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A Review on Fatigue Analysis of Connecting Rod

Ahamad Sadique*
shabaansari8855@gmail.com
Department of Mechanical Engineering, Bansal Institute of Engineering & Technology, Lucknow, India
Kapoor Anil
raj321anil@gmail.com
Department of Mechanical Engineering, Bansal Institute of Engineering & Technology, Lucknow, India

Abstract: *The connecting rod serves as a bridge between the piston assembly and the crankshaft, making it one of the most crucial parts of the entire engine assembly. Throughout its lifespan, it also experiences significant tensile and compressive stresses. Therefore, a thorough study is required right now. The connecting rod is a high-volume production, a critical component in internal combustion engines and compressors that is periodically subjected to high tensile, compressive, and bending loads brought on by the thrust and pull of the piston as well as the centrifugal force of the rotating crankshaft. This topic deals with the past literature survey that demonstrates this. This article offers a summary of the advancements made in the field of analysis, potential weight and cost savings measures, and improved connecting rod material options. However, the application will determine which technique and material should be used, as well as how the connecting rods are created. Most connecting rods now in use are made of carbon steel. Strong and lightweight alloys include those made of aluminium and titanium. Titanium is used in high-performance automobiles where components must be both lightweight and strong. The analytical tool used to determine Von Mises stress, strain, and deformation is called ANSYS.*

Keywords: Connecting Rod, Fatigue analysis, Finite Element Analysis, ANSYS Workbench.

1. Introduction

An essential component of an internal combustion engine, the connecting rod serves as a connection between the piston and crankshaft. Three primary zones exist on connecting rods. the large end, the middle shank, and the piston pin end. The middle shank has an I-cross shape, the piston pin end is the small end, and the crank end is the big end. The connecting rod is a pin-jointed strut, and as a result, greater weight is positioned at the crank end. As a result, the connecting rod's CG point is located further towards the large end. For production engines, connecting rods are often constructed of steel, although they can also be cast iron, aluminium, or titanium for high-performance engines. They are either castable, powder metallurgically manufactured, or forged. However, casting-produced connecting rods frequently feature blow holes, which are detrimental from a fatigue and durability perspective. Forgings have an advantage over cast rods because they generate superior rods devoid of blow holes. Blanks made of powder metal offer the advantages of less material waste and being close to net form. However, because of complicated production processes and expensive materials, the cost of the blank is significant. Automobiles should be lightweight to use less gasoline, but because they also need to be comfortable and safe for passengers, the weight of the vehicle sadly increases. This trend in vehicle building encourages the development and use of brand-new, lightweight materials that adhere to design specifications. Lighter connecting rods reduce engine lead since they don't need as much weight to balance them on the crankshaft. Utilizing composite materials offers high strength-to-weight ratios, technology, efficient fuel usage, and great engine power [1].

Cost-effective and high-quality products are continuously needed in the automotive business. We now have the chance to research design methods in order to advance and meet industry needs. To survive in this quickly changing market, the time spent on trial and error analysis in the design process must be reduced. Therefore, early in the design process, computational methods were applied. For the modal analysis and structural analysis of a connecting rod, the finite element

* Corresponding Author

method is used. The intrinsic dynamic properties of a system are revealed through modal analysis in the form of natural frequencies, damping factors, and mode shapes. While structural analysis provides information on the distribution of stresses under loading conditions. The selection of the mesh is crucial to ensuring that the optimal mesh size is used to conduct the analysis for other involved parameters. Since mesh quality affects the stability and convergence of different mesh processing programmes, mesh quality needs to be improved periodically [2,3].

The tractor's connecting rods are generally composed of cast iron by powder metallurgy or forging. The fundamental motivation for using these technologies is to build the components as a whole and achieve great productivity at a low cost [4] while also optimising the geometry of the connecting rod. Because the engine is designed to perform in a variety of challenging settings, the connecting rod design is intricate. The inertia force and rod mechanism due to acceleration/retardation in a cycle subject the connecting rod to changing pressure . The fatigue analysis and offered a connecting rod design [5]. The rupture caused by fatigue and a way for adjusting the connecting rod design specifications [6]. The way for enhancing the connecting rod design. The Finite Element Method (FEM) is a recent method for fatigue study of connecting rods and component lifespan estimate. FEM is capable of creating strain/stress distributions across the component, allowing us to accurately locate critical spots [7]. This approach is particularly beneficial when the component's geometrical form is complicated and the loading circumstances are simple. The relevant component parameters, such as material, cross section conditions, and so on, may be changed in FEM, and component optimization under fatigue cycle loading can be done easily and fast [6]. The examination of a component is accomplished in a virtual environment without the need for a prototype in Computer Aided Design [8], resulting in time and cost savings. Because fatigue is the most common cause of connecting rod failure, the used ANSYS software to perform FE analysis on the U650 Tractor connecting rod and found that the critical point under reverse loading (compressive and tensile) is 46. This value can be enhanced by lowering the stress concentration coefficient in order to improve the connecting rod's fatigue life [9]. The fatigue life of a component in service is influenced by a variety of elements, including (i) engineering design, and (ii) construction material (iii) service conditions and environment, (iv) manufacture and inspection and (v) complicated stress cycles. Calculations and simulations are an important part of the current design process. Several attributes, including riding comfort, strength, stress, durability, handling, crash resistance and stiffness, may now be quantitatively analysed to varied degrees of precision. By guaranteeing that some, if not all, of these features meet stated requirements even before the first prototype is constructed, development time can be cut in half. Estimations based on fatigue life and exact loading histories may be utilised to optimise structures and components for durability. Therefore, less conservative designs than those based on conventional criteria can be generated [15].

Calculating stress and strain using the Finite Element Method (FEM) is a well-established approach in fatigue analysis and estimating lifetime. Del Llano-Vizcaya et al. [16] conducted a multi-axial fatigue investigation of helical compression springs after performing stress analysis in the FE code ANSYS. Based on fatigue study, the constructed a connecting rod [17-19]. This case study focused on rear axle shaft failures in scraper-type tractors. Despite laboratory durability tests, the rear axle shafts collapsed after only six months of use. Due to reverse torque, the most common mechanism of failure was fatigue [20].

The fatigue load cycle to optimise the wrist pin end, with compressive gas load matching to tensile load and maximum torque corresponding to maximum inertia load. They evidently employed the engine's maximum loads throughout its entire working range. They produced an estimated design surface for optimization and then optimized that design surface. To get accurate values, the objective and constraint functions were revised. This method was carried out again and again until convergence was reached. Constraints were also introduced to prevent fretting fatigue. Minimum and Maximum values of octahedral shear stress were used to compute the mean and alternate

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components of the stress. Their activity lowered the weight of the connecting rod by about 27%. Figure 1. depicts the early and final wrist pin end designs for connecting rods [21].

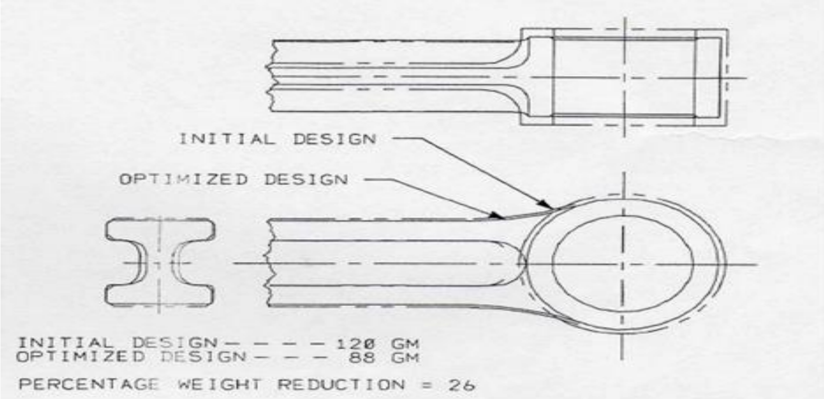

Figure 1. Final and initial designs for the wrist pin end of a connecting rod [21]

A comprehensive FEA of the connecting rod while examining a connecting rod failure that resulted in a catastrophic engine failure. He computed the connecting rod screw threads, connecting rod threads, as well as the diametric interference between the bearing sleeve and screw prestress. The inappropriate screw thread profile according to the research. The connecting rod failed where the FEA predicted it would. The stress concentration factor at the thread root was first calculated using an axisymmetric model. These were utilised to calculate the screw's nominal mean and alternating stresses. A comprehensive FEA was done that included all of the parameters stated above. The appropriateness of a new design was determined by comparing stress amplitude and the mean stress at the threads acquired from this study. Inelastic FEA was also utilised to generate a steady state scenario via load cycling [6].

To determine form design stress sensitivity the results were utilised to numerically solve an optimal design issue using an iterative optimization process called the steepest descent algorithm. The focus was on form design sensitivity analysis using a connecting rod as an example. The major stresses of inertia and firing loads were both subjected to stress restrictions. The other limitation was the thickness constraint, which kept it from becoming zero. They were able to reduce the weight of the connecting rod by 20% in the neck area [22]. Figure 2. depicts the ideal design.

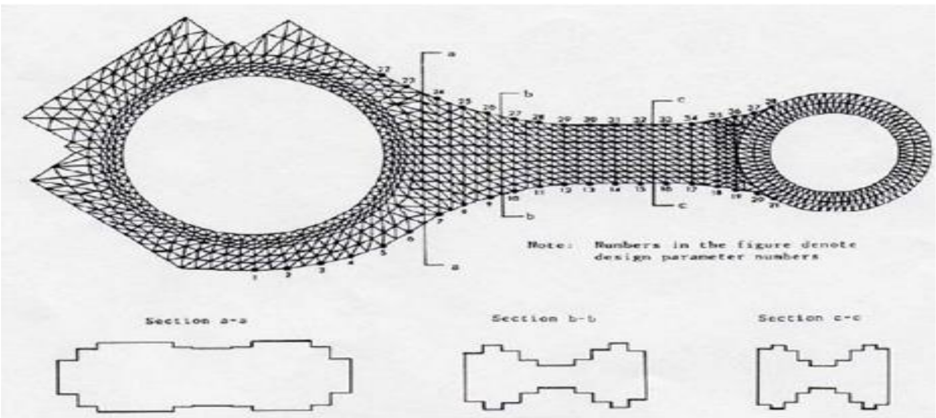

Figure 2. The optimum design obtained [22]

This prototype, fatigue testing and experimental stress analysis were undertaken, and based on the findings, they recommended the final shape shown in Figure 3. They estimated the permitted stress amplitude at crucial sites, taking into consideration the R-ratio, statistical safety factors, and stress concentration, and guaranteed that maximum stress amplitudes were below the allowable stress amplitude.

Figure 3. Design of a PM connecting Rod [23]

Single-cylinder diesel engines are widely employed in agricultural regions for a variety of applications, including water pumping and the operation of auxiliary farm equipment. The failure of two distinct crankshafts in these engines was investigated. To determine the cause of failure, certain characterization investigations and fractographic analyses were performed. The cranks, on the other hand, have some minor design variations, and both breakdowns occur as a result of a fatigue process [24].

The bending stress at the column centre as well as the variation of the connecting rod's stress at the bottom of the column. The data in Figures 4. and 5. demonstrate that the top dead centre at higher engine rpms and 3600 crank angles are not where the highest tensile stress occurs. Additionally, it was found that the R ratio varies with engine speed and that it varies with location. At 12000 rev/min, the maximum bending stress magnitude at the column centre was determined to be nearly 25% of the highest tensile stress for the same cycle (00 to 7200 crank angle).

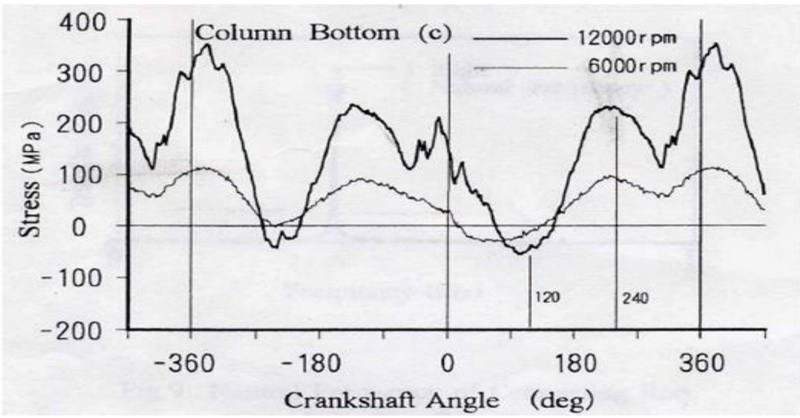

Figure 4. Stresses at the bottom of the connecting rod column [27]

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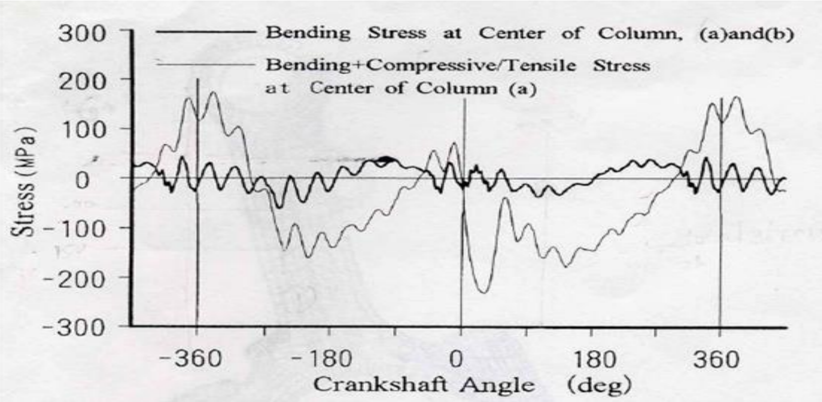

Figure 5. Stresses at the centre of the connecting rod column [27]

2. Introduction of Fatigue Failure

Fatigue is a phenomenon that occurs when a material is subjected to fluctuating loading, or more accurately, cyclic stressing or straining. Similar to how humans become fatigued after doing a task repeatedly, metallic components subjected to changing loads become fatigued, resulting in premature failure under certain situations. Fatigue loading is the most common form of loading that results in cyclic changes in the applied strain or stress on a component. As a result, every fluctuating load is essentially a fatigue load. Moving or rotating components make up the majority of mechanical systems and gadgets. Even though the amplitude of the applied load stays constant, the produced stresses are not constant when they are exposed to external loadings.

2.1 Types Of Cyclic Loading

Calculations for a single stress state are used to understand how fatigue damage develops when stress at a location changes over time [28]. Fatigue loading is divided into four categories.

1. Non-constant amplitude with Non-proportional loading
2. Constant amplitude with Non-proportional loading
3. Non-constant amplitude with Proportional loading
4. Constant amplitude with Proportional loading

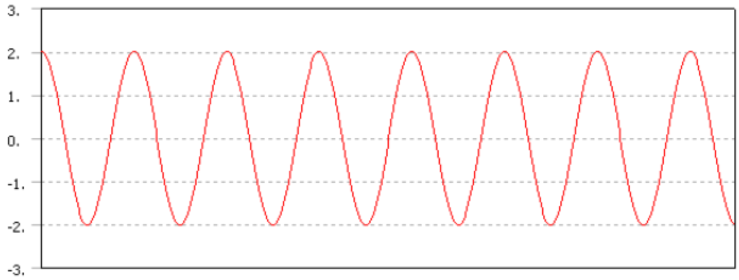

Figure 6. A constant amplitude loading [28]

2.1.1. Constant amplitude with Proportional loading

The traditional "back of the envelope" calculation indicating whether the load has a fixed maximum value or continuously varies with time is constant amplitude, proportional loading, as shown in Figure 6. Because just one set of FE stress measurements and a loading ratio are necessary to calculate the alternating and mean values, the loading is of constant amplitude. The loading ratio (LR = L2/L1) is the proportion of the second load to the initial load. Because only one set of FE findings is required, loading is proportionate. Fully reversed and zero-based loading are two common kinds of constant amplitude loading. A single set of FE findings may be used to identify significant fatigue sites because loading is proportionate. There are just two loadings, therefore neither cumulative damage nor cycle counting are necessary.

2.1.2 Constant Amplitude with Non-Proportional Loading

Constant Amplitude with non-proportional loading, as illustrated in Figure 7, examines exactly two load scenarios that do not require a scaling factor to be connected. The loading has a constant amplitude but is not proportional since the main stress or strain axis might vary between the two load sets. There is no need to count the cycles. This sort of fatigue loading may be used to describe a variety of fatigue loadings, including:

1. Switching between two different load situations
2. Superimposing an oscillating load on a static load.
3. Analyses in which the loading is proportionate but the outcome is not. This occurs when the relative stress distribution in the model changes due to changes in the direction or magnitude of loads.

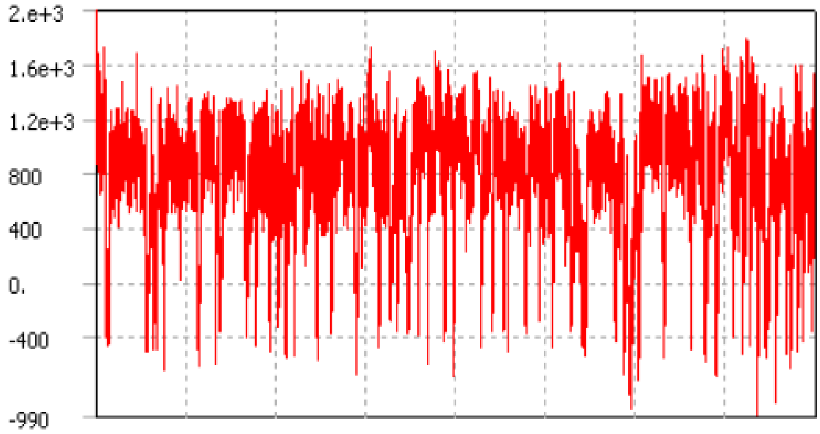

Figure 7. A constant amplitude, non-proportional loading [28]

2.1.3 Non-constant amplitude with Proportional Loading

Only one set of FE findings is required for non-constant amplitude, proportional loading. The load ratio fluctuates with time, rather than employing a single load ratio to calculate alternating and mean values. Consider it as combining a FE analysis with strain-gauge data acquired over a period of time. Because loading is proportionate, a single set of FE findings may be used to determine the critical fatigue position. The generate that damage, cumulative damage calculations must be performed Cycle counting is a technique for breaking down a long load history into a series of occurrences that can be compared to constant amplitude test data.

The ANSYS Fatigue Module's Non-constant amplitude with Proportional Loading employs a "fast counting" approach to significantly save runtime and memory. Before partial damage is assessed, alternating and mean stresses are classified into bins in rapid counting. Data is not sorted into bins until partial damages are discovered if rapid counting is not done. For an appropriate number of bins is employed when counting, the accuracy of rapid counting is typically quite excellent. Bin size, strictly speaking, refers to the number of divisions in the rain flow matrix. The precision of a bigger bin size is higher, but it takes longer to solve and uses more memory. The default bin size is 32, which means the Rain flow Matrix is 32 × 32 in size. When doing a variable amplitude fatigue analysis, another option is to specify the value used for infinite life for Stress Life. Because many materials do not have an endurance limit, this adds an extra layer of protection. If you set a greater value, tiny stress cycles will be less destructive if they occur frequently. The findings of the Rain flow and Damage Matrix may be used to determine the impact of tiny stress cycles in this loading history.

2.1.4 Non-constant amplitude with Non-Proportional Loading

The most typical instance is non-constant amplitude, non-proportional loading, which is identical to Constant Amplitude, non-proportional loading, but there are more than two separate stress scenarios involved in this loading class that have no relation to one another. The load combination that produces the most damage is also unclear, in addition to the position of the critical fatigue life. Therefore, more complex cycle counting techniques are required, such as multi-axial critical plane methods or route-independent peak methods.

2.2. Fatigue Failure – Mechanism

A fatigue failure starts with a little fracture; the initial break may be so small that it is undetectable. The fracture commonly appears at a location of localised stress concentration, such as a keyway, or a hole, a change in cross-section in the material. The stress concentration effect increases when a fracture develops, and the crack propagates. As a result, the strained region shrinks, the stress increases in amplitude, and the fracture spread faster. Until the remaining region can no longer support the load and the component fails abruptly. As a result of fatigue loading, failure occurs suddenly and without warning.

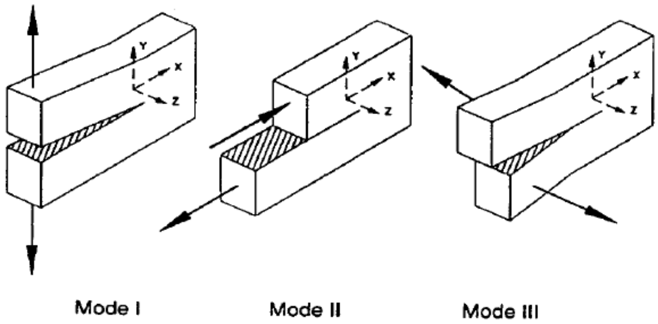

Figure 8. The three cracking modes that fracture mechanics uses. [29]

Crack initiation: notches, Fillets, bolt holes, keyways, and tool marks or even scratches, which have localised stress concentrations, are probable fracture initiation zones. A crack can also be caused by a geometrical discontinuity or a metallurgical stress raiser, such as inclusion sites. Slip happens during plastic stretching, resulting in planes gliding one over the other (dislocation motions). Slip saturation occurs with cyclic strain, making further plastic deformation impossible. As a result, the material undergoes intrusion and extrusion, resulting in a notch-like discontinuity.

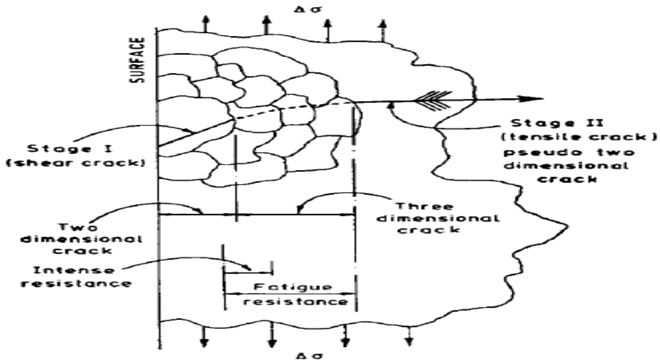

Figure 9 The transition form of crack growth. [29]

Crack propagation: In a fatigue test, Static Linear Elastic Fracture Mechanics gives numerical criteria for the start of catastrophic failure. If a fracture propagates under repeated loading, the value of a will slowly grow, as will the value of K when the dynamic load is at its maximum. The fracture will extend catastrophically when this value, KMax, hits KIc, a material property. However, Linear Elastic Fracture Mechanics has a larger role in fatigue. The range of crack tip intensity factor, say K, is the difference between these. The value of da/dN may be estimated since the rate of crack propagation da/dN is dependent on K. The rate is determined by s and the crack length a, which increases as the crack grows longer. To conduct tests at a fixed K crack length, the range of load must be reduced in proportion to a1/2.

Figure 10. displays typical test findings for experiments performed at constant ΔK. Three regions are present. The relationship is linear for ΔK at the middle of its range. Given that both scales are logarithmic, the expression for this centre part is:

$$da/dN = C(\Delta K)m$$

where m are material properties, a = current crack length, and C, da/dN = current rate of crack propagation. The graph deviates from a straight line at high values of ΔK. Since the fracture is expanding so quickly in most real situations, significant changes to the formula utilised here have no impact on the expected life. The departure from the straight line at low K values is much more significant. If the line turns vertical, which happens in many reported data sets, there is a value of K below which the fracture growth rate is zero.

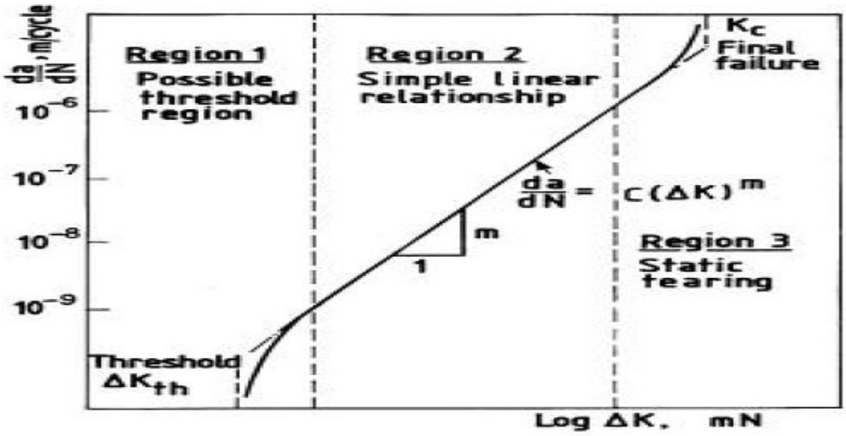

Figure 10. Crack Propagation Rate at constant ΔK. [29]

Final fracture: An abrupt fracture of the component occurs as the region becomes too small to continue withstanding the produced stresses.

2.3 Stress-Life Based Approach

There are various available approaches for the fatigue design and components. All call for the same kinds of data. Identification of potential failure sites, load spectrum for the component or structure, strains or stresses brought on by the loads at the potential failure sites, temperature, a methodology, material behaviour, and corrosive environment that combines all of these effects to provide a life prediction are some of these factors [25]. A stress versus number of cycles to failure curve can be drawn using the data from these experiments. The spread of the data collected for this straightforward fatigue test is shown by this curve. Figure 11. displays typical S-N material data. The method referred to as the "stress-based approach" is still widely employed for designing aluminium structures. Therefore, issues that fall under the umbrella of high-cycle fatigue are best suited for the nominal stress method. One of the two fatigue regimes that are often taken into consideration for metals and alloys is high cycle fatigue. After more than 10^4 to 10^5 cycles, it fails due to presumably linear elastic behaviour. This regime, which has modest loads and lengthy life spans, or a high number of cycles, results in fatigue failure. The cycles-to-failure rise with decreasing loading amplitude.

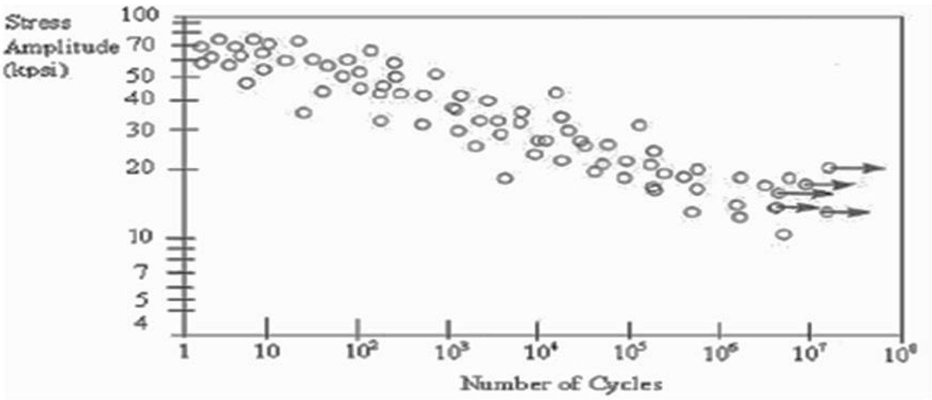

Figure 11. A typical S-N material data [25]

2.4 Fatigue Design Process

One of the observed modes of mechanical failure in real-world situations is fatigue design. For numerous constructions, such as vehicle frames, bridges, aero planes, automobile suspensions, train cars, and fatigue becomes an obvious design factor as a result. There are identified cyclic stresses for these structures that, if the design is inadequate, could result in fatigue failure. Figure 12. provides an illustration of the fundamental components of the fatigue design method.

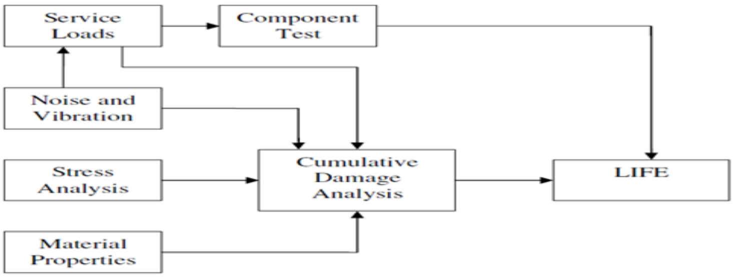

Figure 12. The fundamental components of fatigue design methodology [30]

First, a description of the service environment is obtained. Next are service loads, noise, and vibration. The objective is to create a precise simulation of the vibration, strains, loads, noise, deflections, etc. that would probably be encountered throughout the component's entire functioning life. From load recorded and histories measured during particular processes, loading sequences are created. Understanding the mechanics and modes of component and structural behaviour is also impacted by vibration and noise. In terms of amplitude and frequency data, the vibration systems may be objectively described.

Stress analysis: How a component or structure responds to service loads in terms of deflections, strains, and stresses depends on its geometry and boundary conditions. There are experimental and analytical techniques to measure this behaviour. When components or structures are present, experimental approaches may be applied. To measure strains at such crucial locations, strain gauges can be deliberately placed.

Material properties: Every durability research must consider the link between strain, stress, and fatigue life for the material being considered. The strains and stresses experienced in crucial areas of a structure or component have a significant impact on fatigue, which is a highly localised process. For a particular material, the connection between uniaxial stress and strain is distinct, stable, and, for the most part, relatively location-independent. As a result, a small specimen tested in the lab under straightforward axial conditions can frequently be utilised to accurately reflect the behaviour of a component or structure's critical area of an element made of the same material. Even with uniaxial loading, the most crucial areas are found at notches.

Cumulative Damage Analysis: There are multiple intricately linked processes that make up cumulative damage analysis or the fatigue life prediction method for a crucial area in a component or structure. A combination of the load history, stress concentration parameters, and cyclic stress-strain characteristics of the materials may be used to model the local uniaxial stress-strain response in critical locations.

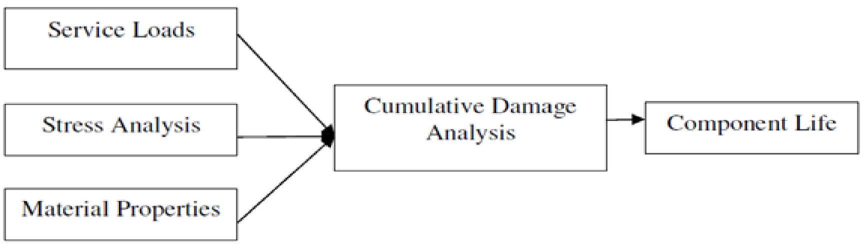

Figure 13. The cumulative damage analysis process [30]

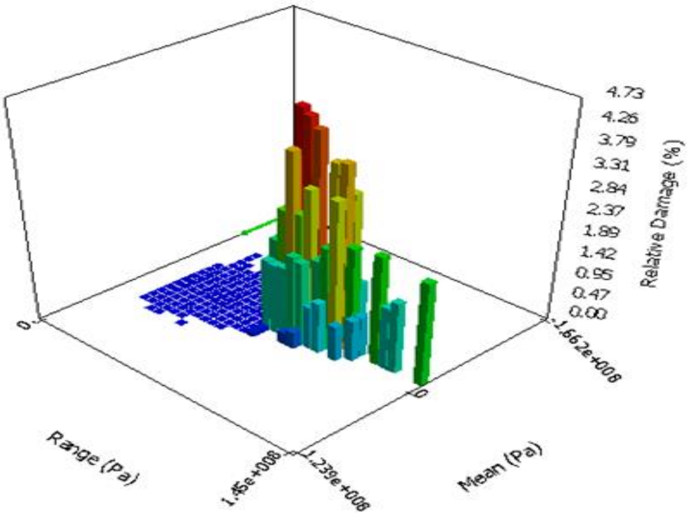

Figure 14. The cumulative damage Matrix [28]

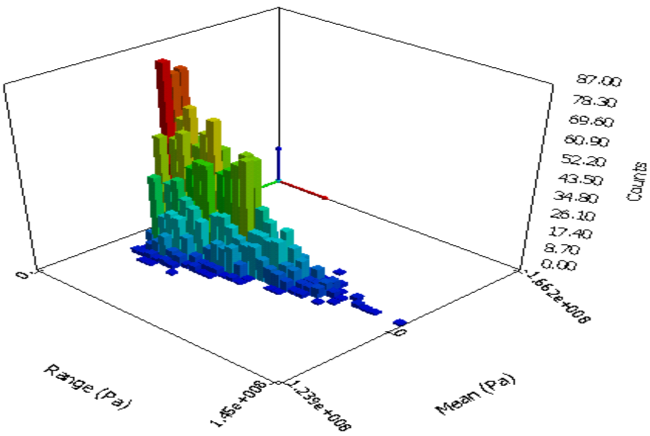

Figure 15. The Rain Flow Matrix [28]

Engineering design frequently calls for the use of fatigue life predictions, particularly when examining test designs to make sure they are resistant to cracking. The necessity for cracking problem troubleshooting in service models or prototypes of machinery, structures and vehicles is comparable. Figure 16. functional diagram illustrates the purpose of life prediction in the initial design phase as well as in the subsequent evaluation-redesign cycles, eventually field testing and component laboratory testing of composite or assemblies vehicles.

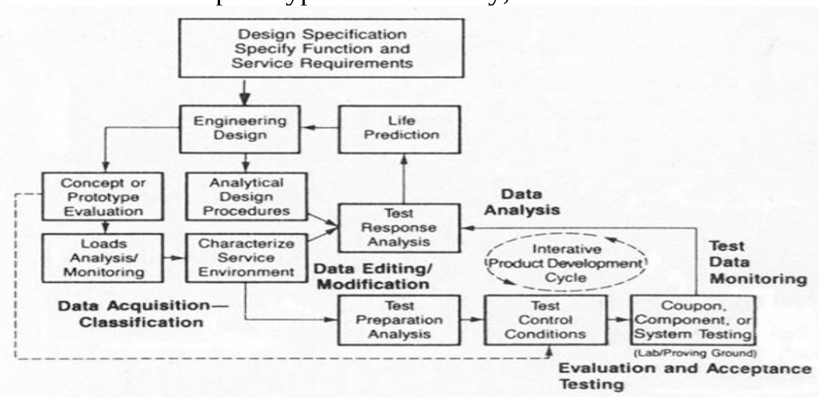

Figure 16. Functional diagram of engineering analysis and design [30]

3. Finite Element based Fatigue Design

In order to experience fatigue, a crack must first begin and expand until it reaches a crucial size, occasionally leading to separation into two or more halves. Although there are other criteria for

the deterioration that may apply in some cases, this applies to parts made of aluminium, steel, and iron, which are by far the most prevalent materials. Slip-on crystal planes, regulated by time-varying shear loads, is what causes the initiation process in these crystalline metals. Thus, the onset of a fatigue failure is a locally specific process that is also reliant on the dynamics of the system. The key issue is the time history of strain or stress at the precise point where a fracture is going to begin, and the distribution of these parameters generally across the component is only of minor importance. FEA is crucial in this field for precisely this reason. An analyst can focus attention on any area of a model using FEA, taking advantage of the method's inherent capacity to incorporate dynamic effects.
The aforementioned metals have been the focus of the majority of fatigue research. Elastomers and polymers are more challenging to study because of their non-linear behaviour at relatively low loads; as a result, applying Finite Element Analysis to these materials is more of a research topic than a typical design exercise. Thermal and Mechanical effects also contribute to some difficulty. The primary purpose of today's commercial Finite Element fatigue codes is to allow thermal analysis stresses to be employed independently of temperature to calculate fatigue life. Thermal creep, changing material characteristics, and oxidation/corrosion are effects that are difficult to incorporate since they will promote crack extension (may enhance or retard crack growth). Research programmes frequently focus on these issues. Some contemporary software development projects integrate thermal-mechanical effects.

3.1 The Elements Of A Life Estimation System In Finite Element Analysis
For a long time, it was believed that the fatigue analysis procedure followed the logic shown in Figure 17 The three input parameters, loading, materials, and geometry, are seen as serving comparable purposes in this perspective. In reality, most analyses have complied with the model depicted in Figure 18.
To create a strain-time (e-t) or stress-time (s-t) history at a point likely to be crucial, the geometry and loading are first combined. Then, in order to estimate life, material fatigue properties are introduced.

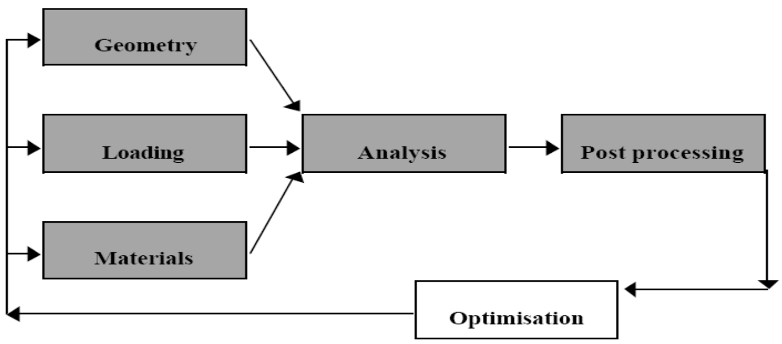

Figure 17. A Conventional View of Fatigue Analysis Process [29]

It has historically been necessary to employ a number of approaches, some with a solid mathematical foundation and many with a straightforward empirical base, to move from overall generalized loading and geometry to a comprehensive map of local strain and stress in a component. A new set of uncertainty arises if the loading changes over time, as it always will when tiredness is present. Using FEA affords greater control over the transition from loading and global geometry to local parameters and enables more analytical handling of dynamic factors.

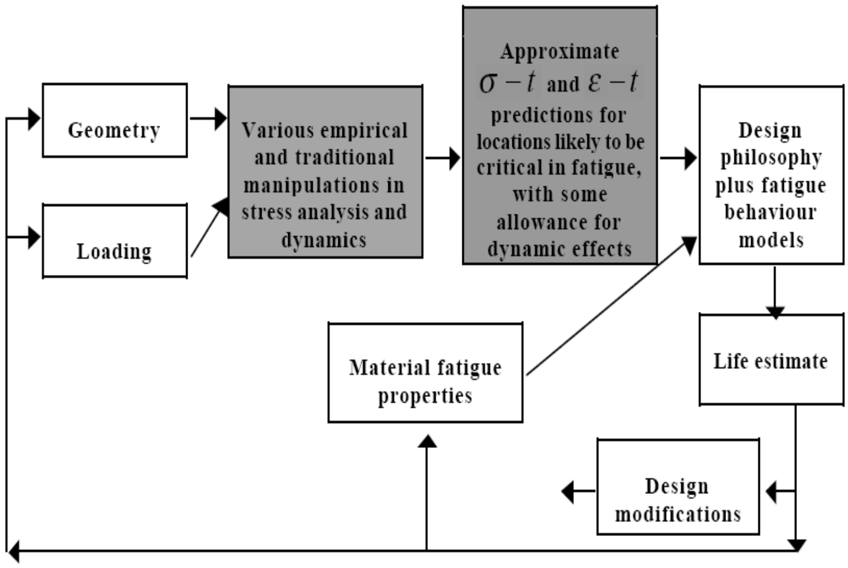

Figure 18. A View of Traditional Life Estimation Procedure [29]

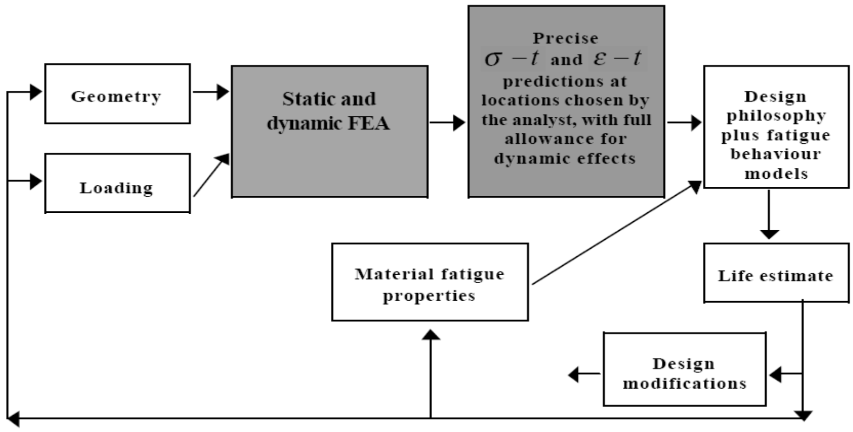

Figure 19 A View of Life Estimation Procedure Using Finite Element Analysis [29]

The process is then depicted using a model similar to Figure 19, which emphasizes the value of FEA in circumstances when analysis at specific places is crucial. A component that has straightforward geometry and straightforward loading and is intended for use in a scenario where failure would only result in little annoyance may be produced and put into service solely on the basis of a calculation. This is especially true if the object will only be produced in modest quantities. The need for verification of the calculation through testing arises when the issue is more complicated and the penalty for incorrect estimations are greater. Even if FEA is unlikely to be used in this situation, a straightforward test might still be sufficient.

A more common scenario is when a component with complex geometry and numerous loads needs to be made in large quantities, have a low weight requirement, and be utilised in an application that requires safety. Then, prototype parts or whole assemblies must be put through testing with loads that are as close as possible to those that are anticipated in service. This procedure is highly pricey. This kind of testing has the substantial disadvantage of having to wait until there is a prototype, in addition to being expensive. It will probably be challenging and expensive to fix any design flaws that do arise. Less late adjustments are anticipated to be required as the life forecast procedure improves in accuracy and reliability. The fundamental benefit of FEA-based fatigue tools is that they make it possible to perform accurate fatigue life predictions early in the development phase, before tests are even an option.

3.2.An Overview Of The Finite Element Analysis Based Fatigue Environment

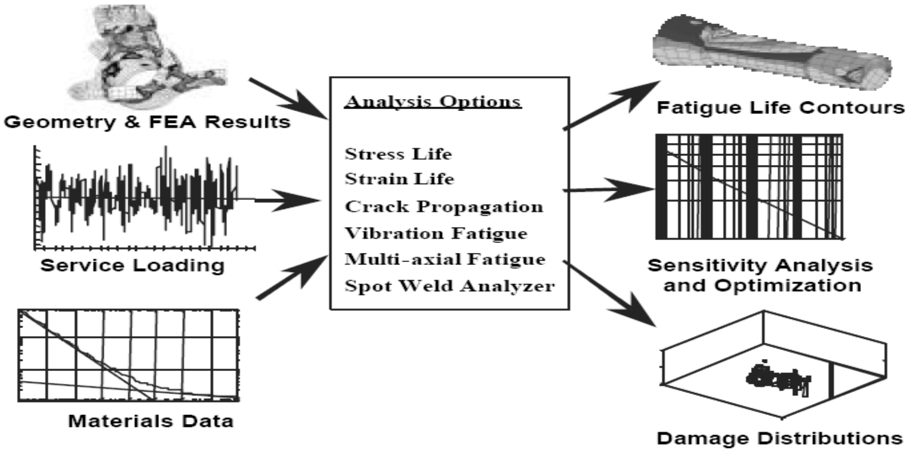

Figure 2.15: An overview of the Finite Element Analysis based fatigue environment [29]

An overview of the Finite Element Analysis -based fatigue environment is shown in Figure 16. The three graphs on the left show the materials data, applied loading, and Finite Element Analysis results. The three plots to the right illustrate the various methods of result visualisation. The sorts of fatigue calculations that can be performed are shown in the centre box. The, Crack-Propagation, Strain-Life, or Stress-Life methods are the three conventional life estimation approaches that form the basis for all of the fatigue procedures shown in Figure 20.

4. Conclusion

The analysis of the connecting rod has been documented in the literature. The recommended study of the connecting rod has been beneficial in reducing weight, raising von Misses stresses, lowering von Misses strain, and minimizing deformation, among other things. The connecting rod will be improved and developed thanks to this investigation. The use of modal analysis, static and thermal analysis, as well as the confirmation of results, can enhance the characteristics of connecting rods. The connecting rod may be simply modelled for the stress analysis in any CAD programme, such as CATIA, Pro/E, etc., and then it can be examined in any FEA programme, such as ANSYS. We can obtain precise results with FEA. The midsection of the rod is subjected to minor loads, but the tiny end is exposed to maximal strains.

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