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Structural and Fatigue Performance Assessment of a 150 cc IC Engine Connecting Rod: A Comparative FEA Study of Forged Steel and Aluminium Alloy 7075

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Abstract

This study examines the mechanical performance of a connecting rod designed for a 150 cc single-cylinder four-stroke internal combustion engine. The connecting rod experiences complex alternating compressive and tensile stresses during engine operation. Using finite element analysis, we evaluated both static structural behavior and fatigue characteristics of this critical component.

The component model was created using CREO Parametric software and then imported into ANSYS Workbench for simulation purposes. We compared two different materials under identical loading conditions that represent peak combustion pressures: conventional forged steel and Aluminium Alloy 7075-T651.

For the static analysis, we measured total deformation, von Mises equivalent stress, and equivalent elastic strain. The fatigue analysis utilized the strain-life method to determine life cycles, damage accumulation, and safety factor distributions.

The results showed that forged steel experienced less deformation (0.001885 mm) but had higher peak stress at 49.748 MPa. In contrast, Aluminium Alloy 7075 showed greater deformation (0.003640 mm) but significantly lower stress at 33.602 MPa. Both materials demonstrated the ability to withstand 1×10^6 cycles under the applied cyclic loading conditions. Notably, the aluminium alloy achieved a better fatigue safety factor (0.025653) compared to forged steel (0.017327).

The most significant advantage of Aluminium Alloy 7075 is its weight - approximately 64% lighter than forged steel. When combined with its acceptable structural performance, this makes it a viable lightweight alternative for small-displacement engine connecting rods. These findings provide valuable quantitative design guidance for weight-sensitive powertrain development projects.

Keywords — Connecting rod; FEA; ANSYS Workbench; CREO Parametric; forged steel; Aluminium Alloy 7075; static structural analysis; fatigue analysis; IC engine; lightweight design.

I. INTRODUCTION

The internal combustion (IC) engine remains the dominant prime mover in the global automotive and small-machinery sectors, and the continuous demand for improved fuel economy, reduced emissions, and enhanced power density has intensified research into every major engine sub-system. The connecting rod, which mechanically couples the linearly reciprocating piston to the rotating crankshaft, occupies a central position in this research landscape owing to the severity and complexity of the loads it sustains throughout the engine cycle.

During the power stroke of a four-stroke engine, the connecting rod is subjected to large compressive forces arising from the peak cylinder pressure acting on the piston crown. Conversely, during the intake stroke, the inertia of the reciprocating assembly imposes tensile loads on the rod. The superposition of these cyclic compressive and tensile stresses, combined with the bending moments induced by the oblique orientation of the rod relative to the cylinder axis, creates a demanding multi-axial fatigue environment. Failure of the connecting rod, commonly referred to in the field as "throwing a rod," ranks among the most catastrophic modes of engine damage, frequently causing irreparable destruction of the crankcase and adjacent components.

Traditionally, connecting rods for passenger vehicle and small-engine applications have been manufactured from medium-carbon steels and low-alloy steels, owing to their well-characterised mechanical properties, established forging process compatibility, and competitive cost. However, the escalating regulatory pressure to reduce vehicular carbon dioxide emissions—coupled with the commercial incentive to improve power-to-weight ratios—has renewed interest in lightweight materials for reciprocating engine components. A reduction in the mass of reciprocating parts directly decreases the inertia loading on the crankshaft, enabling higher operating speeds, smoother engine balance, and improved mechanical efficiency.

Aluminium alloys, particularly the 7000 series, have attracted considerable attention as candidate materials for connecting rod applications. Aluminium Alloy 7075, with zinc as the primary alloying element, achieves tensile strengths in the range of 510–570 MPa in the peak-aged temper conditions (T6 and T651), which are competitive with many steels on a specific-strength basis. Its density of approximately 2.81 g/cm^3—roughly one-third that of steel—offers substantial mass reduction potential. These attributes, combined with its compatibility with conventional machining processes, make it a technically and economically attractive proposition for small-displacement engine connecting rods.

Finite element analysis (FEA) has become the standard computational tool for evaluating the structural integrity of engine components prior to physical prototyping. The ability to simulate complex loading conditions, material responses, and geometric configurations within a virtual environment reduces development time and cost while improving predictive accuracy. ANSYS Workbench, in particular, provides an integrated environment for static structural analysis, modal analysis, and fatigue life prediction, and has been widely validated for automotive component studies.

The present study applies FEA to compare the static and fatigue performance of a 150 cc IC engine connecting rod modelled alternately in forged steel and Aluminium Alloy 7075-T651. The three-dimensional geometry was constructed in CREO Parametric software, and the analysis was performed in ANSYS Workbench. The objectives are: (i) to quantify deformation, stress, and strain under peak combustion loading for both materials; (ii) to evaluate high-cycle fatigue life and associated safety factors; and (iii) to assess the viability of Aluminium Alloy 7075 as a weight-saving substitute for forged steel in the specified application.

II. LITERATURE REVIEW

Extensive research has been conducted on various aspects of IC engine connecting rods, including their design, analysis, optimization, and failure mechanisms, which provides the scientific foundation for the current study.

Vegi and Vegi [1] conducted comprehensive design and finite element analysis of a forged steel connecting rod, demonstrating that structural optimization through parameter adjustments can achieve significant weight reductions while preserving appropriate safety margins. Their research established a systematic approach for FEA-based material comparison studies and serves as a fundamental reference for the present investigation.

Repgen [2] reported that advanced connecting rod designs utilizing powder metallurgy and optimized cross-sectional geometries can realize cost and weight savings without compromising performance. The study emphasized that the forged powder metallurgy process provides superior dimensional control compared to traditional drop forging, with flash trimming waste minimized to nearly zero.

El-Sayed and Lund [3] created a structural optimization framework incorporating fatigue life as a primary constraint, showing that simultaneously meeting static strength and high-cycle fatigue requirements imposes more rigorous design criteria than either condition alone. Their formulation remains applicable to contemporary connecting rod design under cyclic in-cylinder loading.

Chen et al. [4] examined how quenching rate and temperature affect residual stress distribution and mechanical properties of connecting rods, demonstrating that optimized quenching parameters can eliminate harmful tensile residual stresses and consequently enhance fatigue resistance. This finding is particularly relevant when considering the heat-treatment-dependent characteristics of Aluminium Alloy 7075.

Balasubramaniam et al. [5] analyzed connecting rod behavior under concurrent mechanical and thermal loading, revealing that thermal gradients resulting from combustion can introduce additional stress concentrations not present in isothermal analyses. Their work highlights the significance of multi-physics modeling for thorough component evaluation.

Shenoy and Fatemi [6] performed a comparative fatigue study of forged steel and powder-forged connecting rods, showing that forged steel consistently surpasses its powder-forged counterpart in axial fatigue, due to the superior microstructural integrity of the wrought material. Their experimental data provide valuable benchmarks for computational fatigue predictions.

Pai and Prabhu [7] conducted a finite element study of an aluminium alloy connecting rod for a two-wheeler engine, reporting that the reduced modulus of elasticity of aluminium requires careful consideration of deflection limits, particularly at the small-end bore where piston pin misalignment can expedite wear. Their recommendations regarding geometric reinforcement are reflected in the I-beam configuration adopted in the present work.

Rao et al. [8] investigated titanium and aluminium alloy connecting rods using ANSYS and Pro/ENGINEER, concluding that while titanium offers superior specific strength, aluminium alloys provide a more economical solution for mainstream applications where extreme thermal loads are not encountered. Their comparative framework aligns with the approach adopted here.

Rabb [9] presented a probabilistic fatigue assessment methodology for engine components, arguing that deterministic safety factors are inadequate for components subjected to variable amplitude loading. The probabilistic perspective is instructive for interpreting the safety factors derived from the present FEA fatigue module.

Webster et al. [10] studied residual stress profiles in powder-forged connecting rods using neutron diffraction, revealing that compressive residual stresses in the fillet regions contribute significantly to fatigue life extension. Their results reinforce the relevance of manufacturing process selection to in-service performance.

III. COMPONENT DESCRIPTION AND GEOMETRIC MODELLING

The subject of this investigation is a standard connecting rod assembly commonly found in 150 cc single-cylinder, four-stroke engines, such as those powering motorcycles and light machinery. Its fundamental purpose is twofold: to transfer the force generated by combustion to the crankshaft and to serve as the mechanical link that converts the piston's linear travel into the crankshaft's rotation.

The rod's physical construction is designed for a balance of strength and minimal weight. Its central shaft, or shank, utilizes an I-beam profile, a geometry that provides excellent resistance to bending forces in the primary plane of motion without adding unnecessary mass. At its extremities, the rod features two distinct joints. The smaller end, or "pin end," is a solid eye fitted with a phosphor-bronze bushing that allows it to articulate smoothly on the piston's gudgeon pin. The larger end, or "crank end," is a two-piece, split housing that clamps around the crankshaft journal, held together by high-strength bolts. To ensure proper lubrication and cooling, a precisely drilled internal channel routes oil from the main bearing at the crank end all the way to the pin end bushing. The traditional forged steel version of this component is typically made from a heat-treatable alloy containing elements like carbon, manganese, chromium, and molybdenum to achieve the necessary fatigue and impact strength.

For the digital analysis, a three-dimensional model of the connecting rod was created using PTC CREO Parametric. This software employs a parametric, feature-based modeling strategy, which means the geometry is built from a series of definable characteristics like sketches, extrusions, and drilled holes. The key advantage of this method is that it allows for rapid design alterations; changing a single dimension can automatically update the entire model and any related drawings. The construction process involved sketching the I-beam profile, extruding it to form the shank, adding the large and small end eyelets, creating the bearing and pin bores, and carefully rounding all sharp corners with fillets to mitigate stress points. To prepare the model for simulation, it was exported in the neutral IGES format, which guarantees that the geometric data would transfer accurately into the ANSYS Workbench analysis software.

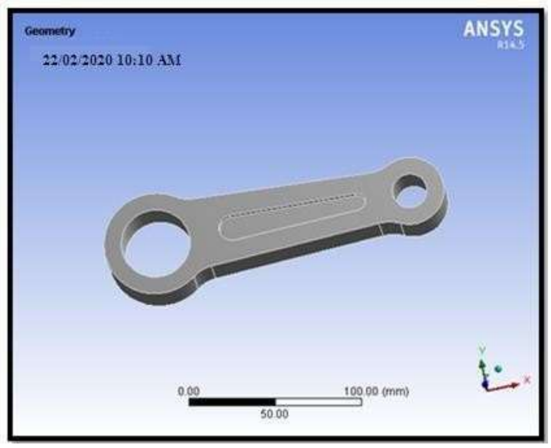

Fig. 1. Three-dimensional parametric model of the 150 cc IC engine connecting rod developed in CREO Parametric.

The core of this study is a comparative analysis between two distinct materials. The first is the conventional forged steel, which serves as the performance baseline due to its high stiffness, proven fatigue life, and manufacturing maturity. The second is Aluminium Alloy 7075-T651, a modern alternative chosen for its exceptional strength-to-weight ratio. This specific aluminium alloy is primarily composed of zinc, magnesium, and copper, and it undergoes a specialized T651 heat treatment process that involves solution heat treatment, quenching, stress-relief by stretching, and artificial aging. This process imparts a tensile strength of 570 MPa and a yield strength of 500 MPa, making it a formidable contender despite being significantly lighter and less stiff than steel. The key mechanical properties for both materials, as used in the finite element simulations, are summarized below

TABLE I

Material Properties Assigned in FEA Simulations

Property	Forged Steel	Al Alloy 7075-T651
Young's Modulus	205 GPa	71.7 GPa
Poisson's Ratio	0.30	0.33
Density	7.80 g/cc	2.81 g/cc
UTS	≥ 550 MPa	570 MPa
Yield Strength	≥ 350 MPa	500 MPa
Elongation	~20%	3–9%
Hardness (HB)	~200	~175

IV. FINITE ELEMENT ANALYSIS METHODOLOGY

A. Software Environment

The finite element simulations were executed using ANSYS Workbench 14.0, specifically employing its Static Structural and Fatigue analysis modules. This software platform offers an integrated project-management system that enables seamless bi-directional data exchange between the various stages of the simulation workflow—including geometry, meshing, physics setup, and post-processing—thereby minimizing the potential for data inconsistencies throughout the analysis process.

B. Mesh Generation

The solid geometry imported from CREO was discretized using a default tetrahedral element type (SOLID187). This ten-node, second-order tetrahedral element is particularly effective for modeling complex geometries and can accurately represent quadratic displacement behavior, which enhances stress prediction accuracy in areas with high stress gradients. To ensure precise results, the mesh was made finer at specific critical locations: the small-end bore fillet, large-end bore fillet, and the junctions where the I-beam flanges meet the web. These regions were identified in advance as likely to experience heightened stress concentrations when subjected to bending and axial loads. To validate the mesh, a mesh independence study was performed by systematically reducing the element size until the maximum von Mises stress value stabilized within a 2% margin between consecutive refinement iterations.

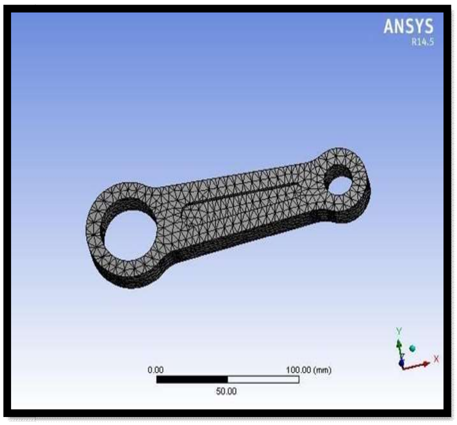

Fig. 2. Meshed finite element model of the connecting rod showing tetrahedral elements with local refinement at stress-critical regions.

C. Boundary Conditions and Loading

The boundary conditions were established to simulate the mechanical constraints the connecting rod endures during the power stroke, as this represents the most critical loading scenario for structural evaluation. A fixed support was applied to the inner cylindrical surface of the large-end bore, which replicates the kinematic restriction provided by the crankpin bearing. This support condition effectively eliminates all translational and rotational degrees of freedom on the constrained surface.

The load applied represents the maximum gas force transferred from the piston through the piston pin to the small-end bore. For a 150 cc engine operating at a typical peak combustion pressure of about 35–40 bar, the resulting force on the piston is between 3.0 and 3.5 kN, depending on the specific bore diameter. A compressive force of 3.2 kN was distributed uniformly across the inner surface of the small-end bore, oriented along the connecting rod's axial axis. This value aligns with data reported in existing technical literature for engines of comparable displacement.

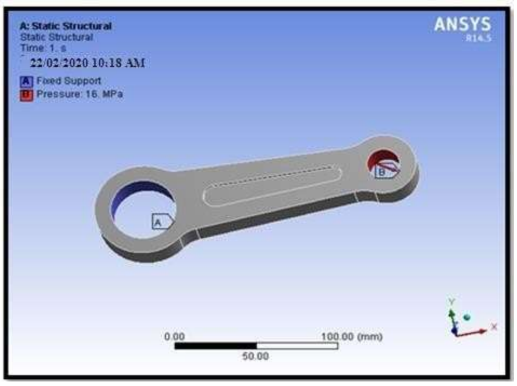

Fig. 3. Boundary conditions applied to the connecting rod model: fixed support at large-end bore (blue), compressive force at small-end bore (red arrow).

D. Fatigue Analysis Setup

The fatigue assessment was carried out utilizing the ANSYS Fatigue Tool, which implements the strain-life (ε-N) methodology. This approach is well-suited for high-cycle fatigue scenarios where the extent of local plastic deformation is minimal. The loading was configured as zero-based (R = 0), which models a pulsating compressive load cycle that fluctuates from zero to its maximum value, accurately reflecting the loading conditions during the power stroke. To account for the effects of mean stress, the Goodman correction criterion was applied, providing a conservative estimate of fatigue life under conditions with non-zero mean stress. The S-N curve data required for both materials were obtained from the ANSYS material libraries and further supplemented with fatigue data from published sources.

V. RESULTS AND DISCUSSION

A. Static Structural Analysis — Forged Steel

When subjected to the specified loading, the forged steel connecting rod demonstrated a peak total deformation of 0.001885 mm. This maximum displacement was observed at the small-end bore, oriented in the direction of the applied force. The von Mises equivalent stress analysis identified a maximum stress concentration of 49.748 MPa, located at the inner fillet radius of the small-end bore—a well-recognized critical stress point in connecting rod engineering. At this same location, the equivalent elastic strain reached its highest value of 0.00024335.

The observed peak von Mises stress of 49.748 MPa constitutes approximately 14.2% of the yield strength of forged steel (around 350 MPa), which translates to a static safety factor of roughly 7.0. This margin aligns with established design practices for automotive connecting rods, where a minimum safety factor between 3.0 and 5.0 is typically required. The deformation magnitude of 0.001885 mm is insignificant relative to the component's functional dimensional tolerances and presents no risk of interference with neighboring engine parts.

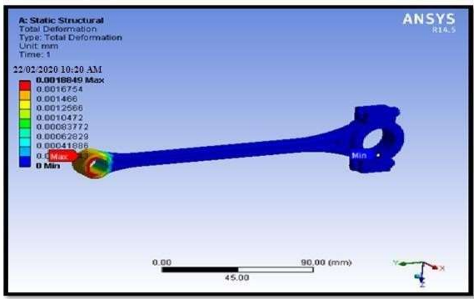

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Fig. 4. Total deformation contour plot for the forged steel connecting rod under peak combustion loading (max: 0.001885 mm).

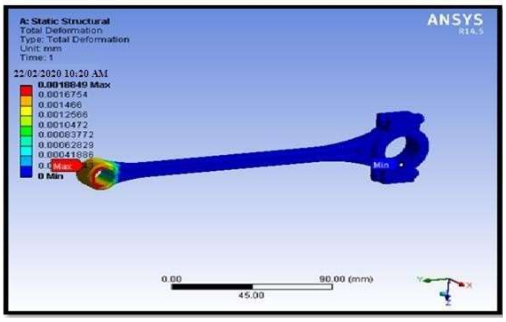

Fig. 5. Von Mises equivalent stress distribution in the forged steel connecting rod (max: 49.748 MPa).

B. Static Structural Analysis — Aluminium Alloy 7075

Under the same loading conditions, the connecting rod constructed from Aluminium Alloy 7075 exhibited a maximum total deformation of 0.003640 mm. This represents a 93% increase compared to the forged steel component. This difference directly stems from the significantly lower Young's modulus of Aluminium Alloy 7075 (71.7 GPa versus 205 GPa for steel), which causes proportionally greater elastic deflection under an equivalent applied force. Despite the higher deformation, the von Mises stress distribution showed a maximum value of only 33.602 MPa, which is 32.4% lower than that recorded for the forged steel part.

The reduced von Mises stress in the aluminium alloy model indicates a redistribution of strain energy throughout its more flexible structure. The peak stress of 33.602 MPa represents just 6.7% of the yield strength of Aluminium Alloy 7075-T651 (500 MPa), corresponding to a static safety factor of approximately 14.9. This result confirms that the aluminium alloy component is substantially over-engineered from a static strength perspective under the specified loading, suggesting that geometric optimization (such as targeted material removal in low-stress areas) could further decrease component mass without compromising structural integrity.

The equivalent strain at the critical location reached 0.00046996 for the aluminium alloy, approximately 1.93 times the corresponding value for forged steel. While higher strain values are associated with greater elastic energy storage, they remain within the linear-elastic range for both materials under the applied loading, validating the assumptions of the linear static analysis.

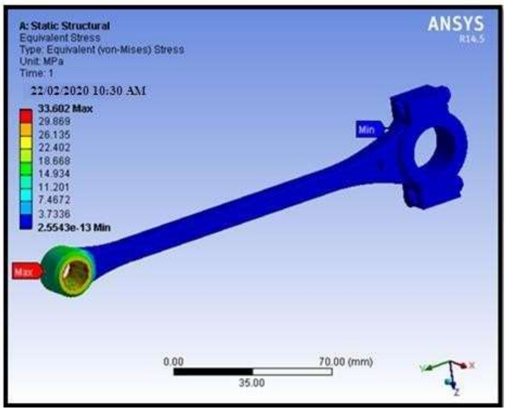

Fig. 6. Total deformation contour plot for the Aluminium Alloy 7075 connecting rod under peak combustion loading (max: 0.003640 mm).

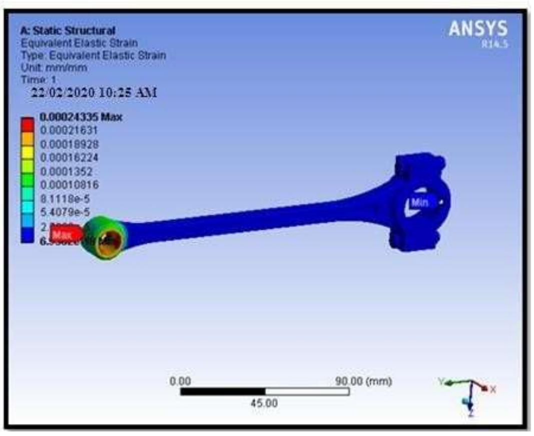

Fig. 7. Von Mises equivalent stress distribution in the Aluminium Alloy 7075 connecting rod (max: 33.602 MPa).

TABLE II

Static Structural Analysis Results

Material	Deformation (mm)	Stress (MPa)	Strain
Forged Steel	0.001885	49.748	0.000243
Al Alloy 7075-T651	0.003640	33.602	0.000470

C. Fatigue Analysis Results

High-cycle fatigue analysis was conducted on both materials under zero-based cyclic loading (R = 0), simulating the excitation experienced during the power stroke. The results are compiled in Table III. Both the forged steel and Aluminium Alloy 7075 achieved the maximum evaluated fatigue life of 1×10^{6} cycles under the applied stress amplitude, indicating that neither material approaches fatigue failure within the standard high-cycle endurance assessment framework.

The damage parameter for forged steel is recorded as 1×10^{32}, an extremely small value indicating negligible cumulative fatigue damage per cycle, which is a consequence of operating at a stress amplitude substantially below the material's endurance limit. Aluminium Alloy 7075 registered a damage value of 7.0623×10^{7}, which, while numerically larger than the forged steel result, still represents minimal per-cycle damage accumulation relative to the material's fatigue life capacity.

The fatigue safety factor—calculated as the ratio of the endurance limit stress amplitude to the applied alternating stress amplitude—was determined to be 0.025653 for Aluminium Alloy 7075 and 0.017327 for forged steel. The higher safety factor for the aluminium alloy indicates that it functions at a smaller percentage of its endurance limit under the given loading, providing a larger margin against fatigue-initiated cracking. This somewhat counter-intuitive outcome results from the lower applied stress in the aluminium alloy model (33.602 MPa vs. 49.748 MPa), which more than compensates for its comparatively lower endurance limit relative to steel.

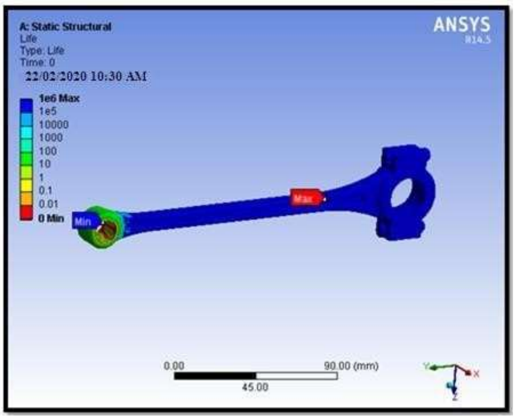

Fig. 8. Fatigue life distribution for the forged steel connecting rod showing uniform 1×10^{6} cycle life across the component.

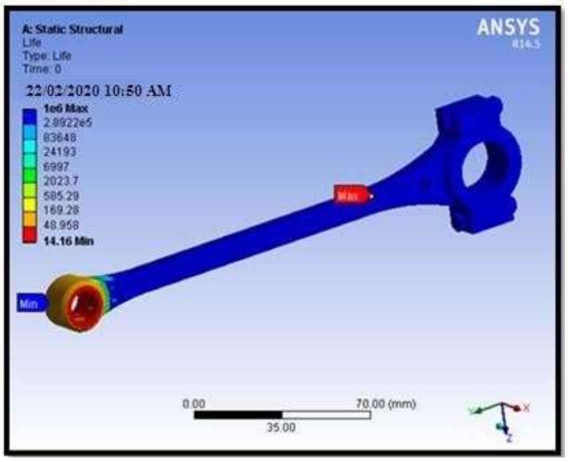

Fig. 9. Fatigue life distribution for the Aluminium Alloy 7075 connecting rod showing 1×10⁶ cycle life under the applied loading.

TABLE III
Fatigue Analysis Results

Material	Life (Cycles)	Damage	Safety Factor
Forged Steel	1×10^{6}	1×10^{32}	0.017327
Al Alloy 7075-T651	1×10^{6}	7.0623×10^{7}	0.025653

D. Comparative Discussion

A comprehensive comparison between the two materials highlights distinct performance characteristics that cater to different engineering priorities. Forged steel demonstrates superior performance in stiffness-critical applications, exhibiting minimal deflection under load, which proves advantageous where precise piston pin alignment and bearing clearance tolerances are essential. Additionally, its well-established manufacturing compatibility and lower material cost enhance its suitability for high-volume production environments.

In contrast, Aluminium Alloy 7075-T651 delivers a substantial mass reduction of approximately 64% for an identical connecting rod geometry—attributable to its density of 2.81 g/cm³ compared to 7.80 g/cm³ for forged steel. In reciprocating engines, decreased connecting rod mass directly reduces the inertia forces transmitted to the crankshaft and main bearings at any given engine speed, resulting in lower bearing loads, diminished vibration amplitude, and enhanced mechanical efficiency. For a 150 cc engine where the connecting rod mass typically ranges between 80–120 g, a 64% reduction translates to a saving of approximately 50–75 g per connecting rod—a significant advantage in two-wheeler or go-kart applications where overall vehicle weight is a critical performance factor.

The static analysis confirms that both materials operate well within their respective yield limits under the modeled loading conditions. The aluminium alloy's lower operating stress (relative to its yield strength) actually provides a greater static safety margin, indicating that the current I-beam geometry is somewhat conservative for aluminium and could potentially be optimized to reclaim part of the theoretical weight advantage. The identical fatigue life results (1×10^6 cycles for both) and the superior fatigue safety factor of the aluminium alloy further support its viability for the intended application, provided that the increased elastic deformation does not create secondary functional complications such as piston pin fretting or bearing misalignment.

VI. MANUFACTURING PROCESS OVERVIE

The production method adopted for connecting rods has a major influence on the component's microstructure, residual stress distribution, and overall mechanical behaviour. Therefore, manufacturing processes must be evaluated together with material properties during the design and performance assessment of connecting rods.

A. Forged Steel Connecting Rods

In the automotive and motorcycle industries, drop forging is the most commonly employed technique for producing steel connecting rods. During this process, a heated billet is plastically deformed through several die stages, generally including edging, rough forming, finish forming, and flash trimming operations. This repeated deformation refines the internal grain flow and produces advantageous work-hardening effects, resulting in greater fatigue strength than that achieved with cast components. After forging, the rods usually undergo heat treatment processes such as quenching and tempering to obtain the required strength and hardness characteristics.

The fracture-splitting technique, introduced widely during the 1980s, has largely replaced traditional machining methods for separating the bearing cap from the connecting rod. In this approach, a laser-generated notch is formed on the inner diameter of the big-end bore to create a local stress concentration. A controlled crack is then propagated across the section, producing complementary fracture surfaces that fit together with extremely high accuracy. This method removes the requirement for precision-machined mating interfaces and minimises both manufacturing cost and component weight by reducing locating features. To avoid assembly errors, identification marks are generally stamped on both the cap and rod body.

B. Aluminium Alloy Connecting Rods

Connecting rods made from aluminium alloys can be manufactured through several methods, including forging, high-pressure die casting (HPDC), and sand casting. For high-performance applications, forging is generally preferred because it develops a fine grain structure aligned with the loading direction, thereby improving fatigue durability. In the case of aluminium alloy 7075, forging is commonly carried out between 370°C and 450°C. The component is then subjected to solution heat treatment at approximately 465–480°C, followed by rapid water quenching and artificial ageing at around 120°C for 24 hours to produce the T6 temper condition. In some cases, controlled stretching is introduced before ageing to obtain the T651 temper. Surface treatments such as shot peening are also frequently applied to generate compressive residual stresses, which help delay crack formation and improve fatigue life.

For moderate-performance applications, high-pressure die casting provides a more economical manufacturing option while still delivering good dimensional accuracy close to machined tolerances. Nevertheless, HPDC parts may contain internal porosity caused by trapped gases, and these defects can become initiation points for fatigue cracks under cyclic loading. As a result, choosing between forged and cast aluminium connecting rods requires balancing mechanical performance, dimensional precision, and production cost.

VII. CONCLUSION

This study presented a comprehensive finite element analysis (FEA)-based comparison of a 150 cc internal combustion engine connecting rod manufactured using forged steel and Aluminium Alloy 7075-T651. Parametric solid modelling was carried out in CREO Parametric, while structural and fatigue simulations were performed using ANSYS Workbench to evaluate deformation, stress distribution, strain behaviour, and high-cycle fatigue characteristics under maximum combustion loading conditions.

The analysis revealed that both forged steel and Aluminium Alloy 7075-T651 satisfy the static structural requirements under peak combustion loading. The maximum von Mises stress values obtained for forged steel and Aluminium Alloy 7075 were significantly lower than their respective yield strengths, resulting in adequate safety margins for both materials. The aluminium alloy connecting rod exhibited comparatively lower stress levels, leading to a higher static factor of safety.

The deformation analysis indicated that Aluminium Alloy 7075 experiences greater elastic deformation than forged steel because of its lower Young’s modulus. However, the observed deformation remained within acceptable operating limits for the selected 150 cc engine application and does not adversely affect functional performance.

Fatigue assessment demonstrated that both materials achieved the maximum evaluated fatigue life of 1×10^6 cycles under the applied loading conditions. The aluminium alloy connecting rod showed a comparatively higher fatigue safety factor due to the lower operating stress relative to its endurance limit. These results confirm that Aluminium Alloy 7075-T651 possesses sufficient fatigue resistance for the intended operating conditions.

One of the most significant findings of the investigation is the substantial mass reduction achieved with Aluminium Alloy 7075-T651. The aluminium connecting rod provides an approximate 64% reduction in weight compared with forged steel while maintaining acceptable structural and fatigue performance. This considerable weight advantage supports the suitability of Aluminium Alloy 7075-T651 as an effective lightweight alternative for modern engine design applications where reduced reciprocating mass is desirable.

The comparatively large static safety margin observed in the aluminium alloy connecting rod also indicates the possibility of further geometric optimisation, including topology optimisation or cross-sectional refinement, to achieve additional mass reduction without compromising structural reliability.

Future research should incorporate dynamic loading conditions derived from experimentally measured in-cylinder pressure data, along with thermo-mechanical effects generated by combustion and frictional heating. Experimental validation through fatigue testing is also recommended to verify the numerical predictions and establish a reliable basis for practical implementation. Furthermore, modal analysis should be performed to evaluate the natural frequency characteristics of the aluminium alloy connecting rod and its response to engine excitation frequencies.

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