

APPLICATION OF CAE PROCESSES

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Introduction

In this assignment, both structural and thermal validation tests using analytical as well as computational methods will be conducted to ensure accurate and realistic results can be obtained using Ansys Computer Aided Engineering (CAE) software for simulations and analysis. Following that, the SolidWorks assembly provided (which models a singular piston, gudgeon pin and conrod, connected to a crankshaft from an inline four, four stroke internal combustion engine) will be used as the geometry for detailed kinematics, structural and thermal studies in Ansys. The assembly is highly realistic, which will have a positive effect on the accuracy of the results obtained. The piston within the assembly will be selected for further in-depth analysis and iteratively improved using the data gathered from each previous test to improve its structural performance, whilst optimizing its mass. This data will then be analysed and presented in a clear and comprehensive format.

Task 1: Validation Testing

In CAE, validation is important as it ensures that the results from simulations can be trusted to be accurate and that designs based on them will perform as expected in real-world conditions. Whilst validation tests are set up to the specification stated, simplification of validation examples can negatively affect the accuracy of the results to real life. For this assignment, a structural test and a thermal test will be used for validating the results produced from Ansys.

1.1: Structural Validation

To begin the structural validation, the test specification 0042 – Bending Cantilever with Axial Force from Dlubal, will be used for both analytical and computational, with the results being compared.

1.1.1: Analytical

Material	Steel	Modulus of Elasticity	E	210000.000	MPa
		Poisson's Ratio	ν	0.300	—
Geometry	Cantilever	Length	L	10.000	m
		Cross-section width	w	0.080	m
Load		Transversal Force	F_z	7.650	kN
		Axial Force	F_x	1.600	kN

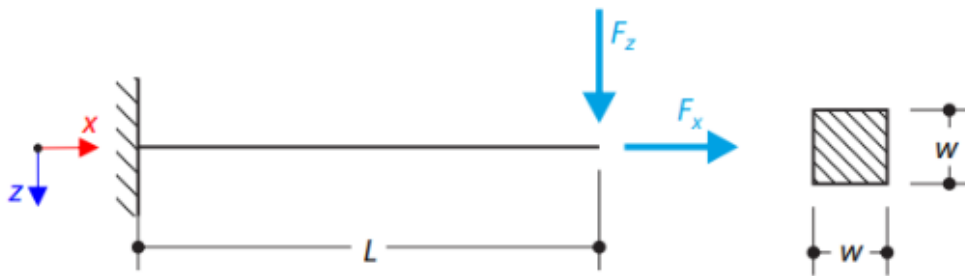


FIGURE 1: STRUCTURAL VALIDATION VALUES TABLE AND PROBLEM SKETCH (DLUBAL, N.D.)

1.1.1.1: Total Deformation

1.1.1.1.1: CROSS-SECTIONAL AREA

$$A = w^2 = (0.08)^2 = 0.0064 \text{ m}^2$$

1.1.1.1.2: MAXIMUM DEFORMATION (X-AXIS)

$$U_{x \max} = \frac{F_x L}{EA} = \frac{1.6 \times 10}{(210 \times 10^9) \times 0.0064} = 0.01190476 = 0.012 \text{ mm}$$

1.1.1.1.3: MOMENT OF AREA ABOUT THE Y-AXIS

$$I_y = \frac{1}{12} w^4 = \frac{1}{12} \times (0.08^4) = 3.413 \times 10^{-6} \text{ m}^4$$

1.1.1.1.4: MAXIMUM DEFORMATION (Z-AXIS)

$$U_{z \max} = \frac{F_z L^3}{3EI_y} = \frac{7.65 \times 10^3}{3 \times (210 \times 10^9) \times (3.413 \times 10^{-6})} = 3.557825122 \times 10^{-3} = 3557.478 \text{ mm}$$

1.1.1.1.5: TOTAL DEFORMATION

$$\delta_{\max} = 3557.478 + 0.012 = 3557.49 \text{ mm}$$

1.1.1.2: Total Stress

1.1.1.2.1: BENDING MOMENT

$$M = F_z L = (7.65 \times 1000) \times 10 = 76,500 \text{ Nm}$$

1.1.1.2.2: SECTION MODULUS

$$S = \frac{w^3}{6} = \frac{0.08^3}{6} = 0.0000853 \text{ m}^3$$

1.1.1.2.3: BENDING STRESS

$$\sigma_{bending} = \frac{M}{S} = \frac{76500}{0.0000853} = 896,734,697.4 \text{ Pa} = 896.7 \text{ MPa}$$

1.1.1.2.4: AXIAL STRESS

$$\sigma_{axial} = \frac{F_x}{A} = \frac{(1.6 \times 1000)}{(0.08 \times 0.08)} = 250,000 \text{ Pa} = 0.25 \text{ MPa}$$

1.1.1.2.5: TOTAL STRESS

$$\sigma_{total} = \sigma_{bending} + \sigma_{axial} = 896.7 + 0.25 = 896.95 \text{ MPa}$$

1.1.2: CAE

The geometry was created in Solidworks, using the measurements stated in the validation specification (Figure 1). The geometry was saved as a .STEP file. In Ansys Workbench, a static structural analysis project was created. A new material was made within the engineering data and the data from figure 1 being used to populate the young's modulus and poison's ratio values for the materials (Steel) linear isotropic elasticity properties. A global mesh element size of 10mm was used.

1.1.2.1: Geometry

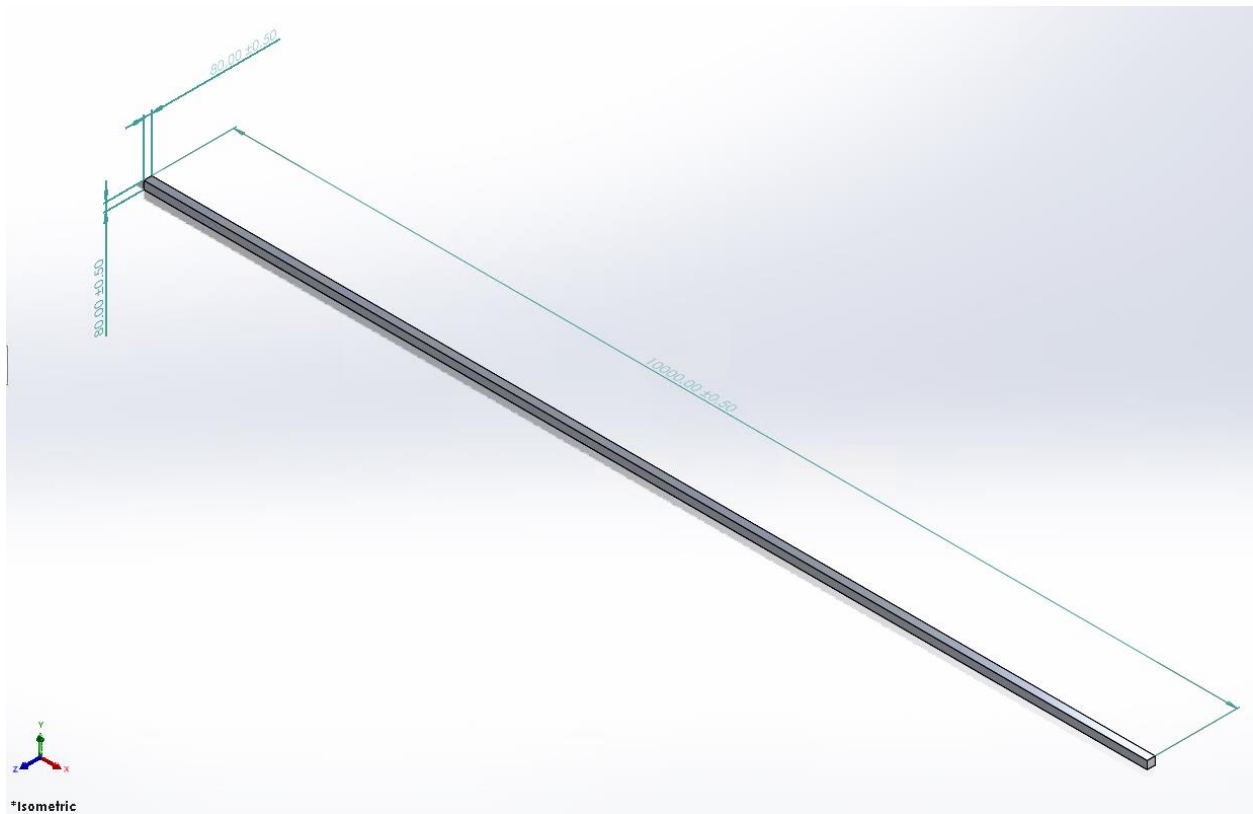


FIGURE 2: STRUCTURAL VALIDATION BEAM GEOMETRY

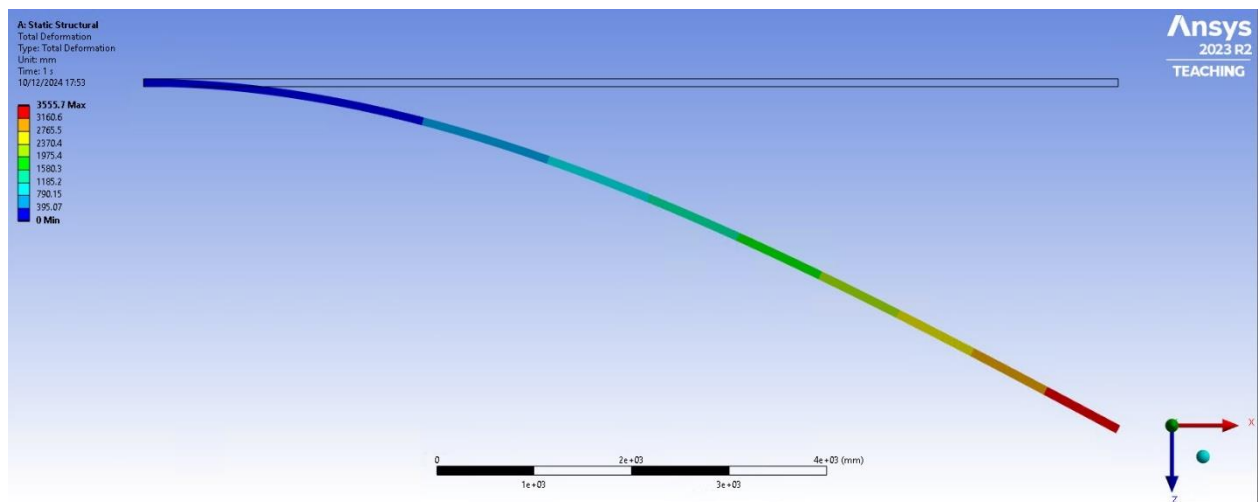


FIGURE 3: BEAM STATIC STRUCTURAL TOTAL DEFORMATION

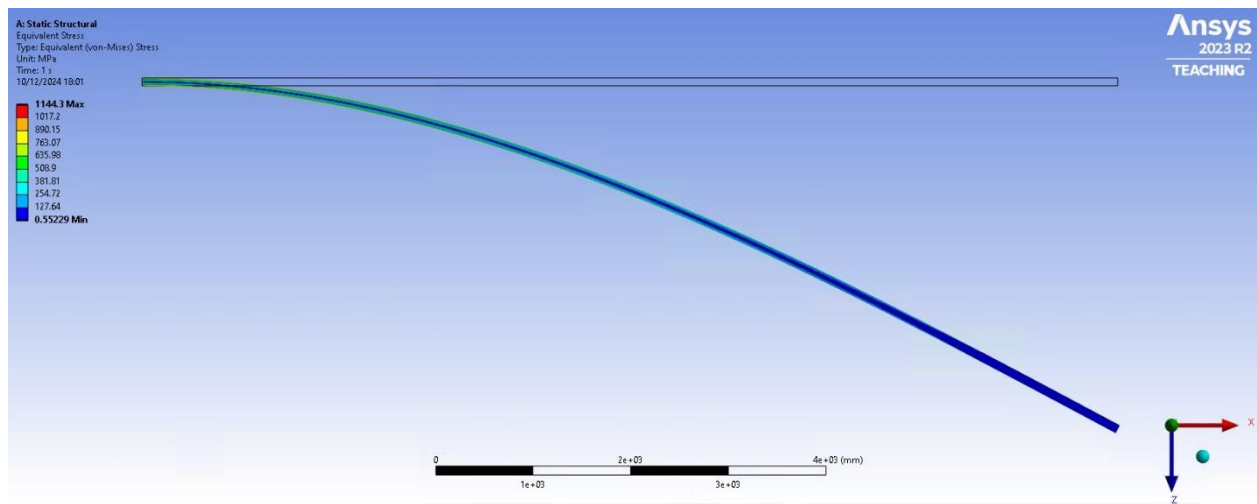


FIGURE 4: BEAM STATIC STRUCTURAL EQUIVALENT (VON-MISES) STRESS

A global mesh element size of 50mm was used.

1.2: Thermal Validation

Following the structural validation, the 0078 – Bimetallic Strip specification by Dulbal was used to validate the thermal studies, both analytically and computationally. The Strip is composed of an Invar strip on top of a Copper Strip.

Material	Invar	Modulus of Elasticity	E_I	137000.000	MPa
		Poisson's Ratio	ν_I	0.280	—
		Coefficient of Thermal Expansion	α_I	1.200×10^{-6}	$^{\circ}\text{C}^{-1}$
	Copper	Modulus of Elasticity	E_C	130000.000	MPa
		Poisson's Ratio	ν_C	0.354	—
		Coefficient of Thermal Expansion	α_C	2.000×10^{-5}	$^{\circ}\text{C}^{-1}$
Geometry		Cross-section Width	w	5.000	mm
		Layer Thickness	$t_I = t_C = t$	1.000	mm
		Length	L	100.000	mm
Load		Thermal Loading	T_c	100.000	$^{\circ}\text{C}$

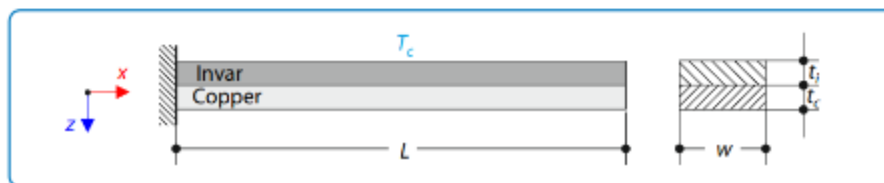


FIGURE 5: BIMETALLIC STRIP THERMAL VALIDATION STUDY

1.2.1: Analytical

$$K_1 = 4 + 6 \frac{1}{1} + 4 \left(\frac{1}{1} \right)^2 + \frac{130000}{137000} \times \left(\frac{1}{1} \right)^3 + \frac{(137000 \times 1)}{(130000 \times 1)} = 16.00275126$$

$$u_{z \max} = \frac{(6 \times ((1.200 \times 10^{-6}) - (2.000 \times 10^{-5})) \times (1 + 1) \times 100)}{(1^2 \times 16.00275126)} \times \frac{100^2}{2} = -7.049 \text{ mm}$$

1.2.2: CAE

1.2.2.1: Geometry/Assembly

Figure 6 Shows the Bimetallic Strip geometry, made to the specifications in Figure 5, within SolidWorks.

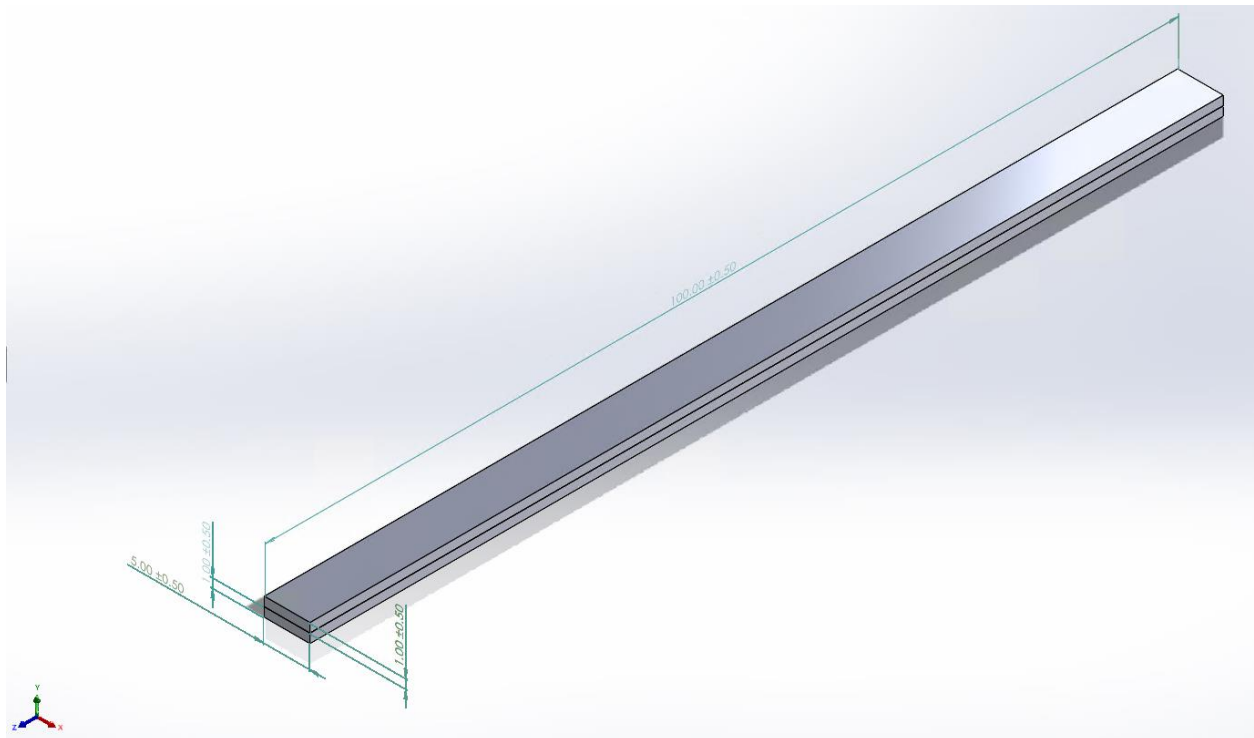


FIGURE 6: BIMETALLIC STRIP DIMENSIONS

1.2.2.2: Boundary Conditions

The boundary conditions, shown in Figure 7, were set as the same as stated by the validation specification.

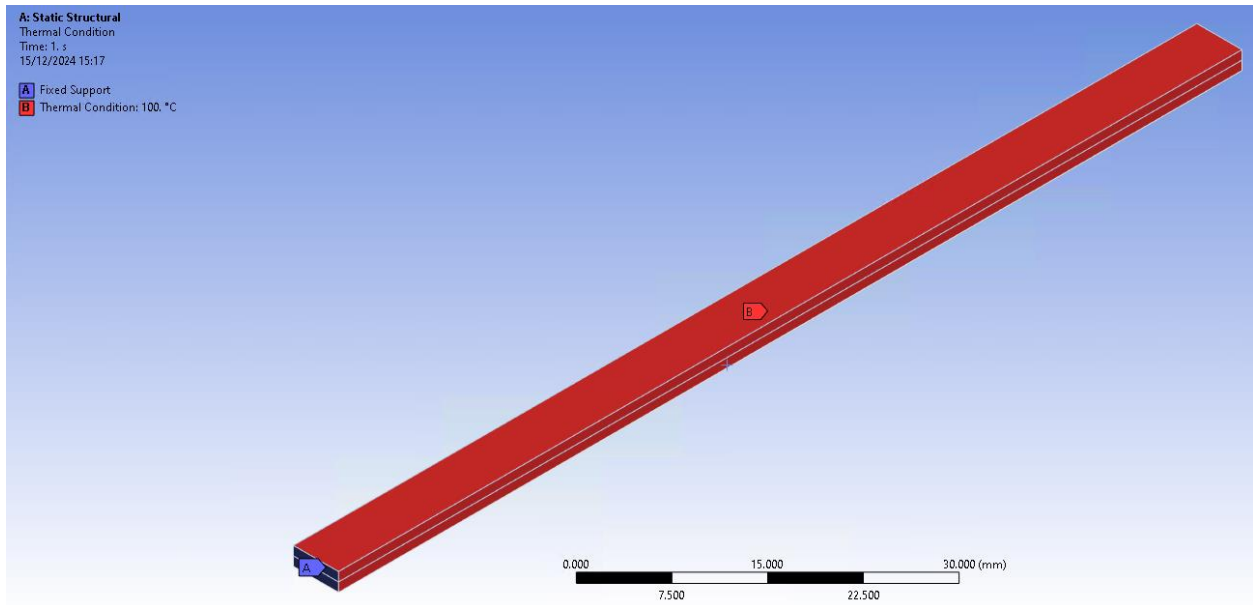


FIGURE 7: BIMETALLIC STRIP BOUNDARY CONDITIONS

1.2.2.3: Mesh Independence Study

A study was conducted to find the point of mesh independence for the Bimetal Strip, with mesh sizes from 2 to 0.1mm. 1mm mesh element size was found to be optimal as smaller element sizes increased the meshing time significantly, whilst the deviation change was small.

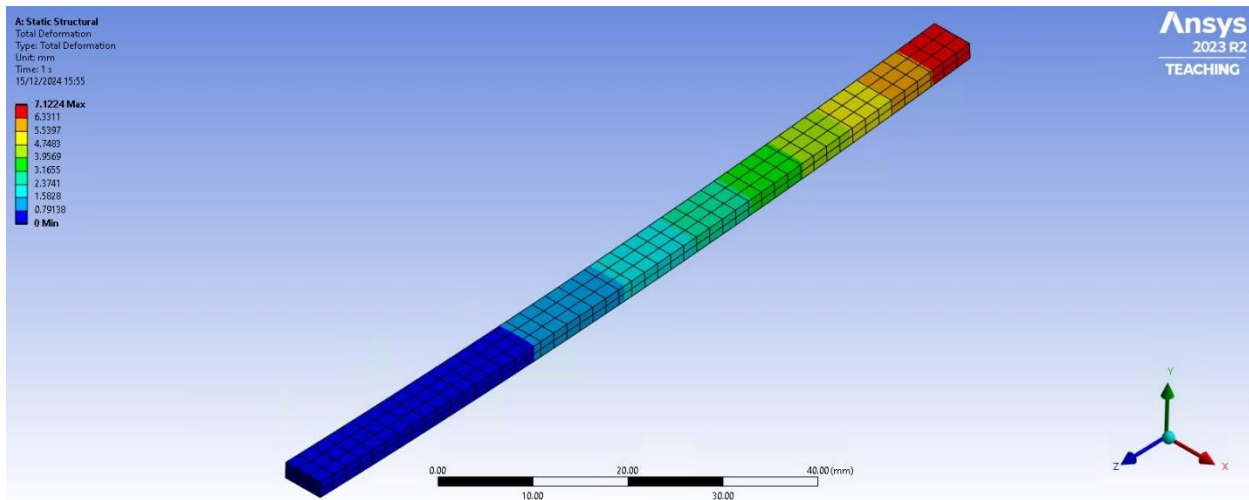


FIGURE 8: BIMETALLIC STRIP 2 MM MESH

$$\frac{7.049}{7.1224} = 989.694 \times 10^{-3} \text{ mm}$$

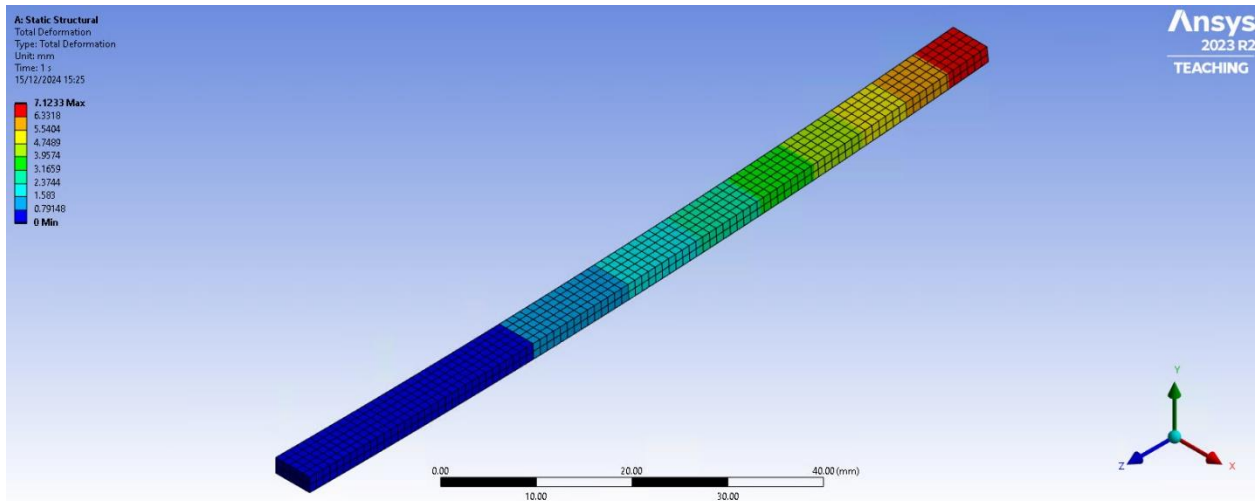


FIGURE 9: BIMETALLIC STRIP 1 MM MESH

$$\frac{7.049}{7.1233} = 989.569 \times 10^{-3} \text{ mm}$$

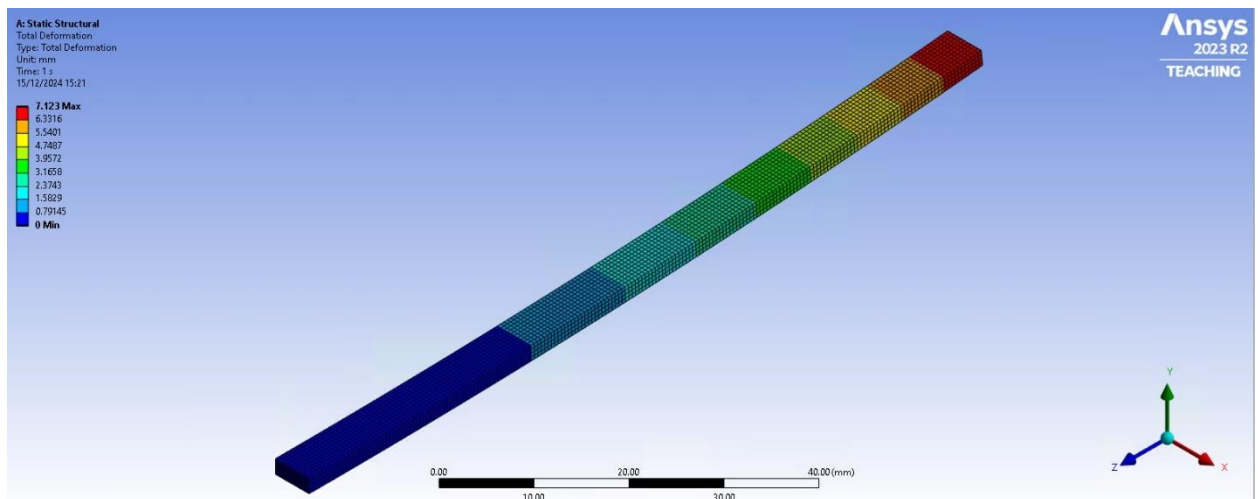


FIGURE 10: BIMETALLIC STRIP 0.5 MM MESH

$$\frac{7.049}{7.123} = 989.611 \times 10^{-3} \text{ mm}$$

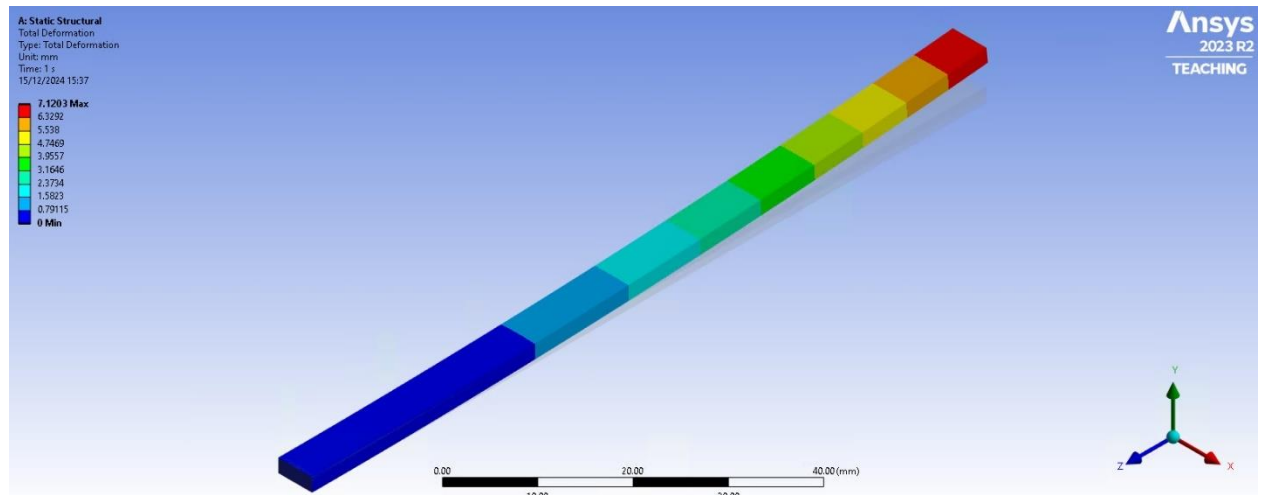


FIGURE 11: BIMETALLIC STRIP 0.1 MM MESH

$$\frac{7.049}{7.1203} = 989.986 \times 10^{-3} \text{ mm}$$

Task 2: Assembly Kinematic Analysis

Following validation, the provided assembly was then used for a baseline Kinematic Analysis using Ansys. Kinematics is important as it “provides fundamental information that is required for the dynamics evaluation and design of components, as it provides information that is required for a performance analysis through a phenomenological, i.e., thermodynamic, simulation” (Rufno & Ferreira, 2018)

2.1: Material Selection

The material for each component in the assembly was applied prior to the Kinematics Study. The material type and properties have a major impact on the entire study as it can affect the mass of the component as well as the structural and thermal performance.

A custom 6061 T6 Aluminum material was made in Ansys, which was used for the original piston and the first piston design change. The data was sourced from the Piston Thermal Study document (Andrew, n.d). The density value for the material was sourced from Ansys Granta’s 6061 T6 Aluminium.

Aluminum is a commonly used material for ICE pistons. McCune & Weber states that “Automotive engine pistons are most frequently made from aluminum alloys” (McCune & Weber, 2001). More specifically, pistons are produced from cast or forged, high-temperature resistant aluminum silicon alloys. (European Aluminium Association, 2011) Due to this, 6061 was the chosen aluminum alloy as it contains silicon as one of its major alloying elements.

The material used for the Gudgeon Pin and Conrod was Low Alloy Steel, AISI 4140, Oil quenched & tempered at 540°C. Myagkov explains that piston pins in ICE’s are typically made from alloy carburized steel. (Myagkov, 2014) Whilst McCune & Weber states that “coupling to the piston is usually through a hardened steel gudgeon pin through the piston body.” (McCune & Weber, 2001)

For the crankshaft, carbon steel, AISI 1040, annealed, was used as “in low and medium speed engines, crankshafts are frequently made of low alloy carbon steels such as 1040.” (Myagkov, 2014)

2.2: Assembly Kinematics Study

A joint probe, measuring force, was placed onto the joint between the piston and gudgeon pin. This will show the amount of force being enacted on the piston during the engine cycle. The assembly within Ansys can be seen in Figure 12 below.

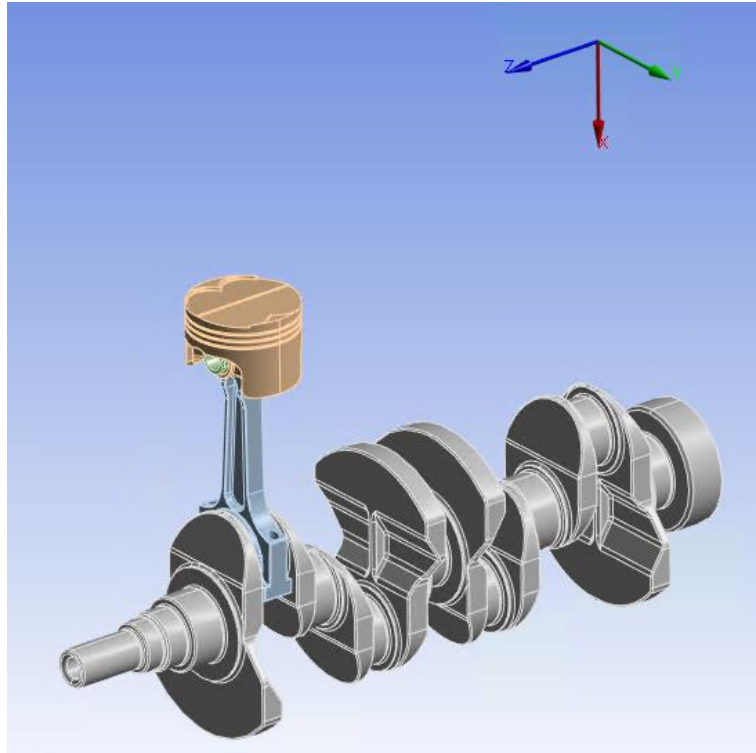


FIGURE 12: ENGINE ASSEMBLY WITHIN ANSYS

2.3: Results

At 4000 RPM, the maximum and minimum total force measured from the joint probe during the engines cycle was shown as 2369.3 N and 56.403 N, respectively. These results will be compared with the results of the other design iterations.

Task 3: Component Static Structural and Thermal Study

Using the results from the kinematic analysis above, a static structural and thermal assessment on the piston from the assembly was conducted. The piston was chosen as the component to further analyse, through Structural and Thermal studies, as “Modern engines can now achieve specific power output and peak pressures in the combustion chamber that were previously unheard of outside of motorsport. This exposes the pistons to extreme loads, but the high requirements for service life and cost efficiency remain unchanged for these components.” (MAHLE GmbH, 2016). This makes the piston an extremely important and pivotal part to understand through CAE, within the operation of an Internal Combustion Engine (ICE).

3.1: Thermal Study

A global mesh element size of 4 mm was used on the piston for the thermal study, with the thermal boundary conditions, such as heat transfer coefficient and temperature, sourced from the Piston Thermal Study Data (Andrew, n.d).

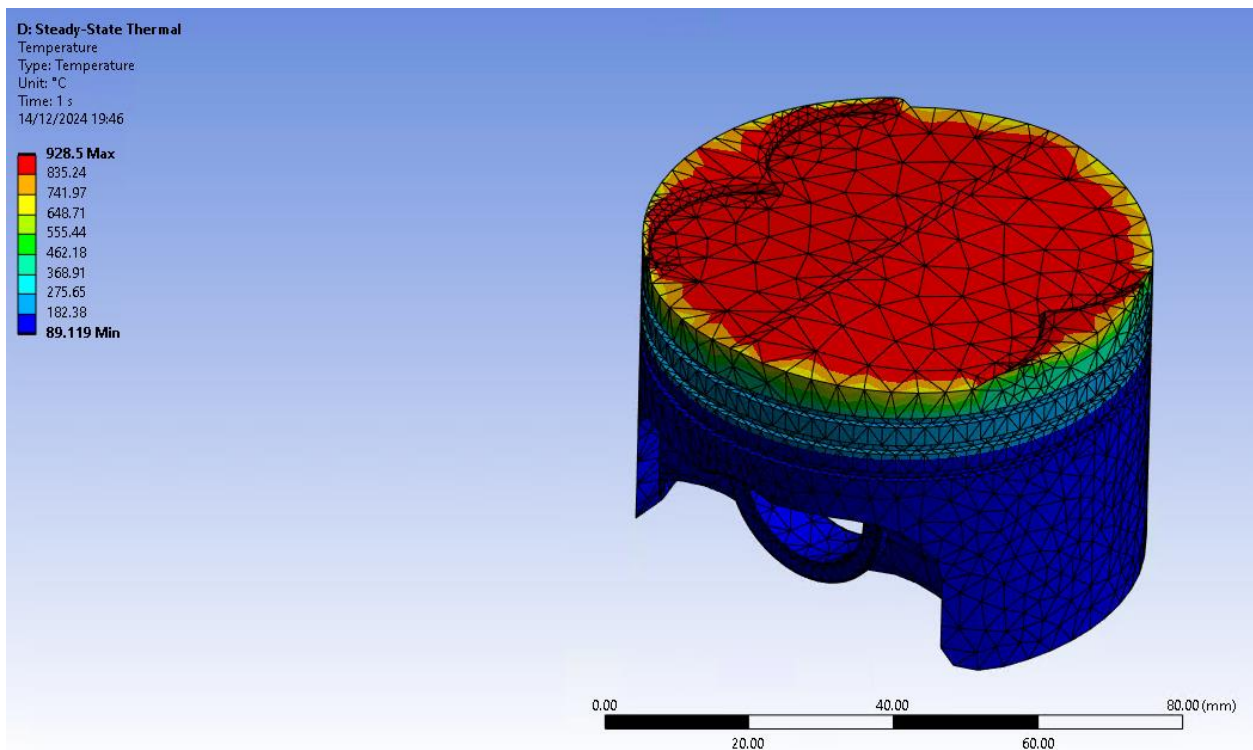


FIGURE 13: PISTON STEADY-STATE THERMAL TEMPERATURE

3:2: Static Structural Study

For the static structural study, a 4 mm global mesh element size was also used, while a finer 2 mm mesh was applied on the piston crown. This was to create a more detailed set of results on the piston crown as this is a key area of the piston, while maintaining high solver efficiency for the rest of the piston. The boundary conditions, such as Max Pressure, were obtained from the Piston Thermal Study (Andrew, n.d). Before solving, the Total deformation (Figure 43) and Equivalent stress (Figure 15) were selected to be shown following the study being solved.

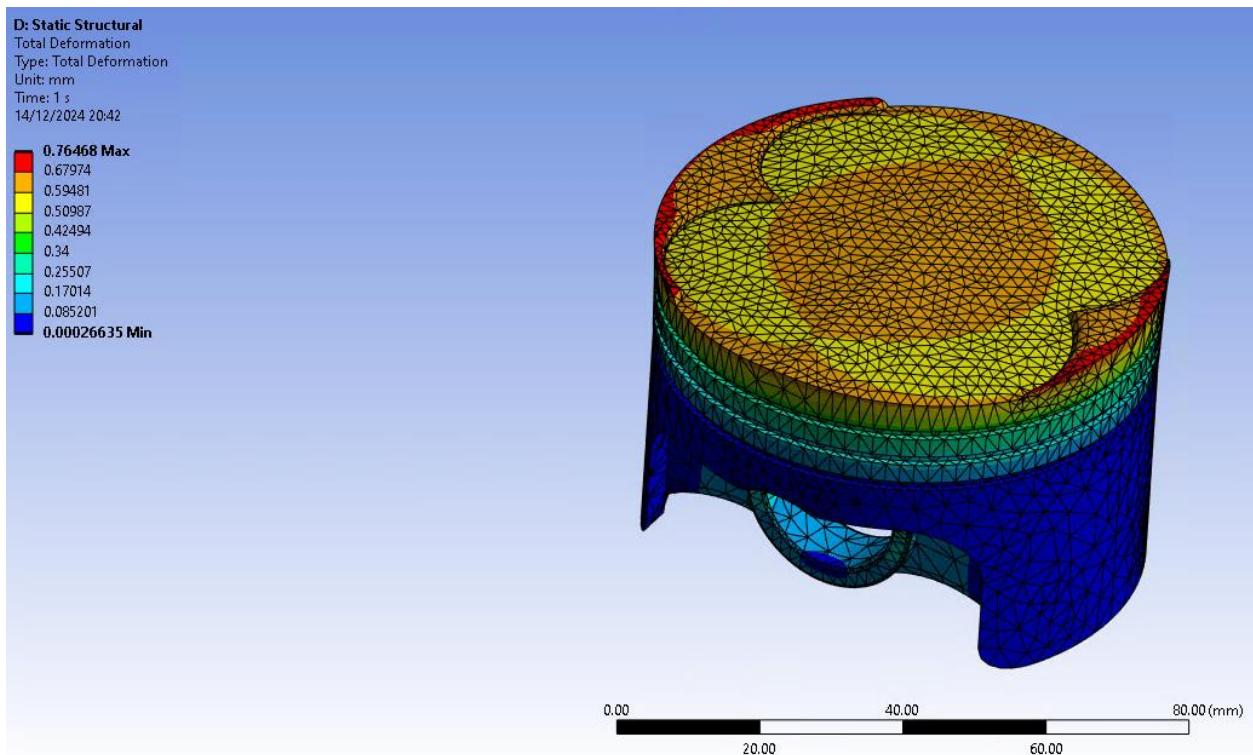


FIGURE 14: PISTON STATIC STRUCTURAL TOTAL DEFORMATION

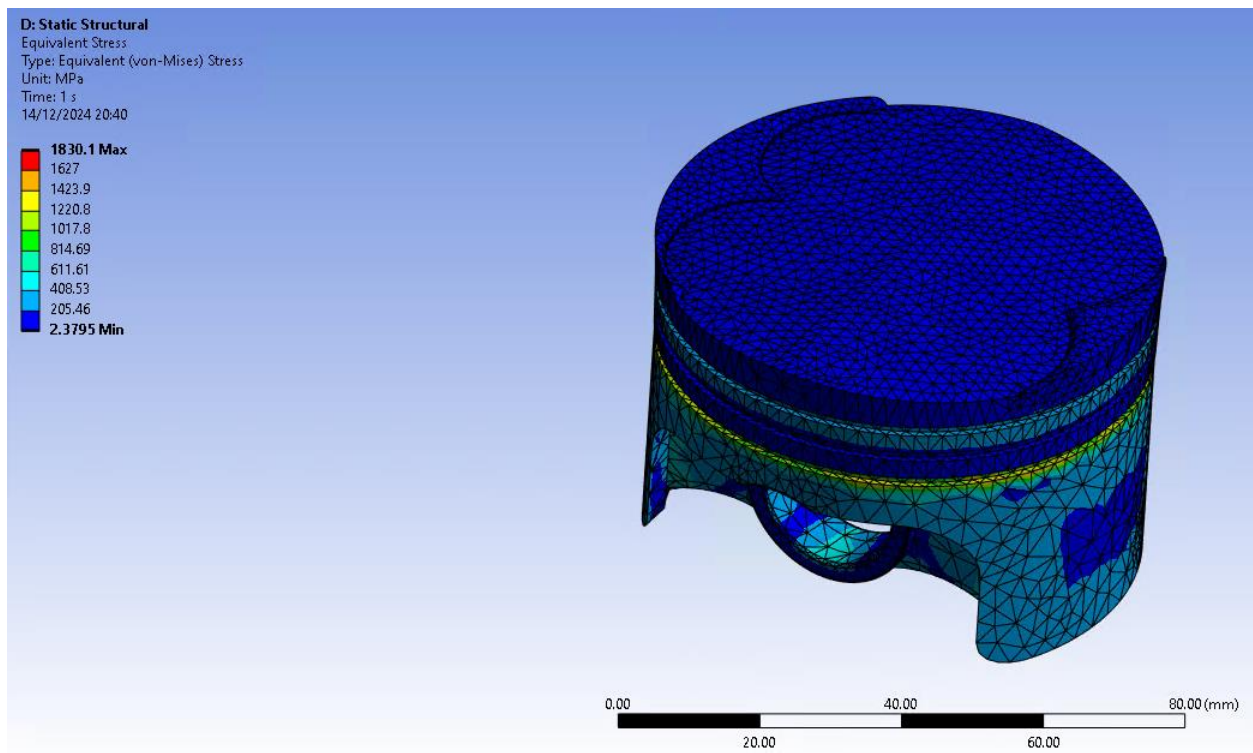


FIGURE 15: PISTON STATIC STRUCTURAL EQUIVALENT (VON-MISES) STRESS

Task 4: Component Optimization and Improvement

Using fully linked studies (Rigid Dynamics, Thermal and Structural) in ANSYS, the original piston design was iteratively improved upon, by first changing the components geometry and then changing the piston, to improve structural performance, while reducing the mass.

4.1: Geometry Modification – Valve Reliefs

Valve reliefs, as seen in figure 16, are cutouts on the top surface of the piston. They provide additional clearance for the piston when it moves within the cylinder. The removed material also reduces the pistons mass. The original material, 6061 T6 Aluminum, was retained as the material. After gathering the mass of both designs, the valve reliefs reduced the overall Piston mass by 8.25 grams.

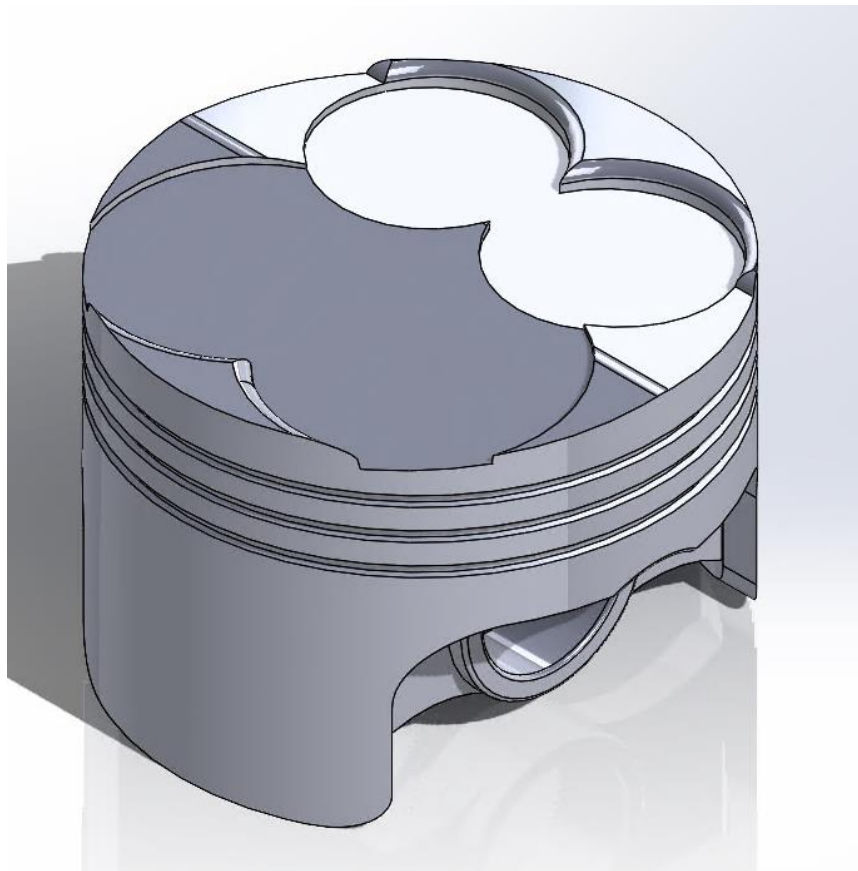


FIGURE 16: PISTON VALVE RELIEFS GEOMETRY

Following the kinematics study, the maximum total force measured was 2293.3 N, while the minimum was 56.11 N. The maximum total force was observed to happen when the piston is at TDC which makes sense, as this is when there is a direction change as well as the piston being at the highest point.

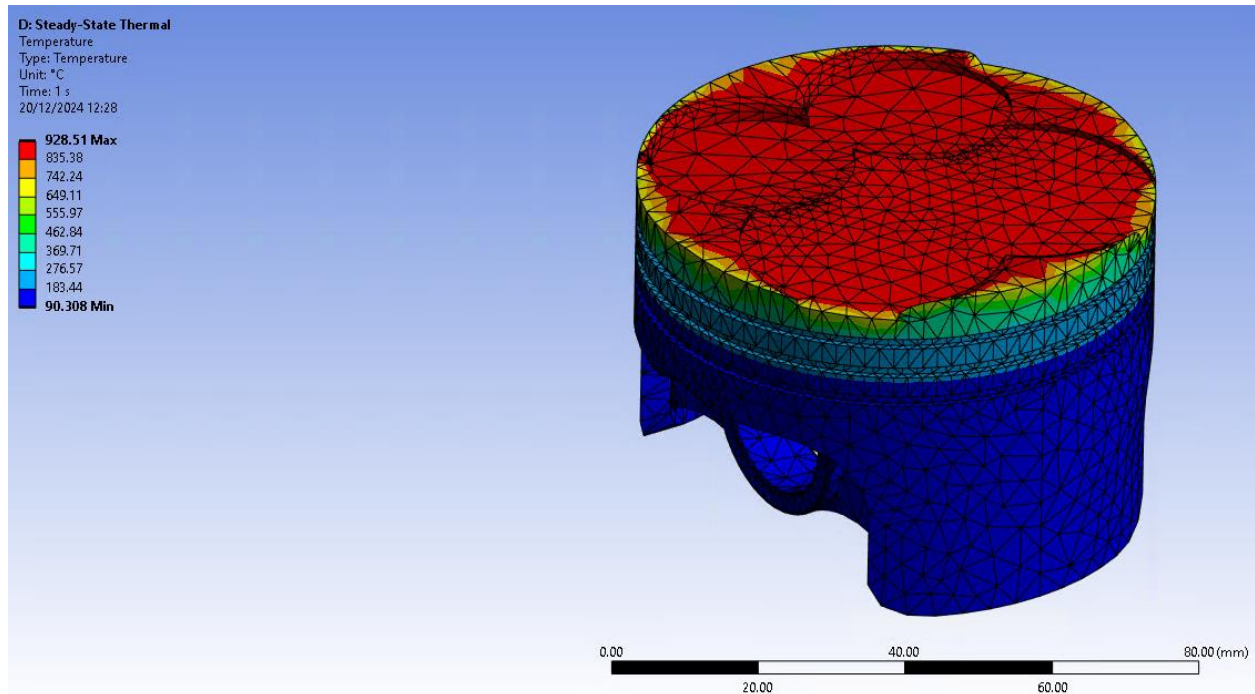


FIGURE 17: PISTON VALVE RELIEFS STEADY-STATE THERMAL TEMPERATURE

A 4mm global mesh size was used for the thermal study. The average temperature was found to be 239.03°C.

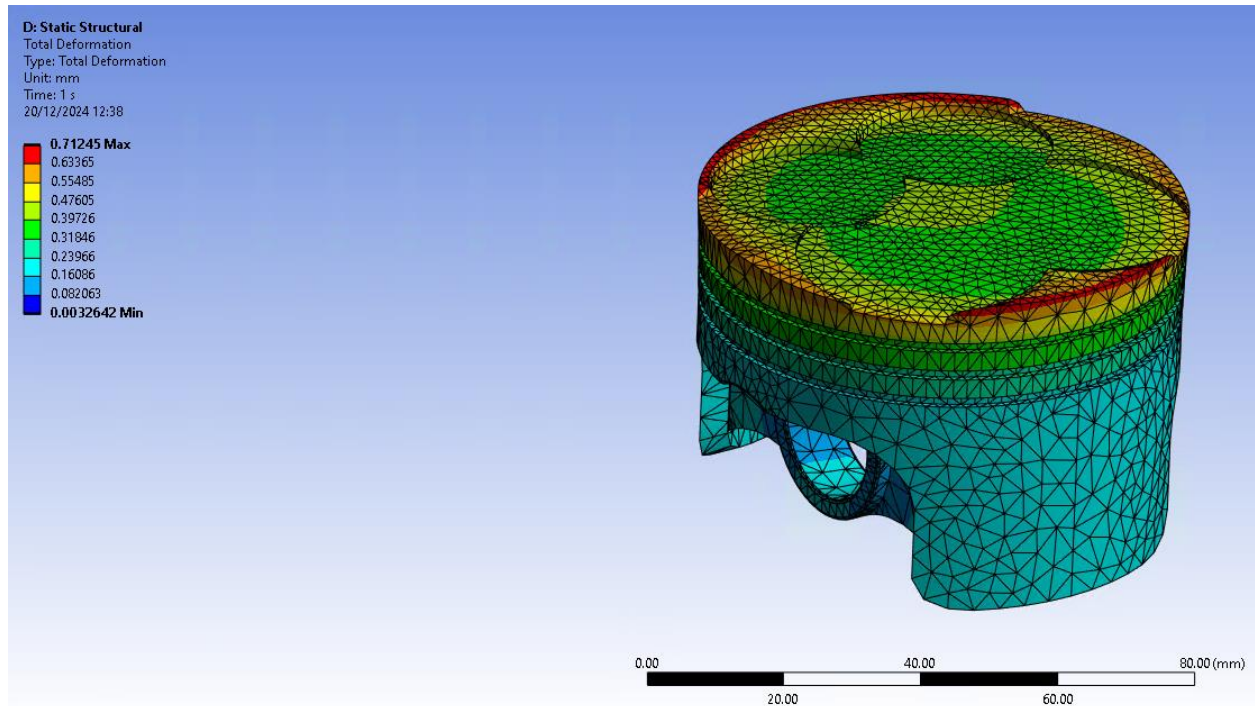


FIGURE 18: PISTON VALVE RELIEFS STATIC-STRUCTURAL TOTAL DEFORMATION

The average Total Deformation measured following being solved was 0.24881 mm.

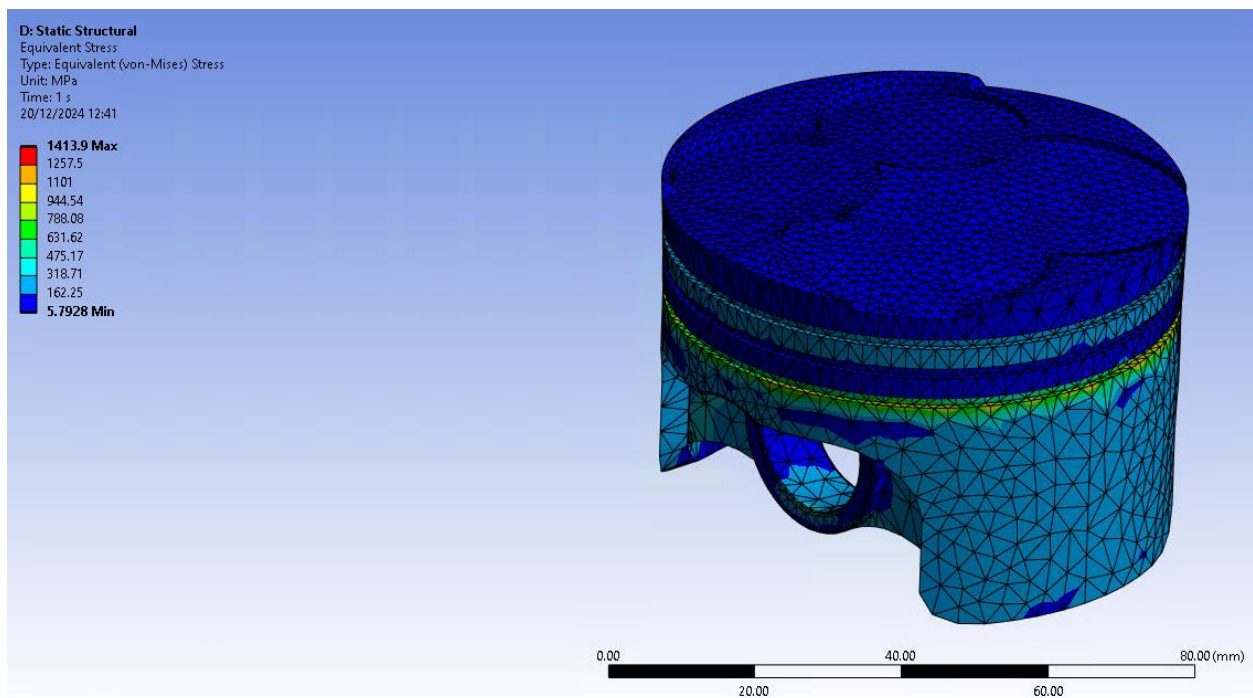


FIGURE 19: PISTON VALVE RELIEFS STATIC STRUCTURAL EQUIVALENT (VON-MISES) STRESS

The average stress measured was 188.92 MPa.

4.2: Material Change – Magnesium Alloy WE34 T6

For the final design iteration, the material for the Piston, with valve reliefs, was changed from 6061 T6 Aluminium to WE34 Magnesium Alloy. WE34 has a variety of uses across a number of areas in engineering such as Aerospace and Motorsport. Compared to Aluminium, WE34 Magnesium Alloy has increased structural performance. “WE43 is a high strength Magnesium Alloy which offers good mechanical properties both at ambient and elevated temperatures.” (Smiths, 2023) Magnesium alloy will reduce the components mass, leading to better Kinematics motion load results within an engine. “The alloy is an excellent engineering solution in applications where weight reduction without compromising performance is required.” (Smiths, 2023) The same process of a Kinematics Study, Thermal and then a Structural Study was repeated. For the thermal study, a 4mm mesh element size was used.

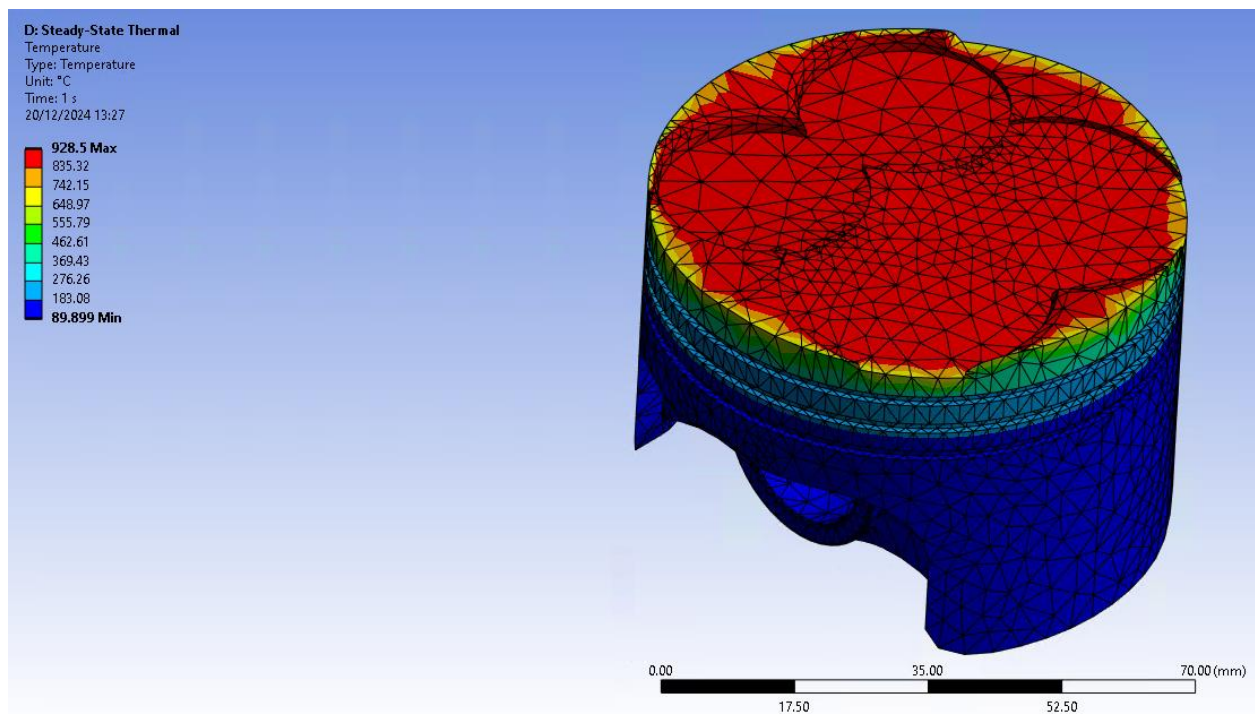


FIGURE 20: MAGNESIUM ALLOY PISTON STEADY-STATE THERMAL TEMPERATURE

An average temperature of 239.97°C was found following the study being solved.

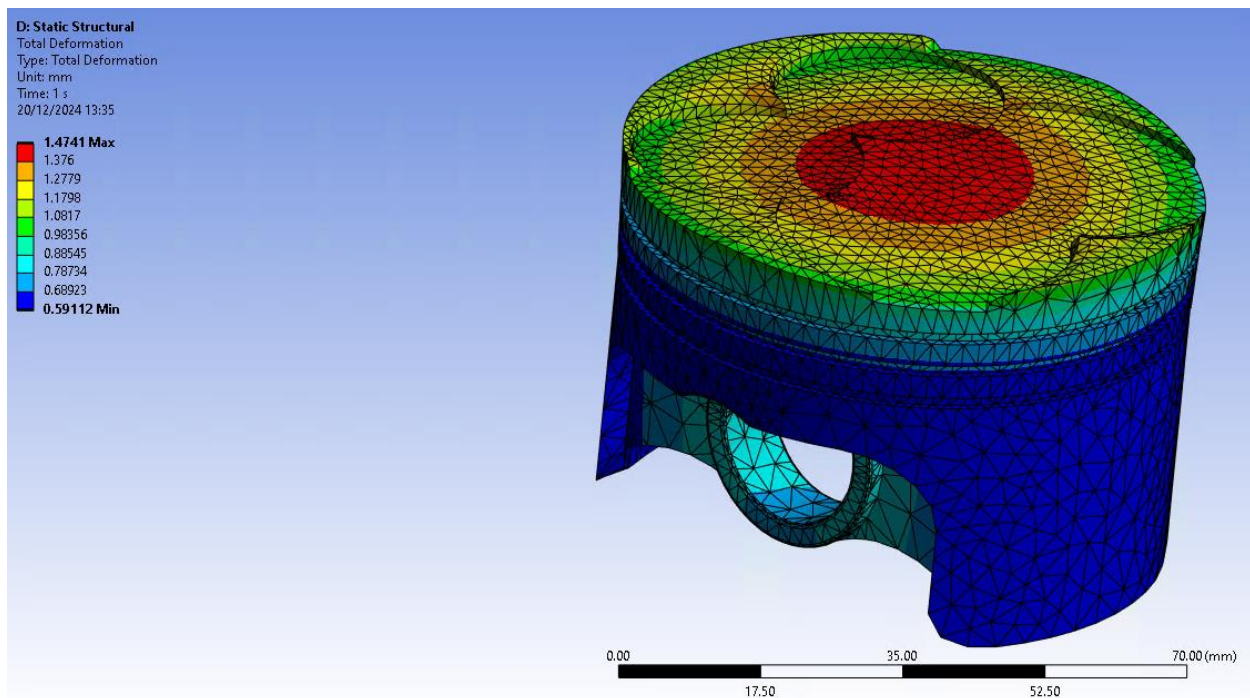


FIGURE 21: MAGNESIUM ALLOY PISTON STATIC-STRUCTURAL TOTAL DEFORMATION

Following being solved, an average total deformation was stated as 0.90546mm

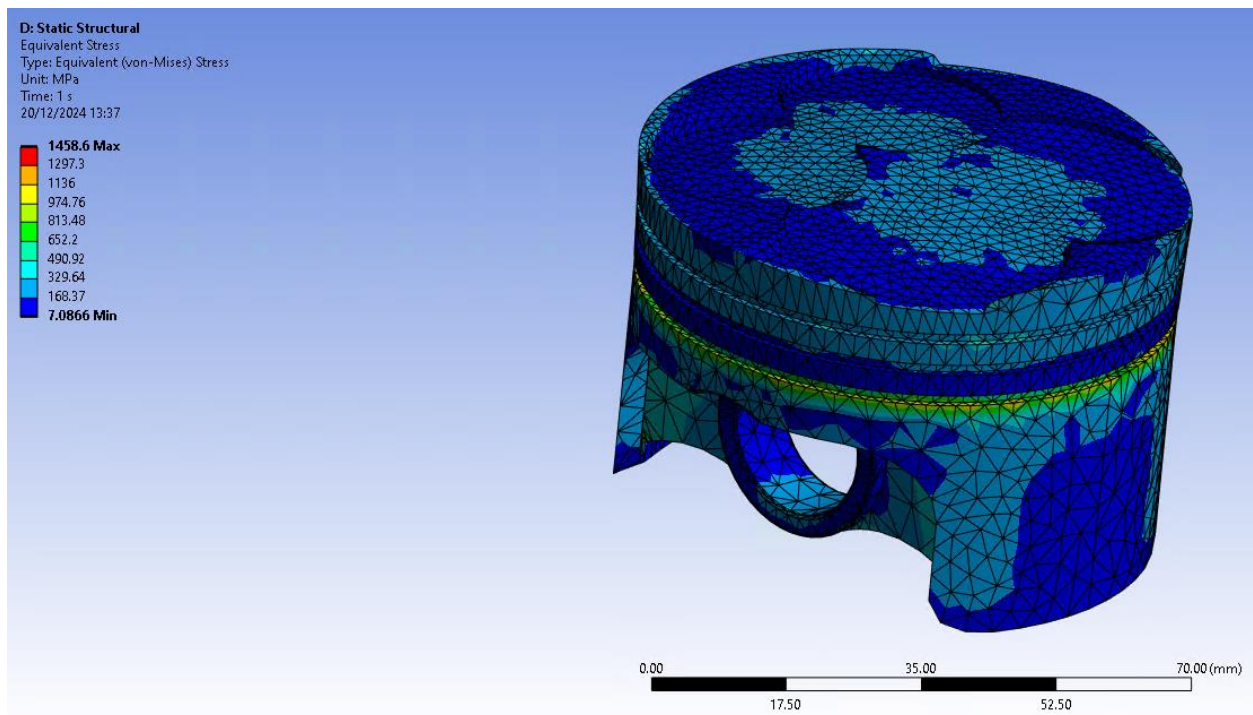


FIGURE 22: MAGNESIUM ALLOY STATIC STRUCTURAL EQUIVALENT (VON-MISES) STRESS

The average Stress value from this study was found to be 215.98 MPa.

4.3: Design Iterations Analysis and Comparison

The mass value of each piston design iteration was gathered and placed into a bar chart, figure 23, for visual comparison. The chart shows that whilst the valve reliefs decreased the mass by removing material, the replacement of 6061 T6 Aluminium with WE34 Magnesium Alloy has a significant effect on the mass of the piston.

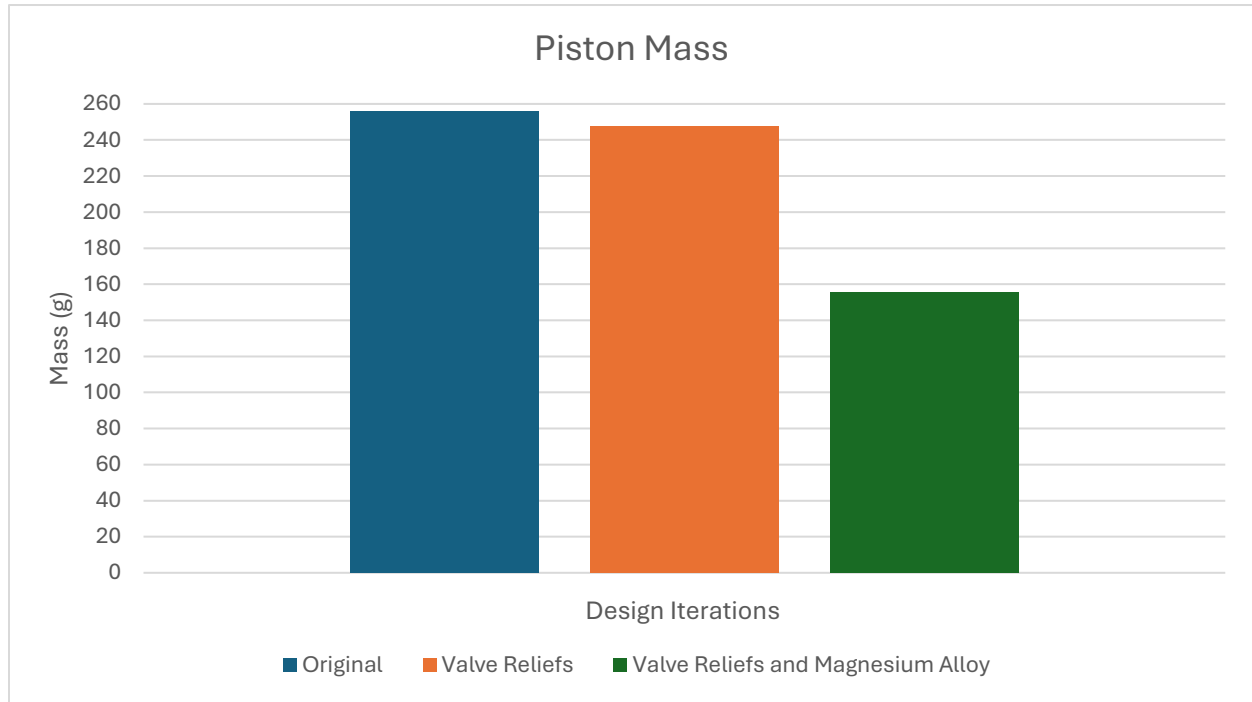


FIGURE 23: PISTON DESIGNS MASS COMPARISON

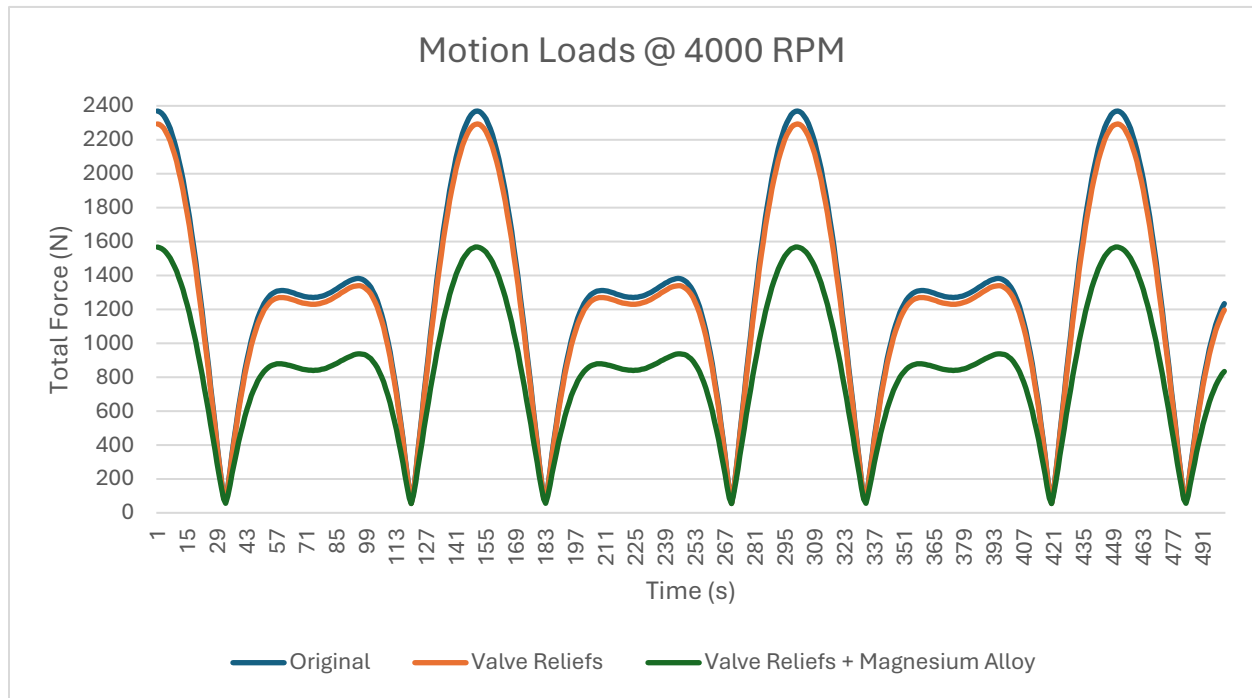


FIGURE 24: PISTON DESIGNS MOTION LOADS @ 4000 RPM COMPARISON

As can be seen in figure 24 above, the highest peak motion load during the engine cycle was with the original piston. This is due to having the highest mass compared to the other iterations. Whilst the piston with valve reliefs decreased the motion loads, the third iteration with valve reliefs and magnesium alloy shows significantly decreased motion loads due to having a significant reduction in the pistons mass.

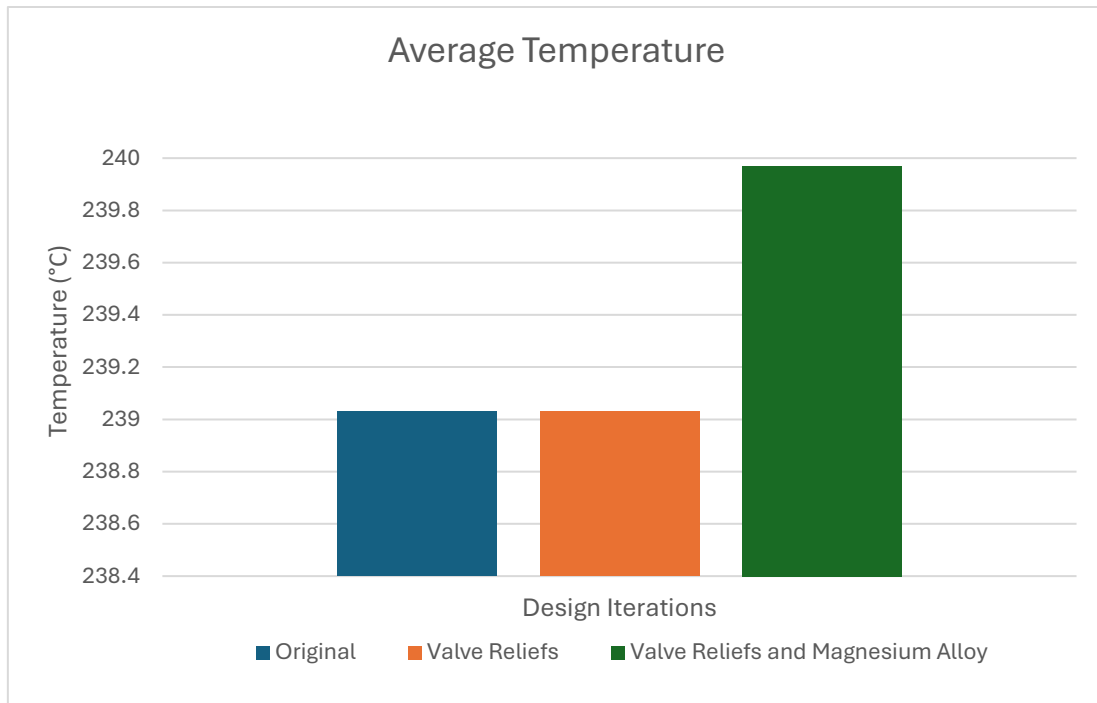


FIGURE 25: PISTON DESIGNS AVERAGE TEMPERATURE

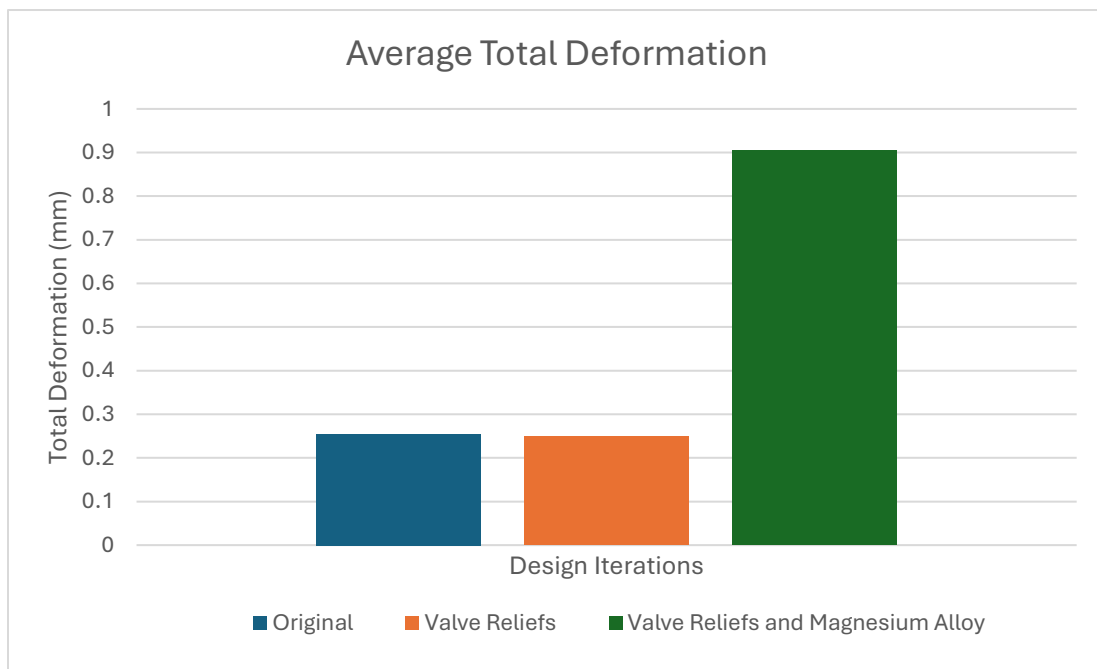


FIGURE 26: PISTON DESIGNS AVERAGE TOTAL DEFORMATION

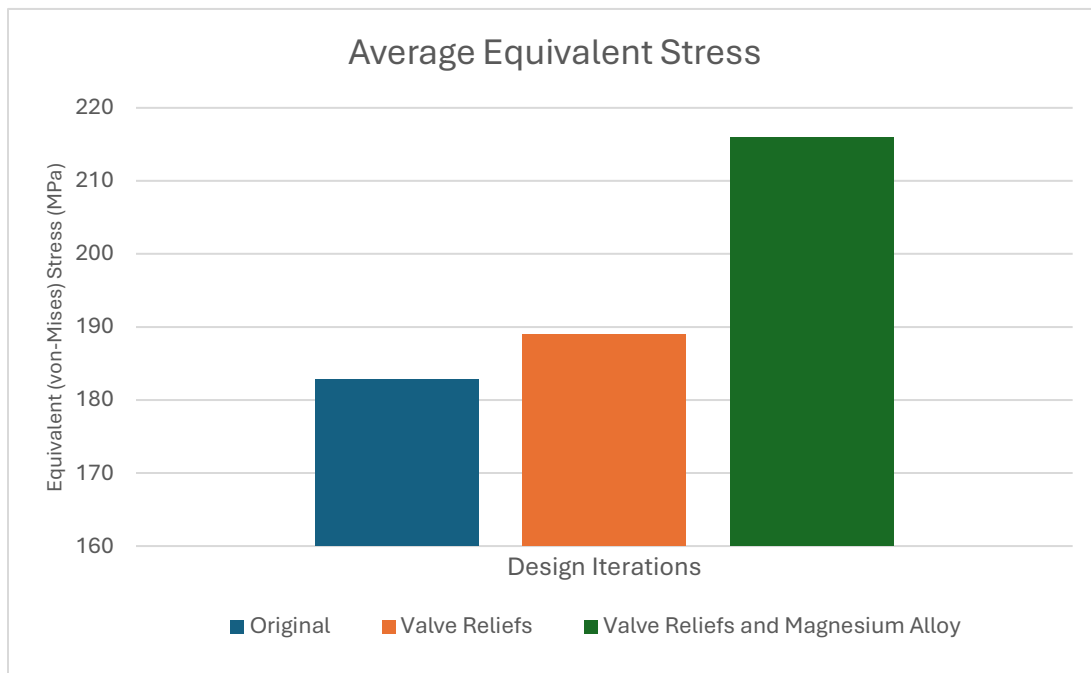


FIGURE 27: PISTON DESIGNS AVERAGE EQUIVALENT STRESS

Role and Limitations of CAE Tools in the Design Process

In the design process, Computer Aided Engineering follows Computer Aided Design of Components but before Computer Aided Manufacturing programming. As shown in this assignment, it can replace or work alongside analytical calculations.

The benefits of using CAE tools over conventional analytical methods are that it can improve accuracy by removing human error in the solving of calculations. It can allow for better tracking of workflow, easy documenting of assorted designs and facilitates better transfer of knowledge. Furthermore, as seen in this assignment, it can also make changing components within an assembly easy, repeatable, and fast (such as when conducting different kinematic studies with the different piston designs).

The main benefit of CAE is that it can reduce the overall cost and time of the design process. “CAE is a technology that innovatively reduces the time and cost required for prototyping and testing by allowing the performance and quality of a product or part designed in the course of product development to be predicted on the computer and reflected in the design before making a real product.” (Tung, Cho, Kim, & Gim, 2022) All of this can improve productivity compared to solely using analytical methods.

However, compared to purely analytical methods in the design process, CAE can have a high initial cost due to purchasing the software and hardware required. Industry level CAE software is also complex, requiring expertise to perform high level simulations and studies. For example, Tung explains that CAE has practical limitations that demand substantial engineering expertise and significant computing resources, it is continually being used and providing realistic results. (Tung, Cho, Kim, & Gim, 2022)

CAE meshing and solvers can also be limited, such as solving time or minimum mesh size. This was proven in figure 10, for the thermal validation, where the mesh size 0.1 mm and below significantly increased meshing and solving time. A major limitation for CAE is the dependency on input data and geometry. If the input data and/or the geometry is incorrect, unrealistic, or too simple, the generated data will be inaccurate. All these limitations can be exacerbated if there is an over-reliance on CAE over conventional analytical methods, which is becoming increasingly common.

Conclusion

To conclude, figures 23 to 27 show that while the third piston design iteration is significantly lighter, the average total deformation, stress and temperature is much higher, thus meaning a piston made from WE34 Magnesium Alloy has worse structural performance than a 6061 T6 Aluminium piston. With that in mind, the valve relief iteration has a negligible amount of increase in average Total deformation, stress, and thermal temperature, meaning it is the most suitable iteration out of the three studied. Further geometry changes could be made to reduce the components mass. Another material could also be evaluated with better structural performance than WE34, while having the same or lighter mass.

To build upon the validation testing, kinematics validation could be conducted to confirm the accuracy of the assembly kinematics analysis. This could be achieved by designing a basic assembly consisting of a weight attached to a point which can rotate around its axis, to simulate the motion loads of a crankshaft to piston assembly. Also, further kinematic studies could be undertaken, at a range of different RPM values, which could then be plotted to compare each assembly's motion loads. The range of piston design iterations could also be expanded, implementing further geometry changes and more materials.

References

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