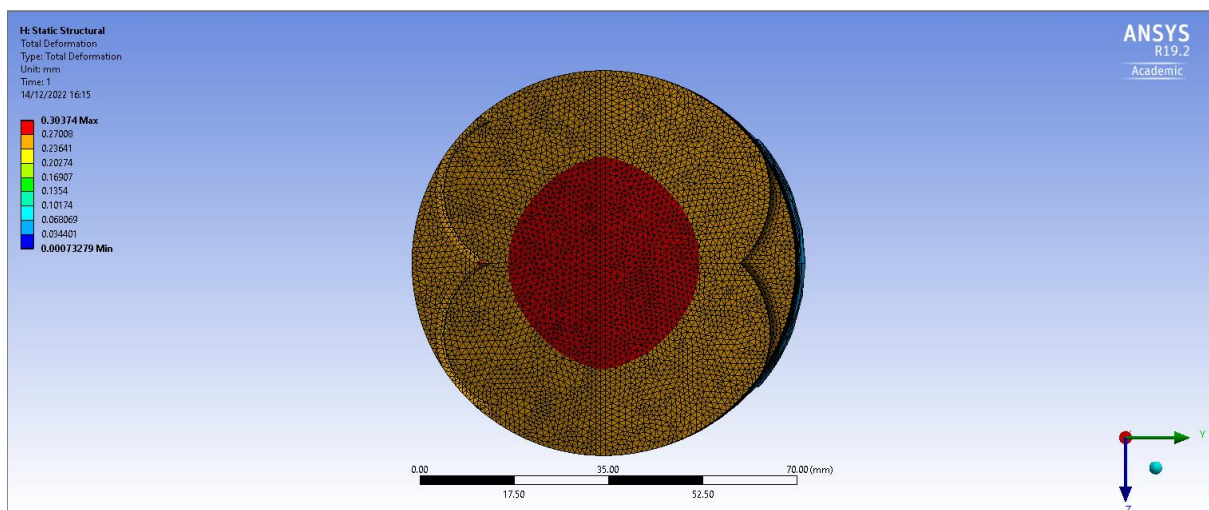


Figure 9-18 - 4032 Total Deformation Top Profile

9.5.3 Equivalent Stress

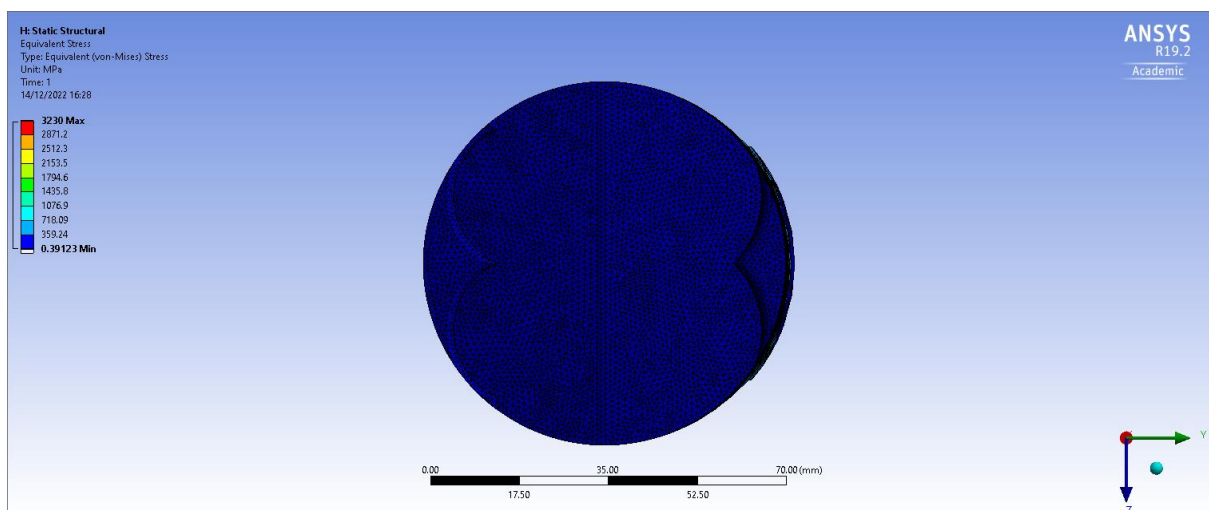


Figure 9-19 - 4032 Equivalent Stress Top Profile

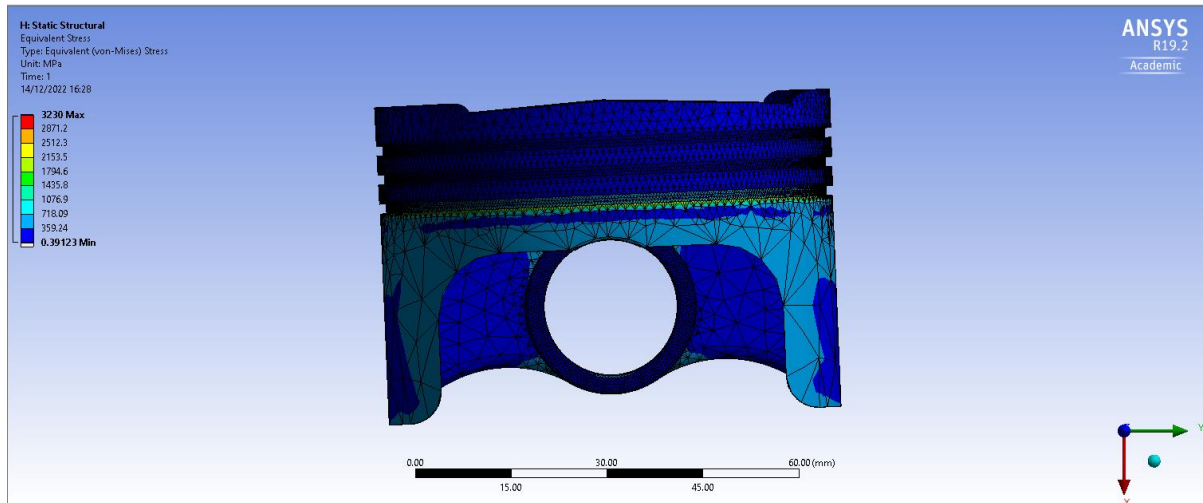


Figure 9-20 - 4032 Equivalent Stress Side Profile

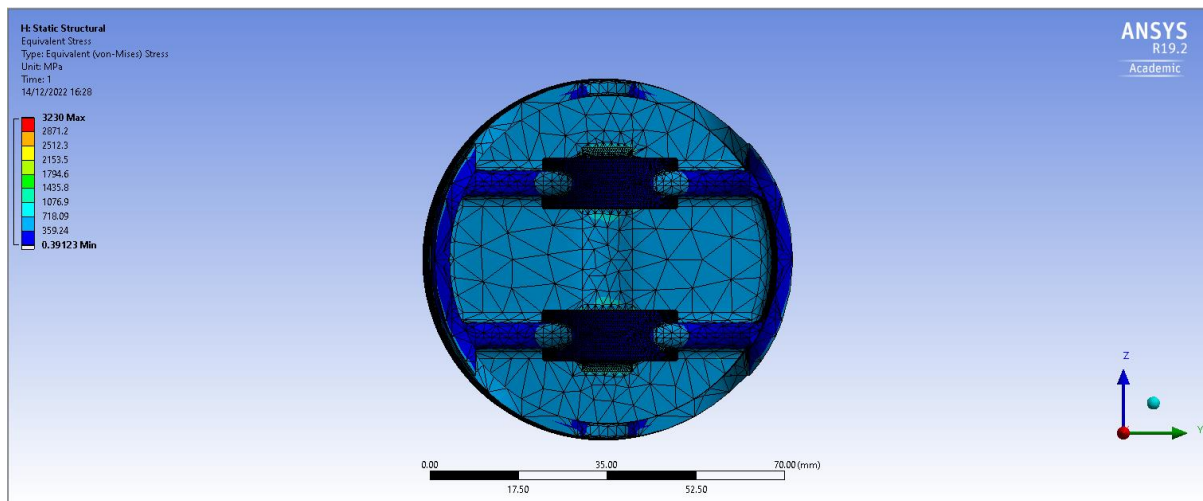


Figure 9-21 - 4032 Equivalent Stress Underneath Profile

9.6 Cast Iron

9.6.1 Material Properties

Table 9-2 - Cast Iron Material Properties

Property	Value
Density	7.05g/cm ³
Poisson's Ratio	0.30
Young's modulus	170Gpa
Thermal Conductivity	36W/m-K
Thermal Coefficient of expansion	1.18E-05 °C ⁻¹

(Edupack, 2022)

9.6.2 Total Deformation

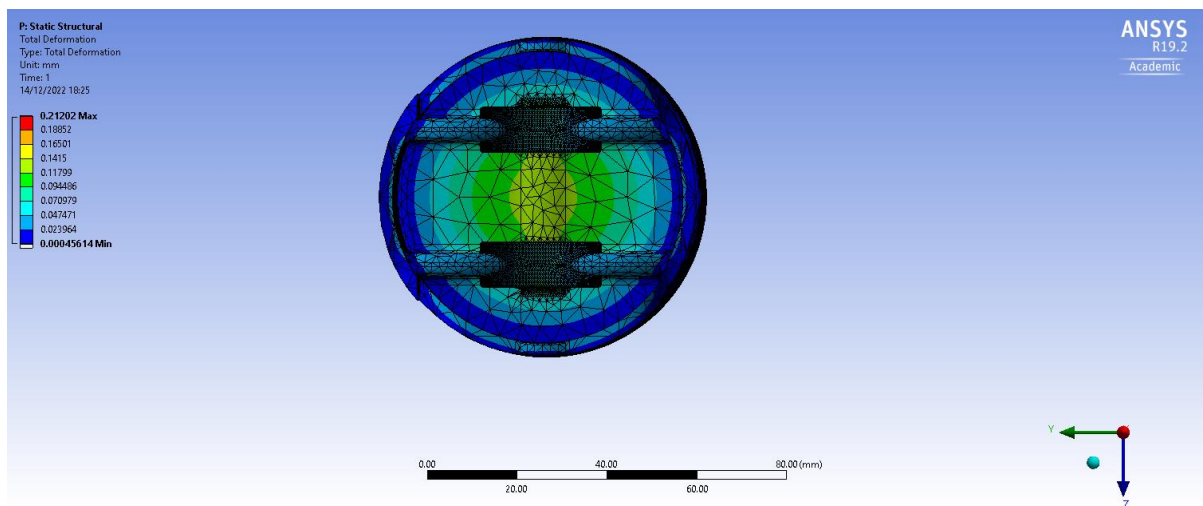


Figure 9-22 - Cast Iron Total Deformation Underneath Profile

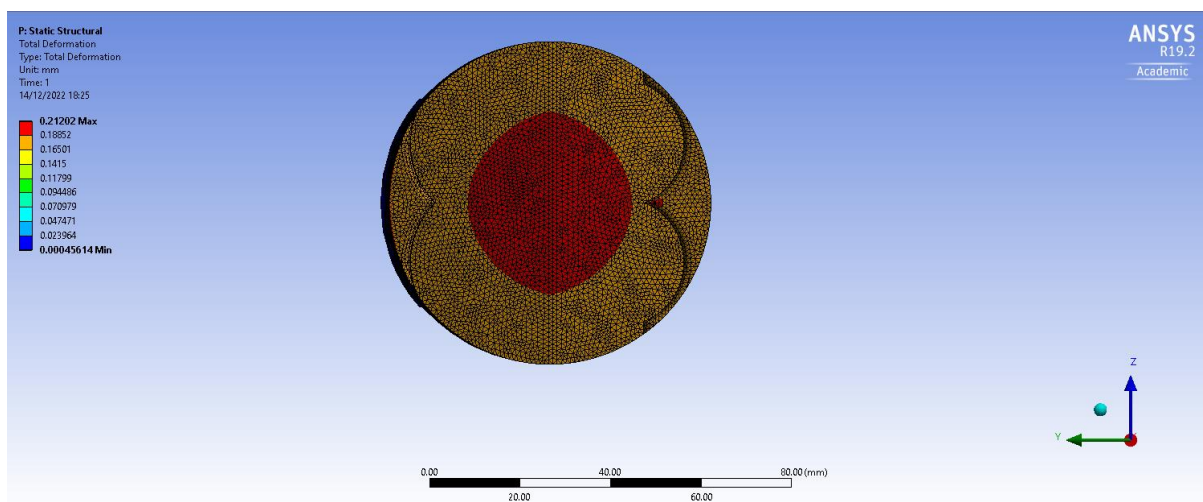


Figure 9-23 - Cast Iron Total Deformation Top Profile

9.6.3 Equivalent stress

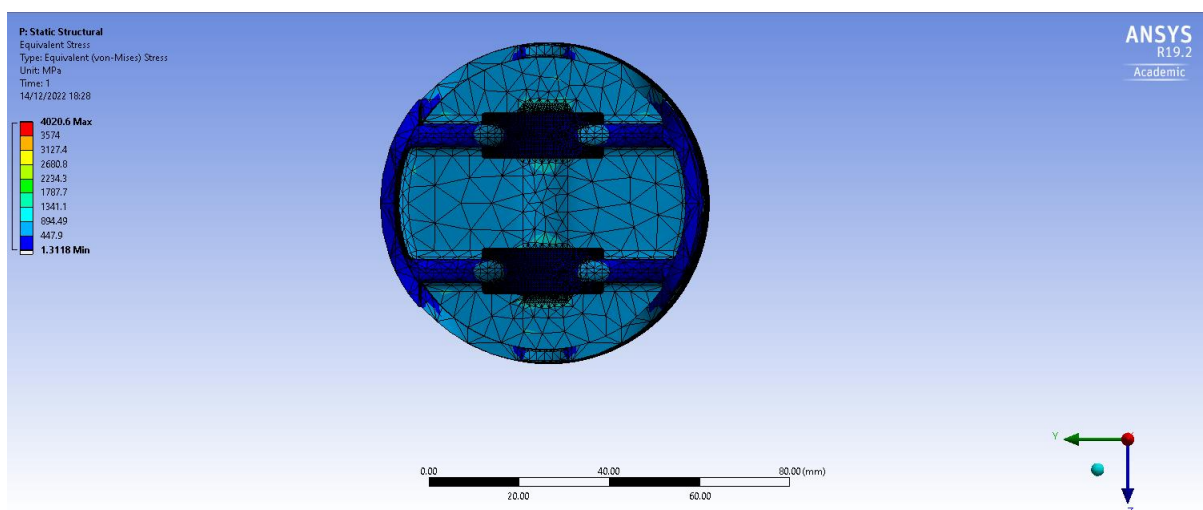


Figure 9-24 - Cast Iron Equivalent Stress Underneath Profile

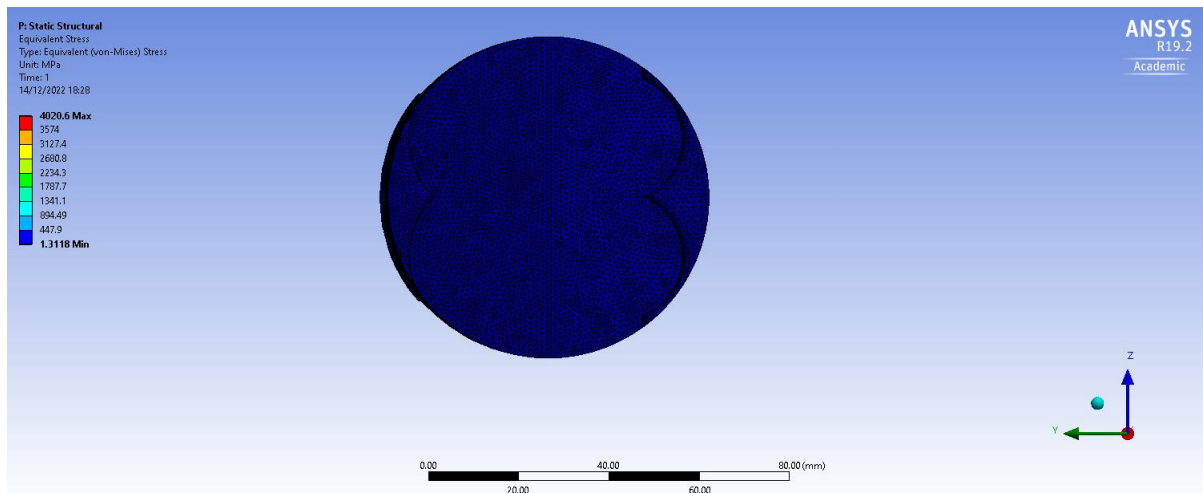


Figure 9-25 - Cast Iron Equivalent Stress Top Profile

9.7 2618 Aluminium

9.7.1 Material Properties

Table 9-3 - 2618 Aluminium Properties

Property	Value
Density	2.75 g/cm ³
Poisson's Ratio	0.33
Young's modulus	74.5Gpa
Thermal Conductivity	146W/m-K
Thermal Coefficient of expansion	2.2E-05 °C ⁻¹

(Smithmetal, 2022)

9.7.2 Total Deformation

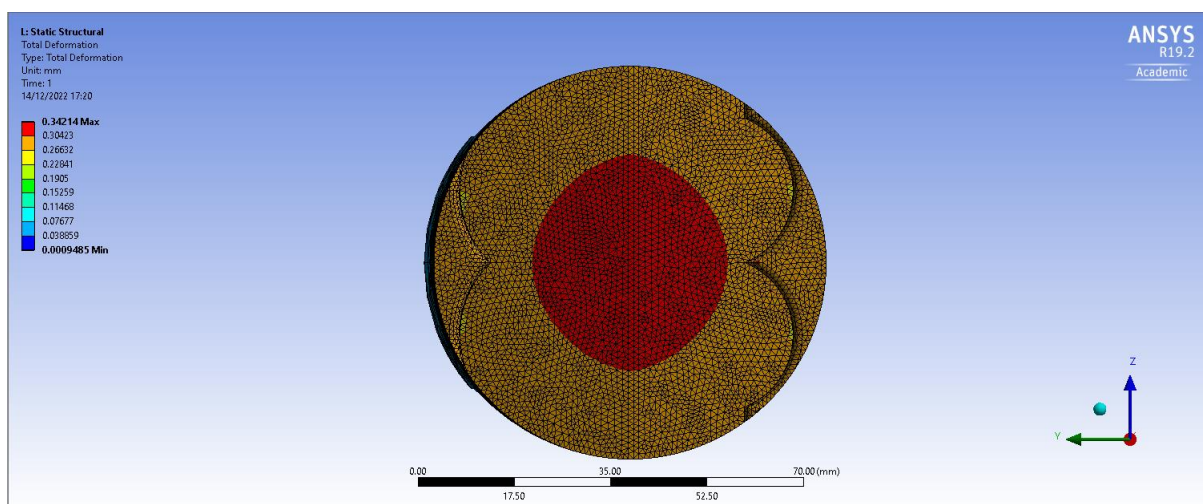


Figure 9-26 - 2168 Total Deformation Top Profile

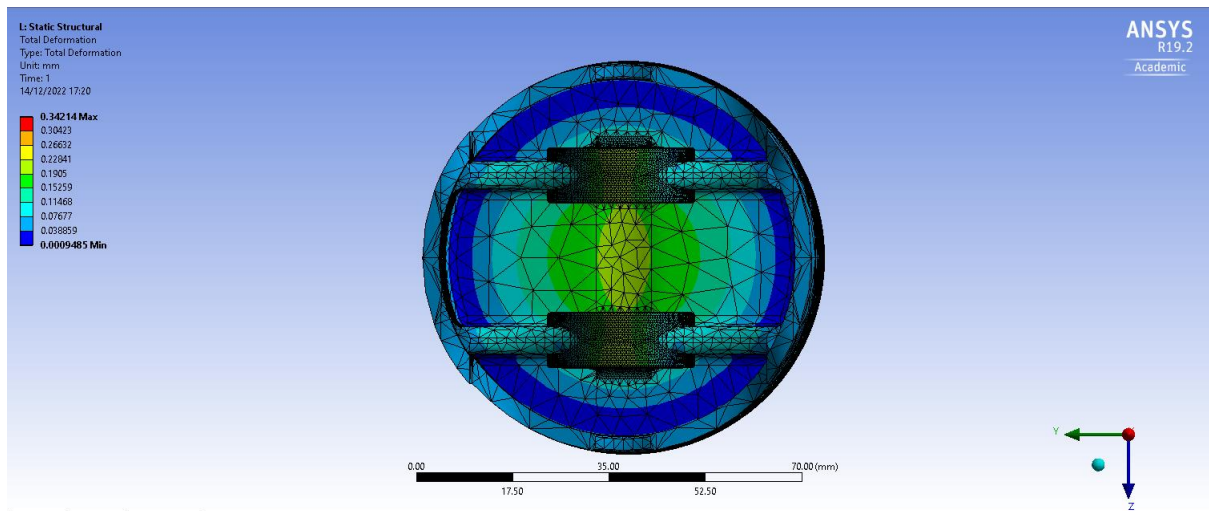


Figure 9-27 - 2168 Total Deformation Underneath Profile

9.7.3 Equivalent stress

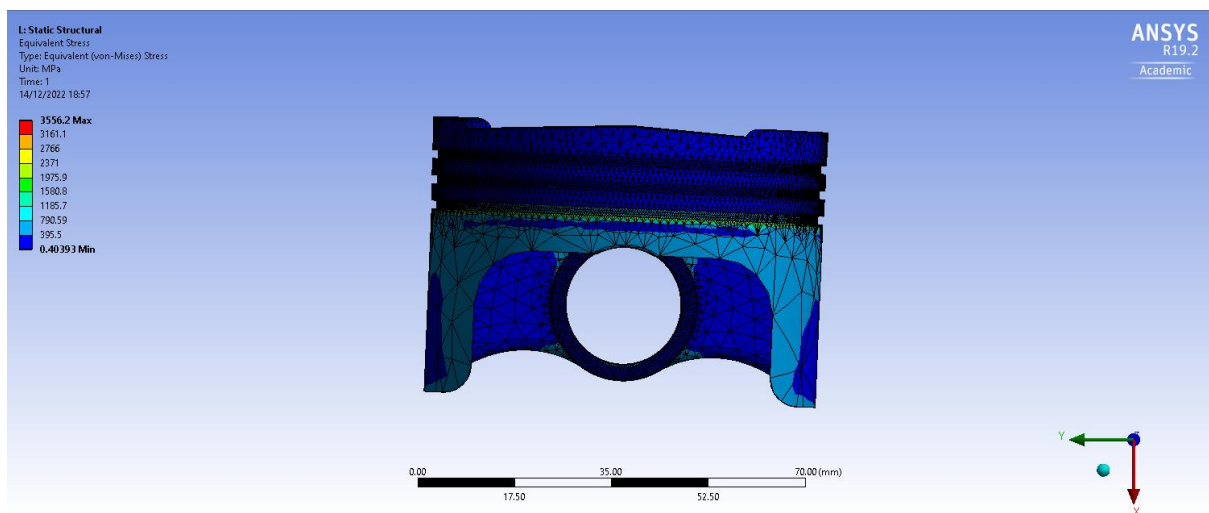


Figure 9-28 - 2168 Equivalent Stress Side Profile

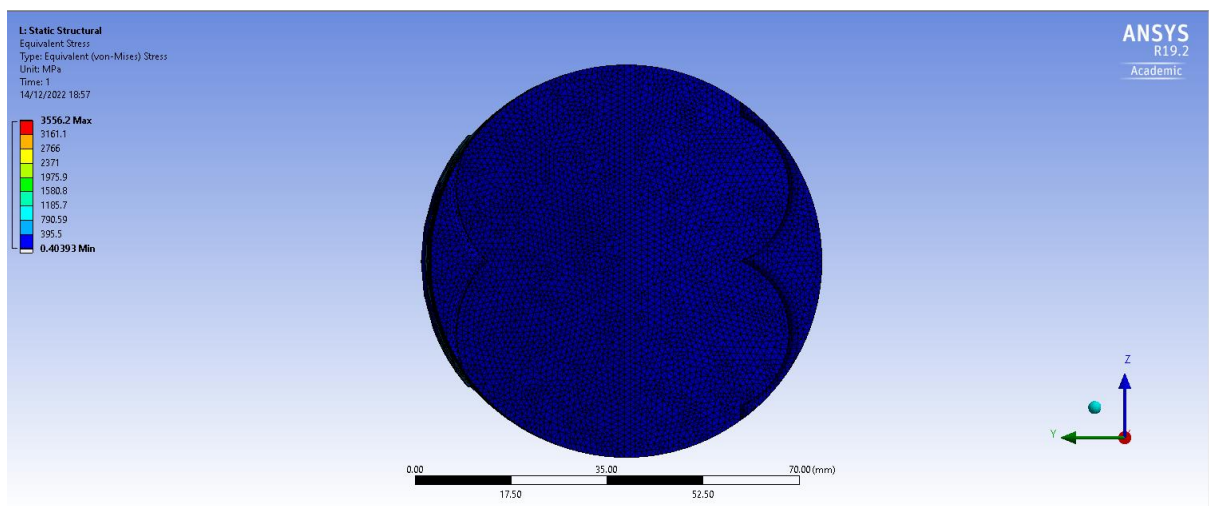


Figure 9-29 - 2168 Equivalent Stress Top Profile

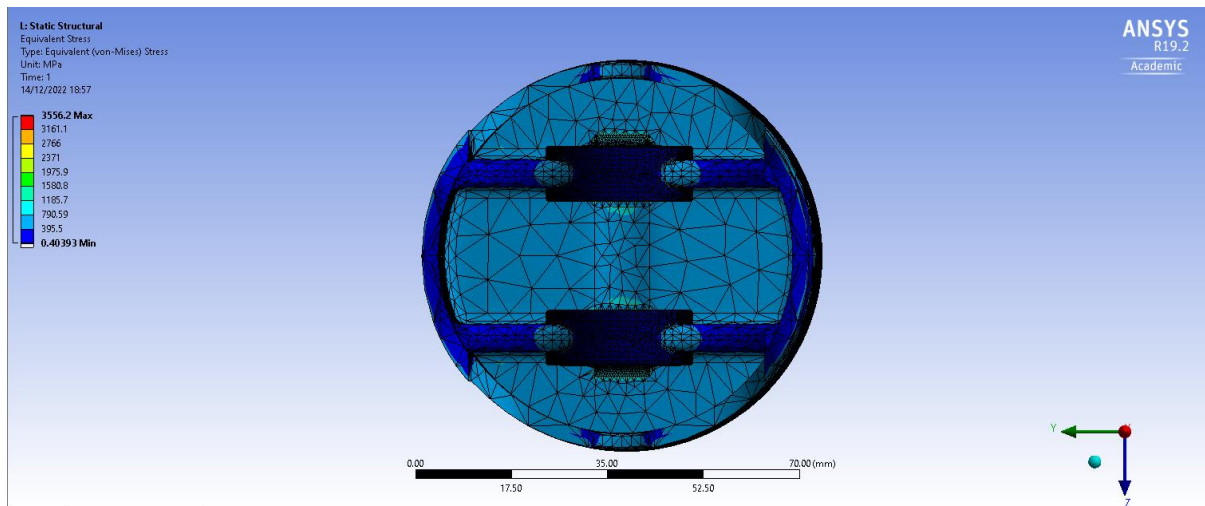


Figure 9-30 - 2168 Equivalent Stress Underneath Profile

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