

University of Wales Trinity Saint David

Wales Institute of Science and Art



Prifysgol Cymru

Y Drindod Dewi Sant

University of Wales

Trinity Saint David

Structural Design and Fluid Analysis

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Nathan Evans 2204179

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1 Introduction

Finite element analysis is a key tool in modern engineering, allowing complex thermomechanical behaviour to be assessed with far greater detail and safety than traditional testing. This assignment uses a structured and validated approach in ANSYS Workbench to examine mechanical, thermal and structural performance across several case studies. The work begins with validation through mesh-sensitivity, boundary-condition checks and comparison with analytical and published data to ensure numerical reliability. A full piston assembly is then analysed using linked rigid-dynamics, thermal and structural solvers to compare material responses. The study concludes with a conceptual topology optimisation to explore potential mass-reduction opportunities.

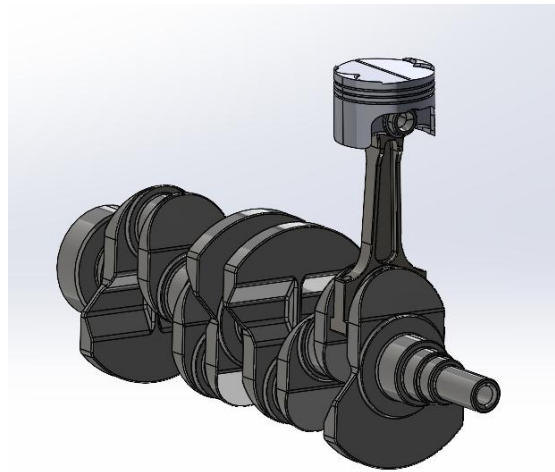


Figure 1 Piston assembly used for the linked thermomechanical and structural analysis in this study.

1.1 Aim

- The aim of this assignment is to evaluate the capability and limitations of finite element analysis within ANSYS Workbench for predicting the performance of a piston assembly.

1.2 Objectives

- Validate the numerical accuracy of the ANSYS solvers through mesh quality assessment, boundary condition verification and comparison against analytical expectations.
- Assess how material properties influence temperature, deformation and stress behaviour.
- Identify key modelling limitations and assumptions that affect result accuracy.

2 Validation Study

Validation is a critical requirement when applying Computer Aided Engineering (CAE) tools, ensuring that the solver accurately reproduces known physical behaviour before being used for more complex engineering simulations. A thermomechanical validation case was selected to demonstrate the software's ability to couple thermal loading. The analytical bending deflection of the strip is 7.049 mm (Software 2017). This provides a clear benchmark for assessing solver accuracy.

2.1 Mesh Study

A mesh-sensitivity study was carried out to assess how element size influences the accuracy of the displacement and stress predictions. This forms a fundamental part of the validation process, as the finite element method relies on the discretisation of geometry, and solution accuracy is directly affected by mesh quality, element formulation and refinement strategy.

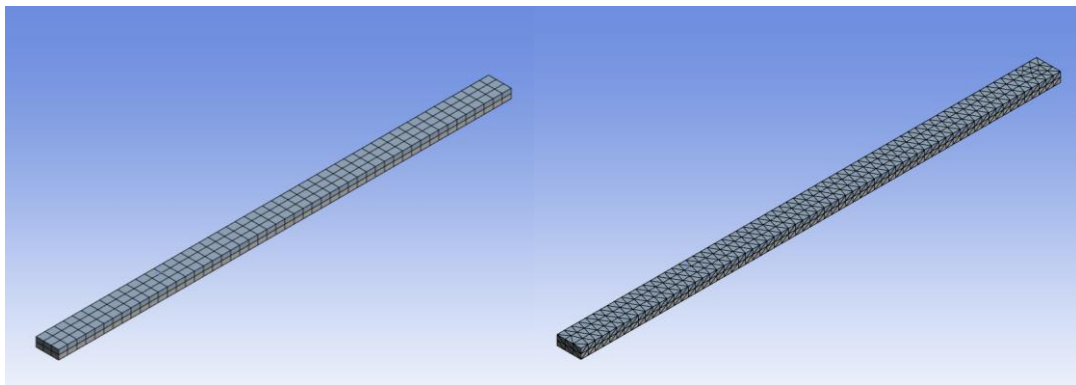


Figure 2 Shows the different mesh methods used to conduct a mesh study. (Automatic - Hex Dominant and Tetrahedron) (ANSYS 2021).

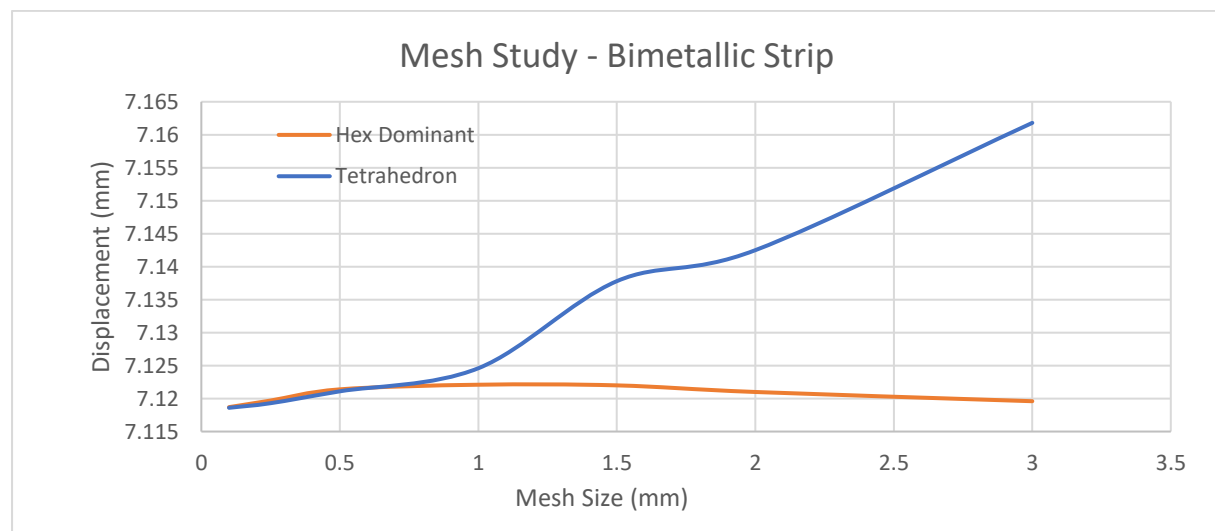


Figure 3 Mesh study for the bimetallic strip showing displacement variation with mesh size for Hex-Dominant and Tetrahedral meshes. Hex-Dominant elements remain stable across all sizes, while Tetrahedral elements show greater sensitivity to refinement.

The mesh study compares Hex-Dominant and Tetrahedral meshing strategies to evaluate their influence on predicted displacement of the bimetallic strip. The Hex-Dominant mesh shows minimal variation across all mesh sizes, indicating that it reaches mesh independence quickly and provides stable displacement results even at relatively coarse densities. This behaviour is expected for structured hexahedral elements, which generally offer superior numerical accuracy for simple geometries.

In contrast, the Tetrahedral mesh displays a clear increase in displacement as the mesh becomes coarser, deviating progressively from the refined-mesh prediction. This sensitivity reflects the element's formulation. Tetrahedral elements are more distortion-prone and typically require much finer refinement to achieve comparable accuracy (Aman Dutt, 2015). The divergence with mesh coarsening also demonstrates that tetrahedral meshes may artificially stiffen or soften the model depending on element quality.

Overall, the results show that the Hex-Dominant approach is better suited to this geometry, achieving accurate and mesh-independent solutions with far fewer elements. The Tetrahedral mesh highlights how element choice can significantly influence numerical stability and should be used cautiously unless sufficient refinement is feasible.

2.2 Boundary Conditions

Boundary conditions are fundamental to the accuracy and physical realism of any finite element simulation, particularly in thermal–structural problems. To assess their influence, a boundary-condition sensitivity study was performed to examine how different thermal loads and constraint applications affect the structural response. This validation step ensures that the modelling behaviour is not distorted by overly simplified or inappropriate constraints.

Table 1 Shows the Material properties, dimensions and thermal loading applied to the component within ANSYS (Software 2017).

Invar	Modulus of Elasticity	137000	MPa
	Poisson's Ratio	0.28	N/A
	Coefficient of Thermal Expansion	1.2×10^{-6}	°C-1
Copper	Modulus of Elasticity	130000	MPa
	Poisson's Ratio	0.354	N/A
	Coefficient of Thermal Expansion	2×10^{-5}	°C-1
Geometry	Cross Section Width	5	mm
	Layer Thickness	1	mm
	Length	100	mm

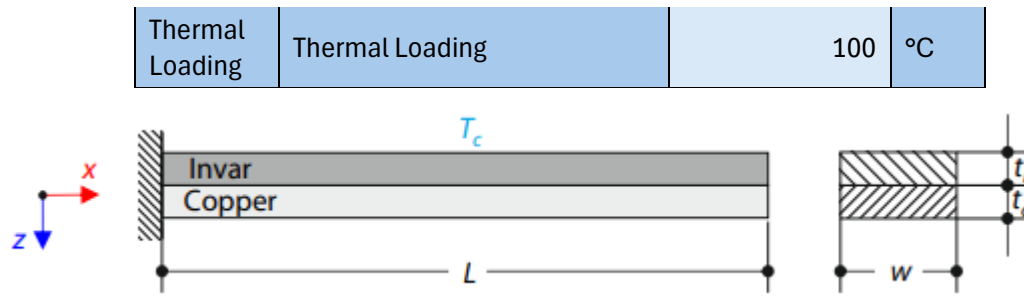


Figure 4 Depicts the bimetallic strip configuration used in the analysis, featuring fixed supports and prescribed thermal loading within ANSYS Static Structural (Software, 2017).

Table 2 Simplified boundary conditions are applied to the model. This table shows the percentage difference to the validated model of a max displacement in the Z direction of 7.049mm when a 78°C thermal load is applied.

Boundary Conditions - Hex Dominant Mesh (Automatic)			
Start Temp: 22 °C		Ramp Temp: 100 °C	
Mesh Size (mm)	Maximum (mm)	Average (mm)	Percentage Error (%)
0.1	5.5526	1.8589	126.95%
0.25	5.5534	1.8604	126.93%
0.5	5.5547	1.8628	126.90%
1	5.5552	1.8663	126.89%
1.5	5.5552	1.8695	126.89%
2	5.5544	1.8724	126.91%
3	5.5533	1.8784	126.93%

Table 3 Shows the correct boundary conditions being applied to the model with the percentage differences against the validated example with a 100°C thermal load is applied.

Boundary Conditions - Hex Dominant Mesh (Automatic)			
Start Temp: 22 °C		Ramp Temp: 122 °C	
Mesh Size (mm)	Maximum (mm)	Average (mm)	Percentage Error (%)
0.1	7.1187	2.3833	99.02%
0.25	7.1197	2.3851	99.01%
0.5	7.1214	2.3882	98.98%
1	7.1221	2.3927	98.97%
1.5	7.122	2.3969	98.98%
2	7.121	2.4005	98.99%
3	7.1196	2.4082	99.01%

Tables 2 and 3 present the temperature ramps applied to the model while all other modelling parameters were held constant. This controlled setup made it possible to isolate and evaluate the influence of the thermal boundary condition itself. Across both loading scenarios, the displacement predictions remained extremely stable for all mesh sizes. Such behaviour indicates that the global thermally induced deformation is largely insensitive to mesh refinement (Fang, Su et al. 2024). This is

expected, as thermal expansion generates a uniform strain field dominated by temperature change rather than localised geometric features, making it less dependent on element size or shape.

The deformation varied between the two temperature ramps, which reflects correct physical behaviour. In ANSYS Static Structural, the ambient temperature is fixed at 22 °C, so applying 100 °C produces only a 78 °C rise unless the ambient value is accounted for. To match the intended 100 °C temperature difference from the validation study, the load was increased to 122 °C. With this correction, the predicted displacement aligned closely with the benchmark, confirming correct thermal–structural coupling.

2.3 Bimetallic Strip – Conclusion

The boundary-condition sensitivity study confirmed that the applied thermal loading behaved as expected, with stable displacement responses and predictable changes between temperature ramps. This demonstrated that the thermal constraints were correctly implemented and suitable for use in the wider analysis. When combined with the mesh-sensitivity results, the validation exercise provides a clear assessment of the model’s numerical reliability. Displacement predictions remained consistent across all mesh sizes, with percentage errors below 1.5%, well within the typical 1–5% tolerance for linear static analysis (Dr. Roberto Cammino et al., 2018). This level of accuracy shows that global bending and thermal curvature were captured with high fidelity and were not significantly influenced by discretisation choices.

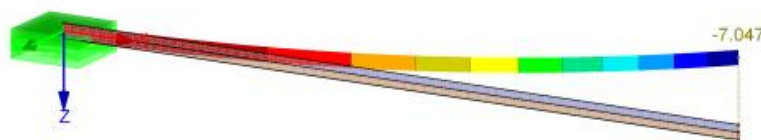


Figure 5 Shows the simulated deformation of the bimetallic strip (Software 2017).

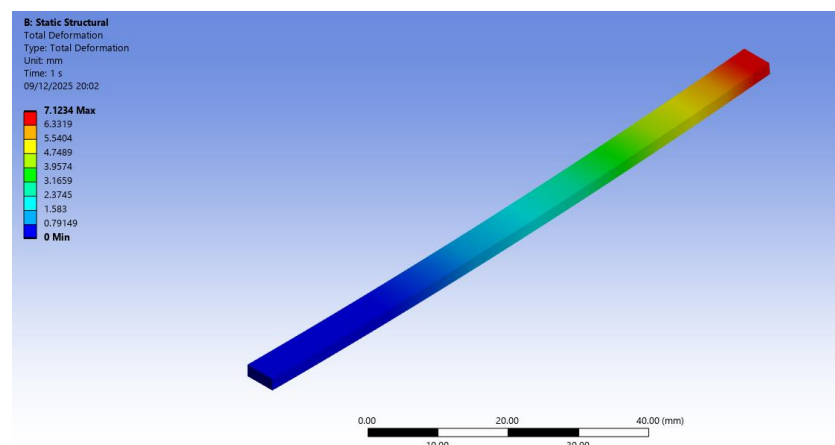


Figure 6 Shows the simulated deformation of the bimetallic strip using ANSYS Static Structural.

3 Axial Forces

Alternatively, an additional validation exercise was performed using purely axial loading conditions. In this study, a mesh-sensitivity analysis was conducted on a simple cantilever beam subjected to varying axial forces to assess how mesh refinement influences displacement and stress predictions. The resulting trends show clear consistency with those reported in Aman Dutt's investigation into the effect of mesh size on the finite element analysis of beams (Aman Dutt, 2015).

3.1 Boundary Conditions

Table 4 Shows the inputs and boundary conditions for the Bending Cantilever with axial forces applied to it indecently (Software 2016).

Material Properties	Steel	Modulus of Elasticity	137000	MPa
		Poisson's Ratio	0.3	N/A
Geometry	Cantilever	Length	10	m
		Cross section width	0.08	m
Load		Transversal Force	7.65	kN
		Axial Force	1.6	kN

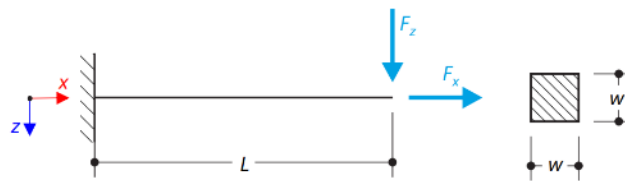


Figure 7 Bending cantilever diagram with forces applied (Software 2016).

3.2 Results

Although the absolute displacement and stress values differ due to variations in geometry, loading and modelling assumptions, the convergence behaviour in both studies remains directly comparable. The relationship between element size and numerical accuracy, as well as the characteristic shape of the convergence curves, follow the same fundamental trends, supporting the validity of the mesh-study methodology applied here. As expected for simple geometries, the Hex-Dominant mesh provides greater stability and accuracy, consistently outperforming the Tetrahedral mesh.

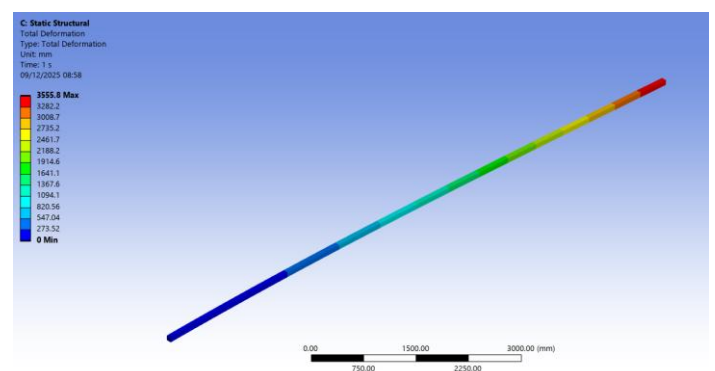


Figure 8 shows the deformation of the beam when subjected to a 7,650N applied load.

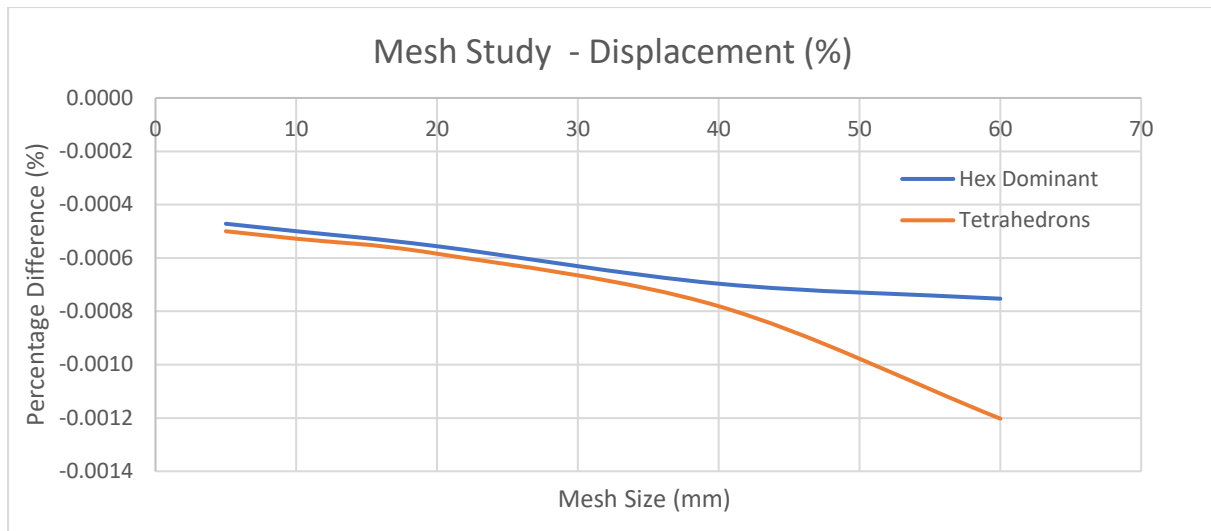


Figure 9 Mesh-size sensitivity of displacement predictions for Hex-Dominant and Tetrahedral meshes. Hex-Dominant elements remain stable across all mesh densities, while Tetrahedral elements exhibit increasing error as the mesh coarsens.

Table 5 Mesh-density sensitivity for the cantilever beam under a 7650 N load. Finer meshes (5–10 mm) produce significantly higher stress accuracy, while coarser meshes demonstrate up to 35% deviation, highlighting the importance of mesh refinement in stress-dominant analyses.

Force: 7650				
Automatic - Hex Dominant				
Mesh Size (mm)	Maximum Deformation (mm)	Stress (MPa)	Average (MPa)	Percentage Difference Stress (%)
5	3555.8000	1461.9	234.2	0.04%
10	3555.7000	1144.3	243.36	-21.70%
20	3555.50	970.57	259.4	-33.58%
40	3555.0000	952.95	284.73	-34.79%
60	3554.8000	954.6	284.66	-34.68%

Table 6 Shows the research on mesh sizing for a beam by (Aman Dutt 2015).

Element Size	Vonmises Stress (MPa)	Error Percentage
2 mm	271.776	0
3 mm	243.405	12.6
4 mm	216.656	20.8
5 mm	197.866	27.2
6 mm	186.964	31.2

The trends observed in this study closely reflect those reported by Aman Dutt (2015), reinforcing the validity of the mesh-sensitivity behaviour identified. In both cases, finer meshes produce higher and more accurate stress predictions, while coarser meshes increasingly under-predict stress as element size grows. This agreement demonstrates a shared underlying numerical behaviour: tetrahedral and coarse meshes struggle to capture bending-dominated stress fields, whereas refined or hex-dominant meshes converge more reliably toward the true solution. Although absolute stress values

differ due to changes in geometry and loading, the shape and direction of the convergence curves remain consistent across both studies, showing that the mesh-dependence observed here aligns with established finite element behaviour.

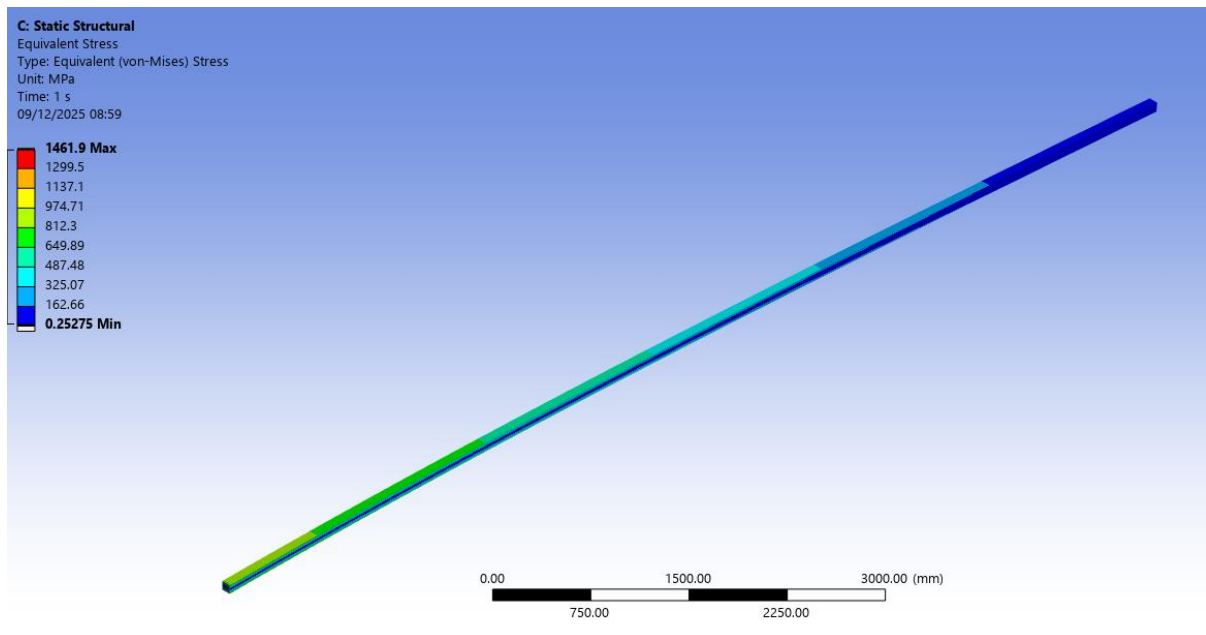


Figure 10 Equivalent von Mises stress distribution in the cantilever under the applied end load.

4 Piston Assembly Study

A fully linked workflow was developed in ANSYS Workbench to replicate piston operating conditions. Temperature-dependent material properties were defined in Engineering Data, and a Rigid Dynamics analysis generated the kinematic loads using crank–rod constraints and an appropriate time step to capture inertial forces at 4000 rpm. Reaction forces at a representative crank angle were then passed to the structural analysis.

Table 7 The analysis settings for the rigid dynamics study used an end time of 0.5 seconds with a step time of 0.0001 seconds to provide sufficient resolution for capturing the inertial forces generated at 4000 revolutions per minute.

Boundary Conditions - Rigid Dynamics		
Analysis Settings		Units
End time	0.5	Seconds
Step time	0.0001	Seconds
Revolution (RPM)	4000	RPM

A Steady-State Thermal study was performed using crown temperature loading and convection on the underside, and the resulting temperature field was imported into the Static Structural solver.

This final stage combined:

1. the kinematic loads,
2. combustion pressure on the crown, and
3. the mapped temperature distribution.

Together, these inputs produced a coupled thermomechanical simulation capable of predicting piston deformation and stress under representative engine conditions.

4.1 Boundary Conditions

Boundary conditions were applied to replicate the dominant loading pathways acting on a piston during engine operation. A pressure load was applied to the crown within the static structural analysis to replicate peak combustion forces ($1.05\text{E}+07$ Pa), while convection and elevated surface temperatures were used in the thermal study to represent heat transfer into and out of the piston. Weak springs were enabled in ANSYS to prevent rigid-body motion and ensure numerical stability. This introduces a small degree of artificial stiffness, representing a limitation of the simulation and a factor that must be considered when interpreting displacement results.

Table 8 Shows the materials tested (Elias Wakshume, Gadisa Sufe). Appendix 11.1

Materials
Aluminium 6061 T6
Aluminium 2618 T6
Ti-6Al-4V

4.2 Mesh Study

A mesh-sensitivity study was performed using the same methodology applied in the bimetallic strip and axial-force validation cases to assess how element sizing influences mesh quality and the reliability of the piston's structural results. Three key metrics; aspect ratio, Jacobian ratio and

skewness were evaluated across multiple mesh densities to quantify element quality. A mesh sizing study was also conducted around the piston crown, body and gudgeon-pin bosses, as these regions contain higher curvature and known stress-concentration features. This combined approach ensured that both global mesh behaviour and local refinement requirements were captured when determining an appropriate mesh for thermomechanical analysis.

4.2.1 Aspect Ratio

The aspect-ratio plot shows only a very small variation across the three mesh-sizing setups, changing slightly from approximately 2.336 at the smallest element size to around 2.34 at the largest size. This minimal shift indicates that increasing the element size has little influence on element elongation, largely because the piston geometry encourages naturally uniform element shapes. Importantly, all aspect-ratio values remain low and well within accepted thresholds for high-quality solid meshes. Values below 3–5 are typically considered acceptable in structural FEA, as discussed by Jansson et al. (2020). The consistently low aspect ratios therefore confirm that the elements maintain good quality across all sizing configurations.

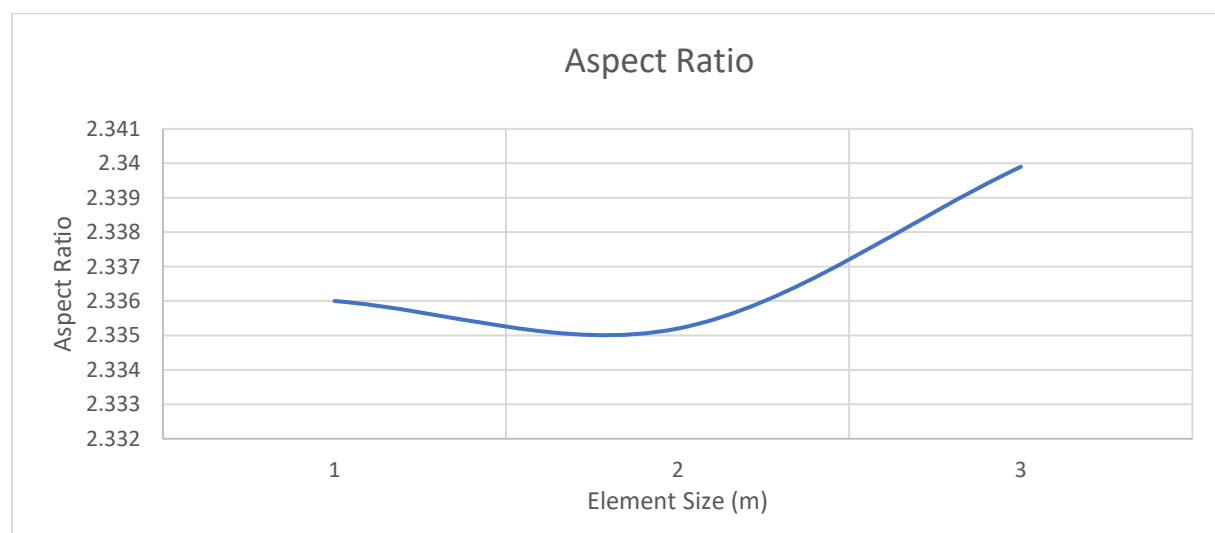


Figure 11 Aspect ratio variation across element sizing setups for the piston model, showing the influence of mesh coarsening on element shape quality.

4.2.2 Jacobian Gauss

The Jacobian values remain high across all three mesh sizes, decreasing from 0.99635 to 0.9962 as the element size increases. This small downward trend indicates a marginal reduction in mapping quality. All values are very close to 1, demonstrating acceptable element geometry and minimal distortion. According to Bucki et al. (2011), Jacobian values above 0.9 indicate highly reliable numerical behaviour, and meshes within this range typically exhibit stable stress and deformation predictions. The gradual reduction seen here simply reflects the expected effect of increasing

element size, but the consistently high values confirm that every mesh configuration retains strong geometric integrity suitable for structural analysis.

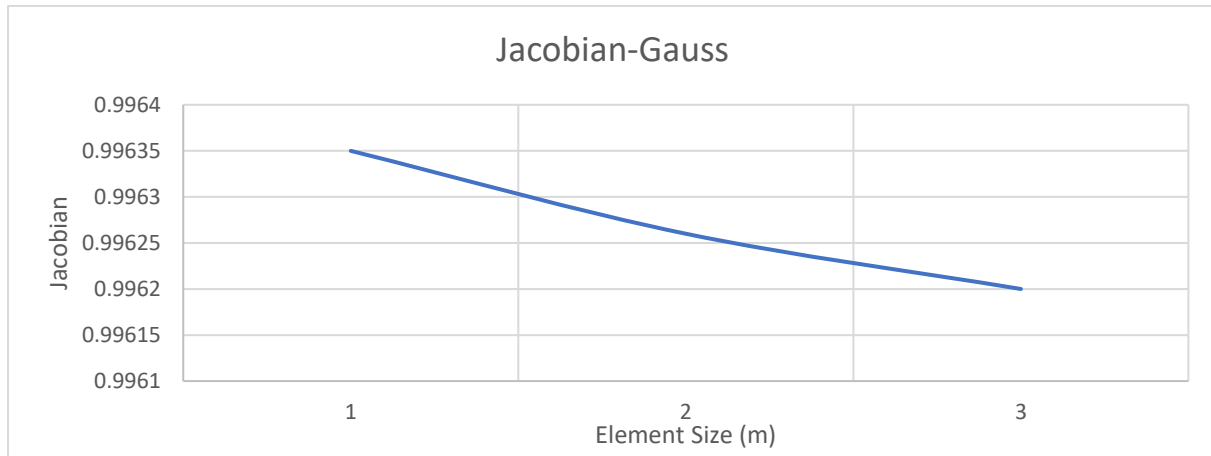


Figure 12 Jacobian values vs element size, showing consistently high mapping quality (0.996–0.9964) across all meshes, with only minor reduction as elements become larger.

4.2.3 Skewness

Skewness increases slightly as element size grows. All values stay low (0.462–0.463), indicating a uniform and highly orthogonal mesh across all configurations. These values are far below accepted quality limits—Fatchurrohman & Chia (2017) classify skewness <0.25 as excellent and up to 0.95 as acceptable, demonstrating that the mesh quality comfortably meets the requirements for stable and accurate finite-element results.

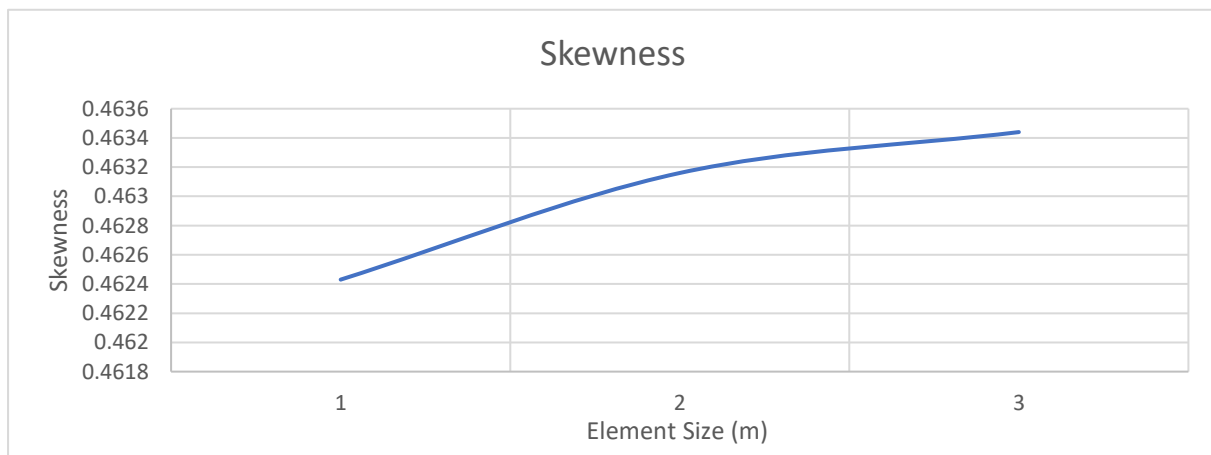


Figure 13 Skewness variation with element size for the piston mesh, showing consistently low values (<0.5) across all mesh configurations, indicating high-quality and well-shaped elements suitable for accurate finite-element analysis.

Table 9 Shows the different mesh sizing setups that were applied through the study.

Setup	Element Size Body (m)	Element Sizing Crown (m)	Element Sizing Gudgeon (m)
1	0.001	0.001	0.0001
2	0.002	0.001	0.0001
3	0.005	0.0015	0.0005

Across all three mesh strategies, global mesh metrics remained within acceptable limits, demonstrating that the piston geometry is not strongly mesh-sensitive within the tested range.

- Aspect ratio remained low for all setups (2.33–2.34), indicating uniformly shaped solid elements. These values fall well within recommended bounds for high-quality tetrahedral and polyhedral meshes (Jansson et al., 2020).
- Jacobian determinants showed minimal variation (0.9964–0.9962 across setups), remaining far above distortion thresholds and confirming robust element mapping.
- Skewness values were stable (0.462–0.463), well below the acceptable limits reported by Fatchurrohman & Chia (2017), who classify <0.25 as excellent and <0.95 as acceptable for nonlinear FEA.

4.2.4 Mesh Sizing – Conclusion

The mesh study confirms that Setup 2 provides the most reliable balance between accuracy and computational efficiency for thermomechanical simulation, particularly due to its fine resolution around the gudgeon-pin bosses. Nevertheless, all three setups passed standard mesh-quality thresholds, demonstrating that the piston model is not highly sensitive to mesh size and that the adopted refinement strategy is appropriate for final analysis.

4.3 Thermal Study

The bar chart compares the peak temperatures reached by pistons manufactured from Ti 6Al 4V, Aluminium 2618 and Aluminium 6061 under identical thermal loading conditions. Unlike deformation-based assessments, this comparison highlights each material's ability to dissipate heat. Similar approaches are reported in studies by Elias Wakshume and Gadisa Sufe. Identical thermal boundary conditions were applied across all simulations including the same applied temperatures, heat transfer coefficients and convection film coefficients, as outlined in the thermal study data (Andrew Noble 2025). This ensures that differences in the resulting temperature fields can be attributed only to intrinsic material properties such as thermal conductivity and specific heat capacity.

However, using uniform thermal coefficients introduces an important limitation. In real operating environments each material interacts with heat differently due to variations in surface emissivity,

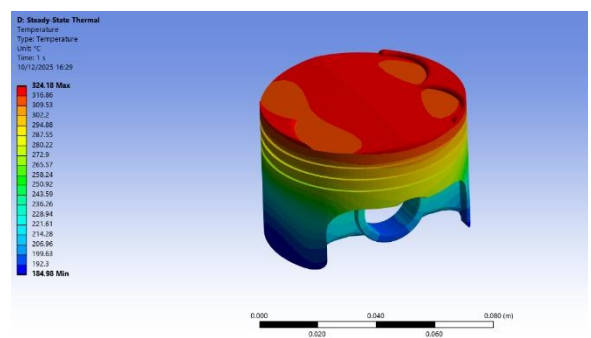


Figure 14 Shows the 6061 Aluminium being tested in steady state thermal. The Film coefficients and temperature boundary conditions can be found in Appendix 11.3.

heat absorption, conduction behaviour and temperature dependent conductivity (Valentin Mereuta 2018). Treating all materials as if they experience the same heat transfer efficiency simplifies the model but can misrepresent the true thermal response of each material type. This may result in peak temperatures being over predicted or under predicted depending on the alloy. For this reason, the temperature values in this study should be considered as comparative indicators rather than accurate representations of real piston temperatures.

4.4 Results

Figure 15 presents the peak temperature recorded for each piston material when subjected to identical thermal loading conditions. Each bar represents the maximum temperature reached within the piston geometry once the steady state thermal solution had converged. This visual comparison provides an initial indication of how effectively each material conducts and distributes heat under the same boundary conditions. It also allows trends in thermal behaviour to be observed before the detailed analysis of material performance is discussed.

Figure 16 shows the steady state temperature field predicted for the titanium piston material under the applied thermal boundary conditions. The crown region reaches the highest temperature with a peak of approximately 578 degrees Celsius while the skirt and underside remain significantly cooler. The steep temperature gradients across the crown and ring belt illustrate the limited thermal conductivity of Titanium 6Al 4V which restricts heat dissipation and results in concentrated thermal loading in localised areas.

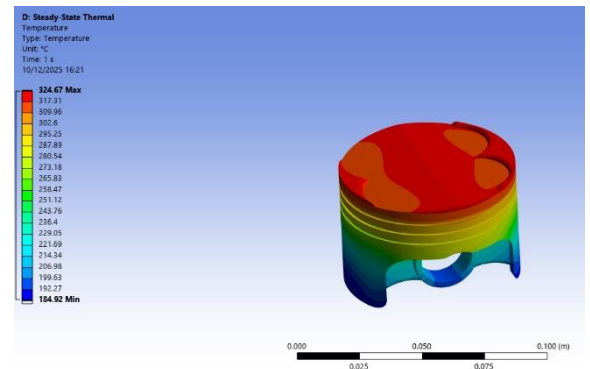


Figure 15 Shows the Aluminium 6061 baseline in steady state thermal. Appendix 11.5.

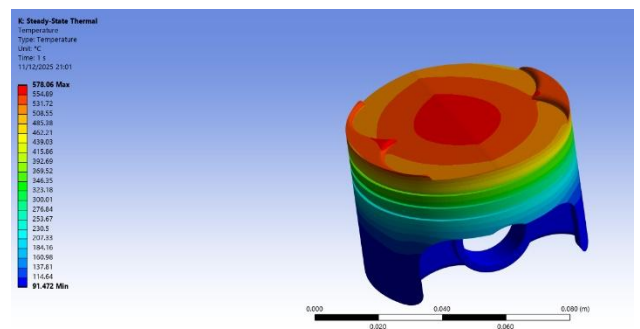


Figure 16 Shows the titanium piston in steady state thermal.

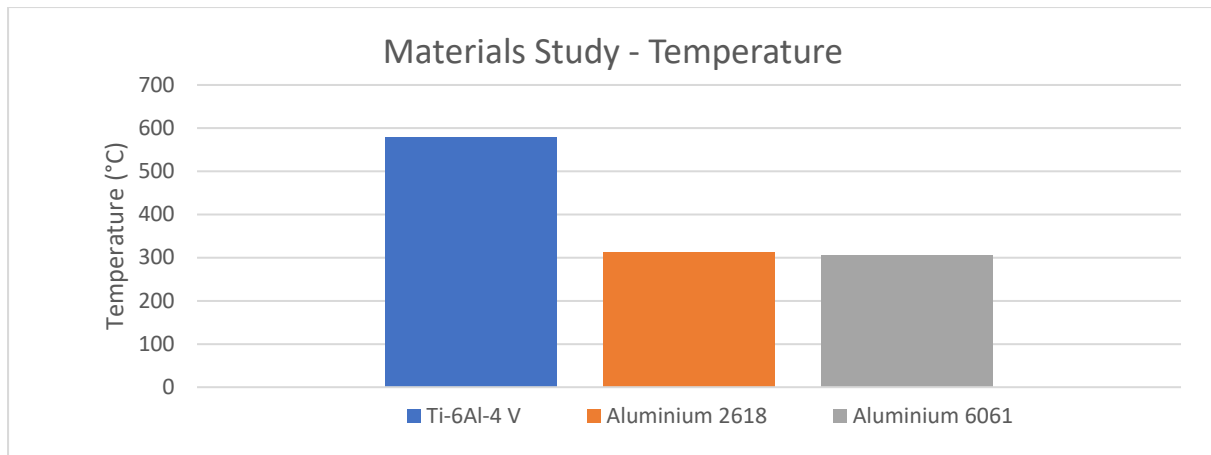


Figure 17 Shows the different temperatures experienced through the material study.

The ANSYS model produced stable and converged results, and the trends observed in temperature and stress agree with published research which indicates that the relative material performance is credible. However, the absolute values must be interpreted with caution. The thermal field is simplified due to steady state loading, identical film coefficients for all materials and limited justification of boundary conditions. These factors, along with weak springs and static structural assumptions, restrict the realism of the thermomechanical response. ANSYS has therefore solved the inputs correctly, but the outputs should be viewed as comparative indicators rather than accurate predictions of real piston temperatures or stresses.

4.5 Deformation

The deformation results show that Aluminium 6061 T6 experiences the highest displacement, Aluminium 2618 T6 is slightly lower and Titanium 6Al 4V shows the smallest deformation. These trends reflect the balance between thermal conductivity and temperature dependent stiffness. The aluminium alloys conduct heat more effectively but lose stiffness at elevated temperature which increases deformation. Titanium retains stiffness and therefore deforms less, although this behaviour is strongly influenced by the simplified thermal conditions applied in the model.

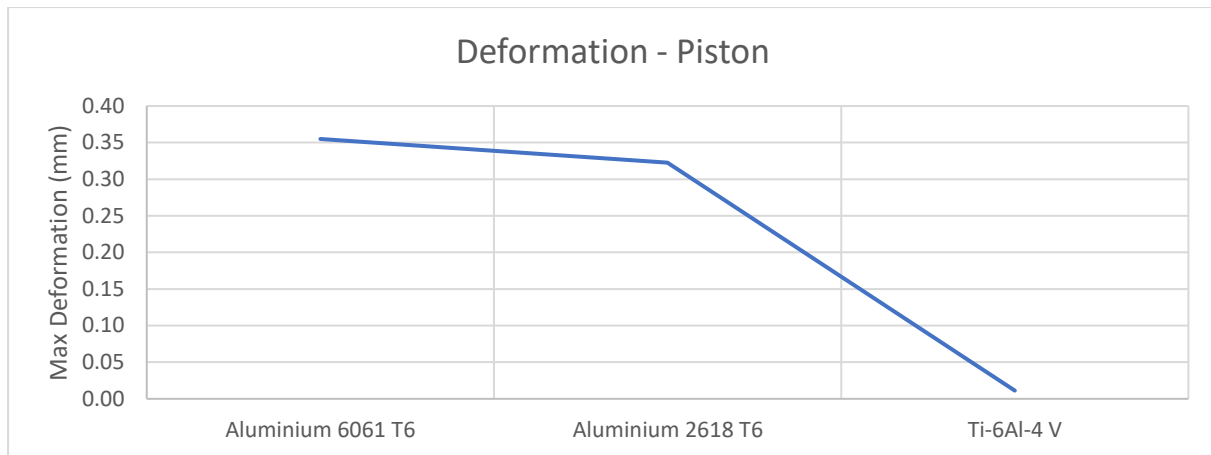


Figure 18 Shows the deformation for each material utilised throughout this study.

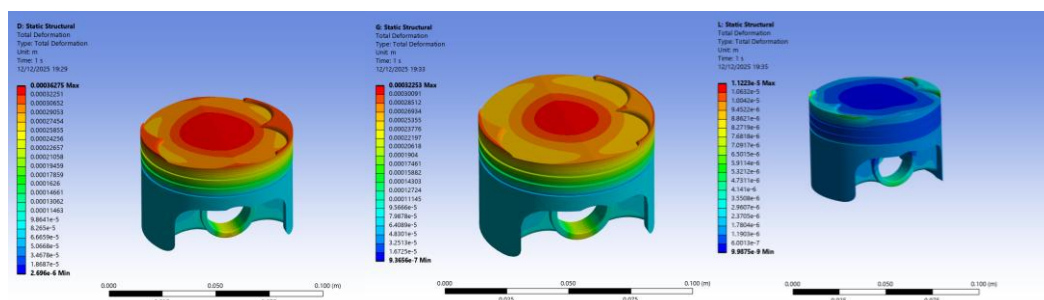


Figure 19 Shows the results from the fully linked system in ANSYS workbench. Piston materials are listed; 6061 T6, 2618 T6 and Ti-6Al-4 V.

The results must be interpreted cautiously. Titanium traps heat due to its low thermal conductivity, and this behaviour is not fully captured in a steady state thermal analysis. The outputs are useful for comparison rather than accurate prediction of in-service piston distortion. Despite these limitations the overall trends align with the findings reported by Elias Wakshume and Gadisa Sufe, which supports the credibility of the comparative results.

5 Optimisation

A simplified piston model was created for the topology optimisation because the primary piston already included refined structural features, leaving little noncritical material for removal and producing fragmented, impractical optimisation results. The simplified geometry provided a uniform design space, allowing the optimiser to identify load carrying regions more effectively. Only basic structural loading could be applied, as introducing thermal or motion loads caused conditioning errors within the solver. As a result, the optimisation outputs should be viewed as conceptual indicators of potential material redistribution rather than manufacturable or validated piston designs.

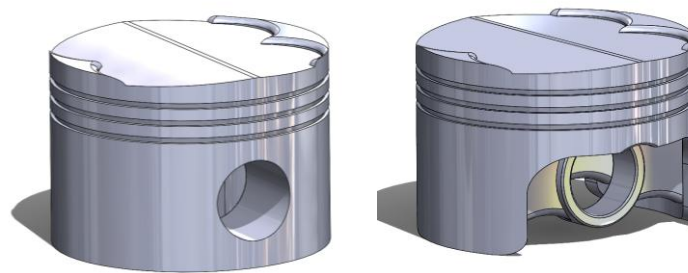


Figure 20 Shows both pistons that have been applied to ANSYS Structural optimiser. Simplified piston (left), standard (right).

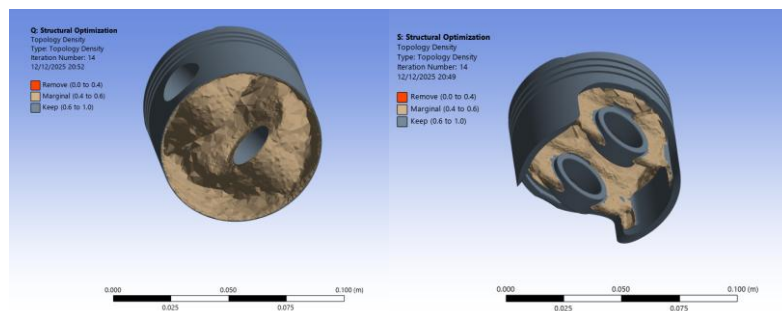


Figure 21 Shows the final models after Structural optimiser has been applied. Simplified piston (left), standard (right).
Appendix 11.8.

Table 10 shows the different designs with 25% reduction in mass using structural optimisation.

Design	Original Mass (kg)	Final Mass (kg)
Simplified	0.65	0.52
Standard	0.42	0.35

The simplified piston was used for topology optimisation with a 25% mass-reduction target while protecting critical external regions such as the crown, ring lands, skirt surface and gudgeon-pin bosses. Material removal was therefore confined to the internal volume. The resulting topology shows significant thinning of the inner skirt and material removal between the pin bosses. For comparison, the standard piston was also assessed with the same mass-reduction target, limited to the region around the gudgeon pins, to evaluate whether the existing design could support further

optimisation. Both cases identify areas that would require detailed deformation and stress evaluation before any redesign could be justified.

Only basic structural loads could be applied, as motion and thermal loads caused solver conditioning errors. Consequently, the optimisation reflects a limited loading environment and does not represent real piston behaviour. The generated geometries should therefore be interpreted as conceptual indications of possible mass reduction rather than validated or manufacturable design solutions.

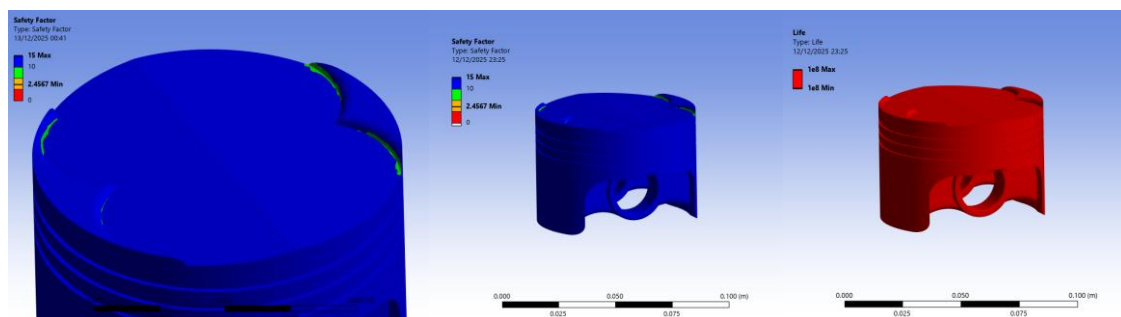
6 Fatigue Study

An initial fatigue and life assessment was conducted using the results from the static structural analysis. The safety factor and life prediction plots indicated extremely long fatigue lives with no clearly defined critical regions, suggesting that the model was not capturing realistic fatigue behaviour. This outcome is primarily attributed to the incorrect minimum and maximum imported motion loads and the simplified boundary conditions applied to the piston. Furthermore, the motion loads were generated at 4000 RPM, a mid range operating speed that does not impose the high inertial forces typically associated with fatigue critical behaviour in piston components. Although these limitations reduce the realism of the fatigue assessment, some degree of fatigue response would still be expected, as suggested by the comparative trends reported in the research shown in Figure 22.

Table 11 Boundary conditions used for the rigid dynamics fatigue analysis. Rotational speed was converted from RPM to rad/s, with step and end times derived from the rotational period. Maximum and minimum reaction forces were exported to the static structural solver for fatigue evaluation.

Boundary Coniditions - Rigid Dynamics Fatigue Test		
Analysis Settings		Units
End Time	0.0015	Seconds
Step Time	0.0000042	Seconds
Revolution	4000	RPM

Figure 22 presents published fatigue results from Lokesh Singh and Suneer Singh Rawat et al., which show broadly similar trend patterns to those observed in this study. Although the magnitudes and local variations differ due to differing materials, geometries and boundary conditions, the general correlation in safety factor and life cycle behaviour provides some confidence that the overall trend prediction is reasonable. However, the limitations in the applied loading conditions mean that these results should be interpreted cautiously.



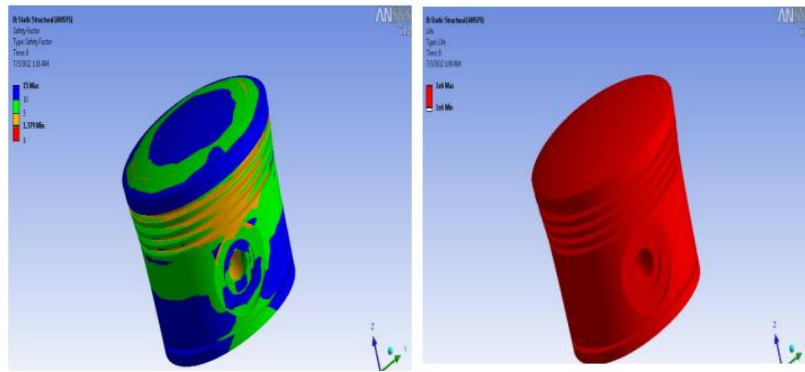


Figure 22 Comparison between the present study and published piston analysis results by Lokesh Singh and Suneer Singh Rawat et al.

7 Limitations and Assumptions

Table 12 Summary of key modelling assumptions and limitations and their impact on the accuracy of the finite element results.

Category	Assumption/Limitation	Impact on Results
Thermal Analysis	Uniform heat-transfer coefficients applied to all materials.	Ignores differences in emissivity, conduction and surface behaviour. Temperature fields become comparative rather than realistic.
Structural Analysis	Weak springs used to stabilise the model. Idealised gudgeon-pin constraints (no lubrication, contact, or compliance).	Adds artificial stiffness and may slightly reduce predicted deformation. Does not capture pin–boss interaction or secondary motion; stresses and deformation become simplified.
Dynamic Behaviour	Rigid dynamics loads transferred for one crank angle only.	Provides only a snapshot of inertial loading; does not capture full engine cycle effects.
Topology Optimisation	Simplified load cases without motion or thermal fields. Subtractive-only optimisation (material removal only).	Optimised shapes do not reflect true engine conditions and cannot be treated as validated design solutions. Cannot add material where stiffness is required; resulting geometry may be unmanufacturable or structurally unsafe.
General Modelling Simplifications	Geometry, loads, constraints and thermal fields simplified for solver stability.	Results are suitable for comparing trends, not for predicting real piston performance or durability.

Overall, the modelling assumptions used in this study mean the finite element results should be interpreted as comparative indicators of thermomechanical behaviour, rather than accurate predictions of in-service piston performance. More advanced transient thermal modelling, realistic constraint definitions, cyclic loading and validated topology conditions would be required for design-level accuracy.

8 Conclusion

The finite element analysis provides useful comparative insight into piston behaviour, but the results must be interpreted cautiously. Although the mesh validation confirmed numerical stability and the linked workflow operated correctly, accuracy is limited by key modelling assumptions. The steady state thermal field, simplified gudgeon pin constraints and restricted loading conditions mean that the predicted deformation, stress and temperature fields do not fully represent real engine behaviour. Material trends remain credible, with aluminium alloys showing greater deformation and titanium retaining stiffness, but these patterns reflect simplified loading rather than full thermomechanical conditions.

The topology optimisation highlights potential mass reduction but is constrained by the absence of motion and thermal loads, making the resulting geometries conceptual only. Overall, the study demonstrates that finite element tools are valuable for understanding comparative behaviour and informing early design decisions, but the outputs are not suitable for design verification without complete loading histories and fatigue aware modelling.

9 Further work

A key area for further development is the investigation of piston behaviour across a wider range of engine speeds. The current analysis was limited to 4000 revolutions per minute, which does not capture the variation in inertial loading, thermal generation and stress fluctuation that occurs across the full operating range. Higher engine speeds produce greater acceleration forces and reduced dwell time at top dead centre, potentially shifting fatigue critical regions, while lower speeds introduce different thermal gradients and load paths.

Further work should apply motion loads from rigid dynamics to both the baseline and optimised piston geometries to evaluate stress, deformation and fatigue life under more realistic operating conditions. This would provide a stronger basis for assessing whether the topology modifications and material choices are suitable for long term engine performance.

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11 Appendix

11.1 Material Properties

Property	Value
Density	2.80 g/cm ³
Tensile strength	440–470 MPa
Yield strength	~ 315 MPa
Fatigue strength	~ 130 MPa
Elastic modulus	71 GPa
Thermal conductivity	~ 145 W·m ⁻¹ ·K ⁻¹
Coefficient of thermal expansion	22 × 10 ⁻⁶ /K
Specific heat	875 J/kg·K
Max operating temperature	~ 300 °C
Corrosion resistance	Very Good
Weld ability	Good

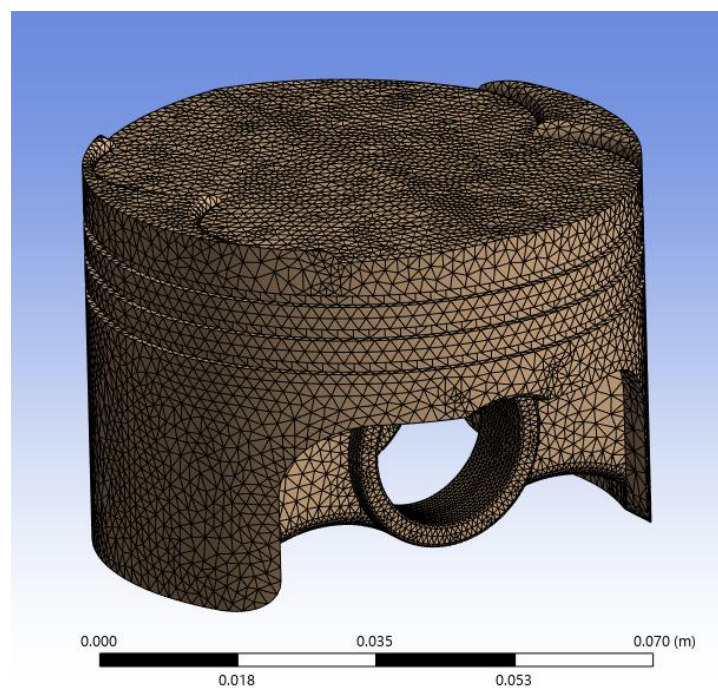
Table 2. Aluminium 2618 properties^{26,27}.

Property	Value
Density	4.43 g/cm ³
Tensile strength	~ 900 MPa
Yield strength	~ 830 MPa
Fatigue strength	~ 510 MPa
Elastic modulus	113 GPa
Thermal conductivity	~ 6.7 W·m ⁻¹ ·K ⁻¹
Coefficient of thermal expansion	9 × 10 ⁻⁶ /K
Specific heat	526 J/kg·K
Max operating temperature	~ 400 °C
Corrosion resistance	Excellent
Weld ability	Good

Table 4. Titanium alloy (Ti-6Al-4 V) properties^{30,31}.

(Elias Wakshume, Gadisa Sufe)

11.2 Final Mesh



11.3 Material/Thermal Properties – Aluminium 6061-T6

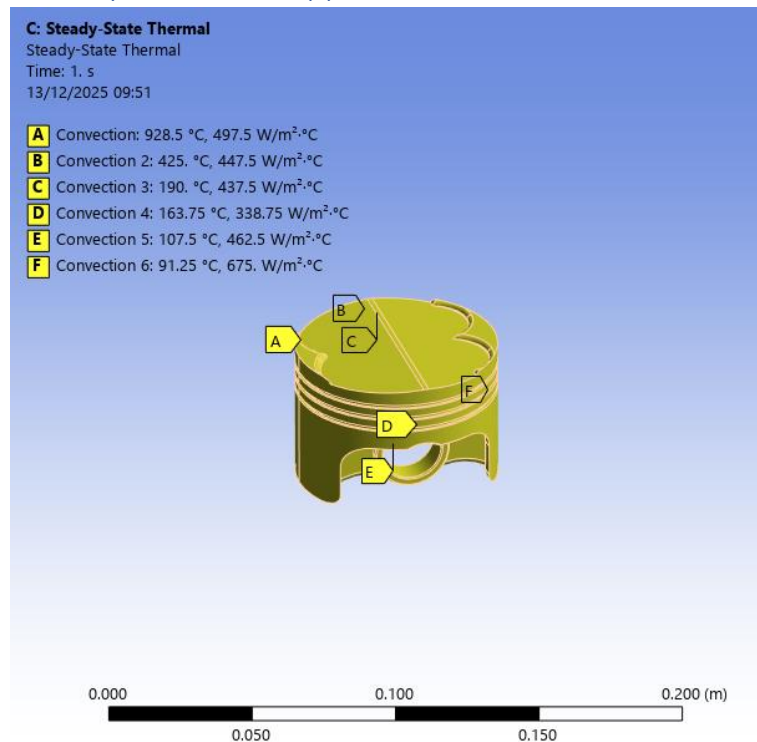
Thermal Study Boundary Conditions										
	Heat Transfer Coefficient					Temperature (Celcius)				
	1	2	3	4	Average	1	2	3	4	Average
Crown	600	350	500	540	497.5			928.5		928.5
Crown Side	500	540	350	400	447.5	250	650	500	300	425
Top Groove	300	650	200	600	437.5	180	150	180	250	190
Middle Groove	300	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

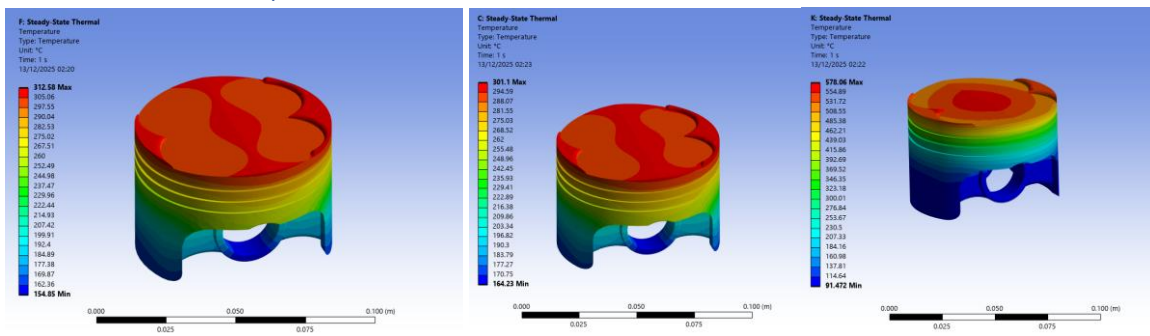
6061-T6 Aluminium Material Properties			
Temp (°C)	Young's Modulus		Poisson's Ratio
	Value	Unit	0.33
22	67	Gpa	Coefficient Thermal Expansion 22°C
100	70	Gpa	
150	68	Gpa	Thermal Conductivity
200	64	Gpa	
250	56	Gpa	Specific Heat Capacity
300	48	Gpa	
350	41	Gpa	2.36E-05 1/°C
400	32	Gpa	
450	21	Gpa	167 W/m-K
500	12	Gpa	
			0.896 J/g-°C

(Andrew Noble 2025)

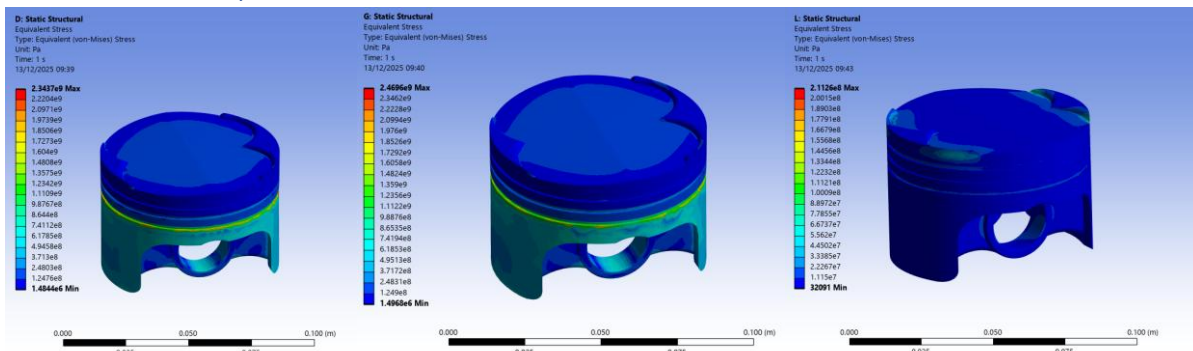
11.4 Thermal Boundary Conditions Applied



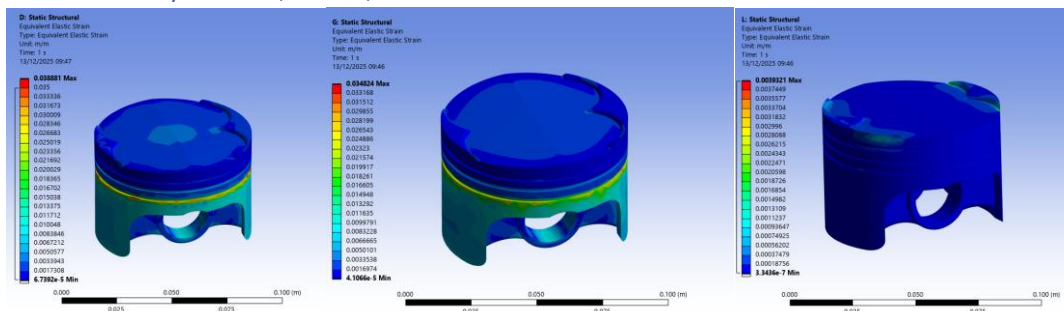
11.5 Thermal Study - 6061, 2618, Ti-6Al-4 V In Order



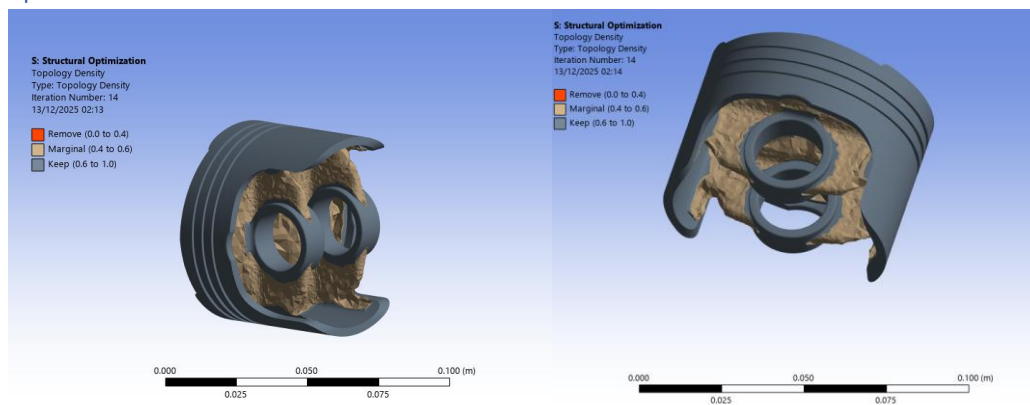
11.6 Stress Study – 6061, 2618, Ti-6Al-4 V In Order

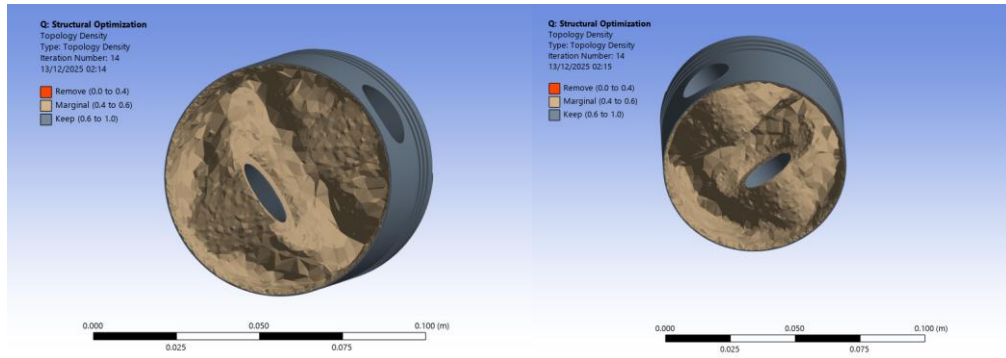


11.7 Strain Study - 6061, 2618, Ti-6Al-4 V In Order



11.8 Optimised Pistons





11.9 Workbench

