FATIGUE LIFE PREDICTION OF HIGHWAY BRIDGE STEEL GIRDER USING ABAQUS

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MAJOR PROJECT REPORT

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DECLARATION

We hereby declare that work presented in this report entitled “FATIGUE LIFE PREDICTION OF HIGHWAY BRIDGE STEEL GIRDER USING ABAQUS” in partial fulfilment of the requirement for the requirements for the award of degree in Bachelor of Technology in the Department of Civil Engineering from Jaypee University of Information Technology Waknaghat, Solan, H.P is an authentic record of our own work carried out under the supervision of Mr. Kaushal Kumar.

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CERTIFICATE

This is to certify that the work which is being presented in the project report titled "FATIGUE LIFE PREDICTION OF HIGHWAY BRIDGE STEEL GIRDER USING ABAQUS" in partial fulfillment of the requirements for the award of the degree of Bachelor of Technology in Civil Engineering submitted to the Department of Civil Engineering, Jaypee University of Information Technology, Waknaghat is an authentic record of work carried out by Kanav Sharma (201638) and Jitender Verma (201612) during a period from August 2023-June 2024 under the supervision of Mr. Kaushal Kumar, (Assistant Professor), Department of Civil Engineering, Jaypee University of Information Technology, Waknaghat.

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ABSTRACT

The fatigue life prediction of highway bridge steel girders is a critical aspect of ensuring the long-term structural integrity and safety of transportation infrastructure. This study employs the finite element analysis software, ABAQUS to develop a comprehensive predictive model for estimating the fatigue life of steel girders under cyclic loading conditions. The analysis considers various factors, including material properties, load spectra, and environmental conditions, to simulate real-world scenarios.

The research involves the creation of a detailed numerical model of the highway bridge steel girder using ABAQUS, incorporating geometric and material nonlinearities. The simulation accounts for cyclic loading patterns representative of actual traffic conditions, enabling a realistic assessment of fatigue-induced damage. The proposed model aims to capture the complex interaction between structural components, providing insights into potential fatigue failure modes and critical locations within the steel girder.

Validation of the predictive model involves comparison with experimental data and established fatigue life prediction methodologies. The study contributes to the ongoing efforts in advancing fatigue life prediction techniques, enhancing the accuracy and reliability of assessments for highway bridge steel girders. The findings offer valuable insights for structural engineers and practitioners involved in the maintenance, design, and optimization of transportation infrastructure, ultimately contributing to the safety and sustainability of highway bridges.

The methodology involves developing a comprehensive computational model of a typical highway bridge steel girder, considering material properties, geometry, and loading conditions. The ABAQUS software is utilized to simulate the cyclic loading that bridge girders experience throughout their service life, with a focus on understanding how different factors such as stress concentrations, weld details, and load magnitudes contribute to fatigue damage.

Parametric studies are conducted to explore the sensitivity of fatigue life to various design and loading parameters, providing insights into critical aspects that may influence the durability of the bridge girders. Additionally, the study investigates the applicability and accuracy of different fatigue life prediction methods within the ABAQUS framework

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LIST OF ACRONYMS AND ABBREVIATIONS

CAD	Computer Aided Design
CAE	Computer Aided Engineering
FEA	Finite Element Analysis
FEM	Finite Element Method
GUI	Graphic User Interface
N	Number of cycle
Np	Crack propagation life
Ni	Crack initiation life
Nf	Fatigue life (number of cycles to failure)
n	Material constant in Basquin's relation
Sa	Stress amplitude
Se	Endurance limit of a machine part
S`e	Endurance limit of the steel specimen
S ut	ultimate tensile strength

CHAPTER – 1

INTRODUCTION

1.1 BACKGROUND

Highway bridges form a critical component of transportation infrastructure, facilitating the efficient movement of people and goods. Among the various elements that constitute a bridge, steel girders play a pivotal role in providing structural support and ensuring the overall stability of the bridge. As transportation networks experience increasing demands, the longevity and reliability of these steel girders become paramount.

Steel girders in highway bridges are subjected to dynamic and cyclic loading conditions due to the constant flow of traffic. Over time, these repeated stress cycles can lead to fatigue damage, potentially compromising the structural integrity of the bridge. Fatigue failure in steel girders poses serious safety concerns and can result in costly repairs or, in extreme cases, catastrophic bridge failures.

Fig.1.1 Steel Grider(Source Wikipedia)

While traditional design approaches have been effective in addressing static loading conditions, the challenges posed by cyclic loading and the need for long service life require a more nuanced understanding of fatigue behavior. This necessitates the development and application of advanced predictive models that can estimate the remaining fatigue life of steel girders accurately. Despite significant progress in structural engineering, the fatigue life prediction of highway bridge steel girders remains a complex and evolving field. Existing models often face limitations in capturing the intricate interplay of factors such as material properties, geometric configurations, and environmental conditions.

1.1(a) Cyclic Loading –

It is a mechanical loading condition in which a material is subjected to repeated variations in stress over time. This loading pattern induces cyclic deformation within the material, causing it to undergo alternating periods of loading and unloading. Cyclic loading can manifest in various forms, including tension-compression, torsional, or bending loading, depending on the specific application and loading environment. The cyclic nature of the loading leads to the accumulation of fatigue damage within the material, ultimately leading to failure if the applied stresses exceed the material's fatigue strength over a sufficient number of cycles.

In cyclic loading, each loading cycle typically consists of several distinct phases, including loading, unloading, and reloading. During the loading phase, the applied stress increases from its minimum value to its maximum value, causing the material to deform elastically or plastically, depending on the applied stress level and material properties. In the unloading phase, the applied stress decreases, allowing the material to partially recover its original shape. However, due to cyclic plastic deformation, some residual strain may remain in the material. Finally, during the reloading phase, the applied stress increases again, initiating a new loading cycle.

Cyclic loading is pervasive in engineering applications, as many mechanical components and structures are subjected to repeated loading and unloading during their service life. Understanding the fatigue behavior of materials under cyclic loading is critical for predicting component lifespan, optimizing design parameters, and ensuring structural reliability in various engineering disciplines, including aerospace, automotive, civil, and mechanical engineering.

Advanced fatigue analysis techniques, such as fatigue life prediction models, stress-life (S-N) curves, and strain-life (ε-N) curves, are utilized to quantify the fatigue response of materials under cyclic loading condition.

1.1(b) Fully Reversed Loading –

It is a specific type of cyclic loading, occurs when the direction of the applied load alternates between tension and compression, with the magnitude of the stress remaining constant in each loading cycle. In fully reversed loading, the material experiences equal and opposite maximum and minimum stresses, resulting in symmetric stress cycles about the zero stress axis.

This loading condition commonly occurs in applications involving oscillatory motion or reciprocating components, where the material undergoes repeated cycles of tension and compression. Examples include components subjected to cyclic bending, torsion, or axial loading with equal magnitude in both directions.

Fully reversed loading induces complex stress states within the material, leading to fatigue damage accumulation and potential failure over time. The symmetric nature of the stress cycles facilitates the formation and propagation of fatigue cracks, particularly at critical stress concentrations or material defects. Therefore, materials subjected to fully reversed loading often exhibit reduced fatigue life compared to uniaxial or constant amplitude loading scenarios.

To analyse the fatigue behavior of materials under fully reversed loading, engineers employ advanced fatigue testing techniques and models, such as the stress-life (S-N) approach or the strain-life (ε-N) approach. These methods quantify the relationship between applied stress cycles and the resulting fatigue life of the material, enabling accurate prediction of component durability and reliability under fully reversed loading conditions. Additionally, design considerations, such as stress concentration mitigation, material selection, and surface treatment, are crucial for optimizing the fatigue performance of components subjected to fully reversed loading in engineering applications.

1.1(c) Pulsating Loading –

Pulsating loading is a type of cyclic loading where the applied stress oscillates between a maximum positive value and a baseline value, which is typically zero or a non-negative minimum stress level. Unlike fully reversed loading, where the stress alternates between equal positive and negative values, pulsating loading involves stress cycles that are always in one direction (e.g., tension) and return to a lower stress level rather than crossing into the opposite stress regime (e.g., compression).

In pulsating loading, each cycle involves an increase in stress from the minimum (often zero) to the maximum, followed by a return to the minimum. This type of loading is common in applications where a component experiences repeated loading and unloading without reversing the direction of the applied force, such as in rotating machinery, pressure vessels, and some types of mechanical and structural elements.

To analyse the fatigue behavior under pulsating loading, engineers use methods such as the stress-life (S-N) approach or the strain-life (ε-N) approach, modified to incorporate mean stress effects.

Experimental data is often plotted on S-N curves, where the number of cycles to failure (N) is related to the stress amplitude.

1.2 Loading and stresses

1.2(a) Traffic Load Modelling:

a. Dynamic Loading: Vehicular traffic induces dynamic loads on the bridge girder. The dynamic nature of these loads, caused by acceleration, deceleration, and variations in vehicle speeds, must be accurately modelled. Dynamic loading can result in fatigue damage accumulation over time.

b. Axle Loads and Wheel Configurations: Different vehicle types impose varying axle loads and configurations. Heavy trucks and concentrated loads from wheel axles contribute to localized stress concentrations. Load distribution models must consider realistic axle configurations and positions.

c. Traffic Patterns: Understanding traffic patterns is crucial for predicting the frequency and magnitude of loads. Peak traffic times, congestion, and traffic flow variations impact the loading conditions on the bridge girder.

d. Load Spectrum Analysis: Analysing the frequency spectrum of traffic loads helps identify dominant frequencies and loading patterns. This information is valuable for assessing fatigue damage, especially in resonance conditions

Fig.1.2HigwayBirdge (source Wikipedia)

1.2(b) Environmental Loads:

a. Wind Loads: Wind-induced vibrations can contribute significantly to fatigue damage. Wind loads vary based on the bridge's geometry and location. Wind tunnel testing or computational fluid dynamics (CFD) simulations help model realistic wind effects.

b. Temperature Variations: Temperature fluctuations lead to thermal expansion and contraction, inducing thermal stresses. Analyzing temperature effects is crucial, especially in regions with extreme temperature variations.

c. Seismic Loads: In seismically active areas, the bridge girder must withstand seismic forces. Earthquake-induced loading introduces complex dynamic effects that contribute to fatigue damage.

1.2(c) Structural Geometry:

a. Stress Concentrations: Geometric features such as notches, welds, and abrupt changes in cross-section can create stress concentrations. Analyzing stress concentration factors is critical for identifying regions prone to fatigue failure.

b. Girder Configurations: The overall geometry of the bridge girder, including its span length, cross-sectional shape, and support conditions, affects stress distributions. Finite Element Analysis (FEA) is commonly employed to model the complex interactions within the structure.

1.2(d) Residual Stresses:

a. Welding-Induced Stresses: Welding introduces residual stresses due to the heating and cooling of the material. These residual stresses can contribute to fatigue crack initiation and growth, particularly in welded regions.

b. Stress Relaxation: Over time, residual stresses may undergo stress relaxation. The understanding of stress relaxation is essential for long-term fatigue assessments.

1.3 Significance of fatigue life prediction in highway bridge girders:

It is crucial for ensuring the safety, durability, and cost-effectiveness of infrastructure. Fatigue failure is a common mode of deterioration in steel structures subjected to repeated loading cycles, and it poses unique challenges in the context of highway bridges. Here's a detailed explanation of the significance of fatigue life prediction in highway bridge girders:

1.3(a) Safety Assurance:

Structural Integrity: Fatigue-induced damage in steel bridge girders can lead to the initiation and propagation of cracks, compromising the structural integrity of the bridge. Fatigue life prediction allows engineers to assess potential failure points, enabling proactive measures to enhance safety.

Avoidance of Catastrophic Failures: Accurate predictions help prevent catastrophic failures by identifying critical regions prone to fatigue damage. This is particularly important for bridges subjected to heavy traffic loads and dynamic environmental conditions.

1.3(b) Economic Considerations:

Maintenance Planning: Predicting the fatigue life allows for informed maintenance planning. By understanding when fatigue-related issues might arise, maintenance activities can be scheduled more efficiently, minimizing disruption to traffic and reducing overall maintenance costs.

Life-Cycle Cost Analysis: Incorporating fatigue life predictions into life-cycle cost analyses helps optimize the allocation of resources. It enables decision-makers to balance the costs of maintenance, repair, and potential replacements over the bridge's operational lifespan.

1.3(c) Design Optimization:

Material Selection: Fatigue life predictions influence decisions related to material selection. Engineers can choose materials with superior fatigue resistance, optimizing the design for longevity and reducing the risk of premature failure.

Structural Configuration: Knowledge of potential fatigue-prone areas allows for design modifications to mitigate stress concentrations

Adjusting the structural configuration, such as enhancing weld details or altering geometry, contributes to a more fatigue-resistant design.

1.3(d) Compliance with Standards and Regulations

Code Adherence: Highway bridge designs must comply with industry standards and regulations. Fatigue life predictions help ensure that bridge girders meet or exceed specified fatigue performance criteria, enhancing regulatory compliance and public safety.

Risk Mitigation: Proactive fatigue life prediction assists in mitigating the risk of non-compliance with safety standards. It provides a basis for design adjustments or retrofitting measures to address potential issues and meet regulatory requirements.

1.3(e) Operational Continuity:

Minimizing Downtime: Fatigue-related failures can result in unplanned downtime for bridge maintenance or repairs. Predicting fatigue life allows for scheduled maintenance interventions, minimizing unexpected closures and disruptions to transportation systems.

Enhancing Serviceability: By extending the operational life of bridge girders through effective fatigue life prediction and management, the overall serviceability and reliability of the transportation infrastructure are improved.

1.3(f) Environmental Impact:

Sustainable Infrastructure: Optimizing the fatigue performance of bridge girders contributes to the sustainability of infrastructure. By reducing the frequency and severity of fatigue-related issues, the need for material replacement and associated environmental impact is minimized.

Resource Efficiency: Efficient resource use is promoted by minimizing the frequency of major repairs or replacements. This aligns with sustainability goals and reduces the environmental footprint associated with bridge maintenance and construction activities.

Fig.1.3 Steel Bridge (Source Wikipedia)

1.4 Importance of accurate predictions

The importance of accurate predictions for ensuring structural safety and longevity cannot be overstated, especially in the realm of civil engineering and infrastructure development. Here is a detailed exploration of why accurate predictions are critical for the safety and longevity of structures:

(a) Prevention of Catastrophic Failures:

Identification of Weak Points: Accurate predictions help identify potential weak points or areas susceptible to failure in a structure. This proactive understanding allows for targeted interventions and reinforcement measures to prevent catastrophic failures.

Public Safety: Catastrophic failures can have severe consequences on public safety. By accurately predicting potential failure modes, engineers can implement preventive measures.

(b) Optimized Design and Construction:

Material Selection: Accurate predictions guide the selection of appropriate materials with properties that match the structural requirements. This optimization contributes to the longevity of the structure by ensuring that materials can withstand anticipated loads and environmental conditions.

Efficient Structural Configuration: Predictive modeling enables engineers to optimize the structural configuration of a design.

(c) Timely Maintenance and Repair:

Scheduled Maintenance: Accurate predictions of structural degradation allow for the scheduling of maintenance activities at the most opportune times.

Cost-Effective Repairs: Early detection of potential problems enables cost-effective repairs. Small issues can be addressed before they become major concerns, saving resources and preventing the need for extensive and costly rehabilitation efforts.

(d) Mitigation of Environmental Impact:

Sustainable Practices: Accurate predictions contribute to sustainable engineering practices. By understanding how structures will perform over time, engineers can implement designs and materials that minimize the environmental impact associated with construction, maintenance, and eventual decommissioning.

Long-Term Resource Efficiency: Predictive models support long-term resource efficiency by guiding decisions on material usage, energy consumption, and waste generation.

1.5 Abaqus simulation modelling

A software suite for computer-aided engineering and finite element analysis is called Abaqus FEA (previously ABAQUS). This software program is used to visualize the results of the finite element analysis as well as to model and analyze mechanical assemblies and components (pre-processing). In the Abaqus/Viewer package, a subset of Abaqus/CAE that just includes the post-processing module can be launched separately. Python is an open-source scripting language that is used for customisation and scripting in the Abaqus products. The fox-toolkit is used by Abaqus/CAE for GUI development.

1.5(a) Overview

Engineering teams frequently use specialized simulation tools from multiple suppliers to replicate different design aspects while conducting product simulations these days. Using software solutions from different vendors results in inefficiencies and raises expenses. Regardless of subject expertise or experience level, SIMULIA offers a scalable portfolio of unified analysis products that enable smooth collaboration and information fidelity-preserving sharing of approved methods and simulation data across all users.

For a wide range of industrial applications, the Abaqus Unified FEA product set provides strong and comprehensive solutions for both simple and complex engineering issues. Using a standard model data structure and integrated solver technology, engineering work groups in the automobile sector can take into account complete vehicle loads, dynamic vibration, multibody systems, impact/crash, nonlinear static, thermal coupling, and acoustic-structural coupling. Abaqus Unified FEA is being used by best-in-class businesses to streamline their operations and tools, cut expenses and inefficiencies, and improve their competitiveness.

1.5(b) Parent Organization

A company that sells computer-aided engineering (CAE) tools is Dassault SystèmesSimulia Corp. Founded in 1978 by David Hibbitt, Bengt Karlsson, and Paul Sorensen, the firm was formerly known as Abaqus Inc. and Hibbitt, Karlsson & Sorensen, Inc. (HKS).

Its headquarters are located in Providence, Rhode Island. Dassault systems established similia, a name that includes all DS simulation solutions, including the Abaqus and Catia Analysis tools, in October 2005 after acquiring Abaqus, Inc. The company that owns Dassault Systems' Similia brand is called Dassault Systems Similia Corp.

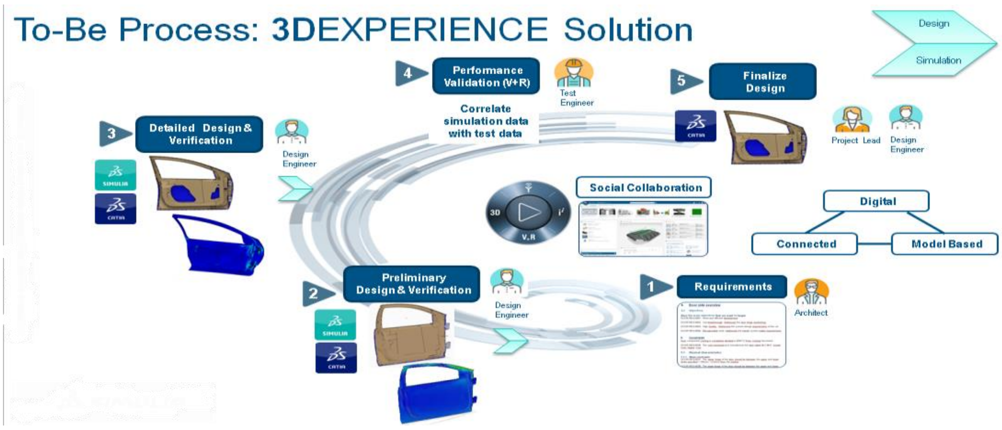

Fig 1.4 Abaqus use

1.5(c) History

Dr David Hibbitt, Bengt Karlsson, and Paul Sorensen established the Abaqus corporation in 1978 under the name Hibbitt, Karlsson & Sorensen, Inc. (HKS). The business was then renamed as ABAQUS Inc. prior to Dassault systems' 2005 acquisition. It then joined Dassault SystèmesSimulia Corp. after that. Up until 2014, the company's headquarters were situated in Providence, Rhode Island. The company's headquarters have been in Johnston, Rhode Island, in the United States, since 2014. Abaqus has been launched in new versions almost annually in recent years.

1.5(d) Abaqus Product Suite

The three main products in the Abaqus suite are Abaqus/Standard, Abaqus/Explicit, and Abaqus/CAE.

Furthermore, Abaqus/CFD is included in more current versions of Abaqus (6.10 and later) for computational fluid dynamic simulations. Every one of these packages includes extra, add-on modules that cater to specific needs that certain clients have.

With the most contact and nonlinear material options available, Abaqus/Standard offers Abaqus analysis technology to solve standard implicit finite element studies, such as static, dynamic, and thermal analyses. In addition, Abaqus/Standard offers optional interface and add-on solutions for design sensitivity analysis, offshore engineering, and software interaction with other programs, such as plastic injection modelling analysis.

With the use of an explicit time integration, Abaqus/Explicit offers analysis technology centered on transient dynamics and quasi-static studies, which is suitable in several applications including drop tests, crushing, and manufacturing processes.

For Abaqus analytical products, Abaqus/CAE offers a comprehensive modelling and visualization environment. For many Abaqus users, Abaqus/CAE is the preferred modelling environment because it offers direct access to CAD models, sophisticated meshing and visualization, and a unique view of Abaqus analysis results.

Abaqus/CFD offers sophisticated computational fluid dynamics capabilities, whereas Abaqus/CAE offers comprehensive pre- and post-processing support. A wide variety of nonlinear coupled fluid-thermal and fluid-structural problems are addressed by these scalable parallel CFD modelling capabilities.

1.5(e) Applications

The automobile, aerospace, and industrial products industries employ Abaqus. Because of the product's extensive material modelling capabilities and program customization options—users can build their own material models, for instance, to enable Abaqus to simulate novel materials—it is well-liked by non-academic and research engineering institutes.
Abaqus is attractive for production-level simulations when various fields need to be coupled since it also offers a good collection of Multiphysics features, including as coupled acoustic-structural, piezoelectric, and structural-pore capabilities.

Abaqus was initially designed to address non-linear physical behavior; as a result, the package has an extensive range of material models such as elastomeric (rubberlike) and hyperplastic (soft tissue) material capabilities.

1.5(f) Solution Sequence

Each comprehensive finite-element analysis has three distinct phases:

- Pre-processing or modelling: This step entails generating an input file containing a finite-element analyser (also known as a "solver") engineer's design.
- Processing, also known as finite element analysis, generates a graphic file as an output.
- Using the output file for post-processing or creating reports, images, animations, etc. The visual rendering stage is this one.

While Abaqus/CAE can monitor, post-process, and pre-process the solver's processing step, other compatible CAD programs or even a text editor can accomplish the first step instead. Processing can be completed using Abaqus/Standard, Abaqus/Explicit, or Abaqus/CFD.

1.5(g) Strengths of Abaqus

It lies in its robust solver technology, which employs finite element methods to discretize complex geometries into smaller, more manageable elements for analysis. The software's extensive library of material models and element types allows engineers to simulate a diverse range of materials and structural configurations accurately. Additionally, Abaqus provides powerful post-processing capabilities, enabling users to visualize simulation results and extract relevant engineering data for interpretation and decision-making.

1.5(h) Future Scope

Abaqus continues to evolve to meet the growing demands of engineering and scientific research. With advancements in computational power and simulation techniques, the software is expected to further enhance its capabilities in modeling and analyzing complex phenomena, such as Multiphysics interactions, advanced material behaviors, and large-scale structural systems. Moreover, Abaqus is likely to play a crucial role in the development of innovative engineering solutions in various fields, including aerospace, automotive, civil engineering, biomechanics, and materials science.

As industries increasingly rely on simulation-driven design and virtual prototyping to accelerate product development cycles and reduce costs, the demand for advanced simulation software like Abaqus is expected to rise. The software's versatility, accuracy, and efficiency make it well-positioned to address the evolving challenges and opportunities in engineering and scientific research. By leveraging Abaqus's capabilities, engineers and researchers can continue to push the boundaries of innovation, driving progress and advancements across diverse industries and disciplines

Perform Structural, Fluid & Optimisation Analysis

Powered by the 3DEXPERIENCE Platform, SIMULIA applications accelerate the process of evaluating the performance, reliability and safety of materials and products before committing to physical prototypes.

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Fig 1.5 Stimulation of Abaqus

1.6 Objective:

Utilize Abaqus finite element analysis (FEA) tools to model, simulate, and analyze the stress amplitude and mean stress of a steel girder subjected to cyclic loading using software Abaqus.

The primary focus is on estimating the remaining fatigue life of the girder IS2062E410 using Empirical approach –

1) Using Goodman’s equation for checking the failure criteria.
2) Using Basquin's Equation to Predict total Fatigue Life.
3) Calculation Damage induced in steel girder Using Miner’s Rule.
4) Calculate Remaining life of steel girder.

CHAPTER – 2

Literature Review

2.1 Previous Studies on Fatigue Life of Steel Materials and S-N Curve:

(a) Fatigue Failure Modes

Numerous tests have been conducted to identify the predominant fatigue failure mode. Barnes & Mays (1999) tested five RC girders and found that fatigue fracture in tensile reinforcements is the most common failure type. Heffernan & Erki (2001), in their study on twelve girders, discovered that the specimens failed due to brittle fracture of tensile rebars. They were able to extend fatigue life by using carbon fibre plate (CFRP), which reduced the stresses on the rebars.

Despite these findings relying on small-scale specimens, Charalambidi, Rousakis, and Karabinis (2016) examined the fatigue behavior of large-scale reinforced concrete girders. Their results indicated that tensile fracture of the steel rebars remained the main cause of failure, regardless of the girder size. This suggests that tensile fracture of steel rebars is the predominant fatigue failure mode in RC girders, irrespective of specimen size.

Fatigue failure modes constitute a vital domain within structural engineering, delineating the myriad ways in which materials succumb to cyclic loading over time. Unlike static failure, which occurs when a material surpasses its ultimate strength under a single, sustained load, fatigue failure unfolds gradually, propelled by the accumulation of cyclic stress cycles. One of the predominant fatigue failure modes entails fatigue crack initiation, wherein minute cracks develop at stress concentrations, such as notches or surface imperfections, due to cyclic loading.

These cracks typically originate at regions where the material encounters the highest stress levels and propagate slowly over time, eventually culminating in catastrophic failure if left unattended. Another prevalent fatigue failure mode encompasses fatigue crack propagation, whereby existing cracks elongate under cyclic loading, fueled by the alternating stress fields acting on the crack tip.

This process entails the repetitive opening and closing of the crack during each loading cycle, gradually expanding the crack length until failure ensues. Additionally, fatigue failure modes may encompass phenomena like fretting fatigue, where cyclic micro-motions at the interface between contacting surfaces induce surface damage and crack initiation, especially prevalent in bolted joints and bearings. Furthermore, corrosion fatigue poses a significant challenge, as the combined effects of cyclic loading and corrosive environments can expedite crack initiation and propagation, markedly reducing the fatigue life of materials.

A comprehensive understanding of the diverse fatigue failure modes is imperative for engineers to devise structures capable of withstanding cyclic loading conditions effectively. Moreover, implementing preventive measures to mitigate fatigue-related failures is crucial, ensuring the enduring integrity and reliability of engineering systems across various applications and industries.

(b) Approaches to Fatigue Life Estimation

Various researchers have developed methods to assess fatigue life. Arteaga, Bressolette, Chateauneuf, & Silva (2008) and Ma, Guo, Wang, & Zhang (2020) proposed probabilistic models for fatigue life assessment of bridge girders and beams using a fracture mechanics approach. V, R, & A (2015) utilized the S-N curve and a nonlinear finite element method to assess the fatigue of an RCC bridge.

Alampalli & Lund (2005) and Zhou (2005) used field strain measurements to calculate fatigue life, employing strain gauges placed at various locations to measure strain and associated stresses. While AASHTO outlines the fundamental strategy, several other approaches are also defined. Many researchers use this method to determine the number of cycles to failure by correlating the stresses on bridge components with the S-N curve.

In the domain of structural engineering, a plethora of methodologies are deployed to estimate the fatigue life of materials subjected to cyclic loading, each offering distinct advantages and challenges. Empirical approaches, grounded in fatigue test data and established correlations like S-N curves (stress-life curves), serve as a pragmatic means to predict fatigue life under specific loading conditions. By associating stress amplitudes with the number of cycles to failure, these empirical models furnish practical estimations of fatigue life, albeit with potential limitations when extrapolated beyond the tested conditions.

In contrast, analytical methodologies harness mathematical models and theoretical principles to prognosticate fatigue life. These methods often entail the computation of stress and strain distributions within the material, while considering factors such as load history, stress concentrations, and material characteristics. While analytical models provide valuable insights into the underlying mechanisms of fatigue damage, their utility may be constrained by simplifying assumptions, thus restricting their applicability in complex loading scenarios.

Computational strategies, such as finite element analysis (FEA) and multiaxial fatigue criteria, offer advanced capabilities for fatigue life estimation. FEA empowers engineers to simulate structural behavior under cyclic loading, furnishing detailed insights into stress distribution, crack propagation, and fatigue damage accumulation. By integrating material properties, geometric configurations, and loading conditions, FEA facilitates precise predictions of fatigue life for intricate structures. Concurrently, multiaxial fatigue criteria extend these capabilities by accounting for the impacts of multiaxial loading on fatigue failure, enabling engineers to evaluate fatigue life under real-world operational conditions.

Synthesizing elements of empirical, analytical, and computational methods, hybrid approaches present a holistic framework for fatigue life estimation. By amalgamating experimental data, theoretical models, and numerical simulations, hybrid methodologies allow engineers to consider complex loading conditions, material variability, and structural intricacies, resulting in more accurate and robust fatigue life estimates.

In summary, the gamut of approaches to fatigue life estimation encompasses a diverse array of methodologies, each endowed with its unique strengths and limitations. Empirical methods provide pragmatic estimations grounded in experimental data, while analytical techniques delve into the theoretical underpinnings of fatigue mechanics. Computational strategies enable detailed simulations of structural behavior under cyclic loading, whereas hybrid approaches offer a comprehensive synthesis of empirical, analytical, and computational methods, facilitating precise and reliable assessments of structural durability in engineering practice.

(c) Fatigue Life Prediction of Different Steel Materials with Variable Amplitude Loadings

The finite element approach (FEA) was used to discuss the fatigue life of various steel materials under variable amplitude loadings (VAL) using a stress-based method. This study involved an infinitely long shell structure (pipeline) and utilized the Goodman and Gerber theories to account for mean stress effects. The analysis demonstrated varying fatigue life predictions through the stress-life curve for three types of low and medium carbon steel materials (ASTM A533, AISI 1020, and AISI 4340) under the same VAL.

The impact of surface conditions (polished, machined, and hot rolled) was also examined. Results indicated that the effect of mean stress correction depends on whether the mean stress is compressive or tensile. Fatigue life predictions were more conservative for tensile mean stress. The Goodman method yielded the most conservative results for primarily tensile mean stress histories, while the Gerber model was conservative for primarily zero mean stress histories.

Material stiffness degrades with accumulated damage after each cycle, though the deformation pattern remains mostly consistent. The fatigue resistance of steel is mainly determined by its material strength; higher ultimate strength and hardness correlate with longer life. Surface quality and residual surface stress from machining operations are critical factors. Hot rolling can result in surface decarburization and residual tensile strains, both of which significantly impair fatigue strength. Polished finishes offer the best fatigue life, while hot rolled finishes provide the shortest.

The task of predicting the fatigue life of various steel materials subjected to variable amplitude loadings is intricate yet vital for structural engineering. Steel materials, known for their strength and durability, are prevalent in infrastructure applications. However, these materials face fluctuating stresses in real-world scenarios, significantly impacting their fatigue life. Understanding the response of different steel grades to variable loadings is critical for ensuring the durability and safety of structures such as bridges, buildings, and offshore platforms.

Variable amplitude loading involves stress levels that change over time, unlike constant amplitude loading where stress remains steady. This type of loading mirrors real service conditions more accurately, as structures encounter diverse stress magnitudes and frequencies from factors like traffic loads, wind, waves, and temperature fluctuations. The variability in loading introduces complex fatigue damage mechanisms, making accurate fatigue life prediction challenging.

Finite element analysis (FEA) tools like ABAQUS are extensively utilized to simulate the fatigue behavior of steel materials under variable amplitude loadings. ABAQUS facilitates detailed modeling of material properties, geometric configurations, and loading conditions, offering insights into stress distribution and potential failure points within the structure. By applying variable amplitude loading conditions in these simulations, engineers can observe how different stress cycles contribute to fatigue damage accumulation. This helps identify critical stress ranges and load sequences most detrimental to the material's fatigue life.

Empirical methods also play a crucial role in fatigue life prediction. These methods depend on fatigue test data and established relationships, such as S-N curves (stress-life curves), which illustrate the relationship between stress amplitude and the number of cycles to failure for a specific material. The Palmgren-Miner rule is a commonly used empirical approach for cumulative fatigue damage under variable amplitude loading. This rule assumes that total fatigue damage is the sum of damage incurred during each stress cycle, enabling a simplified estimation of the material's remaining life.

Combining FEA with empirical methods offers a robust framework for predicting the fatigue life of steel materials under variable amplitude loadings. While FEA provides detailed insights into the material's response to complex loading conditions, empirical methods offer a practical means of incorporating real-world test data into the analysis. This integrated approach enhances the accuracy and reliability of fatigue life predictions.

Different steel grades exhibit varying fatigue behaviors under variable amplitude loadings due to their unique microstructural characteristics and mechanical properties. High-strength steels, for instance, may offer superior fatigue resistance compared to mild steels but can also be more susceptible to specific types of fatigue damage, such as crack initiation at stress concentrators. Factors like surface roughness, residual stresses, and environmental conditions (e.g., corrosion) also significantly influence the fatigue performance of steel materials.

Advancements in fatigue life prediction techniques continue to improve our understanding of steel materials' behavior under variable amplitude loadings. Research focuses on developing more accurate damage models that can capture the effects of complex loading sequences, including load interaction effects and the influence of variable load amplitudes on crack growth rates. Additionally, probabilistic approaches are gaining traction, allowing for the consideration of uncertainties in material properties, loading conditions, and environmental factors in fatigue life predictions.

In summary, predicting the fatigue life of different steel materials under variable amplitude loadings is essential for ensuring the structural integrity and safety of engineering structures. The integration of finite element analysis with empirical methods provides a comprehensive approach to understanding and modeling the complex fatigue behavior of steel under realistic loading conditions. As computational tools and fatigue models evolve, engineers will be better equipped to design and maintain durable steel structures that can withstand the rigors of variable amplitude loadings throughout their service life.

(d) Fatigue Life Estimation of Medium-Carbon Steel with Different Surface Roughness

Medium-carbon steel is commonly used in rails, tire cables, wire ropes, cold heading, forging steels, cold finished steel bars, and machinable steel. Investigating its fatigue behavior and estimating fatigue life is crucial for the equipment industry. This study presents fatigue life estimation using S-N and P-S-N curves for medium-carbon steel with varying surface roughness.

Seventy-five fatigue tests were conducted in three groups with average surface roughness (Ra) of 0.4 µm, 0.8 µm, and 1.6 µm to examine the impact on fatigue life. The fatigue tests established S-N and P-S-N curves. It was shown that increasing average surface roughness from 0.4 µm to 0.8 µm or from 0.8 µm to 1.6 µm resulted in a 15% decrease in mean fatigue life at high stress amplitude (e.g., 500 MPa) and a 30% decrease at low stress amplitude (e.g., 380 MPa).

The Tanaka-Mura crack initiation life model, the Paris law crack propagation life model, and the S-N curve material constants were used to estimate the fatigue life. Six additional fatigue tests validated the model, demonstrating that it can accurately estimate the average fatigue life of medium-carbon steel with varying surface roughness levels, with a maximum estimation error of less than 16%.

Predicting the fatigue life of medium-carbon steel with varying surface roughness is a pivotal aspect of material engineering, crucial for ensuring structural integrity. Surface roughness profoundly influences fatigue performance as it can introduce stress concentrators that expedite crack initiation and propagation. Medium-carbon steel, prized for its strength and ductility, finds extensive use across construction, automotive, and machinery sectors, making understanding its fatigue behavior under different surface conditions imperative.

Surface roughness exerts its influence on medium-carbon steel fatigue life by altering stress distribution on the material's surface. Rough surfaces typically harbor micro-notches and irregularities, acting as stress concentrators under cyclic loading. These concentrated stresses can substantially diminish fatigue life compared to smoother surfaces, which distribute stress more uniformly, mitigating early crack initiation.

Experimental studies often employ fatigue testing apparatuses to evaluate medium-carbon steel specimens with varied surface finishes. These specimens undergo cyclic loading until failure, with the cycles to failure recorded for analysis. By comparing results across specimens with differing surface roughness levels, researchers can quantify the impact of surface roughness on fatigue performance. Generally, smoother surfaces attained through polishing or fine machining exhibit prolonged fatigue lives compared to rougher surfaces produced by coarse machining or grinding.

Finite element analysis (FEA) serves as a valuable tool in comprehending the fatigue behavior of medium-carbon steel with diverse surface roughness. FEA enables simulation of stress distribution and fatigue damage under cyclic loading, predicting high-stress concentration areas and potential crack initiation sites. This simulation approach supplements experimental data, providing a holistic understanding of how surface roughness influences fatigue life.

In addition to experimental and simulation methodologies, empirical models contribute to fatigue life estimation based on surface roughness. These models typically integrate parameters like surface roughness average (Ra) and other roughness metrics to predict fatigue life. Incorporating empirical models with experimental and simulation data enhances the accuracy of fatigue life predictions, facilitating more reliable assessments of medium-carbon steel components.

Moreover, surface treatment techniques like shot peening, carburizing, or nitriding are deployed to enhance the fatigue life of medium-carbon steel. These treatments modify surface roughness and induce compressive residual stresses, effectively retarding crack initiation and propagation. For instance, shot peening creates a compressive stress layer on the surface, countering tensile stresses during cyclic loading, thus augmenting fatigue life.

Furthermore, research delves into the effects of environmental factors, such as corrosion, on the fatigue life of medium-carbon steel with varied surface roughness. Corrosive environments exacerbate surface roughness effects by initiating pits and micro-cracks, further diminishing fatigue life. Studies indicate that combining surface treatments with corrosion-resistant coatings substantially improves the fatigue performance of medium-carbon steel in harsh environments.

In summary, estimating the fatigue life of medium-carbon steel with different surface roughness is a multifaceted endeavor integrating experimental testing, finite element analysis, and empirical modeling. Surface roughness profoundly influences fatigue behavior, with advanced surface treatment techniques and protective coatings offering effective strategies to mitigate its adverse effects and enhance medium-carbon steel component durability. Understanding these relationships is paramount for designing and maintaining robust steel structures across diverse industrial applications.

(e) Fatigue Strain-Life Behavior of Carbon and Low-Alloy Steels, Austenitic Stainless Steels, and Alloy 600 in LWR Environments

Fatigue S-N data for carbon and low-alloy ferritic steels, austenitic stainless steels, and Alloy 600 from the United States and Japan have been collected and classified by material type, loading, and environmental factors. These experimental S-N data are believed to represent the number of cycles needed to initiate a 3-mm-deep surface crack in smooth materials. Statistical models have been developed to evaluate the impact of these variables on fatigue life.

These models were used to estimate the likelihood of fatigue fracture initiation in smooth test specimens. By adjusting the best-fit experimental curve for mean stress effects and adding size, geometry, and surface finish margins, fatigue S-N curves for individual components were established.

The literature data were analysed to assess the effects of size, geometry, and surface polish on fatigue life. The analysis indicates that a factor of 4 can account for these effects. The ASME Code mean curve for carbon steels (CSs) was found to be conservative at stress levels below 60 ksi (414 MPa), predicting shorter fatigue lives than observed experimentally. However, the current ASME Code fatigue design curve does not sufficiently address the environment's impact on fatigue life in high-DO water for CSs and LASs.

For stress amplitudes above 30 ksi (207 MPa), the ASME Code curve suggests a high likelihood of fatigue cracking. The current ASME Code design curve for austenitic stainless steels is nonconservative at stress levels below 150 ksi (1034 MPa), predicting longer fatigue lives than observed experimentally. The ASME Code curve indicates a high probability of fatigue cracking in water at all stress levels and a 25-50% probability of cracking in 290°C air at stress amplitudes of 30-100 ksi (207-690 MPa).

Interim design curves show a reduced chance of cracking in CS components (1-5% likelihood) compared to LAS components (5-25% likelihood) under similar conditions. For Types 304 and 316 stainless steel in water, the interim design curve indicates a 5-20% chance of cracking, with a lower probability for Type 316 NG components. The interim design curves for Alloy 600 may be overly conservative at stress values above 50 ksi (345 MPa).

Statistical models were used to evaluate the significance of the interim fatigue design curves published in NUREG/CR-5999. The fatigue cracking probabilities of austenitic stainless steel, carbon and low-alloy ferritic steel, and Alloy 600 components were assessed under various service conditions. The likelihood of fatigue cracking in PWR and BWR components was estimated and illustrated.

Predicting the fatigue life of steel girders is vital for ensuring the durability and safety of bridge structures under cyclic loads. The integration of finite element analysis (FEA) software like ABAQUS with empirical calculations has proven to be an effective approach in this domain. ABAQUS is widely recognized for its ability to simulate complex behaviors in materials and structures, providing detailed insights into the fatigue life of steel girders.

ABAQUS excels in modeling the intricate responses of steel girders to repeated stress by incorporating precise material properties, geometric details, and specific loading conditions. For instance, the study by Mohammad and Salit (2014) on Austenitic Type 316L stainless steel demonstrates ABAQUS's proficiency in predicting fatigue crack initiation and growth, highlighting the software's detailed material modeling capabilities.

Empirical calculations complement these simulations by utilizing established fatigue theories and stress-life (S-N) curves to estimate fatigue life. These calculations typically involve parameters like stress range, mean stress, and fatigue limit, derived from experimental data and empirical formulas. Kwon, Frangopol, and Soliman (2012) discussed a probabilistic fatigue life estimation method that integrates empirical data with statistical analysis, thereby accounting for material property variability and diverse loading conditions.

Combining ABAQUS with empirical methods enhances prediction reliability. Calibration of finite element models using empirical data allows for validation and increased accuracy. Dattoma et al. (2006) introduced a nonlinear continuum damage mechanics model that integrates variable loading conditions into the fatigue life prediction, showcasing how empirical damage models can be used alongside detailed finite element analysis to capture the complexity of fatigue behavior in steel girders.

Additionally, integrating ABAQUS with empirical calculations facilitates the consideration of various factors affecting fatigue life, such as surface roughness, residual stresses, and environmental influences like corrosion. Bastidas-Arteaga et al. (2009) emphasized the importance of including environmental factors in their probabilistic lifetime assessment of reinforced concrete structures under combined corrosion-fatigue deterioration processes.

In conclusion, the literature supports the effectiveness of using ABAQUS alongside empirical calculations to predict the fatigue life of steel girders. This combined approach leverages the detailed simulation capabilities of finite element analysis and the practical insights from empirical data, resulting in more accurate and reliable fatigue life predictions. Such integration ultimately enhances the design and maintenance strategies for steel structures, ensuring their safety and longevity.

The application of ABAQUS in fatigue life prediction is particularly advantageous due to its ability to handle complex geometries and loading conditions that are difficult to address with empirical methods alone. ABAQUS can model the detailed stress distribution and identify critical regions where fatigue cracks are likely to initiate and propagate. This capability is essential for accurately predicting the lifespan of steel girders, which are subjected to varying loads and environmental conditions. The high fidelity of ABAQUS simulations allows engineers to perform what-if analyses, testing different scenarios and mitigation strategies to enhance the girder's performance and longevity.

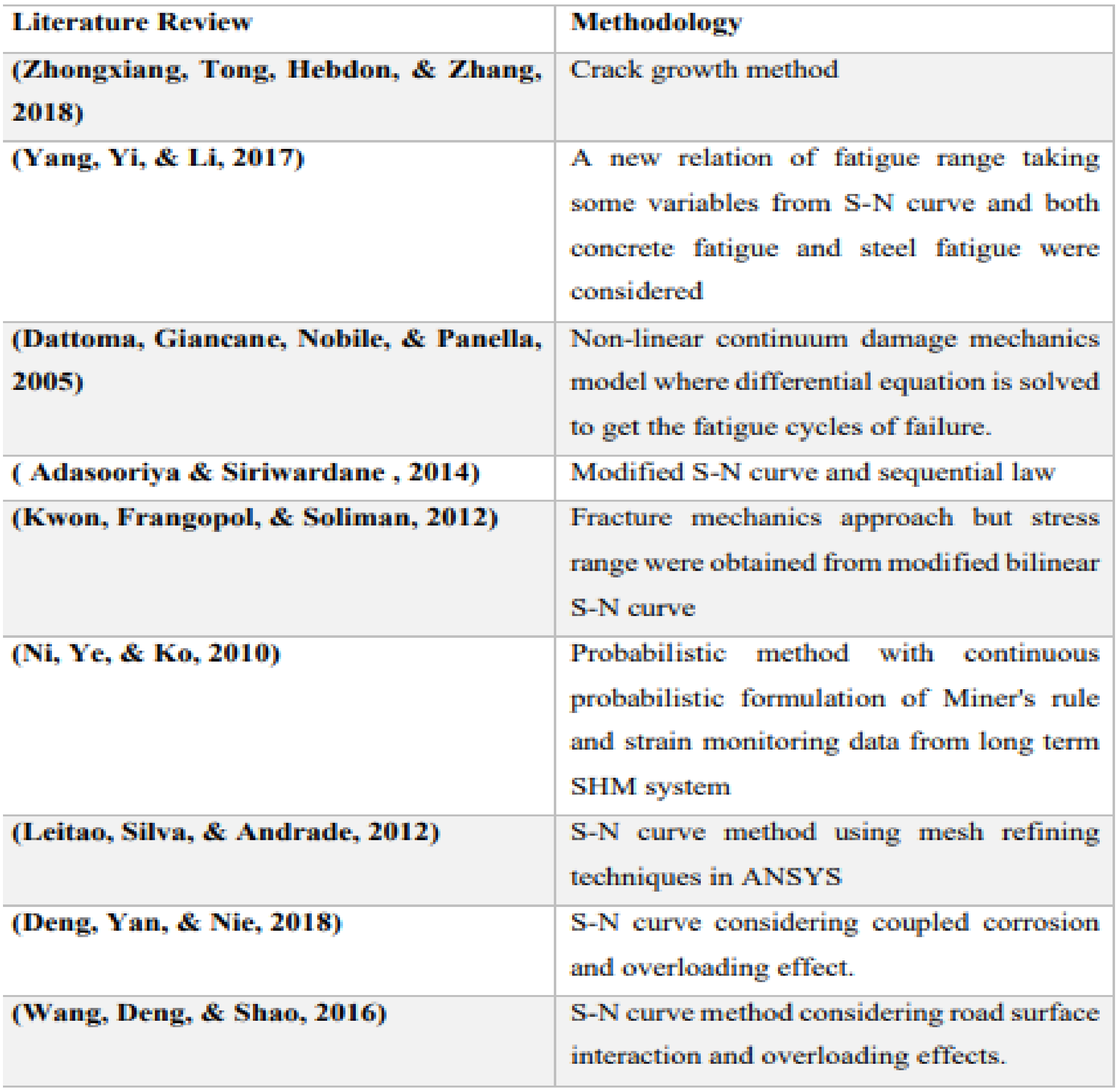
Moreover, the use of ABAQUS helps in understanding the effects of microstructural features on the fatigue behavior of steel. For example, the grain size, phase distribution, and inclusions within the steel can significantly influence its fatigue performance. ABAQUS can incorporate these microstructural details into the simulations, providing a more comprehensive assessment of the material's fatigue life. This level of detail is crucial for developing materials and manufacturing processes that enhance the fatigue resistance of steel girders.

Empirical calculations, while less detailed than finite element analysis, provide a practical approach to fatigue life prediction by utilizing historical data and well-established models. These methods are particularly useful for initial design phases and for structures where detailed finite element modelling may not be feasible. Empirical methods, such as the Palmgren-Miner rule for cumulative damage, offer a straightforward means of estimating fatigue life by summing the damage incurred under varying stress cycles. When combined with the detailed insights from ABAQUS, these empirical methods can validate and calibrate the simulation results, ensuring a more accurate prediction.

In addition to material properties and loading conditions, environmental factors such as corrosion play a significant role in the fatigue life of steel girders. Corrosion can create stress concentrators like pits and cracks, accelerating the fatigue process. ABAQUS can simulate the effects of corrosion on the structural integrity of steel girders, allowing for the assessment of different protective coatings and maintenance strategies. By incorporating empirical corrosion data into the simulations, engineers can predict the combined effects of mechanical loading and environmental degradation, leading to more robust and durable designs.

The synergy between ABAQUS simulations and empirical calculations also facilitates the development of advanced fatigue life prediction models. For example, multi-scale modeling approaches can integrate macroscopic structural analysis with microscopic material behavior, providing a holistic view of the fatigue process. This integration enables the prediction of fatigue life under complex loading scenarios that include variable amplitude loads, multi-axial stresses, and random loading sequences. By combining detailed finite element models with empirical data, engineers can develop predictive tools that are both accurate and practical, aiding in the design and maintenance of safer and more reliable steel structures.

Finally, the continuous advancement of computational resources and software capabilities is enhancing the potential of ABAQUS in fatigue life prediction. High-performance computing allows for more detailed and extensive simulations, reducing the time required for analysis and increasing the accuracy of predictions. As these tools evolve, the integration of ABAQUS with empirical methods will become even more powerful, providing engineers with the insights needed to design steel girders that meet the stringent demands of modern infrastructure. This integrated approach ensures that steel structures can withstand the rigors of their operating environments, ultimately extending their service life and reducing maintenance costs.



Literature Review	Methodology
(Zhongxiang, Tong, Hebdon, & Zhang, 2018)	Crack growth method
(Yang, Yi, & Li, 2017)	A new relation of fatigue range taking some variables from S-N curve and both concrete fatigue and steel fatigue were considered
(Dattoma, Giancane, Nobile, & Panella, 2005)	Non-linear continuum damage mechanics model where differential equation is solved to get the fatigue cycles of failure.
(Adasooriya & Siriwardane , 2014)	Modified S-N curve and sequential law
(Kwon, Frangopol, & Soliman, 2012)	Fracture mechanics approach but stress range were obtained from modified bilinear S-N curve
(Ni, Ye, & Ko, 2010)	Probabilistic method with continuous probabilistic formulation of Miner's rule and strain monitoring data from long term SHM system
(Leitao, Silva, & Andrade, 2012)	S-N curve method using mesh refining techniques in ANSYS
(Deng, Yan, & Nie, 2018)	S-N curve considering coupled corrosion and overloading effect.
(Wang, Deng, & Shao, 2016)	S-N curve method considering road surface interaction and overloading effects.

Table - 2.1 Literature Review

CHAPTER – 3

METHODOLOGY

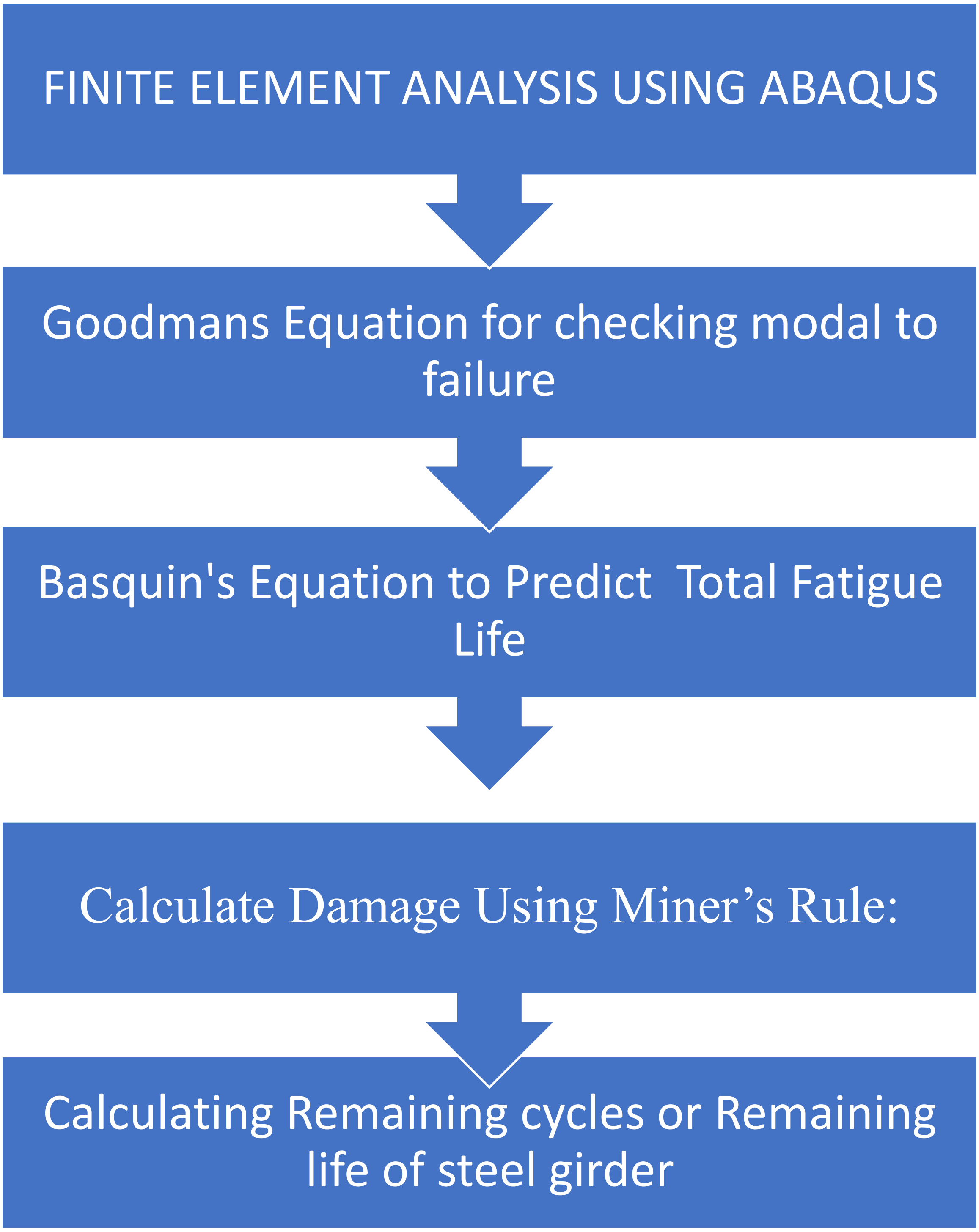


Fig 3.1. Methodology of the study

3.1 Selection of Steel Highway Girder

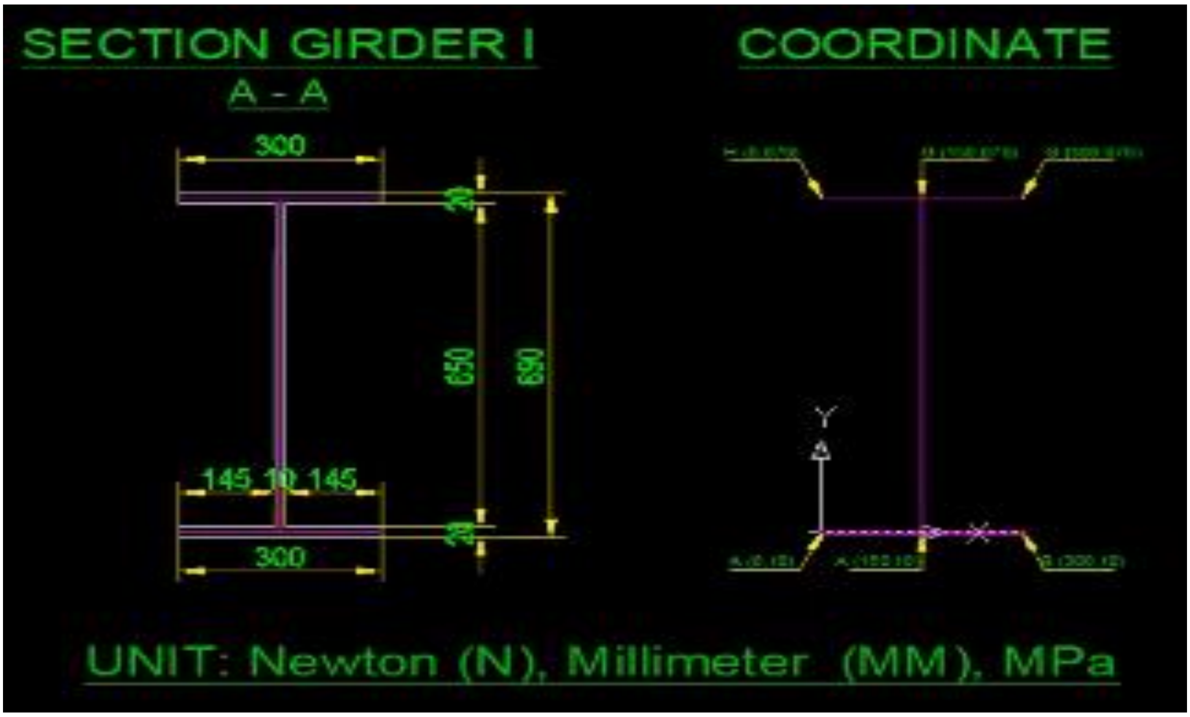


Fig.3.2 c/s of girder

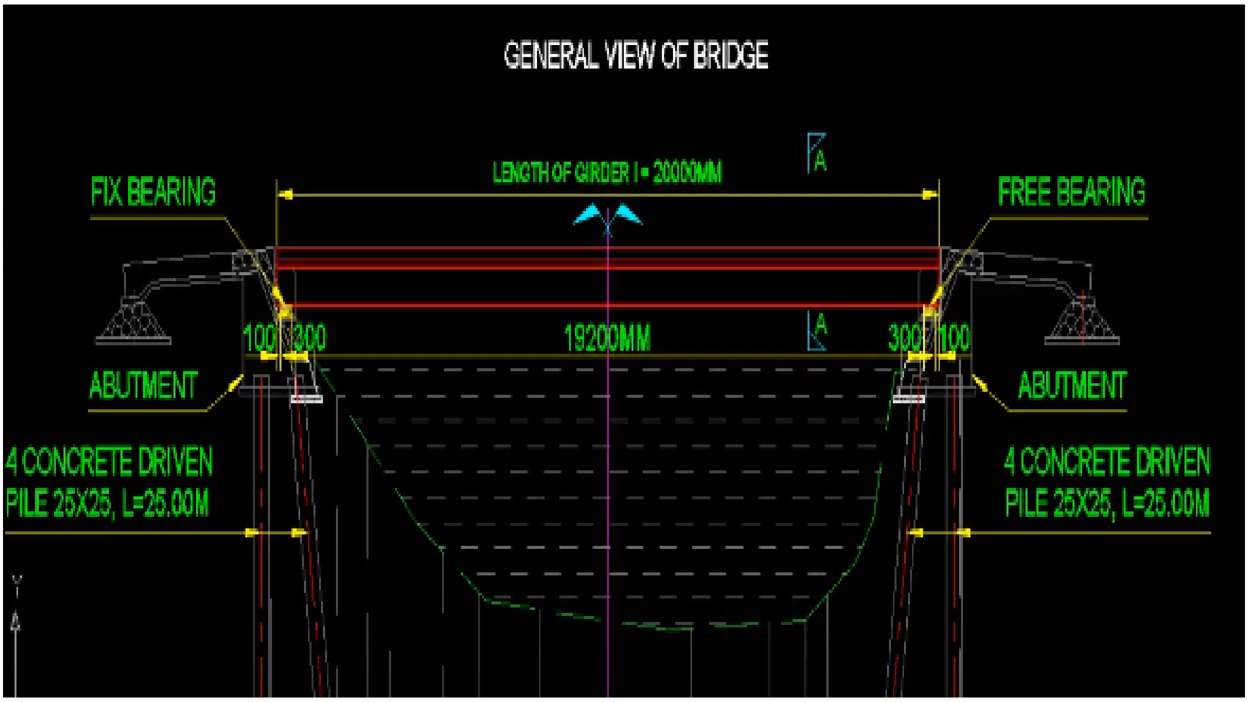


Fig.3.3 General view of bridge

3.2 Finite Element Modelling using Abaqus:

Abaqus Input Data -

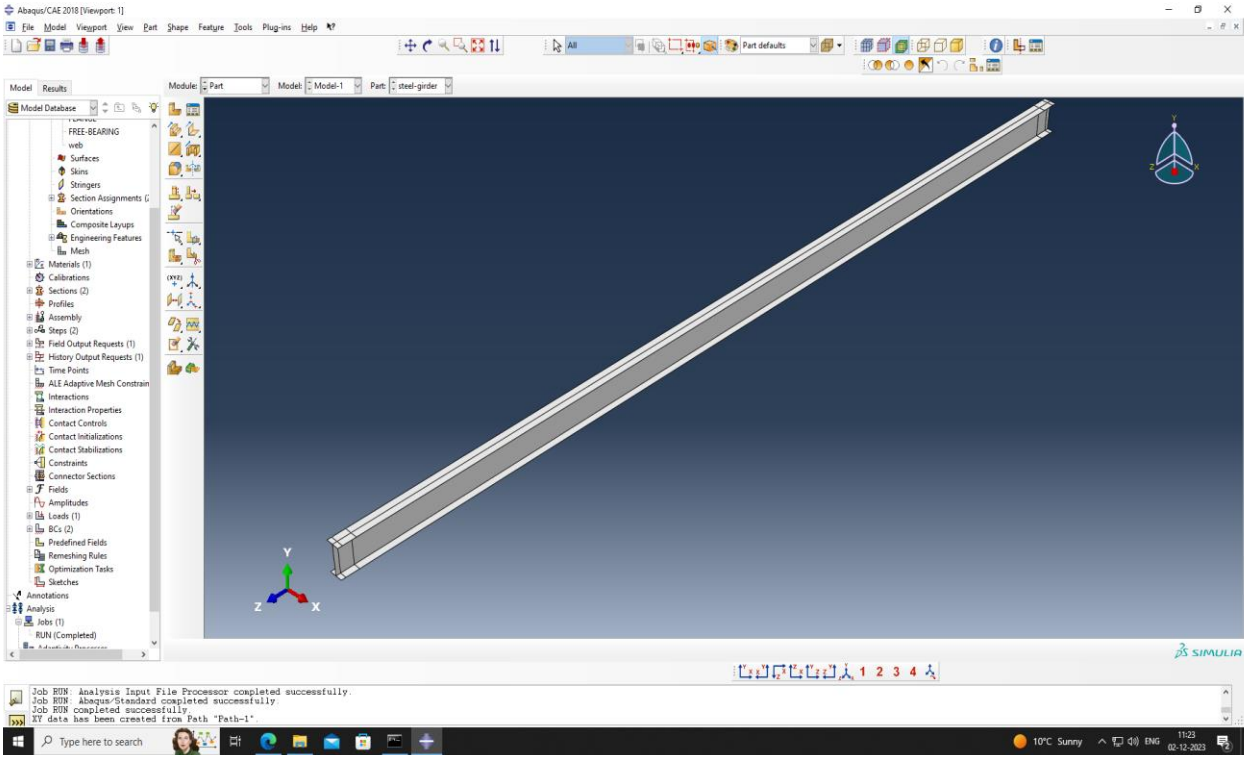
MODEL -	Steel I-Girder (Is 2062 E 410)
Dimensions -	Length – 20 m , width – 0.3 m , depth – 0.69 m
Material property assign -	Elasticity – Youngs modulus (210 Gpa), poisons ratio (0.3) Plasticity – 410 Megapascal Steel Density - 7.85 g/cm3
Meshing size	10 mm
Loadings	Cyclic load – 100 Megapascal Udl amplitude for 100 cycles
Boundary conditions	Fix bearing at one end and free bearing at other end

Table 3.1 Abaqus Input Data

Creating a model of a highway bridge steel girder in Abaqus involves several steps

(A) Create Part:

- Use the 'Part' module in Abaqus to define the geometry of the bridge girder.
- Specify the dimensions, cross-sections, and any additional features such as flanges or stiffeners.



Module: Part

Model: Model-1

Part: steel-girder

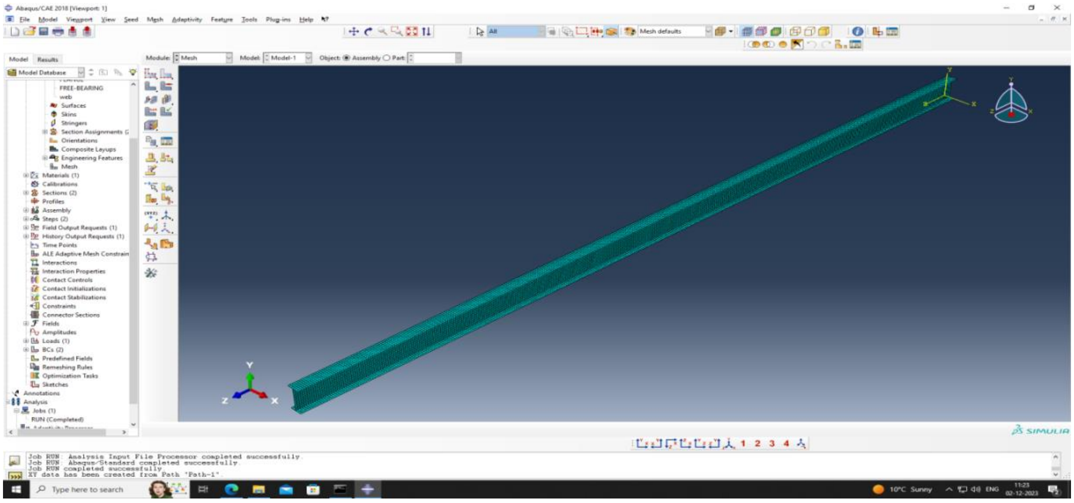
```
Job RUN: Analysis Input File Processor completed successfully.
Job RUN: Abaqus/Standard completed successfully.
Job RUN completed successfully.
XY data has been created from Path "Path-1".
```

Fig.3.4 Create Part

(B) Mesh Generation:

Generate a finite element mesh on the girder part using the 'Mesh' module.

Adjust the mesh density to ensure accurate representation of stress variations and gradients, especially in critical areas like welds and connections.



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Job RUN completed successfully.
XY data has been created from Path 'Path-1'.
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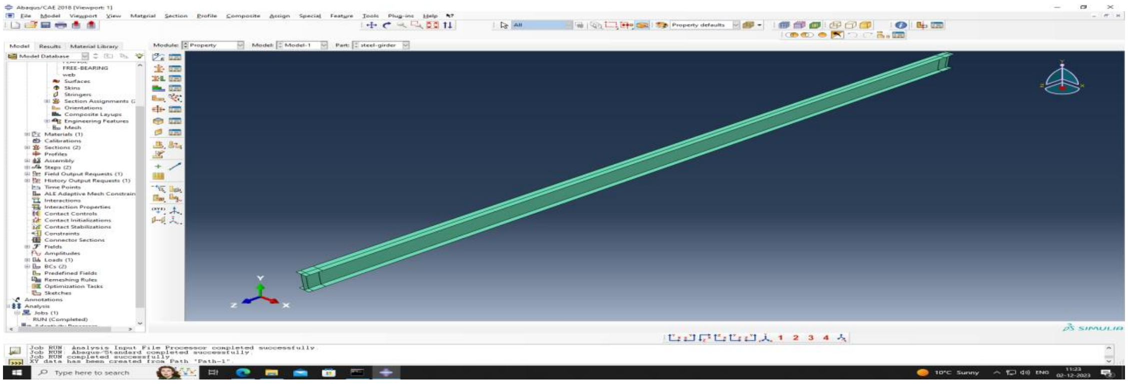
Fig.3.5 Meshing

(C) Material Properties Assignment:

Define the material properties for the steel used in the girder using the 'Material' module.

Specify elastic properties, yield strength, ultimate strength, and any other relevant material parameters.

Implement S-N curves if fatigue analysis is part of your study.



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Job RUN: Abaqus/Standard completed successfully.
Job RUN completed successfully.
XY data has been created from Path 'Path-1'.
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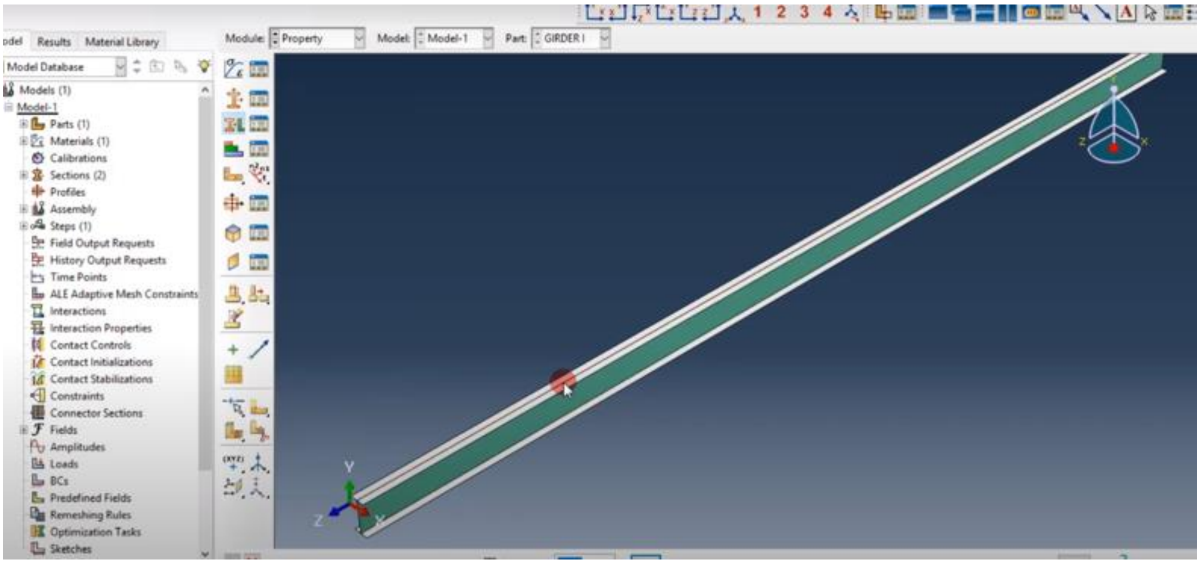
Fig,3.6 Material assignment

(D) Section Assignments:

Assign appropriate sections to different parts of the girder, considering variations in cross-sections along the length.

Define section properties such as area, moment of inertia, and shear area.



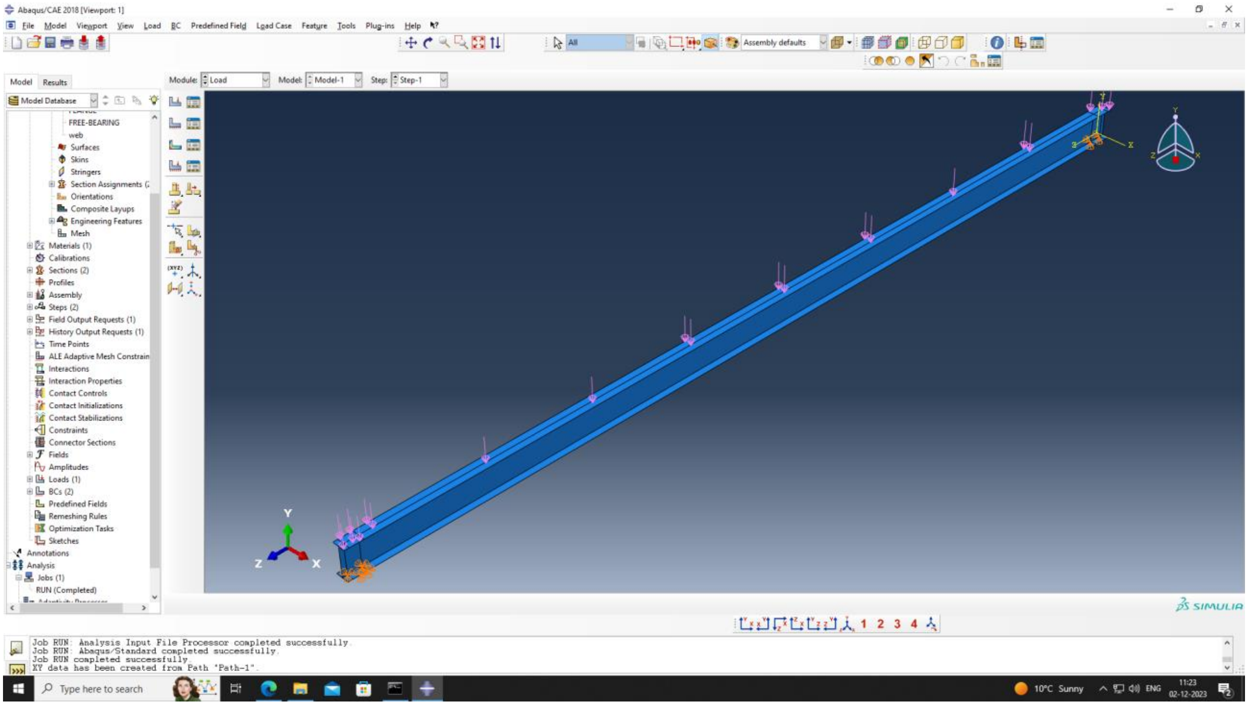
|Fig.3.7 Section Assignment

(E) Boundary Conditions:

- Apply boundary conditions to simulate the support conditions of the bridge. This include fixed supports from both ends.
- Ensure that the model is adequately constrained to represent the physical support conditions.

(F) Loading Conditions:

- Apply realistic loading conditions to the model. This could include traffic loads, environmental loads (wind, temperature), or any other relevant loads.
- Use the 'Load' module to define the magnitudes, directions, and distributions of the applied loads.



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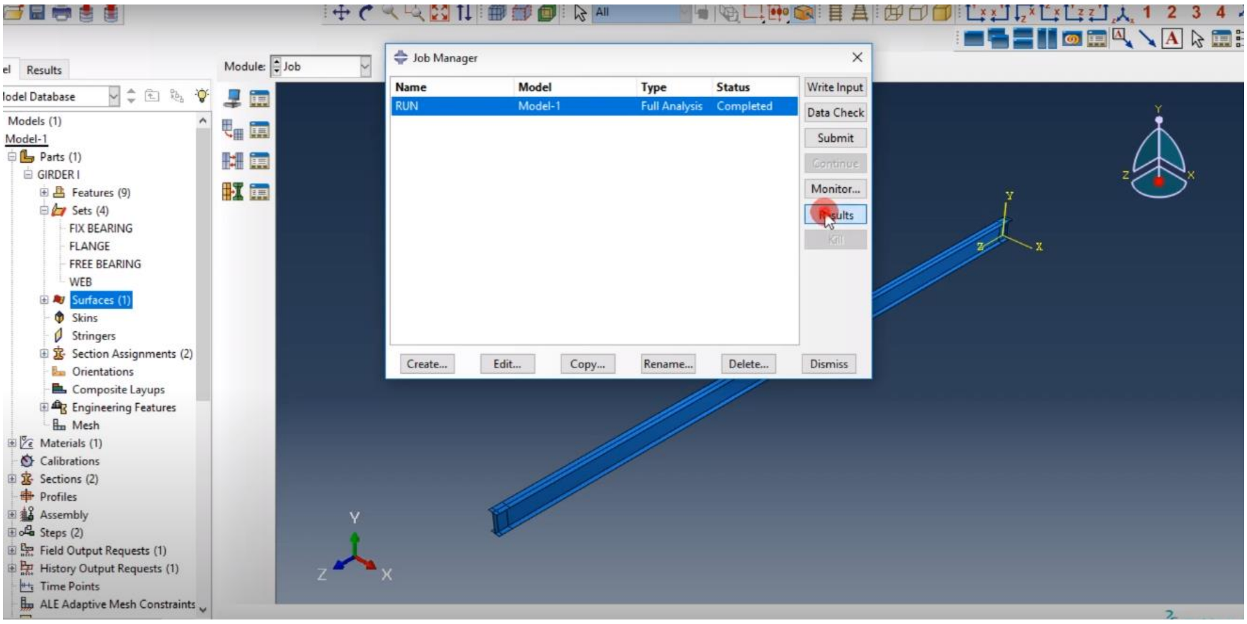
Job RUN: Analysis Input File Processor completed successfully.
Job RUN: Abaqus/Standard completed successfully.
Job RUN completed successfully.
XY data has been created from Path "Path-1".
```

Fig.3.8 Boundary and Loading condition

(G) Run the Analysis:

- Submit the analysis job and allow Abaqus to solve the equations.
- Monitor the convergence and check for any errors or warnings during the analysis.

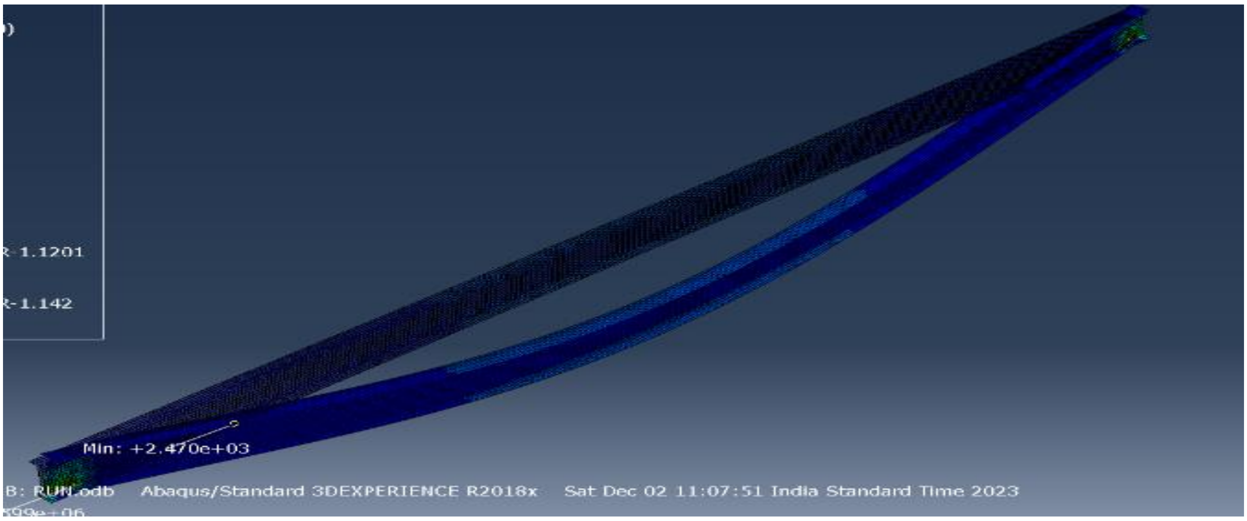


Job Manager

Name	Model	Type	Status
RUN	Model-1	Full Analysis	Completed

Fig.3.9 Analysis

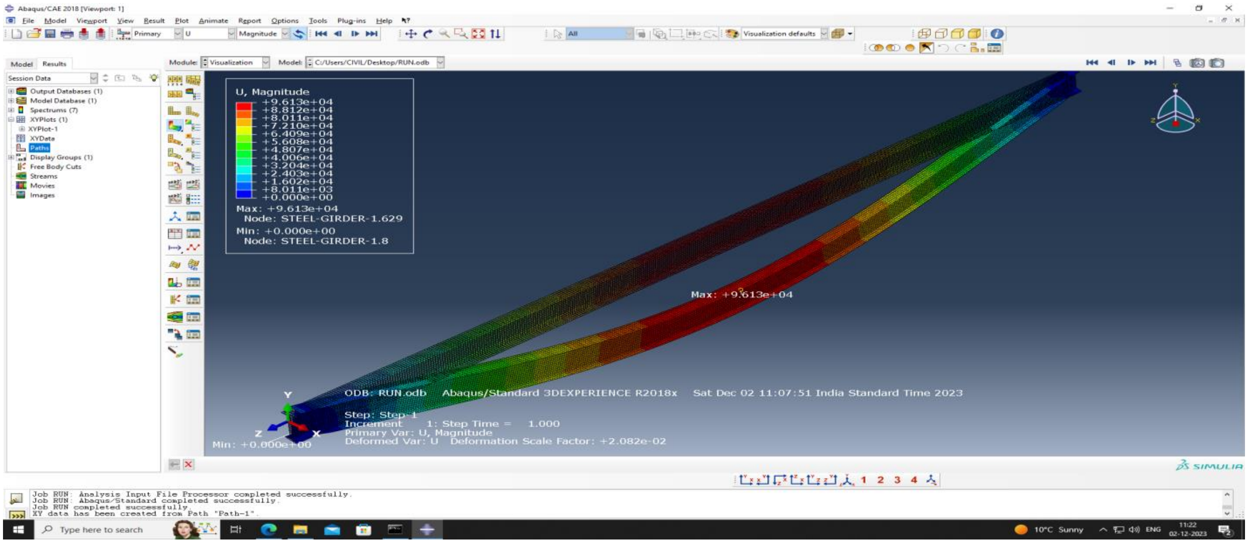
(H) View deformed model



Min: +2.470e+03

B: RUN.odb Abaqus/Standard 3DEXPERIENCE R2018x Sat Dec 02 11:07:51 India Standard Time 2023

Fig.3.10 View deformed model



Module: Visualization Model: C:/Users/CIVIL/Desktop/RUN.odb

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U, Magnitude
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+8.812e+04
+8.011e+04
+7.210e+04
+6.409e+04
+5.608e+04
+4.807e+04
+4.006e+04
+3.204e+04
+2.403e+04
+1.602e+04
+8.011e+03
+0.000e+00
Max: +9.613e+04
  Node: STEEL-GIRDER-1.629
Min: +0.000e+00
  Node: STEEL-GIRDER-1.8
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Max: +9.613e+04

Min: +0.000e+00

```
ODB: RUN.odb    Abaqus/Standard 3DEXPERIENCE R2018x    Sat Dec 02 11:07:51 India Standard Time 2023

Step: Step-1
Increment     1: Step Time =    1.000
Primary Var: U, Magnitude
Deformed Var: U   Deformation Scale Factor: +2.082e-02
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Job RUN: Analysis Input File Processor completed successfully.
Job RUN: Abaqus/Standard completed successfully.
Job RUN completed successfully.
XY data has been created from Path "Path-1".
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Fig.3.11 Deformed model

Obtained results and Calculations are shown in results and calculation

3.3 Goodman’s Equation for checking modal to failure -

Goodman's equation is a mathematical relationship used in fatigue analysis to account for the effects of mean stress on the fatigue life of materials subjected to cyclic loading. It extends the traditional S-N curve (which plots stress amplitude against the number of cycles to failure) to incorporate the influence of mean stress, thereby providing a more accurate prediction of fatigue life under varying stress conditions.

The Goodman diagram visually represents the relationship between mean stress and alternating stress. It plots alternating stress on the vertical axis and mean stress on the horizontal axis, with a line connecting the points where the mean stress is zero and the alternating stress equals the fatigue strength, and where the mean stress equals the ultimate tensile strength and the alternating stress is zero. Any combination of mean and alternating stresses below this line is considered safe, while combinations above the line indicate a high likelihood of fatigue failure.

In practical applications, Goodman's theory is invaluable for design, failure analysis, and maintenance planning. Engineers use Goodman's equation to design components that can safely withstand specified cyclic loads, ensuring that these components have adequate safety margins. By incorporating both mean and alternating stresses, Goodman's theory provides a more accurate prediction of fatigue life, which is crucial for preventing premature failures. When a component fails due to fatigue, Goodman's theory helps analyze the loading conditions to determine if the stress combinations exceeded the material's safe limits.

Steps to Apply Goodman's Equation:

1. Calculate the alternating stress (σa) and mean stress (σm) from the given loading conditions.

2. Identify the fatigue strength (σf) and ultimate tensile strength (σt) of the material from material data or experimental results.

3. Substitute the values of data into equation

4. Compare the calculated sum from equation If the sum is less than or equal to 1, the material is considered safe and not expected to fail due to fatigue under the given loading conditions. If the sum exceeds 1, the material is in the failure region, indicating a high likelihood of fatigue failure.

3.4 Basquin's Equation to Predict Total Fatigue Life –

Basquin's equation is derived from empirical observations and is primarily used to characterize high-cycle fatigue behavior. The high-cycle fatigue region is defined by stresses low enough that the material remains predominantly in the elastic deformation range, with minimal plastic deformation occurring. In this regime, the relationship between stress amplitude and fatigue life follows a power-law form, which is captured by Basquin's equation.

The fatigue strength coefficient and Fatigue strength exponentiate material-specific parameters that are determined through experimental fatigue tests. These tests involve subjecting samples of the material to cyclic loading at different stress amplitudes and recording the number of cycles to failure. By plotting these data points on a log-log scale (log of stress amplitude versus log of cycles to failure), a linear relationship is often observed, the slope of which is the fatigue strength exponent.

Basquin's equation provides a theoretical framework for predicting the fatigue life of materials under cyclic loading by relating the stress amplitude to the number of cycles to failure through a power-law relationship. This model is essential for high-cycle fatigue analysis, where it helps engineers design safer and more reliable components by understanding the material's fatigue behavior.

Basquin's equation is a pivotal tool in fatigue analysis, utilized to forecast the overall fatigue life of materials facing cyclic loading. This equation, devised by Gustave C. Basquin in the early 20th century, represents an empirical relationship between stress amplitude and the number of cycles to failure. It offers invaluable insights into a material's endurance under repetitive stress, finding widespread application across industries like aerospace, automotive, civil engineering, and manufacturing.

At its essence, Basquin's equation establishes a power-law correlation between stress amplitude and fatigue life. In simpler terms, it suggests that as stress amplitude increases, fatigue life diminishes exponentially. The equation's constants, typically determined through experimental testing, are pivotal parameters used for predicting fatigue life based on stress amplitude. These constants are derived from data obtained through fatigue testing, where specimens undergo cyclic loading under varied stress amplitudes. By analysing the relationship between stress amplitude and cycles to failure, engineers and researchers can ascertain the material constants essential for applying Basquin's equation.

One of the notable advantages of Basquin's equation lies in its broad applicability across diverse materials and loading conditions. Whether it's metals, alloys, polymers, or composites, this equation has proven effective in predicting fatigue life across a spectrum of material classes. Its simplicity and versatility have made it accessible to professionals with varying levels of expertise, contributing to its widespread adoption in both academic and industrial spheres.

Engineers and researchers rely on Basquin's equation to assess the durability of components and structures subjected to cyclic loading. It serves as a guiding principle in design decisions and maintenance strategies, offering insights into a material's fatigue behavior. Moreover, Basquin's equation forms the basis for more advanced fatigue life prediction models, incorporating additional factors such as mean stress, stress ratio, and environmental conditions to enhance accuracy.

In conclusion, Basquin's equation remains a cornerstone in fatigue analysis, providing a simple yet powerful means of predicting the total fatigue life of materials. Its empirical nature and broad applicability have solidified its status as a fundamental concept in fatigue engineering, guiding the design and maintenance of robust and reliable structures across various industries.

The steps to apply Basquin's equation involve

1. determining the stress amplitude,

2. obtaining material-specific fatigue parameters, and

3. using these parameters in Basquin's equation to predict the fatigue life of the material under cyclic loading.

3.5 Miner Rule for Damage Accumulation –

In fatigue analysis, the Miner's rule is a widely used method to predict the cumulative damage incurred by a material subjected to cyclic loading over its operational lifespan. This empirical rule is based on the concept that the total damage experienced by a material is the sum of the damage contributed by each load cycle, weighted by its relative importance.

Miner's rule is particularly applicable when a component experiences multiple loading conditions throughout its service life, each characterized by a different stress level and number of cycles. The rule is derived from the assumption that if the damage from each load cycle exceeds one, failure of the material is likely.

To apply Miner's rule, engineers first construct an S-N curve (stress versus number of cycles to failure) for the material of interest, typically obtained through experimental testing. This curve represents the fatigue behavior of the material under various stress amplitudes. Next, engineers identify the different stress levels experienced by the component during its operational life, along with the corresponding number of cycles at each stress level.

Each stress level is then compared to the S-N curve to determine the corresponding damage contribution, typically calculated as the ratio of the number of cycles at that stress level to the number of cycles to failure at that stress level obtained from the S-N curve. The damage contributions from all stress levels are summed to obtain the total damage experienced by the material.

The Miner Rule for Damage Accumulation represents a cornerstone in fatigue analysis, offering engineers a systematic methodology to forecast the cumulative damage experienced by materials under cyclic loading conditions. Originating from the pioneering works of August Wöhler in the late 19th century, and later refined by Stephan Miner in the mid-20th century, this rule provides a structured framework for assessing the fatigue life of structural components and systems. Fundamentally, the Miner Rule postulates that fatigue damage accrues gradually over time due to repeated loading cycles, with each cycle contributing incrementally to the total damage accumulation. This rule operates under the assumption that structural failure occurs once the cumulative damage surpasses a critical threshold, often quantified as a damage sum or ratio.

Application of the Miner Rule entails assigning damage factors to various loading conditions and stress levels. These factors, typically derived from fatigue test data or empirical relationships, denote the ratio of cycles endured under a specific stress level to the cycles required to induce failure at that stress level. By summing these damage factors across all loading conditions and stress levels, engineers can estimate the total damage accumulation experienced by the material. Consequently, when the cumulative damage surpasses a predefined threshold, fatigue failure is expected to occur.

The strength of the Miner Rule lies in its simplicity and adaptability, facilitating its application across diverse materials and loading scenarios. Engineers can readily adjust the rule to accommodate different stress amplitudes, loading frequencies, and material properties, making it a versatile tool in structural design and reliability assessments. Furthermore, the Miner Rule serves as a foundation for more advanced fatigue life prediction models, which incorporate additional factors such as mean stress correction and load sequence effects to enhance predictive accuracy.

Despite its widespread adoption, the Miner Rule is not without limitations. It assumes linear damage accumulation and does not consider interactions between various loading conditions or the influence of variable amplitude loading. Additionally, the rule relies on empirical data, which may not always capture the nuanced fatigue behavior exhibited by real-world materials. To address these limitations, engineers often supplement the Miner Rule with other fatigue analysis techniques, such as finite element analysis and probabilistic methods, to achieve more comprehensive and reliable fatigue life predictions.

In conclusion, the Miner Rule for Damage Accumulation remains a fundamental principle in fatigue analysis, providing engineers with a structured approach to estimate the cumulative damage experienced by materials under cyclic loading. While its simplicity and versatility make it a valuable tool in engineering practice, careful consideration of its assumptions and limitations is necessary to ensure accurate fatigue life predictions. As materials science and engineering continue to evolve, the Miner Rule will likely retain its significance, guiding the design and maintenance of resilient structures across diverse industries.

The steps to follow in using Miner's rule:

1. S-N Curve Construction: Develop an S-N curve for the material of interest through fatigue testing, representing its fatigue behavior under various stress levels

2. Identify Stress Levels: Determine the stress levels experienced by the component during its operational life, considering all loading conditions.

3. Calculate Damage contribution: For each stress level, compare it to the corresponding point on the S-N curve and calculate the damage contribution using Miner's rule

4. Sum Damage Contributions: Sum the damage contributions from all stress levels to obtain the total damage experienced by the material.

5. Compare the total damage to a predetermined failure criterion, often set at one. If the total damage exceeds one, failure of the material is predicted.

3.6 Estimate remaining cycles or remaining life -

The equation (N{Remaining} = {Damage remaining} times N) encapsulates Miner's rule, a fundamental principle in fatigue analysis widely used in engineering. Miner's rule offers a practical method for estimating the cumulative damage a material experiences under cyclic loading conditions throughout its operational lifespan. Essentially, the rule recognizes that a material's remaining fatigue life N/Remaining is directly related to the remaining damage and inversely proportional to the total number of cycles (N) applied.

By multiplying the remaining damage by the total number of cycles, the equation provides a straightforward way to estimate the material's remaining service life. This estimation is critical in engineering practice, guiding maintenance schedules, component replacements, and operational adjustments to ensure the continued reliability and safety of mechanical systems. Miner's rule enables a systematic approach to fatigue management, allowing engineers to monitor damage accumulation and make informed decisions to mitigate the risk of unexpected failures. Through its practical application, Miner's rule significantly enhances the durability and longevity of engineering structures and components subjected to cyclic loading conditions.

In essence, the equation suggests that the remaining fatigue life can be estimated by multiplying the remaining damage by the total number of cycles the material is expected to endure. This provides engineers with a practical tool to assess the current condition of a component and predict its remaining service life based on its fatigue behavior under known loading conditions. Engineers use this equation iteratively to monitor fatigue damage accumulation in materials or components over time. By periodically evaluating the remaining damage and updating the remaining fatigue life estimate, they can make informed decisions regarding maintenance schedules, component replacement, and operational adjustments to ensure the continued reliability and safety of mechanical systems.

3.7 S-N Curve

In fatigue life prediction analysis using Abaqus, the S-N curve (Stress-Number of cycles) plays a crucial role. The S-N curve represents the relationship between the applied stress (or stress range) and the number of cycles to failure for a material under cyclic loading conditions.

Concept: The S-N curve is a graphical representation of fatigue data obtained through laboratory testing. It illustrates the material's fatigue response by showing the stress level required to induce fatigue failure for different numbers of loading cycles.

Axis Definitions:

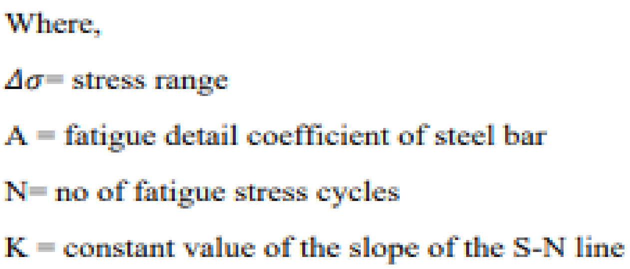
- The horizontal axis typically represents the logarithm of the number of cycles to failure (N) on a logarithmic scale (log(N)).
- The vertical axis represents the alternating stress, stress range, or stress amplitude (S).

Fatigue Life Prediction:

The S-N curve provides a basis for predicting the fatigue life of a material under cyclic loading. By assessing the stress amplitude corresponding to a given number of cycles, engineers can estimate when fatigue failure may occur.

The S-N curve of reinforcement bars has been derived from experimental study by Swiss Society of Engineers and Architects (SSEA) in which they proposed an empirical relationship between fatigue stress and number of stress cycles (SSEA, 1997). The relationship is given as

$$\Delta\sigma = \left(\frac{A}{N}\right)^{1/k}$$



Where,

$\Delta\sigma$= stress range

A = fatigue detail coefficient of steel bar

N= no of fatigue stress cycles

K = constant value of the slope of the S-N line

The stress-life (S-N) curve is an essential tool in engineering for understanding the fatigue behavior of materials under cyclic loading. This graphical representation depicts the relationship between the applied stress amplitude and the number of cycles to failure. The S-N curve serves several critical functions across various engineering disciplines.

Firstly, it assists in material selection and characterization by providing valuable insights into a material's fatigue properties at different stress levels. Engineers use S-N curves to identify materials suitable for applications where durability and fatigue resistance are crucial. Additionally, the S-N curve is vital for predicting the fatigue life of components and structures. By extrapolating data from the S-N curve, engineers can estimate the number of cycles a material can endure before failure under specific stress conditions. This predictive capability is invaluable for designing components with an appropriate safety margin to ensure reliability and longevity in real-world operating conditions.

Moreover, S-N curves aid in optimizing design parameters and developing fatigue-resistant materials through empirical testing and validation. Engineering decisions related to maintenance schedules, component replacements, or operational adjustments are often guided by fatigue life predictions derived from S-N curves. By incorporating fatigue analysis into design and maintenance processes, engineers can reduce the risk of unexpected failures, improve operational efficiency, and enhance the safety and durability of mechanical systems. In essence, the S-N curve is fundamental to engineering practice, providing a comprehensive understanding of material fatigue behavior and enabling informed decision-making to ensure the integrity and reliability of structures and components subjected to cyclic loading conditions.3.9 Finite Element Analysis Types

The Finite Element Analysis initially showed great promise in modeling various mechanical applications pertinent to aerospace and civil engineering. However, the full potential of the Finite Element Method is still being realized. Among the most exciting prospects is its application to coupled problems such as fluid-structure interaction, thermo-mechanical, thermo-chemical, thermo-chemo-mechanical issues, as well as piezoelectric, ferroelectric, electromagnetics, and other pertinent domains.

I. Static Analysis

Static Analysis allows for the examination of linear static and nonlinear quasi-static structures. In linear scenarios with applied static loads, a single step suffices to determine the structural response. This analysis can accommodate geometric, contact, and material nonlinearities. An example application is assessing the bearing pad of a bridge.

II. Dynamic Analysis

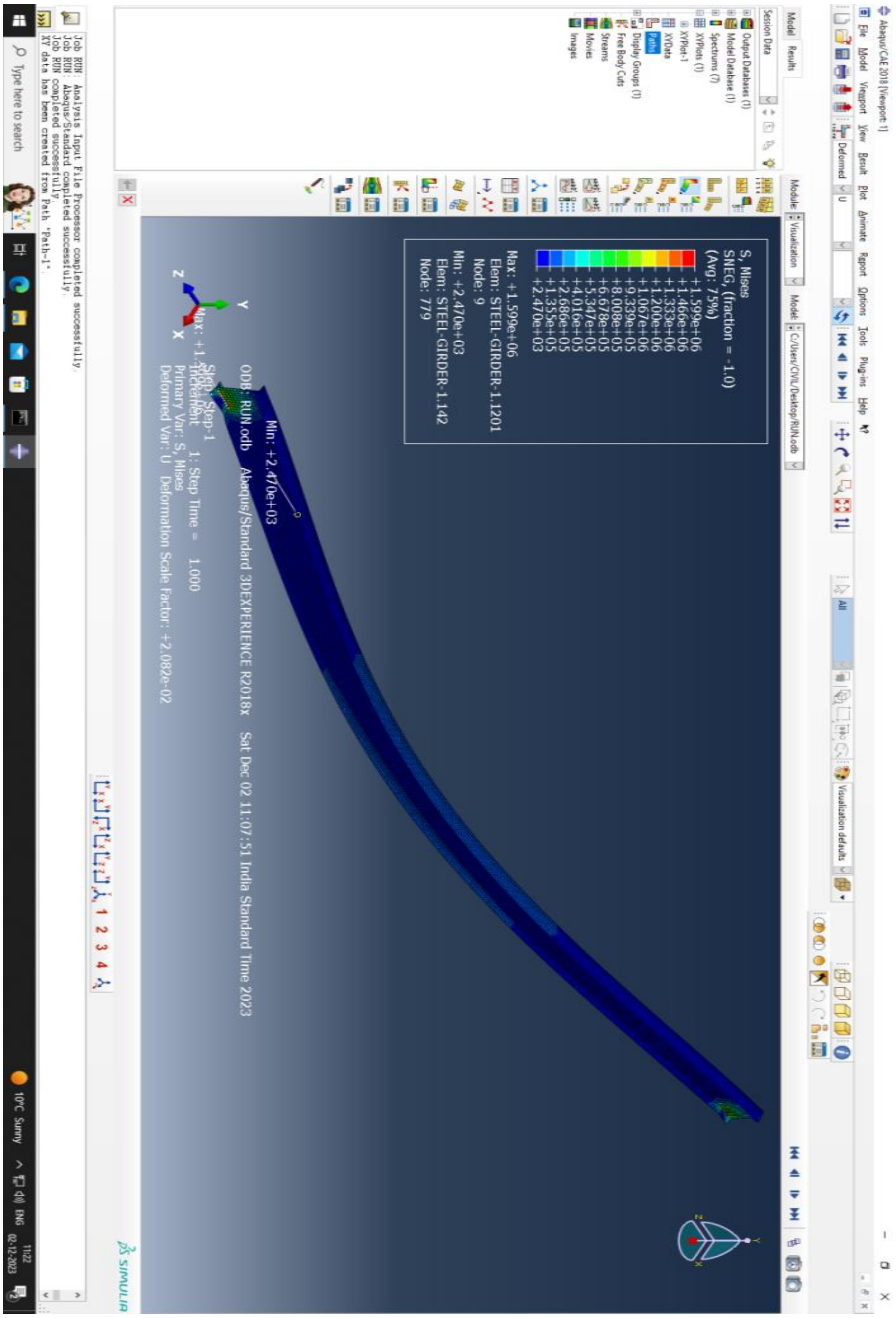
Dynamic Analysis involves examining how a structure responds dynamically to varying loads over a defined period. This method enables a realistic representation of structural issues by assessing both load impacts and displacements. For instance, one might analyze the effects of impact on a human skull, with or without protective headgear.

III. Modal Analysis

Modal Analysis focuses on determining the natural frequencies and modes of vibration within a structure. By employing modal analysis, engineers can simulate the highest response levels of a structure or system when subjected to specific loads, as demonstrated by simulating the engine startup process.

CHAPTER - 4

CALCULATIONS & RESULT



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+1.466e+06
+1.333e+06
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+1.067e+06
+9.339e+05
+8.008e+05
+6.678e+05
+5.347e+05
+4.016e+05
+2.686e+05
+1.355e+05
+2.470e+03

Max: +1.599e+06
Elem: STEEL-GIRDER-1.1201
Node: 9
Min: +2.470e+03
Elem: STEEL-GIRDER-1.142
Node: 779

ODB: RUN.odb Abaqus/Standard 3DEXPERIENCE R2018x Sat Dec 02 11:07:51 India Standard Time 2023

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Increment 1: Step Time = 1.000
Primary Var: S, Mises
Deformed Var: U Deformation Scale Factor: +2.082e-02

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Job RUN: Abaqus/Standard completed successfully.
Job RUN completed successfully.
XY data has been created from Path "Path-1".
```

Fig 4.1 Analysis of stress

4.1 ABAQUS RESULT -

TRUE DISTANCE (X) in meters	STRESS (Y)N/m^2
➢ 1	➢ 70.8
➢ 2	➢ 159.7
➢ 3	➢ 108.6
➢ 4	➢ 75.3
➢ 5	➢ 70
➢ 6	➢ 58.9
➢ 7	➢ 55
➢ 8	➢ 50.4
➢ 9	➢ 48.5
➢ 10	➢ 44.6
11	➢ 40
➢ 12	➢ 53.9
➢ 13	➢ 58.7
➢ 14	➢ 60.1
➢ 15	➢ 66.3
➢ 16	➢ 74.5
➢ 17	➢ 85.2
➢ 18	➢ 98.8
➢ 19	➢ 155
➢ 20	➢ 81.7

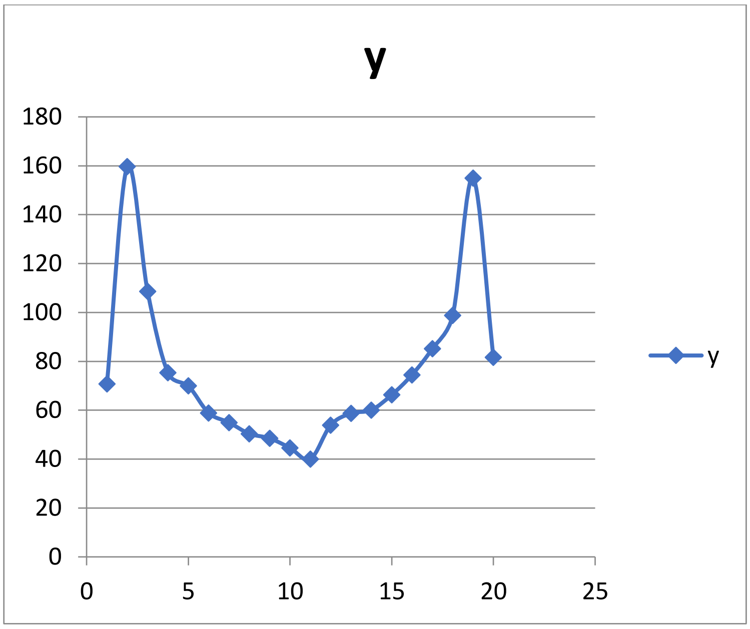

Fig 4.2 STRESS VS TRUE DISTANCE GRAPH

Table 4.1 Stress distribution

Maximum stress (σ max) = 159.7 MPa

Minimum stress (σ min) = 40 Megapascal

Calculate Mean and Amplitude Stresses:

$$\sigma_{mean} = \frac{\sigma_{max}+\sigma_{min}}{2}$$

Where:

- σ_{max} is the maximum stress in the cycle.
- σ_{min} is the minimum stress in the cycle.

$$\sigma_a = \frac{\sigma_{max}-\sigma_{min}}{2}$$

Where:

- σ_{max} is the maximum stress in the cycle.
- σ_{min} is the minimum stress in the cycle.

σ mean = (159.7+40)/2 = **100** Megapascal

σ amplitude = (159.7-40)/2 = **60** Megapascal

4.2 Empirical Calculations –

1. Apply **Goodman's Equation**:

$$\frac{\sigma_a}{\sigma_f} + \frac{\sigma_m}{\sigma_u} \leq 1$$

- σ_a: Alternating stress (stress amplitude)
- σ_f: Fatigue strength (related to the material's endurance limit)
- σ_m: Mean stress (average stress over a loading cycle)
- σ_u: Ultimate tensile strength (maximum stress the material can withstand without failure)

60/250 + 100/410 = **0.48 ≤ 1**,

the stress state is within safe limits according to Goodman's criterion and does not undergo failure.

2. Use of **Basquin's Equation** to Predict Fatigue Life:

$$\sigma_a = \sigma'_f(2N)^b$$

σ a is the stress amplitude = 60 Megapascal

σ f' is the fatigue strength coefficient = 1000 b is the fatigue strength exponent = -0.1

N is the number of cycles to failure, calculating using basaquin's equation we get,

N = 5×10^5

The predicted Total number of cycles to failure N is approximately **500,000 cycles.**

3. Calculate Damage Using **Miner's Rule:**

$$D_i = \frac{n_i}{N_i}$$

Where Di is total damage,

Ni is predicted no of cycles to failure = 500000 cycles

ni is no of cycles undergone at amplitude stress level = 100 Cycles

Di = 100/500000 = 0.0002

Or we can say model undergo total damage, D(total) = 0.0002 at 100 cycles

Remaining damage capacity:

D(remaining) = 1 – D(total) = 1- 0.0002 = 0.9998

Estimate remaining cycles or remaining life :

$$N_{remaining} = D_{remaining} \times N$$

N(remaining)=0.9998 ×5×10 ^5 = **499900 cycles**

The Fatigue life of steel I - girder at the current state is 499900 cycles.

4.3 FINAL RESULT

FINAL RESULTS	
ABAQUS (FEM)	Mean stress – 100 Megapascal , Amplitude stress – 60 Megapascal
Goodman's Equation	$0.48 \leq 1$, The stress state is within safe limits and does not undergo failure.
Basquin's Equation	The predicted number of cycles to failure N is approximately 500,000 cycles. N = 5×10^5
Damage Using Miner’s Rule	0.9998
Remaining cycles or Remaining life	499900 cycles

Table 4.2 Final result data

CHAPTER-5

Conclusion

The study on fatigue life prediction of highway bridge steel girders using ABAQUS has provided significant insights into the structural integrity and safety of transportation infrastructure. By developing a detailed finite element model that incorporates geometric and material nonlinearities, the research effectively simulates real-world cyclic loading conditions experienced by steel girders. This comprehensive approach has highlighted several key findings and contributions to the field of structural engineering:

5.1 Detailed Numerical Modeling:

The creation of a sophisticated numerical model of highway bridge steel girders in ABAQUS, accounting for material properties, geometric configurations, and environmental conditions, has enabled a realistic simulation of fatigue damage under cyclic loading patterns. This model captures the complex interactions between various structural components, offering a robust platform for fatigue life assessment.

52 Identification of Critical Factors:

The study has identified critical factors that influence fatigue damage, including stress concentrations, weld details, and load magnitudes. By analyzing these factors, the research provides valuable insights into the mechanisms of fatigue failure, highlighting potential failure modes and critical locations within the steel girders.

5.3 Parametric Studies and Sensitivity Analysis:

Through extensive parametric studies, the sensitivity of fatigue life to different design and loading parameters has been explored. This analysis aids in understanding how variations in these parameters can impact the durability of steel girders, guiding the optimization of design practices to enhance fatigue resistance.

5.4 Validation and Comparison:

The validation of the predictive model against experimental data and established fatigue life prediction methodologies has demonstrated the accuracy and reliability of the ABAQUS-based approach. This validation enhances the credibility of the model, making it a valuable tool for structural engineers in predicting the fatigue life of bridge girders.

5.5 Practical Implications:

The findings of this study have practical implications for the maintenance, design, and optimization of highway bridges. By providing a deeper understanding of fatigue behavior, the research supports the development of more resilient bridge designs and informed maintenance strategies, ultimately contributing to the safety and sustainability of transportation infrastructure.

5.6 Advancement of Predictive Techniques:

The study contributes to the advancement of fatigue life prediction techniques by integrating sophisticated computational methods with real-world loading scenarios. This approach represents a significant step forward in enhancing the accuracy and reliability of fatigue assessments for highway bridge steel girders.

In conclusion, the research underscores the importance of accurate fatigue life prediction in ensuring the long-term performance and safety of highway bridges. The developed ABAQUS model serves as a powerful tool for structural engineers, enabling them to predict and mitigate fatigue-related issues in steel girders effectively. By addressing the challenges associated with cyclic loading and fatigue damage, this study contributes to the ongoing efforts to improve the resilience and sustainability of transportation infrastructure.

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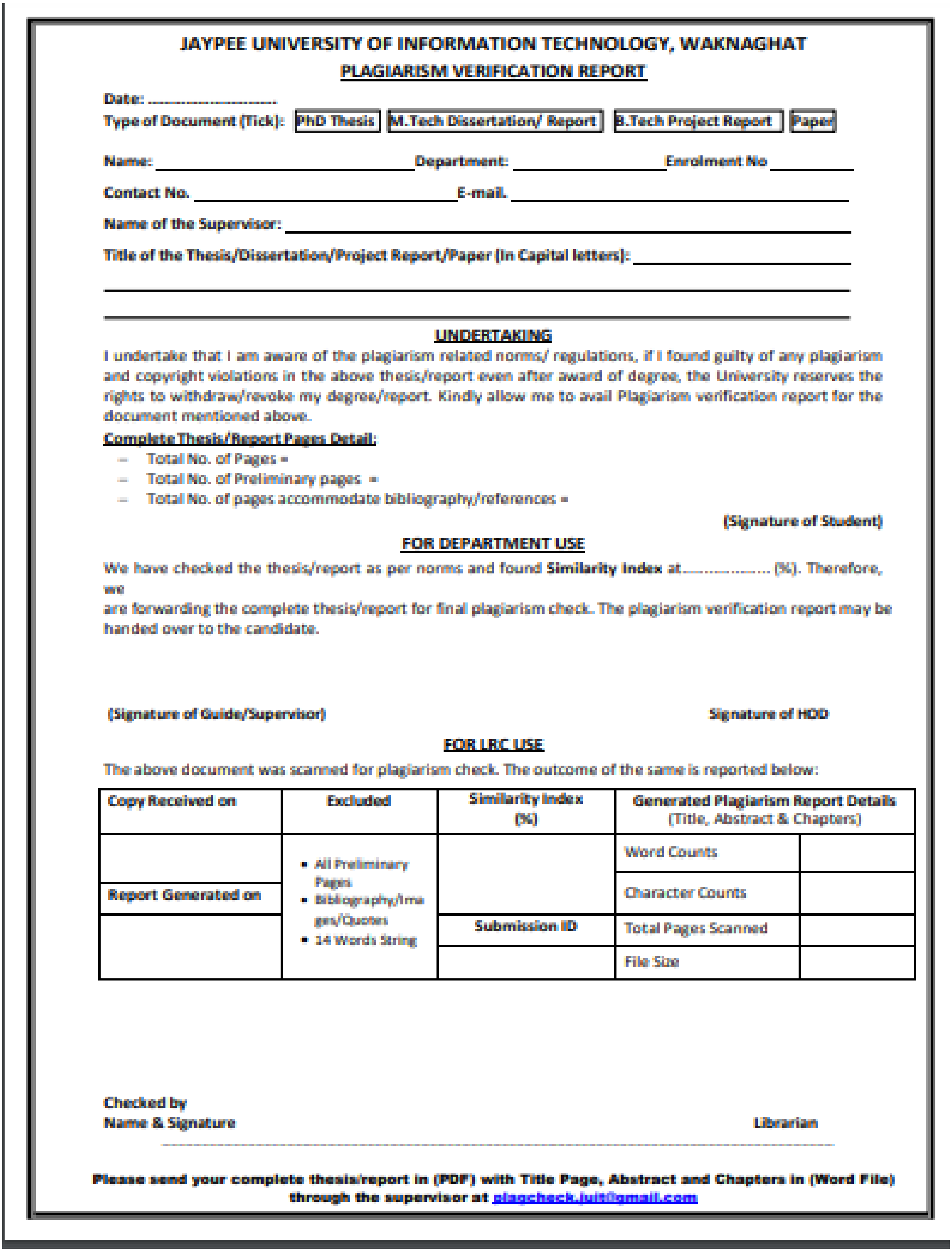

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