Finite Element Analysis of a Crankshaft – AISI 4130 vs Cast Alloy Steel

Introduction

This report presents a detailed finite element analysis (FEA) of a single-throw crankshaft under static loading, comparing two material cases: **AISI 4130 normalized steel** and **Cast Alloy Steel**. The objective is to evaluate how the different material properties (stiffness and strength) influence the crankshaft's structural behaviour under identical geometry and loading conditions. We perform static simulations for each material to examine key results, including stress distribution, deflections, and strain, identify critical regions, and compare performance. This analysis helps determine which material provides better performance (lower stresses, less deformation, higher safety factor) for the given crankshaft design, informing material selection regarding strength and rigidity for such an application. The report is organized into sections covering the geometry, material properties, boundary conditions, mesh quality, result comparisons, and conclusions with recommendations.

Geometry Overview

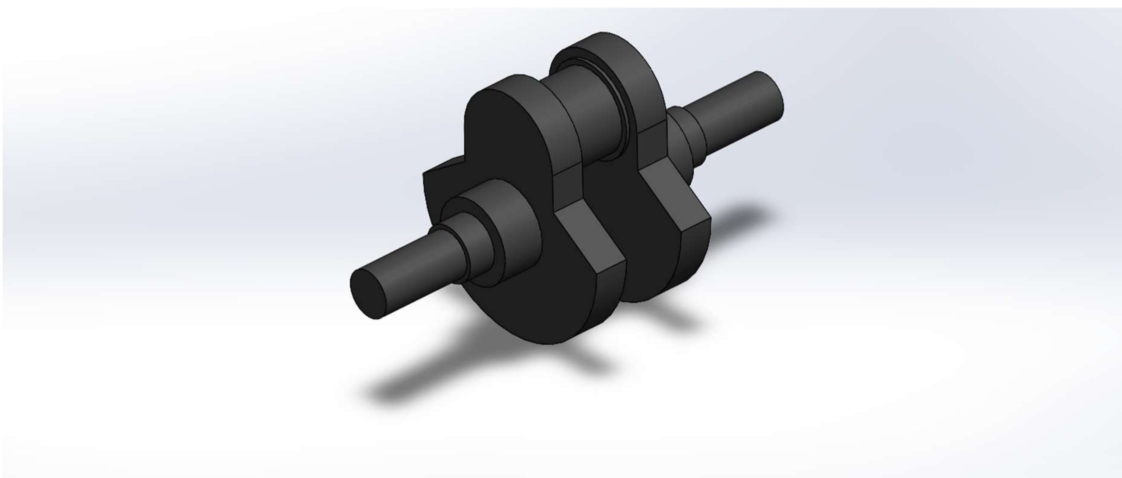

Figure 1: Crankshaft Geometry – Solid Model Overview

Both materials show similar stress distribution but differ significantly in stiffness and safety margin. AISI 4130 results in lower displacement and strain, with a higher yield threshold, making it a better choice for critical applications.

The crankshaft geometry analyzed is the same for both simulations. It is a single-throw (single crank pin) crankshaft, similar to what would be found in a single-cylinder engine. The model consists of two main journals at the ends (supported by bearings) and a crank pin in the centre, connected by crank webs. The crank webs join the crankpin to the main journals and have filleted transitions to reduce stress concentration. All features (journals, pins, webs) are modelled as solid volumes (no hollow sections). The overall geometry is symmetric about the mid-span of the crankpin. The part's volume is approximately 5.7596×10^–4 m^3, with a mass of around 4.2–4.5 kg (depending on material density) as extracted from the CAD model. Key geometric details, such as fillet radii at the journal-web junctions, are included since these are potential high-stress regions. The geometry remains unchanged between the two simulation cases so that any differences in results can be attributed solely to material behaviour.

Material Properties

Two different steel materials are considered: (1) AISI 4130 steel (normalized at ~870 °C) – a medium-carbon low-alloy steel often used in forged crankshafts, and (2) a generic Cast Alloy Steel – representative of cast steel used in crankshafts. Table 1 summarizes the relevant material properties used in the simulations for each material.

Property	AISI 4130 Normalized Steel	Cast Alloy Steel
Density (kg/m^3)	7,850	7,300 (approx)
Young's Modulus, E (GPa)	205 GPa	190 GPa
Poisson's Ratio v	0.27–0.30	0.26
Yield Strength (MPa)	~435 MP	~241 MP
Tensile Strength (MPa)	~670 MPa	~450 MPa

Table 1. Key Material Properties for AISI 4130 Normalized vs Cast Alloy Steel (asm.matweb.com)

The 4130 steel is also slightly stiffer (E ~205 GPa vs 190 GPa) fushunspecialsteel.com. Note the cast steel has a lower density ~7300 kg/m^3pureportal.strath.ac.uk (due to different alloy composition or porosity) compared to ~7850 kg/m^3 for 4130, but this ~7% lower weight is accompanied by significantly lower yield strength.

Both materials are treated as isotropic linear elastic in the static simulations (metal plasticity not considered since stresses will remain well below yield).

Boundary Conditions and Loading

Both static simulations use identical boundary conditions and loading, aside from how the load direction is defined. The crankshaft is supported at the two main journal sections using **fixed hinge** supports. In the FEA model, this was applied by fixing the circular end faces of each main journal such that all translations are constrained (no movement in X, Y, Z) while rotations are free – simulating a pin/hinge support at the main bearings. This makes the crank bend like a supported beam between the two ends.

A static force of **16,000 N** (approximately 1.63 tons) is applied at the crank pin (the centre of the crankshaft throw). The load is distributed over the crankpin's bearing surface and is directed vertically downward (perpendicular to the crank's longitudinal axis), causing a bending moment between the supports. In the first simulation (Static 1 with AISI 4130), the force was applied normally to the crankpin's top face, whereas in the second simulation (Static 2 with cast steel), the same 16 kN load was applied downward using a reference to the global top plane – in effect both cases apply an equal downward bending load in the middle of the span. The loading represents an extreme combustion force or gas pressure transmitted through a connecting rod to the crankpin. Both ends are supported (pinned), and a central downward force corresponds to a worst-case bending scenario for the crankshaft. No torque or other loads were applied in these static cases, so the crankpin experiences a pure bending load between the two main journal supports. Gravity was not included (not significant relative to 16 kN). The analysis assumes static equilibrium (no dynamic effects), and a small deflection theory is used (the large displacement option was off). Contact or interactions are not applicable since it's a single solid part with no assemblies or joints in this model.

Mesh Details and Element Quality

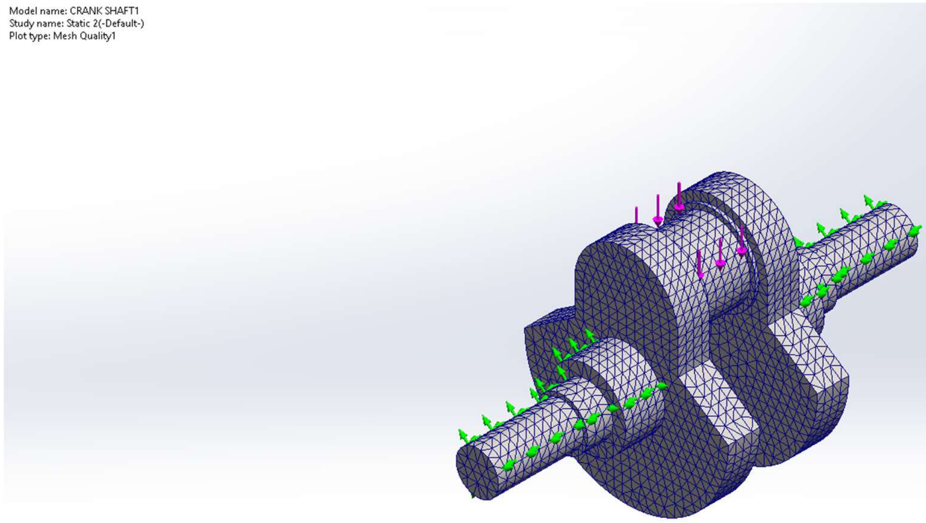

Figure 2: Mesh – Static 1: AISI 4130 Normalized Steel

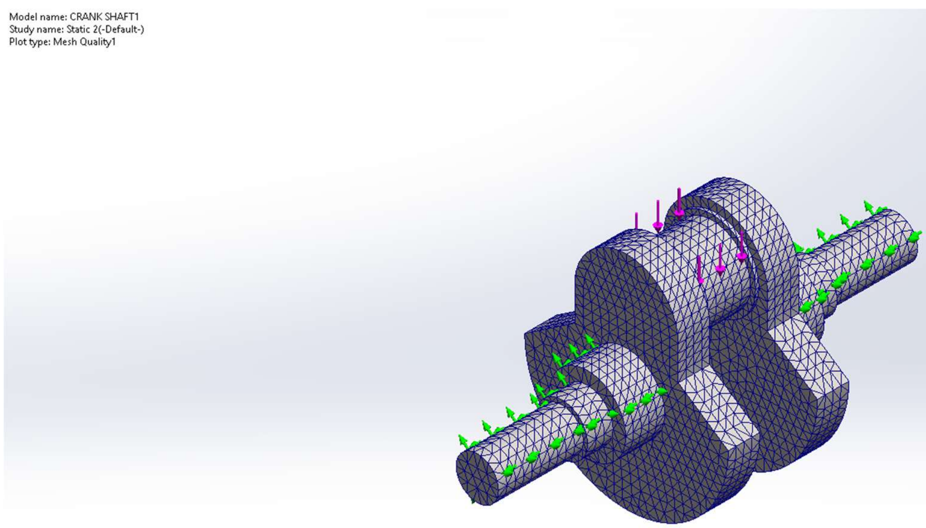

Figure 3: Mesh – Static 2: Cast Alloy Steel

A high-quality mesh was generated for the crankshaft using 3D solid elements. Tetrahedral elements with a second-order formulation (10-node tetrahedra) were used to accurately capture the curved geometry and fillets. An element size of approximately **5 mm** was used as a global mesh control, with finer refinement in fillet areas to capture stress gradients better. The resulting mesh for each simulation consisted of about **33,000 elements** and **50,000 nodes**, which was sufficient after a mesh convergence check. The mesh statistics indicate good element quality: the maximum aspect ratio was ~4.9, and **99.8%** of elements had aspect ratio < 3 (no elements above 10). No highly distorted elements were present (Jacobian > 0.7 for all; element quality metrics were “High”). Figure 1 shows the meshed crankshaft and one of the deformation result plots.

Mesh and Model: The mesh was generated using the standard meshes in SOLIDWORKS Simulation. Automatic transition was off to maintain a uniform mesh. A curvature-based refinement was implicitly applied (16-point Jacobian check for curvature) to ensure the fillet regions were well meshed. The total mesh generation time was only a few seconds, indicating an efficient mesh for this model size. The boundary conditions (hinged supports and force) were applied after meshing. No contact or connectors were needed (single solid body model). The solver used was a direct sparse solver for static analysis.

Results and Discussion

After solving the static analyses for both material cases, the results were post-processed to compare stress, displacement, and strain in the crankshaft. Since the geometry and load are identical, the **stress and strain distribution** pattern is very similar between the two materials – differences arise in the magnitude of displacements and the safety margins relative to each material's strength. Below, we discuss the von Mises stress distribution, the deflection of the crankshaft, and the strain results for each case, highlighting key values (min, max, locations) and comparing AISI 4130 vs cast steel.

Von Mises Stress Distribution

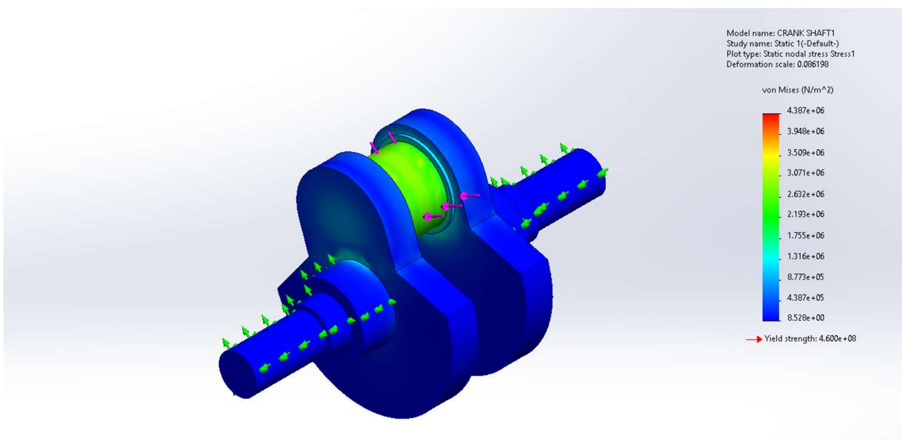

Figure 4: Von Mises Stress – Static 1: AISI 4130 Normalized Steel

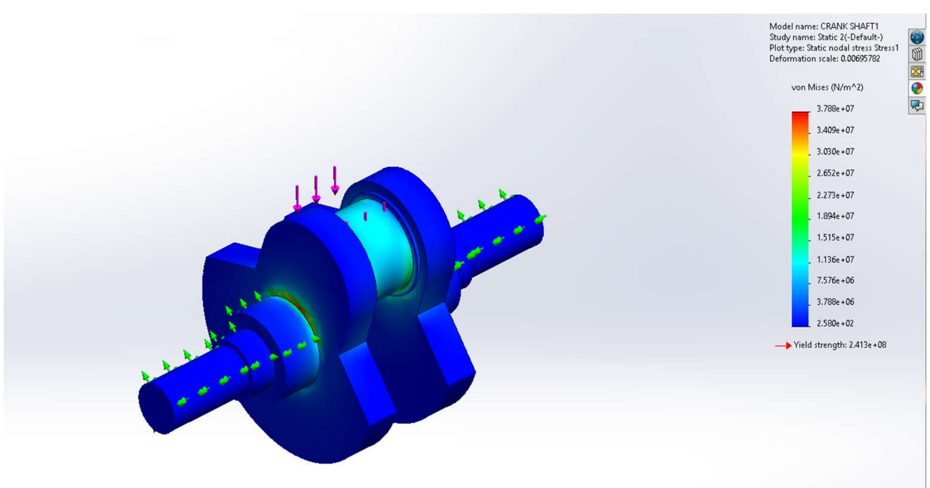

Figure 5: Von Mises Stress – Static 2: Cast Alloy Steel

Von Mises stress distribution in the crankshaft under the 16,000 N bending load (results shown for bending load case). High-stress regions occur at the fillets between the crank pin and the crank webs (red circled areas), while low stress is seen in the interior and mid-span of the pin.

The FEA results show that the **von Mises stress** is highest at the fillet areas where the crankpin meets the crank webs – this is a classic result as these fillets cause stress concentrations mates-conferences.org. The **maximum von Mises stress** occurs in both materials at these fillet hot spots. Numerically, the peak stress is about **37.9 MPa** in both simulations (since the load and geometry are the same). For AISI 4130, the max stress was ~3.79×10^7 N/m^2; cast steel was ~3.788×10^7 N/m^2 (essentially identical). The minimum von Mises stress is near zero (≈0.00026 MPa) and occurs in unstressed regions like the free surfaces far from the load (e.g., at the ends of the main journals). The contour plot (Figure 1) illustrates that most crankshafts experience relatively low stress (blue-green regions in the 5–15 MPa range), and the critical stress is localized at the inner fillet of the crank web. This makes intuitive sense – the crankshaft behaves like a supported beam, with the top of the crankpin in tension and the bottom in compression. The fillet at the top of the crank web (directly under the load) sees the highest tensile bending stress. In the model, that maximum ~38 MPa stress is well **below the yield strength** of both materials (38 MPa << 241 MPa and 435 MPa), indicating a **very safe static design** in terms of strength (safety factor on yield > 6 for cast steel, > 11 for 4130).

While the peak stress values are essentially the same for both materials, it is worth noting that in the cast steel model, this peak is a slightly higher percentage of its yield strength (38 MPa is about 15.7% of cast steel's 241 MPa yield) compared to the 4130 model (only ~8.7% of 4130's ~435 MPa yield). Thus, the cast material operates closer to its yield limit under an identical load than the 4130 steel. Both, however, are in the elastic range with a large safety margin. Another observation is that the stress distribution pattern (contour shape) is the same, which is expected for linear elastic analysis – material stiffness does not affect the equilibrium stress under a force-controlled load. The small difference in Poisson's ratio (0.30 vs 0.26) had a negligible effect on stress distribution. Any minor variations (on the order of a few tens of Pa) are due to numerical round-off. We can conclude that **both materials experience the same stress profile** under the given static load, and the crankshaft's critical stress location is the crank web fillet in both cases.

Displacement (Deflection) Results

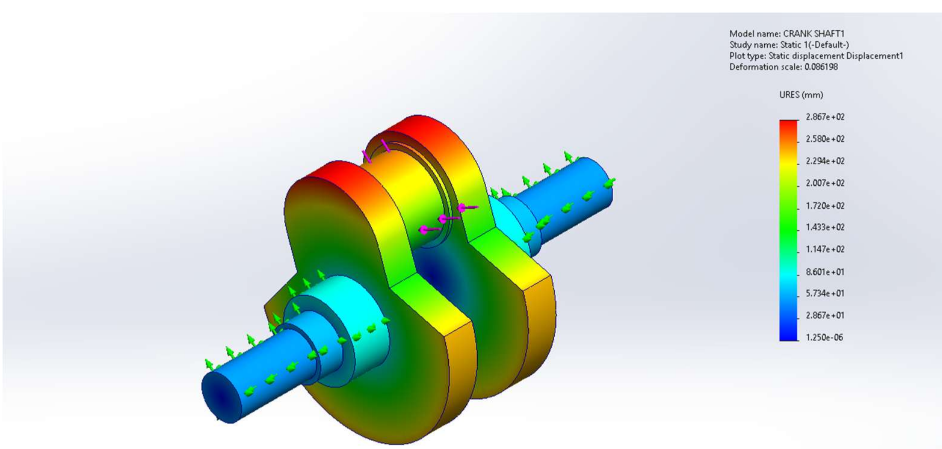

Figure 6: Resultant Displacement – Static 1: AISI 4130 Normalized Steel

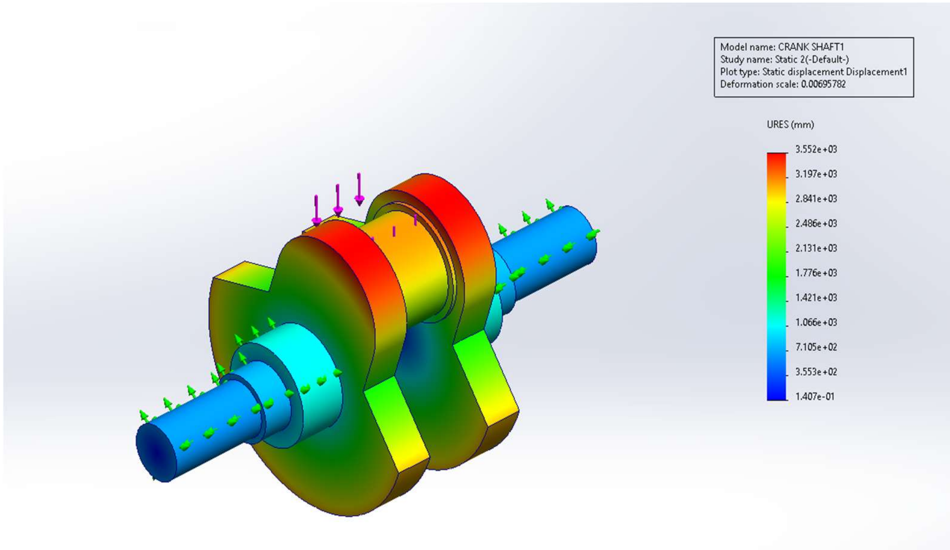

Figure 7: Resultant Displacement – Static 2: Cast Alloy Steel

Deformed shape of the crankshaft under load (exaggerated for visualization), with a colour contour showing the resultant displacement magnitude. The maximum deflection occurs at the mid-span (crankpin) and is minimal at the supported main journals.

Because the cast steel is less stiff, it exhibits a larger deflection under the 16 kN load. In the AISI 4130 case, the **maximum displacement** was about **3.2–3.3 mm**, whereas in the cast alloy steel case, the maximum displacement was about **3.5 mm** (roughly 7–8% higher). These displacements occur at the mid-point of the crankpin, i.e. the location on the crankpin directly under the applied force (the crankpin bends downward). The minimum displacement is essentially zero at the supported journal faces (by definition of the support BCs, the hinge support prevents any translation at the ends). The deflected shape is that of a supported beam with a central load – the crankshaft sags in the middle. Figure 2 depicts the exaggerated deformation shape; a ~3 mm deflection is small relative to the crank length (~200 mm span), but the FEA visually scales it for clarity.

For context, the deflection can be compared to an analytical beam calculation: for a supported beam with load P at mid-span, deflection δ_max = P·L^3/(48·E·I). Here, the crankshaft has a complex cross-section, but the trend is that the cast steel (lower E) yields a larger δ. The ratio of deflections matches the inverse ratio of Young's moduli (approximately 205/190 ≈ 1.08), consistent with the ~8% difference observed. Both absolute deflections (~3 mm) are quite small, meaning the crankshaft is stiff under this load. Such small bending deflection would likely be acceptable in service (unlikely to cause misalignment issues). It is also noted that no permanent deformation would occur (stresses are low), so the crank would spring back once the load is removed. The difference in deflection might matter in scenarios where clearances or vibrations are a concern; the 4130 steels would maintain slightly better alignment due to its higher rigidity. In summary, **AISI 4130 steel leads to a stiffer crankshaft (lower deflection)** under the same load, whereas the cast steel results in a bit more flex – though both are within elastic limits and the deflections are small in absolute terms.

Strain Distribution

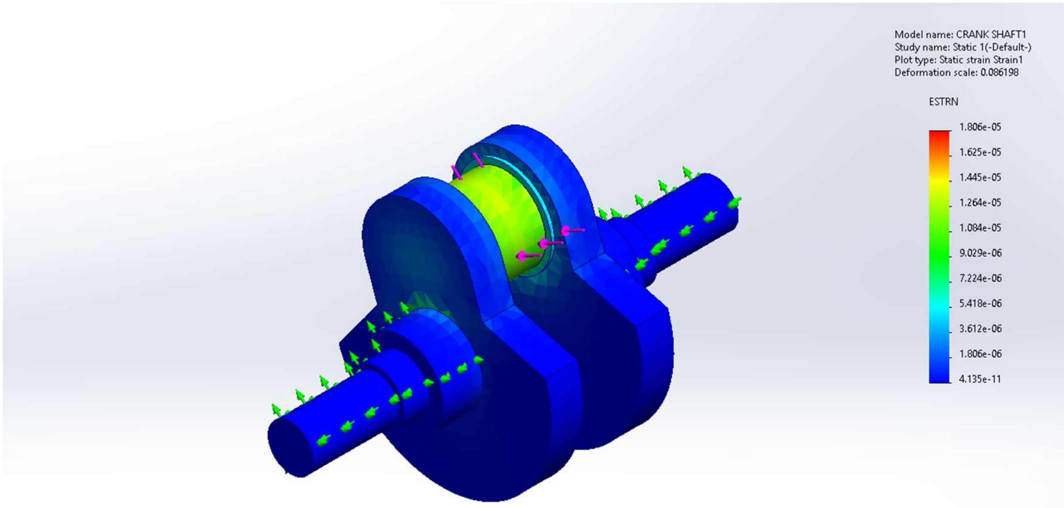

Figure 8: Equivalent Strain – Static 1: AISI 4130 Normalized Steel

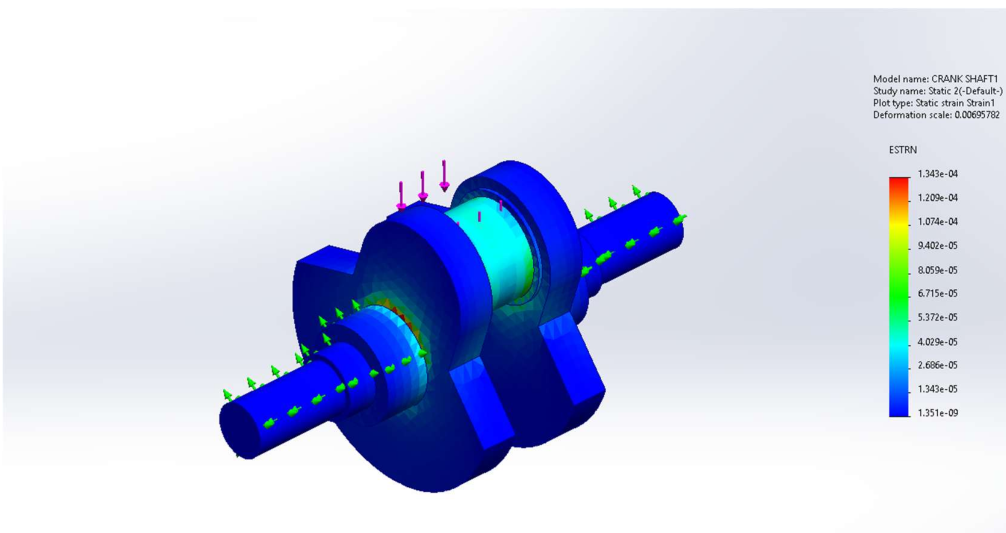

Figure 9: Equivalent Strain – Static 2: Cast Alloy Steel

Equivalent strain (von Mises strain) distribution in a section of the crankshaft (fillet region) under load. The strain pattern mirrors the stress distribution – the highest strains occur at the same crank web fillets (yellow areas) and are very low in most other regions.

Because the analysis is in the elastic regime, the **strain distribution** follows the stress distribution closely. The maximum equivalent strain in the cast steel simulation was about **1.34×10^–4** (dimensionless), whereas for AISI 4130, it was slightly lower at around **1.25×10^–4**. These values correspond to about 134 με (microstrain) and 125 με respectively – again roughly an 8% difference, directly proportional to the ratio of moduli (since ε_max ≈ σ_max/E for a given peak stress). The location of maximum strain is the same as that of max stress: the inner fillet on the crank web experiences the highest tensile strain. The minimum strain is essentially zero in unstressed regions (for example, deep inside the webs or at the very ends). The strain contour plot (Figure 3) looks identical in shape to the stress plot, with just a different scale. This confirms no plastic deformation occurs (strains are very small, well below yield strain). For instance, the yield strain of the cast steel would be $\sigma_y/E \approx 241$ MPa / 190 GPa = 0.00127 (0.127%), an order of magnitude above the max strain here (~0.0134%), so the material is deforming purely elastically with plenty of safety margin.

Comparing the two materials, the cast steel shows slightly higher strain for the same load (due to its lower E), meaning it will experience more elongation per unit stress. The 4130 steel is stiffer and has lower strain under the same stress. However, since the stress is the same in both cases, the strain ratio is inversely proportional to stiffness. Both materials exhibit low strains in absolute terms, highlighting the crankshaft's robustness under static load. The regions of highest strain (crank fillets) would be the points to inspect for fatigue in a real engine scenario, but under one-time static loading, there is no concern. In summary, **AISI 4130 experiences ~7–8% less strain than the cast steel** under the same load, but both remain safely in the elastic range with maximum strains on the order of 1e-4 (0.01%).

Conclusion

The FEA results allow a clear comparison of the crankshaft's performance with the two materials:

- **Stress:** Both materials experience the same maximum von Mises stress (~38 MPa) at the crank web fillets, and the overall stress distribution is identical. The crankshaft's design is safe in static strength for both materials (max stress is far below yield in each case). However, regarding the safety factor, the 4130 steel provides a larger margin (SF ≈ 11.5) than the cast steel (SF ≈ 6.4) for this loadasm.matweb.comdiva-portal.org. If much higher loads were applied, the cast steel would reach yield long before the 4130 would.
- **Displacement:** The AISI 4130 material results in a slightly smaller deflection (about 3.2 mm vs 3.5 mm in cast steel) due to its higher rigidity. This means the 4130 crankshafts will maintain alignment better under load, whereas the cast steel crankshaft flexes more (about 8% more deflection under identical loading). In applications where stiffness is critical (to reduce vibrations or clearance issues), the 4130 is advantageous.
- **Strain:** Similarly, cast steel sees higher elastic strain in the critical regions (by ~8%). While both are elastic, the higher strain in cast steel could indicate lower fatigue life (since cyclic strain correlates with fatigue damage). The 4130's lower strain for the same load suggests it could endure more cycles before crack initiation, all else being equal.
- **Weight:** The cast alloy steel is slightly lighter (density 7300 vs 7850 kg/m^3) purported.strath.ac.uk, so the crankshaft would weigh ~7% less if made of cast steel. In this model, that's on the order of 0.3 kg difference (not very significant). Given the huge difference in strength (4130 has ~1.8× the yield strength of the cast steel), the modest weight saving does not benefit this design.
- **Manufacturability:** (Not captured in FEA results, but noteworthy) 4130 is typically forged or machined, whereas cast alloy steel implies the crank could be cast to shape. Cast cranks are cheaper to produce but usually have lower strength. The FEA confirms the lower strength in terms of allowable stress. If the design needed to be optimized, a cast steel crank might require larger dimensions to achieve the same safety factor as a 4130 crank, potentially negating weight advantages.

Recommendation: AISI 4130 normalized steel is the superior choice for high-performance or heavy-duty applications as it yields lower deflections and higher safety against yielding. The crankshaft made of 4130 can sustain the 16 kN load with ample margin and minimal bending, which is beneficial for durability and performance. While the cast alloy steel crankshaft meets the requirements in this scenario (since stresses are low), it is closer to its material limits. In a design scenario where loads might increase (shock loads, additional bending or torsion, fatigue over time), the 4130 steel provides more robustness. If cost or weight is a primary concern and the loading conditions are well within the safe range, a cast steel crank could be acceptable for light-duty implementations, but one should carefully evaluate fatigue life in that case.

In conclusion, the FEA comparison demonstrates that **material selection has a noticeable impact on deformation and safety factors, though not on the basic stress pattern**. The AISI 4130 steel crankshaft exhibits better overall performance (stiffer and stronger), whereas the cast steel crankshaft is slightly more flexible and would reach its yield point at a much lower load. These insights can guide engineers in choosing an appropriate material depending on the required performance criteria for the crankshaft in service.