Experimental Investigation of Fatigue Behavior in Materials Using a Rotating Bending Test

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HIGHLIGHTS

- *Analyzed the fatigue life characteristics of EN19, EN354, and EN36C alloys using a rotating beam fatigue tester.*
- *Probabilistic Fatigue Assessment Employed an advanced Bootstrap methodology and virtual subsample enhancement.*
- *Devised an advanced statistical technique for fitting S-N curves with life distribution data and limited-sample fatigue data.*
- *Investigated fatigue strength of several alloy steels subjected to cyclic loading and influence of notch size on this property.*
- *The results elucidate methods for predicting fatigue failure in essential mechanical components used in construction and heavy machinery.*

Abstract: A mechanical machine needs to consider effect of cyclic stress to avoid failures, the machine considered in this work is rotating beam fatigue tester to know the fatigue life of EN19, EN354, EN36C alloy materials Large scale mechanical equipment's service integrity can only be guaranteed by probabilistic fatigue evaluation, nevertheless, in real engineering, probabilistic fatigue models combined with multiaxial stress circumstances and tiny sample information features are still insufficient. As a result, the virtual subsample augmentation technique is in combination with the enhanced Bootstrap technique to provide a generic probabilistic fatigue assessment procedure. In particular, the small sample is first expanded using the random sample regeneration method. sample fatigue data is combined with life distribution data at various stress levels. The integrated approach is used to fit the S-N curve, which is based on the backwards statistical inference method. information about life dispersion. Furthermore, a novel fatigue damage metric grounded in the inhibition A function is suggested to forecast tiredness to alter the curve. In the interim, alloy steel with various notch sizes needs to undergo a fatigue test for various materials, including EN19, EN354, and EN36C allot. The findings demonstrate how the size and notch. This apparatus demonstrates material's fatigue strength after repeated loads at different stress levels, fatigue properties of a material evaluated by subjecting it to a stress level under its ultimate strength. Stress cycles are used to examine impact of repeated exposure to diverse pressures on machine components, the performance of EN19, EN354, and EN36C alloys is analyzed herein.

Keywords: Fatigue Life Prediction, Material Fatigue Behavior, Applied Load vs. Fatigue Cycles, Stress Strain Analysis, Fatigue Failure Mechanism,

INTRODUCTION

The predominant studies analyzed used a rotating beam fatigue tester as their primary instrument [1-2], researchers may determine the longevity of materials under various loads by using this equipment to subject specimens to cyclic loading in a controlled setting [3-4]. Despite variations in the kinds of rotating beam fatigue tests used in various investigations, the fundamental concept remains consistent: expose a specimen to a regulated rotating bending force until failure occurs [9]. To elucidate the relevant criteria for conducting such tests, it is essential to establish a standard [5-6]. A significant aspect influencing fatigue behavior is the loading frequency [4]. It is essential to specify the specific frequency used in each study and provide an appropriate reference. An alternative is to use real-time monitoring of the test to track stress, strain, and other relevant indicators as they transpire [7-8]. This kind of monitoring would enhance the precision and thoroughness of the study [9-10]. Almost any scrap may be examined to show that yield strength of material is often exceeded at stresses lower than those at which breakdowns occur. "Fatigue" is name given to this intricate occurrence. Up to 90% of in-service part failures in industry are caused by fatigue. The fact that fatigue fracture did not exhibit obvious plastic deformation was regarded as strange in 19th century, which led to mistaken belief that fatigue was only an engineering issue. They weren't entirely incorrect, though, as the capability of the time's tiny apparatus was very restricted. Additionally, few prominent researchers conducted fatigue experiments this century; the most well-known of them is work of August Wohler, who would later come up to the concept of the S-N Curve, or stress-lifetime curve. 20th century saw a significant advance in our knowledge of fatigue failure process, as a result of development of more potent tools like computers, sophisticated microscopes, sophisticated numerical analysis techniques, and a great deal more research (John Mann is used up to 100,000 sources in one of his works), fatigue started to be understood as a material and design phenomenon rather than an engineering issue. Even though fatigue failure has been the subject of extensive investigation, its real nature is still unclear, however reports of damage, cracks, and even total failure from cycle loads are frequent. There must be a reason if the issue persists after a century of research in the preceding century. The goal of this thesis work is to approach the issue from a fresh angle rather than to offer solutions to the open-ended concerns. This includes setting up a verification test for the servo-hydraulic dynamic testing machine (still under construction) in the mechatronics laboratory of HAMK University of Applied Sciences, explaining the complex nature of fatigue failure, introducing the fundamental idea of engineering design against fatigue failure, and explaining the known techniques of fatigue testing. Additionally, it involves planning a laboratory fatigue test exercise appropriate for a machine course material in material science or design. Machine parts are frequently subjected to cyclic loads, and the cyclic stresses that occur from this can cause microscopic physical damage to the materials in question. Usually, fatigue fractures happen at the notches, which include grooves, holes, etc. The projections of fatigue life are impacted by the notch's shape and other features. The nominal stress multiplied by the elastic stress concentration factor, t k, equals the stress at the notch. Naturally, this increase in stress will have a negative impact on tiredness, but it is unable to directly indicate the effective stress range in fatigue. Thus, it is necessary to incorporate the fatigue strength reduction factor f k [10-15].

When a material is subjected to recurrent stress under its strength, it undergoes fatigue and ultimately fails, fatigue failure often occurs abruptly and with severe consequences. Under stress, a minute fissure will develop (crack nucleation), propagate (crack development), and ultimately lead to specimen's failure. The fatigue life of the concerned component is comprised of entire process. According to Jaap Schijve, fatigue must be understood as both a material phenomenon and an engineering challenge, involving a process that starts with an unseen microscale fracture and progresses to a macroscale fatigue failure. Only then can reasonably fatigue prediction be made for design or analysis [15-16].

Objectives and Outcomes

Fatigue failure analysis of notched specimens with different materials is a critical aspect of materials science and engineering, aimed at understanding how materials behave under cyclic loading conditions, particularly when subjected to stress concentrations induced by notches. In this comprehensive analysis, we delve into the objectives, methodologies, outcomes, and significance of such studies, elucidating their role in enhancing the reliability and performance of engineering components across various industries [17].

Introduction to Fatigue Failure Analysis

Fatigue failure refers to the gradual and progressive weakening of a material under cyclic loading, leading to crack initiation and propagation, ultimately culminating in failure. This phenomenon is prevalent in numerous engineering applications, ranging from aerospace and automotive to civil and mechanical engineering. Notches, which are geometric irregularities or stress concentrators, exacerbate the effects of fatigue by locally increasing stress levels, thereby accelerating crack initiation and propagation [18].

Objectives of Fatigue Failure Analysis

The primary objective of fatigue failure analysis with notched specimens is to characterize fatigue behavior of different materials and assess performance under cyclic loading conditions. Specifically, objectives include [19-20]:

- Characterization of Material Fatigue Behavior: Understanding how different materials respond to cyclic loading and identifying key parameters such as fatigue life, stress levels leading to failure, and fatigue crack growth rates.

- Determination of Fatigue Life: Quantifying number of cycles a material can withstand before failure occurs under various stress amplitudes and notch geometries, typically represented by S-N curves.
- Evaluation of Notch Sensitivity: Assessing the influence of stress concentrations induced by notches on material performance and determining the notch sensitivity factor (Kt) for different materials and notch configurations.
- Study of Crack Initiation and Propagation: Investigating the mechanisms of crack initiation and propagation, including the critical locations and stages involved in the fatigue process.
- Validation of Predictive Models: Validating theoretical models and predictive tools for fatigue life estimation by comparing experimental results with predictions, thereby enhancing the accuracy and reliability of fatigue life predictions.
- Optimization of Material Selection and Design: Utilizing the insights gained from fatigue failure analysis to optimize material selection, notch design, and component geometry to improve fatigue resistance and durability while minimizing weight, cost, and manufacturing complexities.

Significance of Fatigue Failure Analysis

Engineering components' performance, safety, and dependability are crucially dependent on fatigue failure study using notched specimens in a variety of sectors. Engineers can design structures and components that can withstand cyclic loading conditions by using insights from these analyses, which help to minimize the risk of fatigue-related failures and ensure long-term durability. These insights include information on fatigue behavior of materials and the mechanisms of crack initiation and propagation [26]. A critical component of materials science and engineering is the study of fatigue failure of notched specimens made of various materials. This analysis aims to comprehend and minimize the impacts of fatigue on engineering components. These investigations offer important insights into material behavior, fatigue life, and fracture propagation through experimental testing, numerical simulations, and analytical modeling. This information helps engineers build safer, more dependable, and more effective engineering solutions [27].

METHODS

- Objective Definition Define the objective of the fatigue failure analysis, which includes studying the fatigue behavior of notched specimens made from different materials using a rotating beam fatigue testing machine. Specify the materials to be tested, the types of notches (e.g., single-edge notched specimens), and the fatigue loading conditions (stress amplitudes, frequencies) to be applied during testing.
- Material Selection and Specimen Preparation Select the materials based on their relevance to the application and availability. Procure specimens of consistent dimensions, free from defects. Prepare notched specimens using precision machining techniques according to relevant standards (ASTM E466 for metallic materials, for example). Ensure the notch geometry and dimensions adhere to the testing standards and desired stress concentration factors.
- Experimental Setup Set up the rotating beam fatigue testing machine according to the manufacturer's guidelines and testing standards (ASTM E466 or equivalent). Calibrate the machine to ensure accurate load application and data acquisition throughout the testing process. Verify the alignment and condition of the rotating beam, grips, and specimen mounting fixtures.
- Specimen Mounting and Conditioning Mount the notched specimens securely on the rotating beam fatigue testing machine using appropriate grips or fixtures. Ensure that the specimens are aligned properly and securely clamped to prevent any slippage during testing. Condition the specimens if required (e.g., thermal cycling, preloading) to simulate real-world operating conditions or to stabilize material properties.
- Fatigue Testing Procedure Conduct fatigue tests on the notched specimens using the rotating beam fatigue testing machine. Apply a cyclic loading regime with defined stress amplitudes and loading frequencies based on the intended application or industry standards. Record number of cycles to failure for each specimen. Perform tests with multiple stress levels to establish fatigue curves and assess material behavior under varying conditions.
- Data Acquisition and Analysis Use the data acquisition system of the rotating beam fatigue testing machine to monitor applied loads, cycles, and specimen responses during testing. Record any visual

observations such as crack initiation, crack propagation, or final fracture. Analyze the collected data to determine fatigue life, stress-life (S-N) relationships, and fatigue strength for each material and notch configuration.

- Notch Sensitivity Evaluation Evaluate the notch sensitivity of materials by comparing the fatigue performance of notched specimens with unnotched specimens tested under similar conditions. Calculate stress concentration factor (Kt) for the notched specimens based on notch dimensions and geometry. Assess the reduction in fatigue life due to notches and characterize the notch effect on different materials.
- Failure Mode Analysis After fatigue testing, conduct post-test examination and analysis of failed specimens. Identify the dominant failure modes such as fatigue crack initiation at notches, fatigue crack propagation, or final fracture. Document and analyze the failure modes to understand material behavior under cyclic loading.
- Comparative Study and Interpretation Compare the fatigue behavior of different materials based on the experimental results obtained from rotating beam fatigue testing. Evaluate factors such as fatigue life, fatigue strength, notch sensitivity, and fracture characteristics for each material. Interpret the findings in relation to material properties, notch geometries, and loading conditions to draw meaningful conclusions.
- Validation and Reporting Validate the experimental results against established fatigue models or standards applicable to rotating beam fatigue testing. Compare the experimental fatigue life data with predicted fatigue life using fatigue models such as the Basquin equation or Miner's rule. Prepare a detailed report documenting the methodology, experimental setup, test results, statistical analyses, failure mode descriptions, and conclusions. Include graphical representations (fatigue curves, microscopy images) to support key findings and provide recommendations for further studies or design improvements.

Experimental Implementation

Materials:

EN19:

EN19, a high-grade alloy steel with tensile strength as shown in table 1, is suitable for engine gearboxes owing to its ductility and shock resistance, oil and gas corporations are progressively focusing on EN19, known for its excellent machinability and prevalent use in the automotive sector, figure 1 illustrates material's durability and attractiveness.

Properties include: toughness, strength, and wear resistance; high tensile steel; good ductility and shock resistance; good wear resistance; and the ability to be induction hardened.

Applications include: load bearing tie rods; shafts; towing pins; automotive gears and components; and oil and gas sector applications.

EN354:

Medium carbon steel EN354 is well-suited for several technical applications because to its strong wear resistance and moderate strength. This steel is usually utilized in applications requiring high strength, exceptional toughness, and great surface hardness that is attained by heat treatment procedures [28-30].

Properties

It has high strength, high temperature creep resistance, fatigue life, phase stability, resistance to corrosion and oxidation, and usage in gas turbine engine components.

Applications

Plumbing, heating, chemical industry, oil and gas pipeline, and oil and gas industry

EN36C:

The low-level carbon content of 0.12-0.18% is found in EN36C is presented on table 2. The EN36 has 3.00–3.75% nickel, which allows for the application of a high-temperature heat treatment to the material. The material has additional toughness due to its molybdenum and chromium concentration. Levels of phosphorus and sulfur are 0.05 percent maximum it shown in figure 2.

Mechanical Characteristics

- Resistant to abrasion;
- high hardness;
- good machinability when annealed;
- high tensile strength [31-32].

Applications

The industries that include aircraft engineering, shipbuilding, railroads, oil, mechanical engineering, gears, shafts, rollers, and screws

Table-1 Comparison table of Chemical Composition of EN19, EN354, EN36C

		EN19		EN354		EN36C	
S. No	Elements	Min	Max	Min	Max	Min	Max
1	Carbon	0.35	0.45	-	0.2	0.35	0.45
2	Silicon	0.1	0.35	-	0.35	0.1	0.35
3	Manganese	0.5	0.8	0.5	1	0.5	0.8
4	Sulphur	-	0.05	-	0.04	-	0.05
5	Phosphorus	-	0.035	-	0.04	-	0.035
6	Chromium	0.9	1.5	0.75	1.25	0.9	1.5
7	Molybdenum	0.2	0.4	0.1	0.2	0.9	1.5
8	Nickel	-	-	1.5	2	-	-

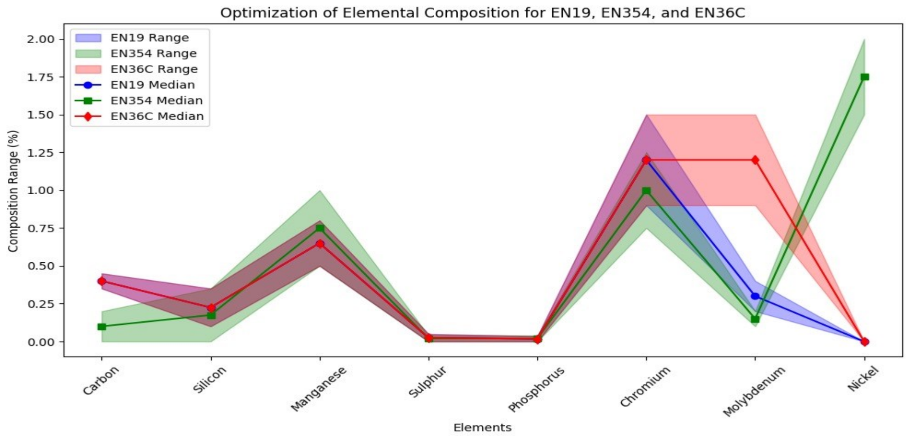

Figure: 1. Optimization of Elemental Composition

Table-2 Comparison table of Mechanical Properties of EN19, EN354, EN36C

		EN19	EN354	EN36C
S.No	Condition	Values		
1	Tensile /mm^2	850-1000 Mpa	540-700 MPa	1100
2	Yield N/mm^2	680 Mpa	355 MPa	-

3	Elongation %	0.13	0.16	15
4	Izpd KCV J	50	-	40
5	Hardness Birnell	248-302	-	341
6	Reduction Area %	-	-	0.5

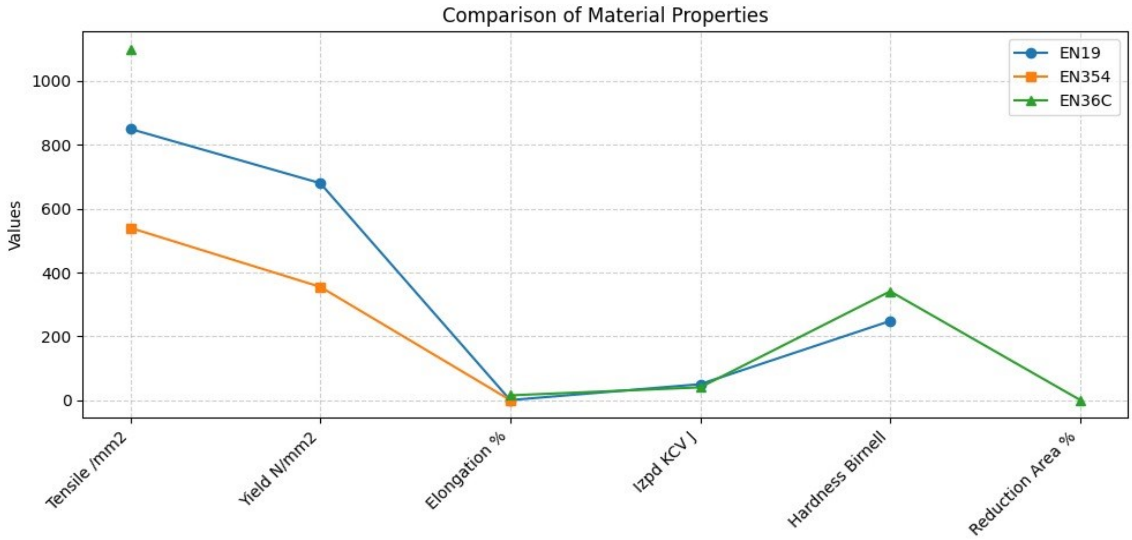

Figure: 2. Optimization of Elemental Composition

The fig. 1and 2 illustrates the variation of critical machine characteristics such as bending stress (MPa), bending moment (Nm), and specimen speed (RPM) across several measurement locations. Testing elevates bending stress from 110 MPa to 2190 MPa, as shown by the red solid line. The bending moment (blue dotted line) ranges from 3 to 55 Nm to illustrate the impact of torque on the specimen. The green dotted line indicates the specimen's speed, ranging from 1000 to 5000 RPM, demonstrating the limitations of rotating speed. The graphic illustrates the operational range of the machine to optimize load application, stress distribution, and fatigue testing. The distinguishing markers and color-coded trends provide a straightforward comparison of these essential parameters in experimental contexts, ensuring accurate control and efficiency [33-34].

Testing procedures

Fatigue Testing Machine

Fatigue tests typically assess number of stacking cycles a material can endure prior to failure; the greatest number of stacking cycles a material can endure is referred to as its fatigue life. Figures 3 and 4 illustrate that a fatigue test necessitates placing a sample in a device, upon commencement of test, loading and unloading continue indefinitely shown its specification on table 3. The test may continue until sample fails or a certain number of cycles has been completed, dependent upon its configuration, rotating beam fatigue tester is operational, functions as a single beam when subjected to symmetrical loading at two locations [35-39].

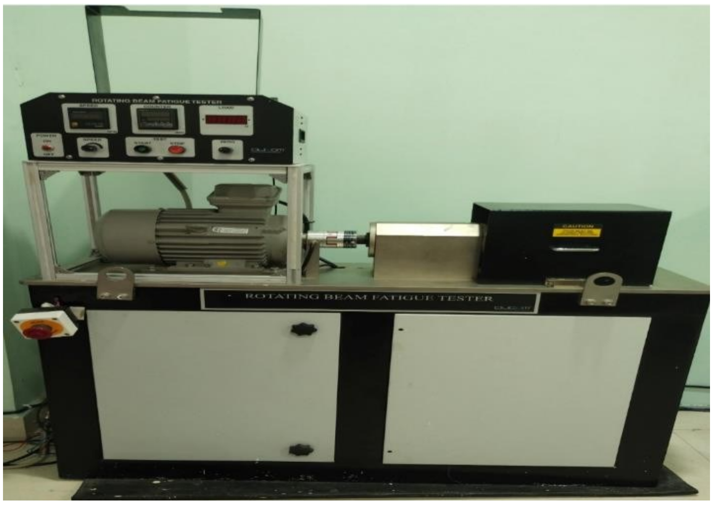

Figure 3: Rotating Beam Fatigue Testing Machine **Figure 4: Samples**

Machine Specification

Table.3 Machine Specification

Machine Specifications	
Specimen material and size	Non heat treated 12.7 and 101.6 mm long
Collect size	13mm
Load:	50 to 1000N (load applied with dead weights)
Loading ratio:	1.5
Specimen speed:	Min 1000 rpm, Max 5000 rpm
Setting block length	40mm
Centre of profile:	19.05mm
Bending moment distance:	Bending distance = loading distance + middle of profile centre
Loading distance	Loading point + Housing Covering plate + Collect length (9.9+9+17) = 35.95mm
Bending distance	35.95+19.05 i.e. 55mm
Counters (counts):	1 to 999999
Bending moment	3 to 55Nm
Bending Stress	110 to 2190Mpa

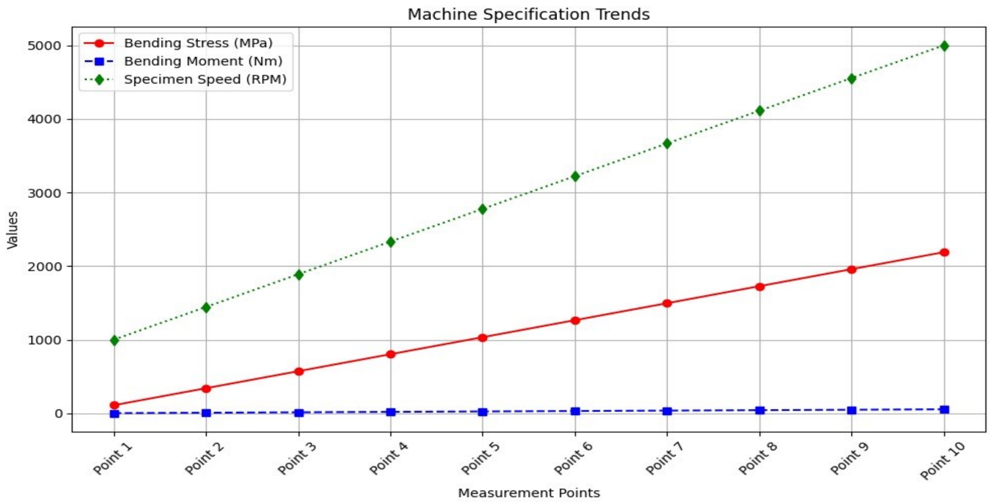

Figure: 5. Optimization of Elemental Composition

Procedure:

A header collects testing sample after a machine rotates it, rotating sample, which is positioned between grips, longitudinally induces strain on top and bottom sections of sample, affecting its measured length. Figure 5 illustrates that surface stress of sample undergoes continuous variation, examination continues until the specimen fails, utilize upset counter [40-44] to determine applied stress per cycle till failure. As sample load rises, cycles to failure decrease. Standard geometry must be used to prepare samples. This encompasses cylindrical grinding achieving a surface roughness of 0.4 microns RA, specimen experiences frustration stress ranging from 5 to 1000N with cycles up to 5000rpm under standard conditions. Plots of S-N (Endurance Strength-No. of cycles) are used to empirically determine specimen's fatigue strength. Comparative analyses are conducted for several materials, including EN19, EN354, and EN36C, and S-N curves are displayed in fig. 6 and 7 [45-51].

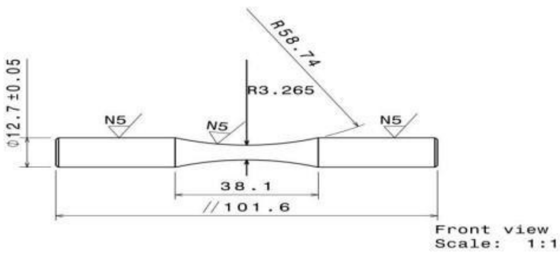

Figure 6: Specimen

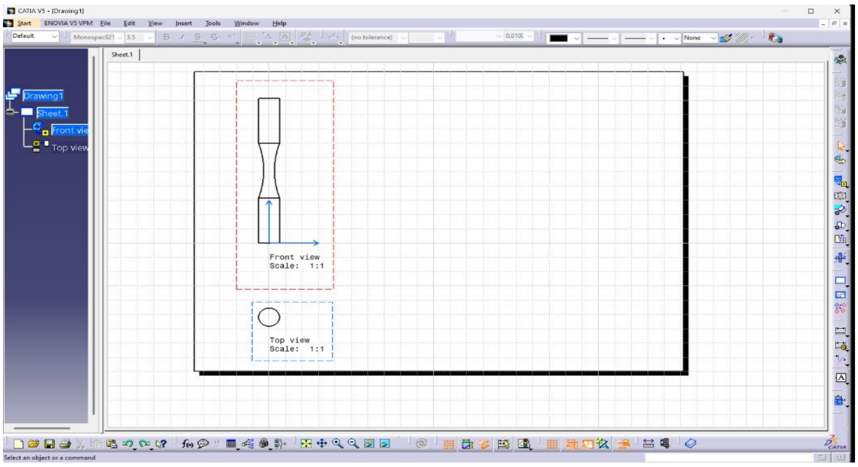

Figure 7: Specimen Design

RESULTS

Table 4: EN19 Steel Rotating Beam Fatigue Testing

Sample No.	Applied Load (N)	Stress (MPa)	Number of Cycles to Failure	Remarks
1	200	500	1,354,230	No failure
2	300	750	678,065	Failed
3	400	1000	467,944	Failed
4	500	1250	167,407	Failed
5	600	1500	52,069	Failed

Table 5: EN36C Steel Rotating Beam Fatigue Testing

Sample No.	Applied Load (N)	Stress (MPa)	Number of Cycles to Failure	Remarks
1	150	400	1,564,020	No failure
2	250	675	1,634,580	No failure
3	350	950	886,540	Failed
4	450	1225	597,688	Failed
5	550	1500	198,590	Failed

Table 6: EN 354 Steel Rotating Beam Fatigue Testing

Sample No.	Applied Load (N)	Stress (MPa)	Number of Cycles to Failure	Remarks
1	100	250	2,324,143	No failure
2	200	500	1,587,925	No failure
3	300	750	1,765,825	Failed
4	400	1000	785,231	Failed
5	500	1250	465,4210	Failed

Table 7: Comparative Analysis of Fatigue Strength

Steel Type	Typical Use	Applied Load Range (N)	Stress Range (MPa)	Cycles to Failure Range	Remarks

EN19	High-strength applications like gears and shafts	200 - 600	500 - 1500	100,000 - 1,000,000	High fatigue strength, excellent toughness, good resistance to wear and impact.
EN36C	Case-hardening for gears, cams, and rollers	150 - 550	400 - 1500	300,000 - 1,500,000	Strong surface hardness after heat treatment, good core toughness.
EN354	General engineering components requiring moderate strength	100 - 500	250 - 1250	400,000 - 2,000,000	Lower carbon content, good toughness, and wear resistance, less strength than EN19 and EN36C.

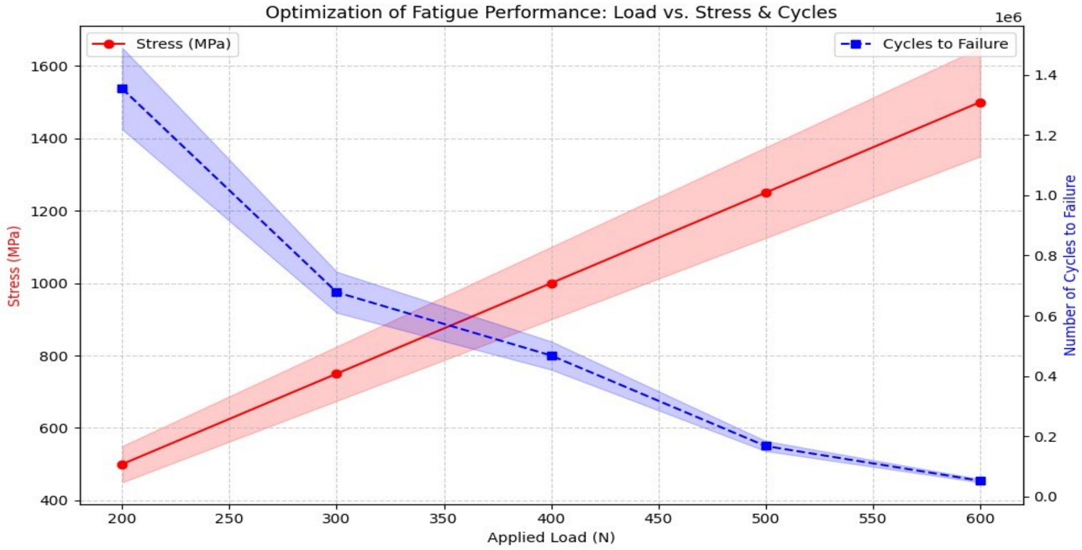

Figure: 8. Optimization of Fatigue Performance

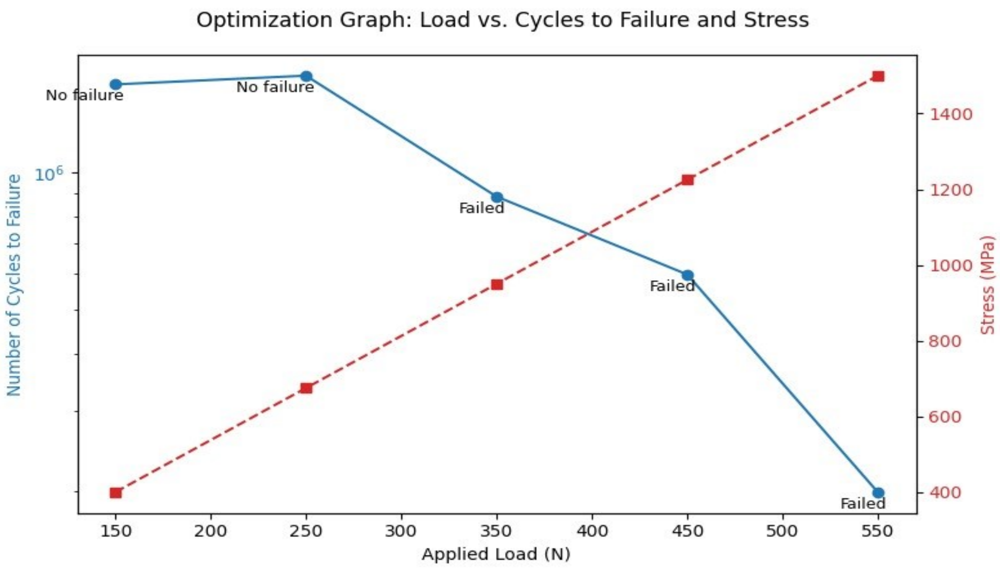

Figure: 9. Optimization of Failure and Stress

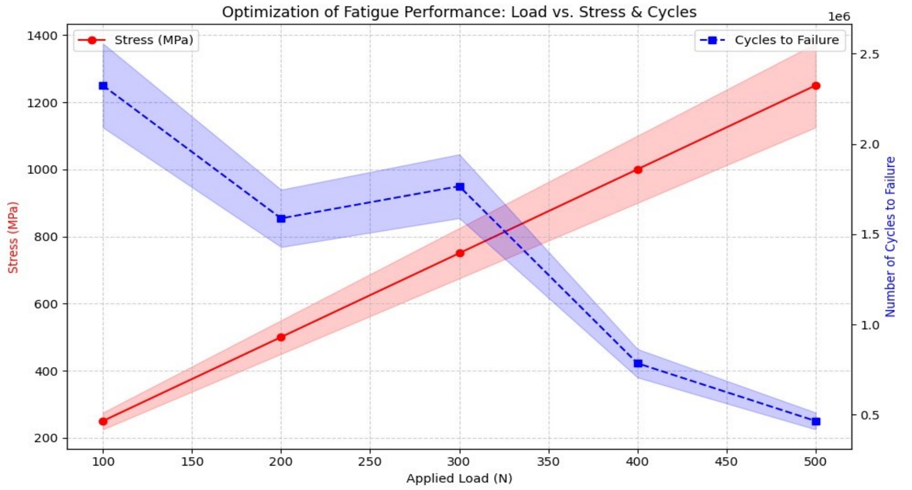

Figure: 10. Optimization of Fatigue Performance

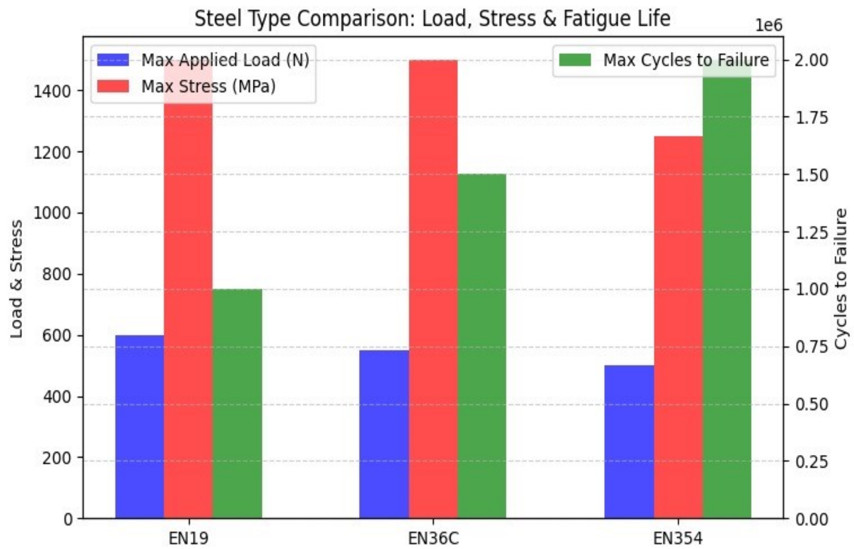

Figure: 11. Comparison of Load, stress and fatigue life

The experimental data presented tables 4-7 it has significantly enhanced our understanding of the fatigue life and strength properties of EN19, EN354, and EN36C alloys its shown figures 8-11. Utilizing graphical representations, such as S-N curves, and statistical summaries is advisable to convey these conclusions clearly and succinctly. Experimental data is required to illustrate the impact of notch size on fatigue strength [14-19]. It is crucial to view the results in the context of prior research on the fatigue behavior of these alloys. It is essential to juxtapose the results of this study with those of other research to determine the consistency and applicability of the findings across various contexts. The ultimate goal of fatigue testing and analysis is to identify methods for predicting fatigue failure and use that knowledge to influence design decisions. The study presents methodologies for predicting fatigue life that include probabilistic assessments and uncertainty. It is essential to communicate these techniques clearly and succinctly while examining their implications for engineering design [18]. Provide illustrated examples demonstrating how these insights might improve the design of mechanical components in construction and heavy equipment [19]. It is essential to address the limitations of the prediction models and potential avenues for further study.

DISCUSSION

The rotating bending test is an effective method for evaluating fatigue properties of materials under cyclic loading, in it investigation, EN19, EN36C, and EN354 steels were subjected to rotating bending test to assess their fatigue strength, endurance limit, and suitability for various engineering applications. EN19 exhibited the highest fatigue strength among the three materials, withstanding higher applied loads and stresses. This makes it highly suitable for components subjected to extreme cyclic loads, such as heavy-duty gears, shafts, and studs. EN36C, particularly after case-hardening, demonstrated excellent surface hardness and fatigue strength. Its performance under cyclic loading was robust, making it a strong candidate for applications like gears and cams that require a tough core with a hard, wear-resistant surface. EN354, while having lower fatigue strength compared to EN19 and EN36C, offered the longest fatigue life at lower stress levels. This makes it suitable for general engineering applications where moderate strength and good toughness are adequate. This experimentation reveals that each steel grade has unique properties that make it suitable for specific applications: EN19 excels in high- stress environments due to its superior fatigue strength. EN36C offers a balance of core toughness and surface hardness, making it ideal for case-hardened components. EN354 provides good toughness and wear resistance at a lower cost, suitable for moderate-load applications.

A comprehensive examination of material properties using rotational bending fatigue testing, focusing on EN19, EN354, and EN36C alloys, work highlights the importance of probabilistic fatigue assessment methodologies, the influence of notch size on fatigue strength, and use of these findings to predict mechanical component fatigue failure. Future study should prioritize enhancements to prediction models, examinations of the effects of ambient and temperature factors on fatigue life, and explorations of innovative materials and manufacturing techniques that enhance fatigue resistance. To progress accuracy and efficacy of fatigue life prediction, it is feasible to explore advanced computational techniques such as finite element analysis. Enhance the precision and relevance of fatigue life prediction models by including more alloys and loading conditions into the fatigue characteristics database.

STATEMENTS AND DECLARATIONS

Ethics approval

The paper has been submitted with full responsibility, following the due ethical procedure, and there is no duplicate publication, fraud, or copying. There are no financial or personal interests.

Data Availability Statement

Since no new data were collected or examined for this study, data sharing does not apply to this article.

Use of artificial intelligence

The authors confirm that they did not use artificial intelligence technologies when creating the current work.

Credit Author Statement

Author have contributed significantly to the research and preparation of this manuscript.

- **G. Hima Bindu:** Methodology, Investigation, Writing Original Draft, Supervision,
- **P. Yashwanth:** Formal Analysis, Writing Review & Editing,
- **P. Dinesh Kumar:** Conceptualization, Methodology, Investigation, Writing Original Draft, Supervision,
- **Hitesh:** Formal Analysis, Writing Review & Editing,
- **G. Vishnu Vardhan Reddy:** Data Curation, Experimentation, Formal Analysis, Writing Review & Editing,
- **Jatoth Heeraman:** Visualization, Resources, Funding Acquisition, Project Administration, Writing – Review & Editing.

Funding Declaration

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

Competing Interests Declaration

The authors declare no competing interests.

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