

Application of CAE Processes

Structural Analysis (ACHA6010)

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Abstract

This report presents the application of Computer Aided Engineering (CAE) methods to the analysis and optimisation of a simplified engine model assembly. A kinematic study was conducted to generate representative loading conditions based on simulated engine motion, with reaction forces extracted for use in subsequent analyses.

A static structural and thermo-mechanical assessment was performed on the piston, selected due to its exposure to significant mechanical loading and elevated operating temperatures. The initial design exhibited peak stresses in regions associated with load transfer through the gudgeon pin, which were reduced following iterative material and design evaluation. The inclusion of thermal effects resulted in increased stress levels, demonstrating the influence of temperature-dependent material behaviour.

Analytical validation, supported by a mesh independence study, confirmed that the numerical approach achieved acceptable agreement with fundamental theory, while highlighting sensitivity to boundary condition definition. Overall, the findings demonstrate that CAE tools are effective for comparative assessment and optimisation but must be applied with careful validation and critical interpretation due to inherent modelling assumptions and simplifications.

1. Introduction

1.1 Background and Context

Computer-aided engineering (CAE) plays a significant role in modern mechanical and vehicular engineering, enabling efficient evaluation and optimisation of components prior to physical testing (Cook et al. 2002; Zienkiewicz et al. 2005). Finite element analysis (FEA) is commonly used to assess stress, strain, and deformation under simulated loading conditions, while kinematic simulations allow representative loads to be generated for complex assemblies (Heywood 1988; Cook et al. 2002). Despite these advantages, CAE methods are subject to limitations relating to modelling assumptions, boundary condition definition, and computational constraints, which can influence result accuracy and interpretation (Cook et al. 2002; Bathe 2014).

1.2 Aims and Objectives

The aim of this report is to investigate how kinematic, thermal, and static analyses can be used to evaluate the performance of selected components and assemblies and inform design and material decisions. In addition, the study assesses the limitations of CAE methods by considering thermal effects, material behaviour, and modelling assumptions to evaluate their reliability in supporting engineering decision-making.

1.3 Scope of Work

This report follows a structured workflow beginning with the use of a provided assembly model. A kinematic analysis is performed to establish representative loading conditions, followed by static structural and thermal analyses of a selected component. Iterative optimisation is then explored through material substitution and proposed geometric modification. The work concludes with a validation study using simplified analytical cases, supported by mesh independence and boundary condition sensitivity assessments, to evaluate the capabilities and limitations of the CAE approach.

2 Background & Literature Review

2.1 Finite Element Analysis in Structural Assessment

Finite Element Analysis (FEA) is widely used in mechanical engineering to predict stress, strain, and deformation by discretising a continuous domain into finite elements, enabling complex geometries and loading conditions to be assessed numerically (Cook et al. 2002; Zienkiewicz et al. 2005). In CAE-driven design, FEA is most effective for comparative assessment, identifying stress concentrations and relative performance trends between design variants.

However, FEA results are inherently sensitive to discretisation, solver formulation, and modelling assumptions. Mesh density and element quality influence solution accuracy, while solver choices such as linear static assumptions limit the ability to capture transient or nonlinear behaviour (Bathe 2014). As a result, verification procedures such as mesh independence studies are essential to ensure numerical error is controlled, and that further refinement does not significantly alter key results (Roache 1998).

Boundary condition definition is a further critical influence, particularly in isolated component analyses. Constraint location and stiffness can artificially redistribute stresses, leading to localised peaks that reflect modelling assumptions rather than true operational behaviour (Cook et al. 2002). These sensitivities reinforce the need for careful interpretation of FEA results.

2.2 Thermo-Mechanical Behaviour of Engine Pistons

Engine pistons operate under combined mechanical and thermal loading, where combustion heat and mechanical load transfer produce complex stress and deformation behaviour. Thermal gradients across the piston generate thermal expansion, which can significantly influence stress levels when constrained by geometry or supports (Heywood 1988; Bergman and Levine 2019).

Thermo-mechanical FE studies consistently demonstrate that temperature effects and constraint-driven expansion strongly affect predicted stress distributions and durability trends. Consequently, piston performance cannot be assessed using mechanical loading alone, and optimisation decisions must consider the interaction between geometry, thermal gradients, and boundary conditions rather than material stiffness in isolation (Cook et al. 2002).

2.3 Kinematic Load Generation and CAE Validation

Kinematic analyses are commonly used to generate representative loading conditions for complex mechanisms by capturing the time-varying forces arising from motion. In slider-crank systems, crankshaft rotation produces cyclic inertial and reaction forces that can be transferred into subsequent structural analyses, enabling consistent load application across design iterations (Heywood, 1988).

Despite this, kinematic solvers typically rely on rigid-body assumptions and neglect material compliance and damping effects. When combined with static structural analysis, these simplifications mean that derived loads are best interpreted as representative trends rather than exact operational values (Cook et al., 2002). Validation against simplified analytical or benchmark cases, alongside mesh convergence studies, is therefore required to establish confidence in numerical predictions and to support the use of CAE as a decision-support tool rather than a source of absolute values (Roache, 1998).

3 Assembly Preparation & Pre-Processing Workflow

3.1 Assembly Overview & Components List

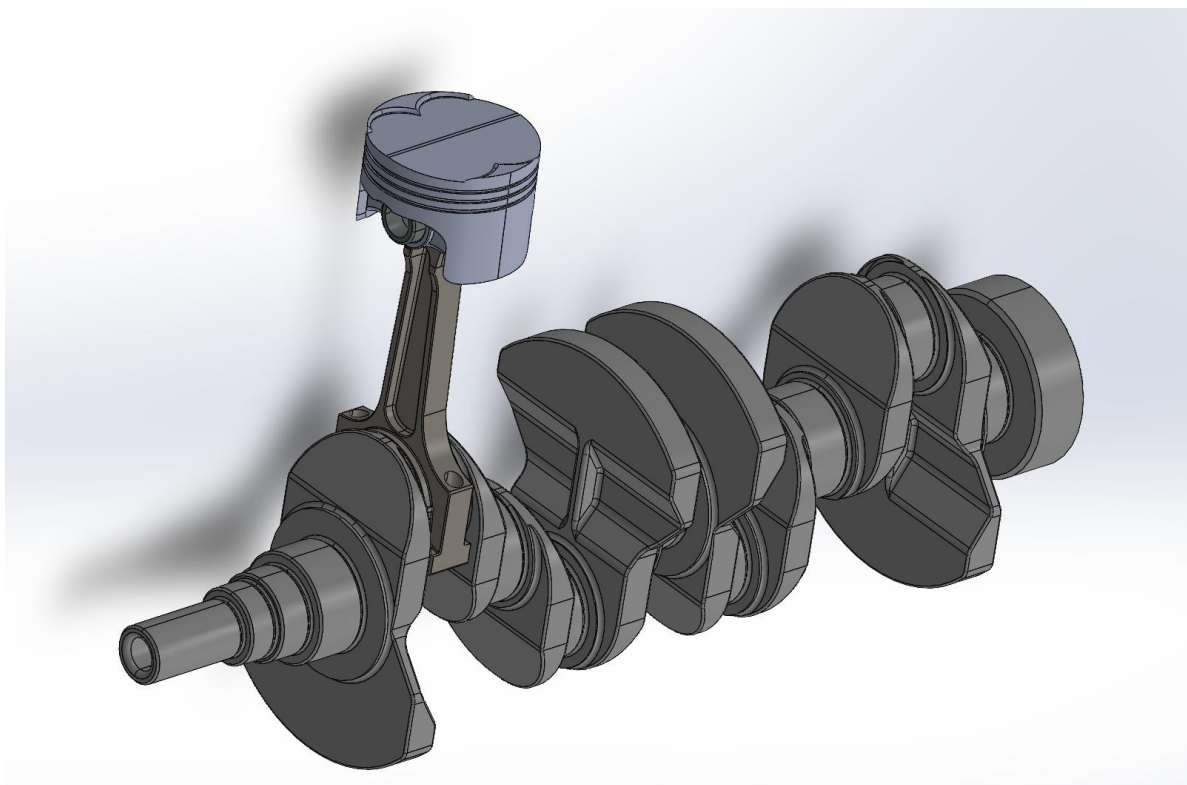


Figure 1: Crankshaft-connecting rod-piston assembly used for kinematic and structural analysis.

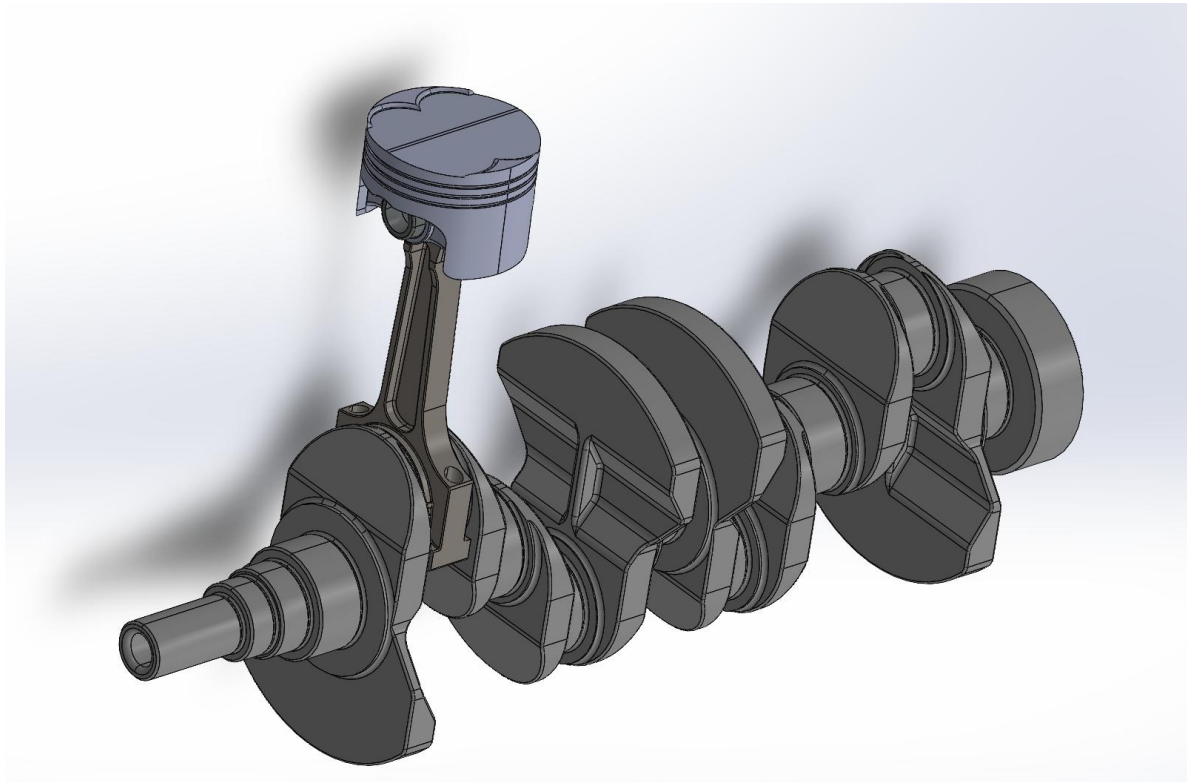


Figure 1: Crankshaft–connecting rod–piston assembly used for kinematic and structural analysis. shows the assembly used for the case study, forming the basis of the kinematic, thermal, and structural analyses. The assembly consists of four components: the crankshaft, connecting rod, gudgeon pin, and piston. Despite its simplicity, the model captures the basic functions, alignments, and connections seen in a complete engine, allowing for realistic loading behaviours during simulated operation (Heywood 1988).

The simplicity of the model also helps isolate the influence of modelling assumptions, boundary conditions, and material definitions discussed later in the report. It provides a clear baseline for examining how CAE tools interpret component relationships and how accurately simplified models can represent real-world mechanical behaviour (Cook et al. 2002).

Component	Description	Original Material
Crankshaft	Converts rotational input into reciprocating motion within the assembly. It provides the driving rotation in the kinematic study and serves as the origin of the applied load on the connecting rod and piston.	Structural Steel
Connecting Rod	Translates rotational motion from the crankshaft into linear loads onto the piston.	Structural Steel
Gudgeon Pin	Forms a pivot between the connecting rod and the piston, allowing relative rotation at the small end to maintain alignment during reciprocating motion	Structural Steel

Piston	Translates the motion from the connecting rod into linear displacement. Within this study, the piston is the primary component used for load retrieval during the kinematic analysis, and it forms the basis of the later thermal and static structural studies.	Aluminium 6061 T6
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Table 1: Component list for the assembly used in the case study.

3.2 Joint Definition and Motion Constraints

Before beginning any simulations, appropriate joints and mechanical constraints must be established between the assembly components to ensure realistic interactions. These definitions allow the rotational motion to propagate through the assembly to the piston, enabling the study to generate representative loading conditions (Cook et al. 2002).

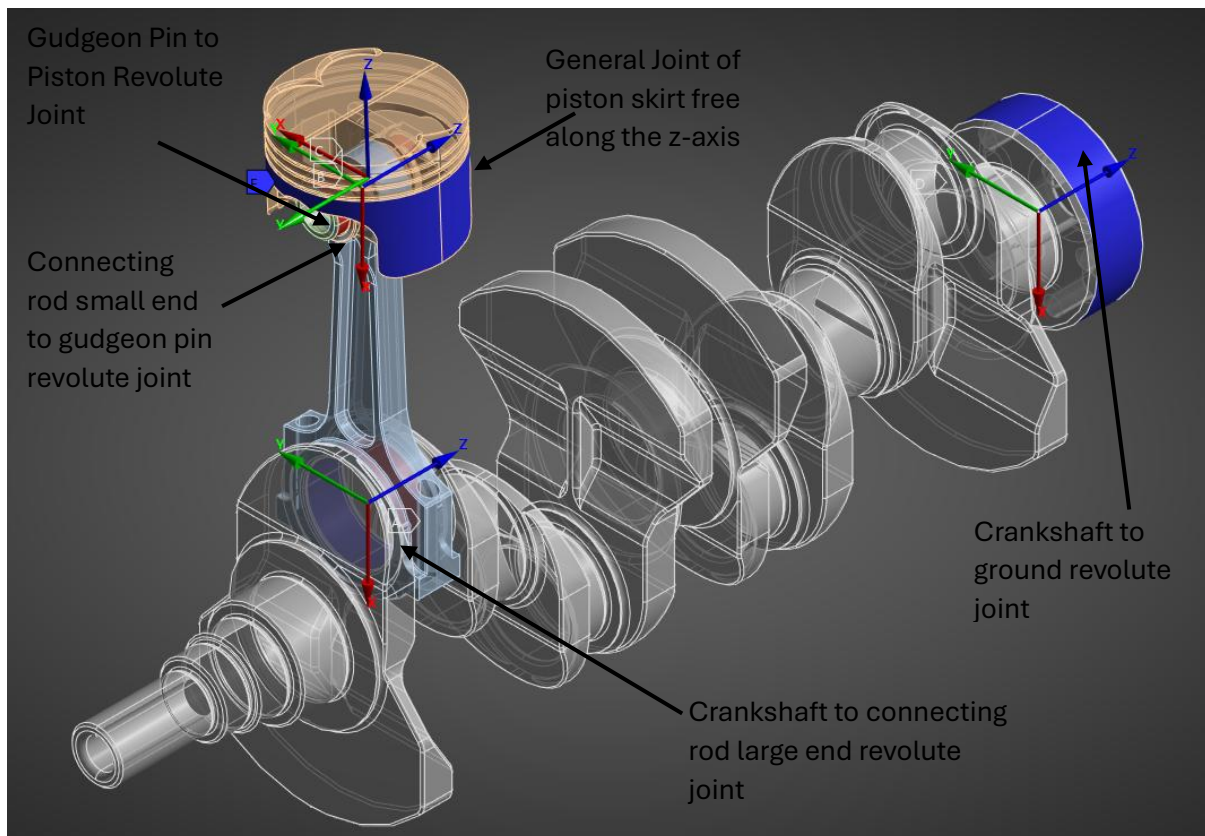


Figure 2: Joints and defined constraints in assembly.

Realistic connections between components were required to compensate for the constraints that were not explicitly modelled in the provided assembly, such as the cylinder bore and crankcase supports. The connections were selected to emulate the mechanical behaviours that would be present in a real engine (Heywood 1988).

Without the crankcase to stabilise the assembly virtually, a body to ground joint was created between the flywheel flange and the simulation space. This removes all unnecessary degrees of

freedom from the crankshaft leaving rotation around the Z axis as the final degree of freedom, which simulates a similar restriction to the crankshaft when the crankcase is bolted onto the engine around the main bearings (Bathe 2014).

As for the piston, the general joint used here, restricts it to just be able to move up and down the X axis as if it were in a cylinder.

The remaining joints for this assembly are all revolute, as seen above in Figure 2. This is to allow for the rotational motion of the crankshaft to be converted into the piston's linear motion while constraining the conrod, gudgeon pin and piston as separate components. If the joints are not defined as such, this part of the assembly would act as a single rigid body, creating a loss of necessary articulation within this model(Cook et al. 2002).

3.3 Kinematic Study and Analysis (2-3 cites)

The kinematic study establishes the loading conditions used in the subsequent structural and thermal analyses. A rotational input of 6000 RPM was applied to the crankshaft, representing a mid-to-high operating speed typical of internal combustion engines. With the defined joint constraints, crankshaft rotation produces a reciprocating piston motion along the X-axis, generating the characteristic inertial loading required for force extraction.

Reaction forces and moments were calculated at the defined joints throughout the cycle. Loads were extracted from a joint probe at the piston–gudgeon pin interface, where peak force transmission is expected, and subsequently applied in the static structural analysis. The resulting force profile (Figure 4) represents a simplified loading condition and neglects effects such as friction, material compliance, and dynamic balancing. These omissions reflect the assumptions inherent to rigid-body kinematic models and contribute to uncertainty in downstream analyses (Cook et al. 2002).

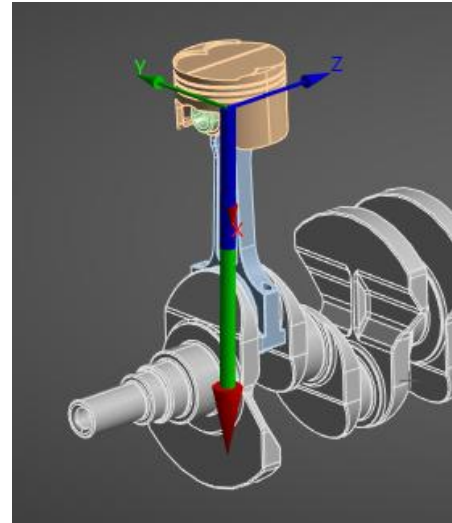


Figure 3: Rigid model displaying axis of oscillation of the piston

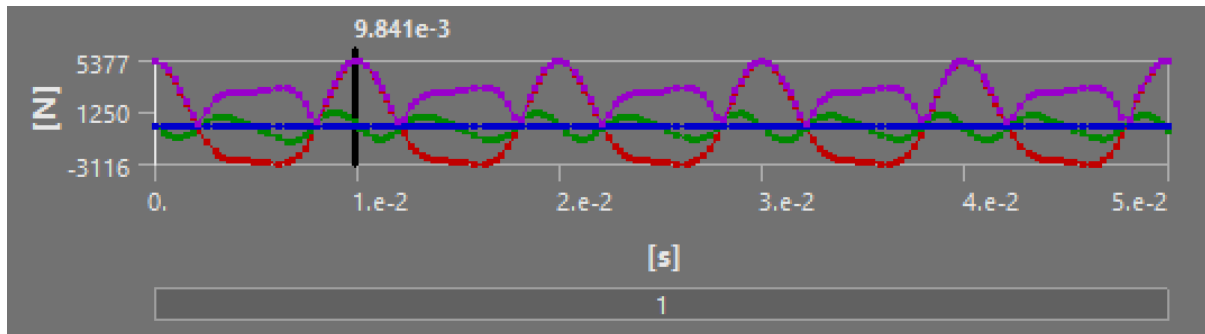


Figure 4: Result plot from the kinematic study displaying force against time.

4 Static Structural and Thermal Methodology and Analysis

4.1 Component Selection

The subsequent studies focus on a component subjected to the highest combined mechanical and thermal loading. Selection criteria included load magnitude, thermal exposure, and suitability for structural modification. These conditions are characteristic of an operating piston, which experiences alternating tensile and compressive forces from the connecting rod and

elevated thermal loading at the crown (Heywood 1988). The piston was therefore selected for further analysis.

4.2 Load Application and Constraints

The mechanical loads applied in this study were taken from the peak reaction forces identified during the kinematic analysis, representing the highest loading experienced over a single simulated engine cycle. This peak force condition defines a worst-case scenario and is therefore suitable for assessing the piston's structural performance (Urgural and Fenster 2003). In addition to these forces, a uniform pressure of 1.05 MPa was applied across the piston crown to emulate combustion loading, with the pressure distribution shown in.

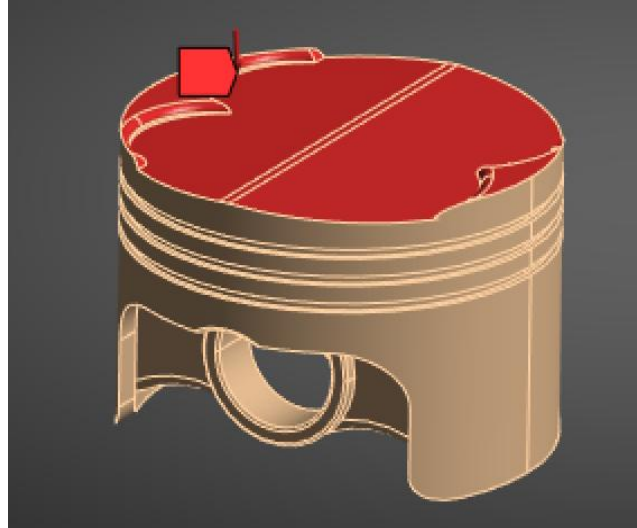


Figure 5: Applied combustion pressure on the piston crown.

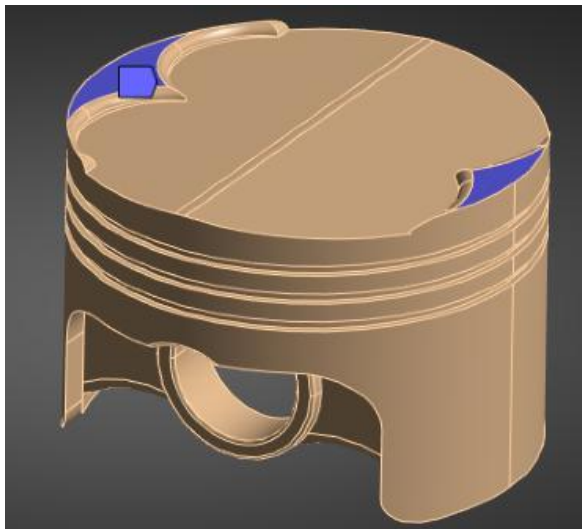


Figure 6: Face selections for fixed supports

The resulting mechanical loads are transmitted through the connecting rod into the gudgeon pin, concentrating stresses at the interface between the gudgeon pin and piston.

To apply the imported loads upon the piston in a static state, displacement constraints were added to the faces shown in **Error! Reference source not found.** to prevent rigid-body motion in the workspace. As the kinematic study already provided the required motion-based forces, there was no need for further motion constraints or joints in this analysis.

Along with the constraints, the remaining components were suppressed to isolate the piston for mesh refinements across the crown and ring recesses and reducing unnecessary computing times.

4.3 Thermal Considerations

To implement the appropriate thermal effects, temperature values were applied across several regions to represent operating conditions. These values were taken from the supporting material property data provided with the assignment brief. The average temperature for the heat transfer coefficient, and temperature are applied across seven regions throughout the piston model, and a summary of these inputs is presented in Table 2.

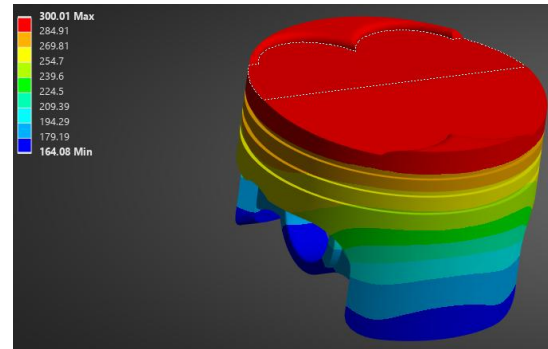


Figure 7: Map of thermal distributions on the piston dissipating from crown to skirt

Piston Region	Heat Transfer Coefficient	Applied Temperature (°C)
Crown	497.5	928.5
Crown Side	447.5	425
Top Groove	437.5	190
Middle Groove	437.5	190
Oil Groove	338.75	163.75
Underside	675	91.25
Skirt	462.5	107.5

Table 2: Thermal boundary conditions applied using provided data.

A steady-state thermal analysis was used to represent the piston under typical operating conditions. A descending temperature distribution was applied, with peak temperatures at the crown and lower values at the skirt and underside to reflect conductive heat dissipation through the component. Convection boundary conditions were applied using the data in Table 2 to approximate cooling. Although simplified, this approach produces representative temperature gradients (Figure 7) suitable for subsequent thermo-mechanical analysis (Heywood 1988).

4.4 Initial Results

4.4.1 Static results

Under mechanical loading alone, the piston would be expected to experience its highest stresses in regions associated with load transfer through the gudgeon pin, which is consistent with the global deformation behaviour (Figure). However, due to the applied boundary constraints, peak stresses are instead concentrated along the edges of the fixed faces, as indicated by the von Mises stress distribution (Error! Reference source not found.). This highlights the strong influence of boundary condition application on stress distribution within isolated component analyses.

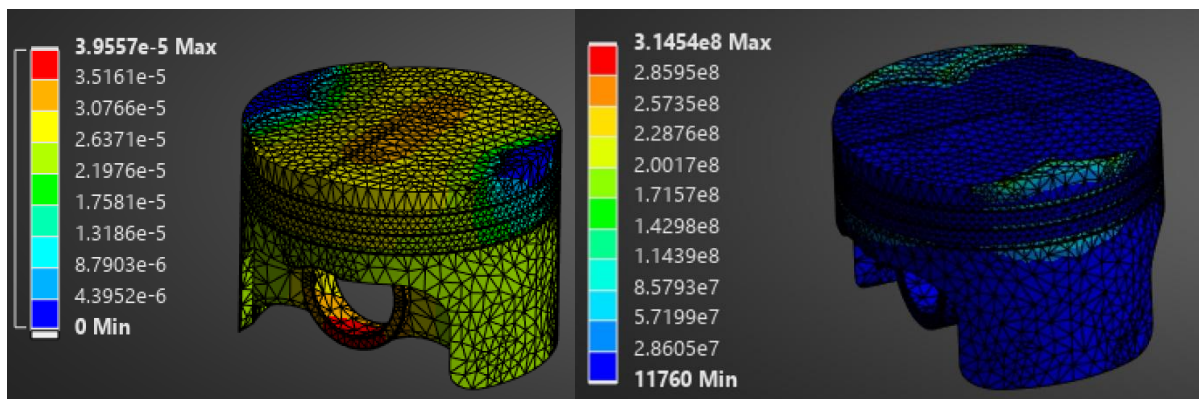


Figure 8: Piston deformation under baseline mechanical loading.

Figure 9: Von Mises stress distribution under baseline mechanical loading.

The static results indicate limited deformation under peak mechanical loading, despite localised stress concentrations influenced by simplified boundary conditions. This suggests that mechanical loading alone is insufficient to represent the piston's critical behaviour, reinforcing the need to include thermal effects for a realistic performance assessment.

4.4.2 Thermal results

When thermal effects are incorporated into the static structural analysis, the piston experiences an increase in both stress (**Error! Reference source not found.**) and deformation (**Error! Reference source not found.**). Like the static-only case, the highest stresses remain concentrated around the fixed faces; however, the thermo-mechanical results show a wider distribution of stress across the skirt and gudgeon pin region. This is accompanied by increased deformation in these areas, indicating the influence of thermal expansion on the piston's structural response.

Thermal loading induces expansion within the piston; however, this expansion is partially restrained by the applied constraints, resulting in additional thermal stresses as thermal strain is converted into stress. In addition, temperature-dependent material softening reduces both Young's modulus and yield strength, increasing deformation under the same mechanical load. The interaction between thermal expansion and constrained regions therefore contributes to elevated stress levels, particularly near fixed faces where expansion is restricted.

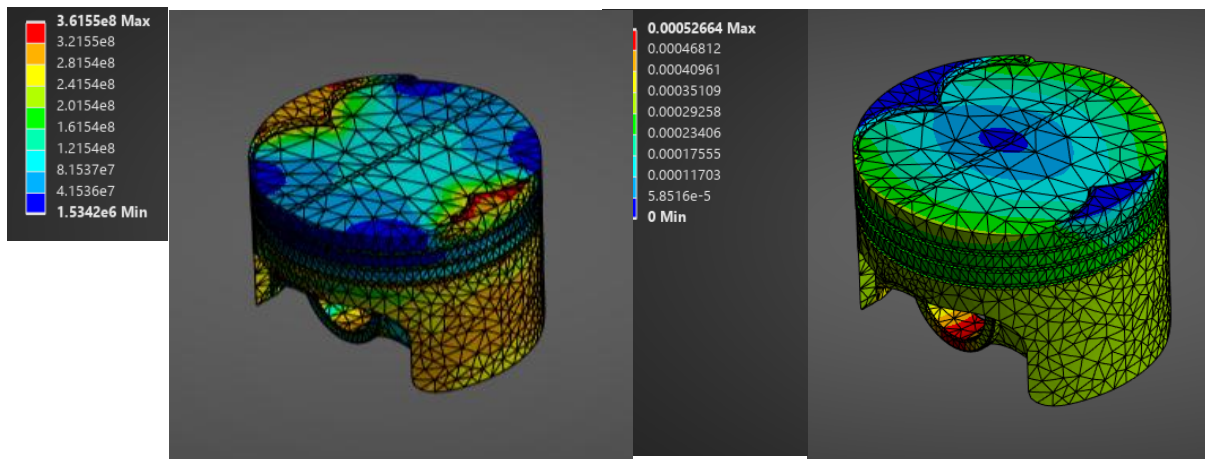


Figure 11: Von Misses after applying thermal effects

Figure 10: Deformation in thermo-mechanical study

Study Type	Temperature (°C)	von Misses Stress (Pa)	Deformation (m)	Factor of Safety	Fatigue Life (Cycles)
Static Structural	22	3.15E+08	3.96E-05	1.1604	848220.00
Steady State Thermal	300.01	3.61E+08	5.89E-04	1.01	19722.00

Table 3: Summary of baseline static and thermo-mechanical results for the piston.

The maximum operating temperature predicted for the baseline material is reported in

Table 3 to provide context for the thermo-mechanical response.

5 Design Development and Optimisation

5.1 Baseline Limitations

Under realistic operating conditions, thermal effects significantly influence stress distribution and deformation within the piston. When thermal loading is included, the results show a 13% increase in peak stress and an almost 100% increase in total deformation. In addition, an approximate 16% reduction in safety factor and a 43-fold reduction in predicted fatigue life are observed. This highlights a key limitation of the baseline design, as long-term durability is strongly compromised under combined thermo-mechanical loading.

These results represent a clear limitation, as a piston exhibiting this level of performance under operating loads would experience a significantly reduced service life. The substantial reduction in safety factor and fatigue life suggests that failure would occur prematurely under sustained operation, rendering the baseline design unsuitable for reliable long-term use (Stephens et al. 2001).

As a result, optimisation is required to improve performance under combined loading conditions. Both geometric modification and material substitution were considered as potential improvement routes; however, material substitution was selected as the initial focus due to its ability to be evaluated efficiently without altering the baseline geometry.

5.2 Optimisation Strategy

Material substitution was used as the initial optimisation strategy to evaluate the influence of material properties without altering the baseline geometry. Candidate materials were selected from the Granta EduPack database to compare mechanical and thermal behaviour under operating conditions (Granta EduPack 2025). This also enabled assessment of whether material changes alone were sufficient or if geometric modification was required to address critical stress regions (Papalambros and Wilde 2000). To maintain realistic design constraints, evaluation was limited to aluminium alloys comparable to the baseline material. The materials assessed were:

- Aluminium 2618-T6
- Aluminium 5182-H16
- Aluminium 8090-T851

A summary of key material properties used to inform the selection process is provided in.

Material	Heat Treatment	Density (kg/m ³)	Young's Modulus (GPa)	Note of Intended Benefit
Aluminium 6061 T6	T6	2.71E+03	66.6-70	Baseline material
Aluminium 2618, T6	T6	2.75E+03	72-76	High temperature strength
Aluminium 5182, H16	H16	2.66E+03	69.2-72.8	Improved ductility
Aluminium 8090, T851	T851	2.54E+03	80-84	High stiffness-to-weight

Table 4: Candidate materials selected for substitution study.

Material selection was informed by property trends obtained from the Granta EduPack database, including stiffness, strength, density, and temperature-dependent behaviour.

5.3 Evaluation of Material Performance

Material performance for the substitutional options was evaluated by applying identical conditions to each candidate material to maintain consistency, with one key caveat of motion loads being exported separately for each material to allow a fair comparison.

Performance was assessed via comparison of, peak stress, total deformation, and predicted fatigue life. Also to be considered is the safety factor although this lines up well with the stress values added a layer of redundancy.

Materials	Load (N)	von Misses Stresses (Pa)	Deformation (m)	Minimum FoS
Aluminium 6061 T6 (Thermal)	5371.2	3.61E+08	5.89E-04	1.01
Aluminium 2618, T6	5454.5	4.316E+08	3.742E-04	0.96686
Aluminium 5182, H16	5277.1	4.44E+08	5.755E-04	0.56557
Aluminium 8090, T851	5036.5	5.68E+08	4.65E-04	0.87297

Table 5: Comparison of thermo-mechanical performance for candidate piston materials.

None of the alternative materials provided a sufficient improvement over the baseline Aluminium 6061-T6 under thermo-mechanical loading. Although Aluminium 2618-T6 and Aluminium 8090-T851 reduced deformation, this was offset by increased stress and safety factors below unity, while Aluminium 5182-H16 exhibited a pronounced reduction in structural margin. This confirms that material substitution alone is insufficient to resolve the dominant thermo-mechanical limitations of the piston design, as improvements in one material property are commonly accompanied by compromises in others (Ashby 2011).

5.4 How CAE impacted results

Material substitution alone was insufficient to address the dominant behaviours governing piston performance. While the alternative alloys exhibited differing stiffness and strength characteristics, the observed stress concentrations were primarily driven by geometric features and constraint-induced thermal expansion rather than material properties. Consequently, reductions in deformation were often offset by increased stress levels and reduced safety factors, indicating that effective optimisation requires geometric modification to manage stress redistribution and thermal expansion in conjunction with material selection.

The performance of several candidate materials was also influenced by the simplified boundary conditions used to analyse the piston in isolation. In a fully assembled engine, load transfer and thermal expansion would be partially accommodated by surrounding components, potentially reducing the localised stress concentrations observed. As a result, materials that underperformed relative to Aluminium 6061-T6 within the constraints of this model may remain viable when combined with appropriate geometric design and system-level compliance (Cook et al. 2002).

5.5 Proposed Design Alterations

Based on the material substitution results, further optimisation should prioritise geometric modification rather than material changes alone. The dominant limitations were driven by stress concentrations and constraint-induced thermal expansion, which cannot be sufficiently mitigated through material selection. Effective optimisation must therefore focus on stress redistribution, controlled compliance, and improved thermal expansion management through targeted geometric changes.

Several geometric modifications are proposed based on the observed stress and temperature hotspots. Increasing the fillet radius around the gudgeon pin bosses would reduce localised stress concentrations and improve fatigue performance. Selective material removal in the gudgeon pin boss support regions may enhance mass efficiency while promoting more uniform load transfer. Additionally, modifying crown thickness offers potential to reduce mass and moderate thermal gradients, contributing to improved thermo-mechanical performance.

When combined with appropriate geometric optimisation, several of the materials evaluated in this study may become viable candidates for piston applications. Future work should therefore consider a coupled optimisation approach, integrating both material selection and geometric refinement within a fully assembled model to better represent operating conditions. This would enable a more accurate assessment of load distribution, thermal expansion behaviour, and material performance within the complete system.

These proposed modifications provide a practical pathway for improving piston performance beyond material substitution alone.

6 Validation Study

6.1 Simplified Analytical Case

The reference cases were recreated within ANSYS using equivalent geometry simplifications, material properties, loading conditions, and boundary definitions to ensure numerical consistency with the provided data sets.

6.1.1 Uniform Load Validation (static structural)

A simplified static validation case was used to compare finite element results against reference data provided in the Dlubal validation dataset supplied for this assignment. Under a uniform load, simulated results were within 0.005% (Table 6) of the reference values, confirming strong agreement and supporting the reliability of the static analysis approach based on established beam theory (Gere and Goodno 2012).

Element size (m)	Deformation	Variation (%)
0.02	0.157143	Baseline
0.02 Tested	0.15715	99.9955%

Table 6: Mechanical validation study goal and results

6.1.2 Thermo-mechanical validation

A simplified thermal validation case was also conducted to compare numerical results against the provided Dlubal reference data set. Under thermal loading, simulated results were within 1% of the reference values (Table 7), confirming strong agreement and supporting the reliability of the thermal analysis approach (Bergman and Levine 2019).

Element size (m)	Deformation	Applied Temperature (°C)	Total Temperature (°C)	Variation (%)
2.50E-04	7.05E-03	100	122	Baseline
2.50E-04	7.11E-03	100	122	99.103026%

Table 7: Thermal validation study goal and results

6.2 Mesh Independence Study

Mesh Level	Element size (mm)	Total Deformation (mm)	von Misses Stress (MPa)	Solve Time
Base	4.00	0.58906	3.613E+08	~5 minutes
Coarse	10.00	0.58193	3.761E+08	~2 minutes
Medium	8.00	0.57947	3.677E+08	~3 minutes
Fine	5.00	0.58965	3.616E+08	~5 minutes
Very fine	2.00	0.59054	3.863E+08	~20 minutes
Base with mesh sizing	4.00	0.59054	3.605E+08	7-10 minute

Table 8: Mesh independence study results

A mesh independence study confirmed that the base mesh produced results within an acceptable range, with diminishing improvements observed under further global refinement. While local refinement in high-stress regions reduced deviation relative to a very fine mesh, it also introduced increased localised stress variability. Mesh density was progressively increased until key result values stabilised, after which targeted refinement was applied only in regions exhibiting high stress gradients. Areas of low stress variation were found to be insensitive to mesh density and did not require additional refinement. A balanced mesh was therefore selected to achieve an appropriate compromise between numerical accuracy and computational efficiency, consistent with established mesh convergence methodology (Roache 1998; Celik et al. 2008).

6.3 Boundary Condition Sensitivity Assessment

A boundary condition sensitivity study was conducted to assess the influence of constraint selection on stress distribution and deformation. Replacing fixed constraints with more compliant supports, and varying their locations, resulted in reduced localised stress concentrations and a smoother overall stress distribution. This highlights the sensitivity of isolated component analyses to boundary condition assumptions and reinforces the importance of appropriate constraint definition when interpreting numerical results (Bathe 2014).

7 Discussion of CAE Methods and Limitations

CAE tools enabled efficient evaluation of the piston's thermo-mechanical behaviour under representative operating conditions, providing insight into stress distribution, deformation, and fatigue trends that would be impractical to assess analytically. Applying consistent loading and boundary conditions across multiple materials proved effective for comparative assessment and optimisation decision-making (Zienkiewicz et al. 2005).

The study also highlighted inherent limitations of numerical analysis. Results were sensitive to mesh density and boundary condition definition, particularly under thermal loading where constraint-driven expansion influenced stress levels. Although mesh convergence was achieved, localised stress magnitudes remained dependent on modelling assumptions, reinforcing the need for mesh independence and sensitivity studies when interpreting CAE results (Cook et al. 2002).

Differences in solver behaviour were also observed between kinematic and structural analyses. While the kinematic solver provided representative load trends, rigid-body assumptions neglect material compliance, and static structural solvers do not capture transient effects present in real engine operation.

Overall, the findings demonstrate that CAE tools are most reliable as comparative, trend-based decision-support methods rather than sources of exact predictive values. Validation against reference data and critical interpretation of modelling assumptions are therefore essential for drawing meaningful engineering conclusions.

8 Conclusions

The generated data indicates that piston structural response is governed primarily by thermal expansion constraints and geometric stress concentrations, rather than material stiffness alone, limiting the effectiveness of material-led optimisation when evaluated through CAE. This establishes that meaningful performance improvement within this application requires geometry modification informed by thermo-mechanical interaction, rather than isolated material substitution.

Validation and sensitivity studies indicate that while CAE provides consistent comparative trends suitable for guiding design decisions, result fidelity remains highly dependent on boundary condition definition and thermal modelling assumptions. Consequently, CAE is most effective as a design-screening and optimisation tool but requires critical interpretation and validation before being relied upon for absolute structural limits.

Use of Generative AI Statement

Generative AI tools were used solely to support research, report structuring, and proofreading, in accordance with the assessment guidance; all technical analysis and conclusions are the author's own work.

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