Analyzing the phenomenal of cracks and its effect on Freight Wagon Coupler Head through Numerical Methods for the case of Ethio Djibouti railway Share Company

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Abstract

The Ethiopian-Djibouti Railway Network is facing a serious problem of operational and economical nature due to failure of coupler heads. From the maintenance report, it was found out that coupler head cracks is one of the major cause more than 34 % of all coupler failures which cause big economical loss. An extensive statistical preliminary failure phenomenal of the field data presented coupler head pinhole as the main locus of failure. Chemical composition test using spectrometric was performed on the material and revealed almost similar with the standard except a slight carbon content deviate from the specified AAR- Grade E steel standard. The analysis of the 3D model at SOLIDWORKS using Finite Element Analysis (FEA) of ABAQUS showed that there is highest stress on the knuckle pinhole (70.8 MPa tensile, 281.2 compressive). Most importantly, it has been shown that the analysis of an already existing crack (7.5x19mm) behaves to intensify the distribution of stress along the crack. In response to this, the geometry modification analyzed at FEA proved a significant decrease of peak stress to (56.5 MPa) during tensile loading and, most importantly, a fundamental change of magnitude in fatigue lifetime over 1,000,000 cycles. This FEA confirms that the proposed design is effective in reducing the concentration of stress as well as improving the long-term performance of the coupler head.

Keywords: Finite Element Analysis (FEA), Stress Concentration, Geometric Optimization, Fatigue life.

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List of Abbreviations

AAR: American Association of Railroads

LEFM: Linear Elastic Fracture Mechanics

FEM: Finite Element Method

FEA: Finite Element Analysis

FE: Finite Element

EDR: Ethio-Djibouti Railway

CAD: Computer Aided Drawing

Chapter one

Introduction

1. Overview

Couplers are mechanical connections that link two individual units, such as Locomotive, coach or wagon, to form a train. Couplers are an indispensable part of the railway system as they are used to transfer load and link wagons together such that they do not separate during travel and can be transferred from one train to another, thus avoiding separation [1]. Couplers are designed to withstand significant dynamic forces, including longitudinal forces exerted during acceleration and deceleration, as well as vertical and lateral forces experienced when running through curves and wavy track surfaces. Accurate alignment of the coupler in the vertical and horizontal planes is important to prevent mechanical malfunction, ensure smooth operation, and reduce wear and tear of both the railcars and track structure. Over the history of railways, many different coupler designs and classifications have been developed around the world [2]. The design requirements of couplers include strength, reliability, easy and efficient handling, and operator safety. Automatic Couplers will engage automatically when the cars are pushed together. In addition to providing a mechanical coupling, modern automatic couplers also couple brake lines and data lines [3]. Knowing the nature and types of loads, and the stresses caused by them, helps in predicting the performance and lastingness of couplers

When a Couplers was exposed to varying loads it will be subjected to various stress types, including tensile, compressive and shear stresses. When a train is accelerated, tensile stress is a major concern, as the coupler must counteract the pulling forces caused by the inertia of the wagons attached to the train. The ability of a coupler to withstand tensile stress without failing is important to maintain the structural integrity of the entire assembly of wagon trains. On the other hand, when a train is braked, compressive stress is of major concern. Increased contact forces between the wagons may cause structural deformation or failure if the contact forces between the wagons are not considered in the design[4]. Shear stress is caused by lateral movements between the Couplers and is of concern when the wagons turn or are jolted suddenly. Forces cause torsional effects on the Coupler which cause wear and fatigue[5]. The combined effects of these stresses cause different stress types, which result in different stress distributions in the material of the

Coupler. Knowing the different types of stresses and how they interact with each other is important when designing Couplers that can withstand the forces experienced in operation.

The cumulative effect of these stresses can cause different failure mechanisms in Couplers. One of the most common failures in railway Couplers is fatigue. This failure occurs when Couplers are subjected to repeat loading and unloading. Over time, cracks start to initiate in the Coupler material[6]. The first locations where fatigue cracks initiate are the points where the local stress exceeds the fatigue resistance of the material. The cracks that initiate at a stress concentration point such as a notch or a surface inclusion will rapidly propagate when subjected to cyclic loading until complete structural collapse if not detected. The way of regular inspections together with the maintenance measures to prevent the structural collapse at the failure points.

Furthermore, other factors such as environment behavior like corrosion induced by the presence of moisture and other contaminants contribute to the degradation of the coupler material[7]. Couplers produced from materials that easily corrode result in pitting and wearing of the surfaces, which increase the likelihood of stress, induced cracks to form. Complete analysis of the coupler material and the operating condition should be accompanied with knowledge of the mechanical and environmental factors influencing them largely because of how they are produced and used, when railway wagon couplers are made from cast iron they tend to fail in various ways. Largely because of how they are produced and used, when railway wagon couplers are made from cast iron they tend to fail in various ways Coming hotfooting out of the mold, cast couplers tend to contain large crystals referred to as coarse dendrites, and spaces within the grain known as shrinkage porosity, which are basically unpreventable[4]. Then the faults identified are the main suspects of the fatigue failure of coupler knuckles as analysis of fracture of failed couplers reveals that corrosion pits on the surfaces courtesy of such events like precipitation can act as a potential source for crack initiation. Add to that the quality of surface of the couplers is another nightmare A few millimeters of roughness is the basic cause of crack initiation and propagation which induces the coupler to crack initiation and propagation which continues to destroy the component[4].

Coupler structures operate generally within elastic range of strains but some specific points experience relatively high stress concentrations may enter into elastoplastic state and affect the structure's function greatly a small variation of local strain may result in a huge impact on fatigue life a 10% variation in strain may mean years of difference [8]. That is why the exact value of strain and stress should be found out. Only by knowing this information, we could build safer and more durable couplers that would stand the test of time and pressure.

In engineering applications, cracks that originate from faults, repairs, corrosion, or other causes often occur and can drastically reduce the fatigue life of a structure or even cause a structure to fail catastrophically[9]. There must be some areas of localized tensile stress concentration when contact pressing happens. These concentrations of tensile stress vary the amplitude of the fatigue cycle, which partially initiates and facilitates the development of fatigue fractures[10]. The development of computational techniques for fracture has triggered the rapid development of numerical modeling as a powerful tool in engineering practice to serve for failure-proof design. Since crack problems have large discontinuity and singularity problems, special technique are needed for effective modeling like enriched element and crack tip element [5][11]..

Lifetime of any structure should be calculated with exact applied loading history including number of cycles for each level and the sequence in which the loading levels are applied. However, several approximations have to be made in forecasting the loading history[12]. The pressure applied on the coupler depends on number of wagons attached, weight of the load, speed of the train etc. Simply coupler force varies due to shocks and sudden acceleration and due to variation in train velocity. Couplers may be subjected to pressures, which are greater than, and less than the yield stress of the material. Therefore, when we are performing fatigue study, we must consider the low-cycle and high-cycle fatigue[12]. Therefore, it is important to understand the types of loads, stress distributions and failure modes to develop an effective design and maintenance strategy for railway couplers.

In our case, the strength behavior of fracture mechanics itself important in understanding how the materials respond to different types of stresses and strains. It is just a matter of looking at the stress, strain and distribution of the loads on the material and being able to predict and prevent failures. When we decompose the stress strain data, we are in a position to identify the safe operating point at which the material will be allowed to deform or fracture permanently. Tensile, compressive, shear stresses, and their strain are used to determine the ability of the material to withstand.

At this moment, Ethiopian-Djibouti Railway Network is experiencing a disturbing trend of coupler failures. This is largely due to the presence of cracking. Railway management has reported that a significant proportion of the couplers are cracked and therefore they are being replaced by new spare components on a weekly basis at the rolling stock maintenance center facilities. This situation is causing a major road block in the railway system because the structural integrity of the coupler connection is critical to safely and reliably convey freight on trains operating throughout the railway system. A critical need exists for the railway enterprise to conduct a failure mode and effects analysis to determine the root cause of the crack, determine the failure frequencies, and assess the operating life of the couplers in question. By applying advanced analytical methods such as finite element analysis, and fatigue life evaluations, the enterprise can develop effective strategies to reduce the risks associated with coupler cracking, improve maintenance practices, and ensure the long-term integrity of the railway system.

1.1. Background

Railway is an important mode of transportation in many countries. The safety of railway components is very important in order to have safe and non-stop train services. Coupler is used to connect wagons and locomotive to the railway system; so it is one of the most important elements of railway system. Couplers should have sufficient structure strength and proper safety margin to prevent train derailment and other hazards during its operation.

Many works has been done on the failure analysis of railway coupler. Many researchers[11] studied the failure of railway coupler by using various methods to find out the crucial region of failure of coupler. The study is on failure analysis of railroad couplers of AAR type E, which are commonly used in United States of America. They employed nondestructive testing method such as visual inspection and magnetic particle inspection to find out the crucial region of failure of coupler. Most of the failure occurred in the region of the coupler knuckle to coupler body transition, as there was high stress accumulation in that region.

The safety and reliability of railway coupler plays a vital role in the safety and reliability of the whole rail transportation system. Failure or fatigue damage of railway coupler will lead to train derailment, which causes huge economic losses, environmental damages, and human lives loss [13], [14]. By knowing the failure of railway coupler and its fatigue behavior will help the researcher and engineer to develop more robust and reliable design for the coupler, optimal maintenance for coupler, and improve the safety and efficiency of the rail transportation system[8], [12].

Table 1: A Summary Table of Studies

Literatures	**Loading**	**Major Failure**	**Finding**	**Method**	**Type of coupler**
[1], [4], [8], [15]	Complex loading and cyclic	Cracking and plastic deformation	Material defects, and design causing failures.	Experimental and structural analysis	AAR type E couplers
Ren et al.	Spectrum load	Crack	Forecast crack growth and fatigue life of heavy couplers.	FEA	AAR type E couplers
Li & Sun	Change with operational conditions	Crack growth	Service life	FEA	No. 17 coupler knuckles
Huang et al.	Longitudinal loading	Brittle fracture	Brittle failure in cast steel knuckles; material microstructure role.	FEA and Experimental techniques	AAR-M201 grade E cast steel Knuckle
Hua et al.	Contact loading	Fatigue failure	Contact stress distribution and deformation	FEA	Type17 coupler
Mohammadi et al.	Change with train speed, acceleration	Cracking	Main areas leading to cracking	FEA and Non-destructive testing	draw-hook couplers

Through an extensive investigation of failure modes and the analysis of the crack propagation behavior of the component fatigue, the root cause of failure of the component can be identified and hence the material type, fabrication procedures and structural design can be optimized to resist the fatigue and wear process by other modes of surface process. An implicit insight into the failure mechanisms and fatigability of railway couplers will help the researchers and engineers to come up with more robust and reliable designs, which will help, sustain the Ethiopian-Djibouti Railway.

1.2. Statement of the problem

The whole world commerce transportation depends on freight trains; however, the safety of the coupling is a big challenge. Coupler malfunctions can lead to severe incidents such as train separations and derailment; therefore, they pose a continuous threat to the railway traffic. A number of elements such as Operational condition, Material degradation, Excessive loads and Environmental influences causes coupler failures. There is an urgent need for improved material specifications, design and maintenance practices to increase the safety and efficiency of the railway traffic.

The Ethiopian-Djibouti Railway Network is currently facing a major problem due to the recurrent failures of the couplers of the rail wagons and this problem entails important costs in terms of operation and finances. The company has stated that many couplers break and must be replaced every week at the maintenance center of the rolling stock. In 2024G. C 246 Coupler failures was recorded and out of this, the coupler head which is the main and expensive component covers 85 in number which is 34.5%(85/246) of the overall failure This problem has become a real drama because the rolling stock maintenance company has exhausted its stocks of spare parts of coupler components. The impact was not just failure of the component (coupler head) rather it was causing many wagons to be detained out of operation and this affect the company's operation economic value

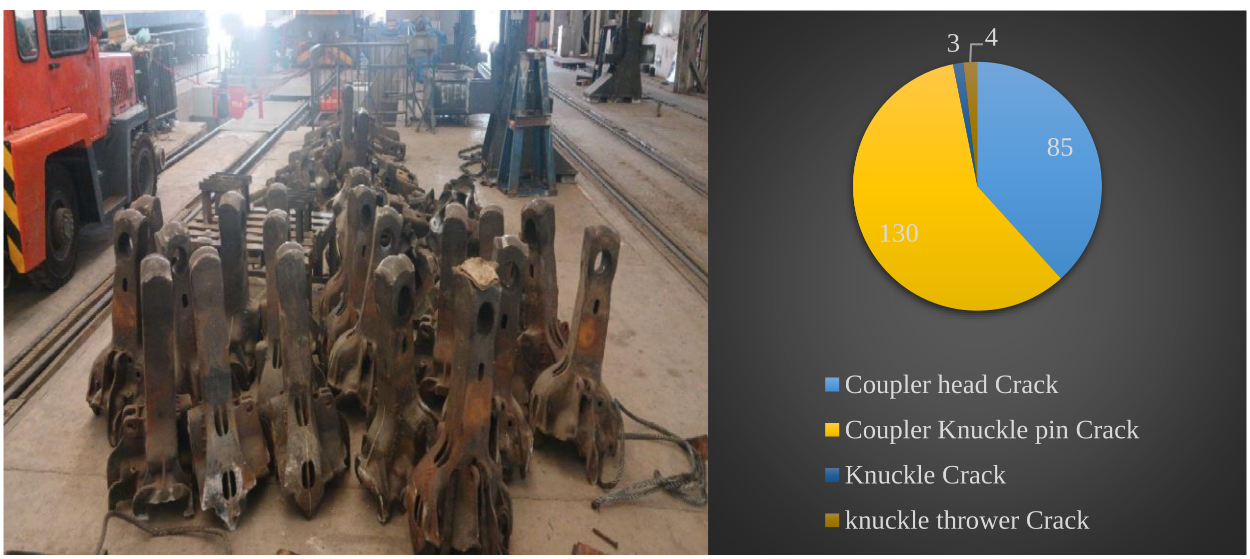

Figure 1: Failed coupler head in rolling stock depot and Cause statistics in 2024 G.C

A bad solution passed by the company to bypass the problem in the meantime is to use spare parts of wagons that have other functional and operational problems. This solution is not acceptable because it depletes the number of available wagons in operation and increases the probability of other failures. Replacing the couplers broken by frequency is also not an acceptable solution because it represents a heavy expense for the purchase of new spare parts and replacements. This situation shows the importance of analyzing phenomenal of crack and its effect by adopting a strategic study approach to coupler failure, design and analysis to ensure the reliability and efficiency of the railway system.

1.3. Research Questions

The following a set of research questions that are addressed under this thesis:

- What are the main causes and core reasons of coupler head failure in the company?
- How do critical operational loads transfer to stress, deformation and fatigue life in coupler head? and where are the precise locations of maximum stress concentration
- What are the basic mechanical effects of pre-formed crack on causing local damage to coupler head and lead to catastrophic failure?
- How much does the geometric modifications to the coupler head component reduce the stress, deformation and fatigue life?

1.4. Objective

1.4.1. General Objective

The general objective of this work is to study the phenomenon of cracks and its impact on Freight Wagon Coupler Head through Numerical Methods for the case of Ethio Djibouti railway Share Company

1.4.2. Specific Objective

To achieve this objective, the study will

1. To Carried out a statistical preliminary failure phenomenal on failed couplers
2. To calculate the stress, deformation and fatigue life experienced on the coupler head when subjected to critical loads.
3. To propose geometric modifications on the coupler head and evaluate the stress, deformation and fatigue life.

With the answers to these research questions and the achievement of the set objective, the railway company will get the needed key to improve the Ethiopian-Djibouti Railway Network in terms of Reliability, Resilience and Cost effectiveness.

1.5. Methodology

The methodological approach used in this work is a multi-stage iterative process, designed to obtain a reliable and verified result as shown in figure 4. The first stage is dedicated to a thorough review of the literature, which will guide the collection of empirical data and the data collection for the geometric data. This data is then used to develop an accurate 3D model in SOLIDWORKS as well. The main tool of analysis used in this work is Finite Element Analysis (FEA); the configuration of the model needs to be validated assessment compared to some standards before any other analysis. After successful validation, the strategic loading and boundary conditions are applied in order to simulate the physiological stresses. The data is then extracted and analyzed. One of the key aspects of this method is a feedback optimization: if the design fails to meet the desired performance criteria, it is modified and subjected to re-simulation. This is done until the design meets the set objectives, finally making a comparative evaluation of the final optimized design in comparison to the initial design and making definite recommendations.

1.6. Scope

This work is dedicated to the performance evaluation and failure analysis of coupler head under its critical operational loads, particularly on the precise locations where the stress concentration would occur. The approach adopted in this study is the finite element modelling and simulation package conducted in the ABAQUS software. The method is based on the accurate 3D model generated in the SOLIDWORKS to characterize the stress-strain behavior of the coupler head under tensile and compressive operational loads for comparison with its actual operational loads. In addition, the crack phenomenon is also carried out for failure analysis of the coupler head and the final solution proposed in this study recommends some specific geometric modification on the coupler head for reduction of stress concentration. The scope of this study is confined only to the coupler head component based on the material properties of grade E steel. The loading parameters and validation data used in this study are exclusively extracted from the operational condition and maintenance data of Ethiopian-Djibouti Railway. The complete lifecycle analysis of the whole coupler assembly component of the coupler system is not within the scope of this study. The other railway components and material properties are also out of the scope of this study.

1.7. Delimitations

In order to make the study focused and confined to a manageable level, the study is confined to the following parameters

- The study is limited to the operating conditions and its related data extracted from the Ethiopian-Djibouti Railway Network
- The study is limited to the Freight wagon coupler head
- The study is limited to the Finite Element Analysis (FEA) study using ABAQUS and 3D model generated from the SOLIDWORKS

1.8. Significance of the study

The safety and efficiency of Ethiopian-Djibouti Railway Network depends on the freight wagon coupler. The importance of this research is that this study begins with a very important preliminary failure analysis on the current coupler heads in the fleet of operation of the company. A first analysis that involves a study of the actual failures in the real world gives the empirical basis of this study. This study goes directly to the cause of component failure by computing stress, deformation and Fatigue life under critical loads and, most importantly, by presenting and examining an initial crack developed on the basis of these actual measurements of failure. This factual methodology results in a better insight into the coupler head longevity. This research directly helps in the elimination of catastrophic failures because of the improved performance of the couplers and their reliability.

1.9. Expected Outcome

To start with, this study will generate a failure analysis report in the first instance, which has an overall picture of the structural integrity of freight wagon coupler heads obtained by carrying out an accurate check on stress concentrations, deformation and fatigue life of the head under critical loads. This will give important information on the possible mechanisms of failure and assist in estimating the life span of the couplers. Second, the research examines the behavior of an existing crack when it is subjected to operational loads and the analysis will cease being an exercise on paper but a practical tool. Third, this study will present optimal coupler designs that will improve the level of strength and lifespan by suggesting and analyzing geometric alterations in the coupler design. Lastly, this study will provide informed recommendations stemming out of a comparative study of available materials to enhance the life and efficiency of the couplers. In summary, this study should make great contributions to the credibility and security of freight transport system of the Ethiopian-Djibouti Railway Network.

1.10. Organization of the study

It is a thesis systematically arranged in five separate chapters that were aimed at presenting the research in the progressive order so that a complete story on the identification of the problem to the conclusion would be offered. The Introduction is the first chapter that lay the fundamental basis of the study. It shows the larger context of the railway coupler systems formulates a specific problem of constant failures and establishes clear goals of the research to overcome this problem. It is based on this that Chapter 2: Literature Review provides a critical and comprehensive analysis of available academic research and industrial activities pertinent to the field.

Method and material explain the methodological idea of the thesis and describe the research style and design. This chapter will clarify the explanation of the work with material properties, calculation of force and formation of an accurate 3D model. Moreover, it also describes the configuration of FEA in detail and the reasons why the certain meshing strategies are chosen and the Boundary conditions. Chapter 4: Results and Discussion is devoted to the presentation and interpretation of the results of the work. The chapter logically shows the information of the huge amount of FEA simulations. Last but not least, the conclusion of the whole thesis in Chapter 5: Conclusion and Recommendation, which summarizes the whole exploration. It gives the brief description of the most concerned findings and explains the conclusion made out of the whole exploration and how the study has managed to achieve what it has been designed to achieve. Then convert such conclusion into actionable and practical recommendations.

Chapter Two

Literature Review

2.1. Introduction

Couplers play a vital role in safe and efficient operation of freight and passenger trains. Coupling devices are used between groups of train cars to allow the sharing and transfer of loads and forces between the vehicles. Couplers reliability and durability are of the utmost importance, because their failure can have very disastrous consequences, which may include derailment of the rail, damage to the rolling stock, and disruption of transportation networks. This literature review paper presents failure of railway couplers and reliability analysis of couplers. It covers main failure modes of couplers, cause and effects of failure and mitigation measures. The studies reviewed adopted comprehensive multidisciplinary approach, which includes consideration of materials science, structural analysis, fracture mechanics and computational modeling to get complete picture on coupler behavior and reliability.

W. Wang et al. 2010[13] studied the influence of high load traction on fatigue life of coupler yoke components and cracks at the junction of the rear corners of the yoke and the frame body as the main failure mode. Huang et al. 2014[7] studied the brittle fracture of grade E cast steel knuckles and discussed the influence of microstructural defects on material security. For example, the coarse dendrites and shrinkage porosity reduce the quality of materials. The paper presented by Ren et al. 2022 [4] studied the residual life of heavy couplers with dynamic loading and crack propagation models. It is important that real-life operational conditions should be considered in the predictor. The conceptual design of a new coupler proposed by Fomin et al. 2020[14] Longitudinal-dynamic loads are expected to be minimized by new coupler, and longitudinal forces in comparison to usual SA-3 couplers will be 30% lower. Oganyan et al. 2019[15] solved the problem of automatic fracture of couplers in severe environmental conditions and apply the deformation criteria to determine lifetime of couplers at cyclic- loading. Similarly Zou, Luo, and Ma 2018[16] explained the behavior of couplers at braking conditions. The dynamic modeling should be accurate to increase the safety of heavy-haul trains. Mohammadi et al. 2019[12] studied failure modes of draw-hook couplers. They did experimental and numerical tests on the predictive structures of fatigue life of couplers. For the calculation of longitudinal force Yadav and Vyas 2023[1] build their multi-body dynamic models of AAR coupler systems including the coupler inertia and the effects of slack to enhance the prediction of in-train forces. A local stress-strain approach by Li and Sun 2020[8] is an estimative method to predict the fatigue life of No. 17 coupler knuckles in the consideration of the stress-strain relationship and cumulative damage theory of the material. The article by Chunduru, Kim, and Mirman 2011[17] was concentrated on the failure analysis of AAR Type E couplers. The study also recommended that changes in the design should be made to minimize stress concentration as well as to increase the fatigue life of the knuckle. To investigate the fatigue crack analysis of Type 17 couplers, Hua, Wang, and Li 2017[10] suggest an enhanced format to decrease the stress concentration on the hook tongue part.

2.2. Loading Scenarios and Force Estimations

Due that railway, couplers running area and types of coupler loading conditions are various and different. Many researchers use different ways; whatever in the process of calculating the forces used in the loading, the type of loads or the empirical formulae used in the models. In this review paper, we will discuss some of most important papers and characterize their premises, equations and software is developed to support the load analysis. Huang et al. 2014[7] stated that traction and compression forces actually do have an influence on the workings of the knuckle, but they do not provide any of their equations. Ren et al. 2022[4] directly draw their loading conditions based on empirical load spectra measured on the China Datong-Qinhuangdao Railway Line, and introduce dynamic loads into their models to simulate the actual operation. Similarly, Fomin et al. 2020[14] computed the longitudinal loads with the help of empirical equations based on the laws of Newton and the fundamentals of train-dynamics balancing the forces of traction, braking and resistance in the mixture.

The durability calculations are actually based on the actual load data of the operation. The study characterize the loading by statistical data on the frequency of tensile and compressive forces of different magnitude appearing in the various operating modes and bundle this into a load block. The loads on the locomotives and cars of automatic couplings that cause to such block are included in the loads stipulated Kostina 1981, in several Standards of 1996 and legislation of GOST 33211 (2014). Oganyan et al. 2019[15] constructed a model of the longitudinal forces that strike automatic couplers during shunting and hauling, draw in statistical distributions of GOST 33211 and GOST 33788 using that. Li and Sun 2020[8], in turn, studied the longitudinal load spectrum of a 20,000-ton freight train, based on experimental results to simulate the effect of the forces acting on a coupler knuckle during a trip.

The forces on draw-hook couplers are worked out by Mohammadi et al. 2019[12] using the speed of trains, acceleration and the number of wagons in the rail. Yadav and Vyas 2023 [1] Introduced harmonic excitation forces to recreate longitudinal behavior of AAR coupler systems, and examine the behavior of contact forces between the couplers and knuckles. Likewise, Chunduru, Kim, and Mirman 2011[17] estimated the drawbar pull force, based on the specification of a GE Dash-eight diesel locomotive, considerations of rolling resistance, torque of the vehicle and the gear ratio.

2.2.1. Types of Loads

Generally, the type of the load, which the railway couplers undergo, can be classified into two classes, which are:

- **Static Loads** which do not vary significantly with time. They indicate the statically loads during the stationary train, including the traction and braking forces as [14]
- **Dynamic Loads**: which vary with time and arise when the engine is in motion, i.e. acceleration and deceleration, and when shunting. [15], [16], [18], [19]emphasize the dynamic load.

Otherwise, if we think about the direction of the force the coupler subjected to is acting as follows:

A. Longitudinal Loads

The forces, which act in the direction of a railway track, is called longitudinal forces. Longitudinal forces have a significant impact on the speed of a train and its safety parameters like derailment coefficient. These forces are mainly two types: one is a compressive force and another is a tractive force. The tractive force acts in the direction of a moving train whereas a compressive force acts in the opposite direction. Acceleration, deceleration of the train and variable braking action by pneumatic brakes are the main causes of huge longitudinal forces [19]. Studies such as [14] and [17] highlight the significance of longitudinal loads, especially during train acceleration, deceleration, and shunting operations.

Fomin et al. 2020[14] calculated longitudinal loads using the following formula:

$$N = \left[\frac{T_k}{Q_0+Q} - W_{cp} - b_T\right].Q + \sum_{i=1}^{n}(Q_i.w_i + B_{ri}) \quad \text{-----------------------[14]}$$

Where Tk is the tangent traction force of a locomotive, kN, Q_i is the weight of a unit of a train with serial number i, for ward direction (at i=0 the main locomotive, i=1, 2, 3,…, n cars), kN; W_{cp}, b_T are, respectively, the average resistance and average braking force per unit weight of the train, kN. n is the number of cars in the train; w_i is the specific motion resistance of a rolling stock unit, taking into consideration the track profile; B_{ri} is the braking tangent forces of a loco motive and cars, kN.

The tangent traction force of a locomotive is determined from formula

$$T_k = P_{max}.\varphi_k = (L.m).\left[0.18 + \frac{4}{22+v}\right]\text{-----------------------}[14]$$

Where P_{max} is the maximum traction force of a locomotive, permitted by the conditions of adhesion between the wheels and rails in KN. and φ_k is the estimated coefficient of adhesion between the wheels and rails. L is the load from the driving wheelset on rails, kN; m is the number of drive wheelsets of a locomotive equal to the number of traction engines; v is the estimated motion speed, km/h. The resistance of locomotive motion is determined from

$$w_l = 1.9 + 0.01v + 0.0003.v^2\text{-----------------------}[14]$$

The resistance of the four axle cars can be found from:

$$w_l = 1.9 + \frac{3+0.1v+0.0025.v^2}{q}\text{-----------------------}[14]$$

Where q is the axial load, KN/axle.

The average braking force per unit weight of the train is determined from

$$b_B = 1000.\vartheta_p.\varphi_{fr}\text{-----------------------}[14]$$

Where ϑ_p is the estimated brake coefficient of a train; φ_{fr} is the estimated coefficient of friction of brake pads.

$$\varphi_{fr} = 0.36.\frac{v+150}{2.6*v+150}\text{-----------------------}[14]$$

B. Lateral Loads

Lateral loads act perpendicular to the train's length and are primarily caused by factors such as curve negotiation, wind forces, and the shifting of cargo. Zou, Luo, and Ma 2018[16] Focused on lateral forces in their simulation of coupler behavior, indicating the importance of understanding these forces for stability and safety. These forces are critical in preventing derailment and ensuring the structural integrity of couplers during dynamic operations.

C. Vertical Loads

Vertical loads are exerted on couplers due to the weight of the railcars and the dynamic effects of the train moving over uneven tracks. Some articles [17] [8] noted the influence of vertical loads on the stress distribution within couplers, especially under heavy-haul conditions. Vertical loads can lead to fatigue failure if not properly accounted for in the design and material selection. Different other studies utilize specific empirical formulas to calculate these loads for example Mohammadi et al. 2019[12] described the net force on the coupler using the empirical formulas listed below:

Figure 2: Schematic of wagon[12]

Applying equilibrium equation on the model, the result becomes as:

$$f_{in} = u + f_p + ma \text{ -----------------------[12]}$$

The traction force of locomotive u and resistance force of each wagon f_p can be determined as:

$$u = (c_0 + c_1 v + c_2 v^2) \sum_{i=1}^{10} m_i \text{-----------------------[12]}$$

$$f_p = m(c_0 + c_1 v + c_2 v^2) \text{ -----------------------[12]}$$

Figure 7 indicates the coupler connected to locomotive force with respect to some velocity variations during train journey for the illustrated train.

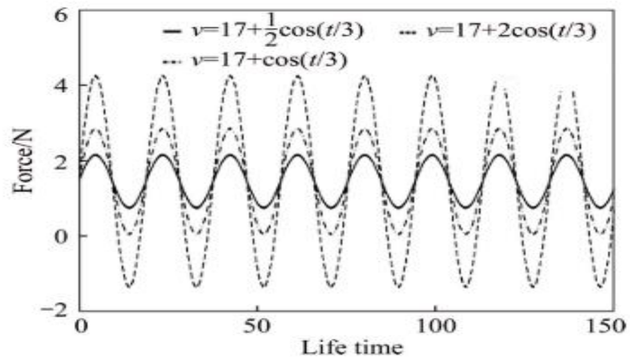

Figure 3: Coupling connected to locomotive force[12]

Assumptions regarding loading conditions can affect the accuracy of predictions for instance Fomin et al. 2020[14] assumed steady motion along a uniform track profile, which may simplify the analysis but does not account for the complexities of dynamic loading. On the other hand, Li and Sun 2020[8] assumed that loading sequences do not significantly affect fatigue life, potentially overlooking the effect of operational variability on coupler performance.

In General based on the findings of the above articles, the main load that cause the coupler cracking and failure is longitudinal load. This kind of load appears mainly from traction and braking forces. Generally, this kind of forces appear in the train operation. For instance, W. Wang et al. 2010[13] highlighted that when the traction load is gradually increased, a considerable longitudinal forces are generated. The fatigue life of coupler is significantly decreased. The coupler presents a sharp decrease in fatigue life with the increase of No. 17 coupler yokes. These forces induce cracks often occur from high-stress areas starting at the interfaces between yoke rear corners and frame body. The facts reveal that tensile forces component perpendicular to the crack plane plays the dominant role in the cracks initiation and propagation. Similarly, Fomin et al. 2020[14] emphasized that increasing longitudinal forces can significantly compromise the integrity of couplers, resulting in higher instances of cracking and failure. They point out that the fatigue life of couplers is notably diminished under these loading conditions. Furthermore, Li and Sun 2020[8] explained the critical stage of stress when the material is longitudinal loaded. Therefore, the longitudinal loading help to initiate and growth the crack in the coupler knuckles so that the design and maintenance should be concerned. The lateral force do not need to be ignore especially when the rail is curved or during other sharp movement of the train; however, according to the current literatures longitudinal loading always be the main cause of the coupler failure; thus, the longitudinal loading to the coupler should be concerned when discussing the design and maintenance of the railway coupler. Only in this way, if we want the rail system has better safety and reliability, we should face the implication of longitudinal loading to the design and maintenance.

2.3. Material Used

One of the most basic parameter, which affect the performance and lifetime of component, is selection of material. Huang et al. 2014[7] used cast steel grade E knuckles in their research. Researchers found that grade E cast steel has high tensile strength and ratio of yield strength/tensile strength is very promising. However, the microstructure also has some effect on its performance. When the material have large coarse dendrites and shrinkage porosity, it will lead to failure of component. Similarly Ren et al. 2022[4] used Cast steel grade E steel in coupler manufacturing for fabrication of railway coupler knuckle. To obtain the input data of tensile strength, fatigue crack growth range and rate, standard test was also performed on the material.

Table 2: Mechanical properties of Casting grade E steel for the coupler[4]

Tensile strength σ_b (MPa)	Yield strength σ_s (MPa)	Elastic modulus E (GPa)	Elongation δ (%)	Poisson's ratio v
806	656	207	12.2	0.28

Table 3: mechanical properties of Grade E steel of coupler knuckle[8]

Performance index	σ_b (MPa)	σ_s (MPa)	δ_4 (%)	ψ (%)
Experimental value	850	755	18	44
AAR-M-2O1-84	≥830	≥690	≥14	≥30

Similarly, [17] and [8] studied grade E steel widely used in manufacture of coupler knuckle and given its mechanical properties such as tensile strength and yield strength noting the uniform fine tempered martensite microstructure which is responsible for its impact strength. On the other hand Hua, Wang, and Li 2017[10] used forged Grade E Steel 25MnNiCrMoA for type 17 coupler which is also having high strength and tough quality of material and given its material properties such as tensile strength, yield strength, impact energy.

Table 4: the main properties of forged Grade E steel 25MnNiCrMoA[10]

σ_b/MPa	σ_s/Mpa	δ(%)	ψ(%)	A_{kv}/J(−40 ℃)
≥850	≥690	≥14	≥30	≥27

From above discussion, it can be concluded that due to its favorable mechanical properties, Grade E Steel is widely used. However, Studies such as [7] and [12] has shown that it is also susceptible to some microstructure defects which may affect its performance. If the material has large coarse dendrites and shrinkage porosity, it will lead to failure of component. It will lead to failure of component in high stress application so it is not reliable in case of high cyclic loading. Forged Grade E Steel[10] has an advantage over cast steel due to its tough nature and less susceptibility to defects. Grain size of forgings is finer as compared to grain size of cast part, which leads to an improvement in fatigue resistance of part and increase in reliability of component under certain application. It also leads to an improvement in fatigue resistance of part and increase in reliability of component under certain application. Cast Grade E Steel is same as grade E cast steel but what is highlighted in [4] is that it can be used in heavy coupler as it can sustain dynamic loading, but all the issues related to casting are applicable to it too.

The other parameter for the material study is the chemical composition of grade e steel, which is the standard material for the manufacture of grade steel. The basic elements found in the chemical composition of C, Si, Mn, P, S, Cu, Cr, Ni and Mo for grade Steel. Nuramin, Utomo, and Karmiadji 2025 [20] conducted a chemical composition test using the specimen AAR-M201 Grade E Steel Casting, as shown in table. 5 obtained from PT. Barata Indonesia.

Table 5: Chemical Composition of (the Association of American Railroads) AAR-M201 Grade E Steel Casting Material Samples by PT.Barata Indonesia

Element	**Weight %**
Carbon, maximum percentage 0.32	0.282
Manganese, maximum percentage 1.85	1.469
Phosphorus, maximum percentage 0.04	0.02
Sulfur, maximum percentage 0.04	0.001
Silicon, maximum percentage 1.5	0.425
Crominum	0.47
Molibdium	0.308
Nickel	0.368
Almunium	0.077
Couper	0.021
Iron	Balance

2.4. Study Methodology

The paper is folded into various papers and write there hold assumptions and empirical formulae in which they operate their models and the FEA software in which they operate their. W. Wang et al. 2010[13] used finite element analysis (FEA) based on ABAQUS package to model the stress intensity factor (SIF) at the crack tip and using Paris equation to calculate the crack propagation life. While Ren et al. 2022[4] used finite element modelling and experimental testing method and applying both classical Paris law and NASGRO equation to predict the rate of crack growth in case of high cycle fatigue. A number of authors have used different approach to determine the coupler loads by different methods and approaches for instance Fomin et al. 2020[14] used both analytical and numerical methods derived longitudinal loads by using empirical formulas and train dynamics was simulated in in Mathcad Solid Works and Cosmos Works.

Mohammadi et al. 2019[12] has done Nondestructive testing (NDT) on failed couplers and finite element analysis based on ABAQUS package was employed to simulate the stress distribution and fatigue life prediction. Yadav and Vyas 2023[1] developed multi-body dynamic models of AAR coupler systems in multi-body dynamic analysis package MSC ADAMS including coupler inertia and slack-induced impacts. Finite element analysis (FEA) based on ANSYS has been employed by Li and Sun 2020[8] to identify stress concentration areas in the knuckle of coupler and then employing local stress-strain method to prediction fatigue life. Theoretical analysis and finite element modeling have been employed by Hua, Wang, and Li 2017[10] including Hertz contact theory to determine contact stress and ANSYS Workbench to simulate the stress distribution on the S-surface of the hook tongue component.

2.4.1. Experimental and Numerical Techniques

In some studies it is seen that both experimental and numerical techniques are used In other words, the result is achieved by using experimental data and then compare it with the numerical model. Mohammadi et al. 2019)[12] applied the experimental results of the critical areas which are prone to crack formation on the draw-hook coupler and finite element method (FEM) analysis based on ABAQUS package to simulate the stress distribution . Nondestructive testing (NDT) methods include non-destructive testing methods such as ultrasonic testing or radiographic inspection. It is used to detect internal flaws in a material without destroying the component being inspected. The experimental and numerical technique is used to validate the numerical model with experimental data.

In contrast, [4], [8], [10], [17] are mainly using numerical modeling methods, finite element method based on ABAQUS software to study the propagation of coupler cracks, method used stress intensity factors (SIF) to study the behavior of the crack in different loading conditions. SIF is an important parameter in fracture mechanics that represents the stress field around a crack tip. The method relies heavily on numerical analysis, which may be limited without experimental validation.

2.4.2. Assumptions and boundary Conditions

Assumptions play a critical role in shaping the methodologies employed. For example, Fomin et al. 2020[14] assumed steady motion conditions when calculating longitudinal loads, which may not account for transient dynamics present in real-life scenarios. Transient dynamics refer to the behavior of systems that change over time, particularly in response to varying forces. Similarly, Li and Sun 2020[8] assumed that the loading sequence does not significantly affect fatigue life, a perspective that may overlook the complexities of operational conditions.

Zou, Luo, and Ma 2018[16] introduced a polygonal contact model to simulate friction and contact forces in couplers, but they also assume idealized conditions like perfect alignment of vehicle centerlines. These assumptions can simplify the analysis but may also lead to oversights in dynamic interactions that occur during actual operations.

In the study by Oganyan et al. 2019[15], the authors focus on analyzing the forces experienced during key operational scenarios in rail transport, specifically during shunting and train haulage. Shunting refers to the process of moving railway vehicles around a yard or between tracks, which often involves coupling and uncoupling trains. This operation can create significant dynamic forces due to the momentum of the vehicles and the abrupt changes in direction. Train haulage, on the other hand, involves moving a train over distances, where forces are exerted as the locomotive pulls the train cars. These forces can vary based on factors such as acceleration, braking, and terrain.

2.4.3. Empirical Formulas

Empirical formulas are frequently employed to estimate critical parameters related to stress and fatigue life. For instance, Ren et al. 2022[4] utilized the Paris law and the NASGRO equation for predicting crack growth rates, which incorporate stress intensity factor ranges and additional parameters to model material-specific behaviors. The Paris law describes the relationship between crack growth rate and the range of stress intensity, making it a fundamental tool in fracture mechanics. This approach allows for a nuanced understanding of fatigue phenomena but requires accurate material characterization to be effective.

$$\frac{da}{dN} = C(\Delta K)^{n} \text{-----------------------[4]}$$

where When a stress intensity range ΔKis the crack length and is the fatigue crack growth for a single load cycle **N** A variety of crack growth equations similar to the Paris–Erdogan equation have been developed to include factors that affect the crack growth rate such as stress ratio, overloads and load history effects.

In their study, Li and Sun 2020[8] apply the Manson-Coffin formula for fatigue life estimation, modified to account for mean stress effects. The Manson-Coffin relationship is particularly useful for materials that experience both elastic and plastic deformations during cyclic loading. They also employ Neuber's rule to relate nominal stress to local stress and strain, a method that enhances the accuracy of fatigue predictions in areas with high stress concentrations. In addition, Hua, Wang, and Li 2017[10] used Hertz contact theory to calculate contact stress and the half-width of the contact area, providing empirical formulas for stress distribution on the S-surface of the hook tongue component. The integration of multiple empirical models enriches their analysis but also introduces complexity in interpretation.

2.4.4. Software Utilization

The selection of software plays a crucial role in implementing above methods. Many studies use ABAQUS and ANSYS, these two tools to make use of their advantages in accurate simulation and rich information guidance on the material behavior and structural strength. Mohammadi et al. 2019[12] used ABAQUS in FEM analysis; it is known that ABAQUS is very powerful in simulating the case of complex geometry and loading conditions. Similarly Li and Sun 2020[8] used ANSYS Workbench in static strength analysis and fatigue life estimation.

Fomin et al. 2020[14] used SolidWorks for spatial modeling. While Oganyan et al. 2019[15] didn't indicate the software used in numerical simulation, which makes the repeatability and validation of their numerical simulation difficult. The openness of the computational tool makes the application of their method limited. Even if the authors manage to obtain some UM, software results and used them in the paper.

Approaches that the researchers think about railway couplers comprise various different approaches and every of them is associated with its benefits and demerits. When we think about the assumptions they make, formulae on which they are based and the software itself, we can actually decide the effectiveness of current research methods. In future, research must focus on these approaches by plugging these loopholes which we have discovered- especially, real world experimentation and improved modelling of natural operating environments. Openness in disciplines and making the process and procedure open will eventually make the trains safer and more reliable.

2.5. Stress Analysis and Contact Mechanics

Knowing the maximum stress level to which couplers have been subjected in service is important in order to ensure their structural integrity. Literature reports show that the maximum longitudinal reaction forces in practice can be significantly higher than the predictions of conventional models. Therefore, it is important that couplers are designed to operate safely with higher levels of stress. For instance, the Type17 coupler study shows that the stresses such as longitudinal tensile stress, bending stress and contact stress will be accumulated in some region and cause fatigue crack [7], [8], [21]. The finite element analysis method used in many articles shows that the stress concentration occurs at the contact areas. At these areas, small areas experience high forces and therefore the risk of failure is increased [8]. It has been observed that the maximum resultant tensile stresses at the coupler result is close to the yield strength of the material. As seen from the finite element analysis of No. 17 coupler, the surface roughness, material homogeneity, design features have a large effect on the stress distribution.

Knowing the contact mechanics and stress distributions in the interaction between the coupler assemblies is important to the understanding of the failure. In the work Hua et al. contact analysis of the interaction between a Type 17 coupler was performed using finite element methods. The contact stress distribution and deformation characteristics under different loading conditions were determined and potential failure regions and stress concentrations in the coupler were identified. This information can be used to predict fatigue life of the coupler.

Similarly, in the work Li & Sun. finite element analysis was used to predict the crack growth life of a No. 17 coupler knuckle used in China. The effects of manufacturing defects and stress gradients inside the component were investigated. Life prediction was performed using a model developed based on fracture mechanics principles, and it was demonstrated that the remaining service life of a coupler knuckle could be estimated.

2.6. Fatigue Analysis

Fatigue Analysis Should be ensured that the railway couplers are safe and in their structural state by determining the fatigue life. The critical review focuses on the specific approaches used in recent articles their overall conclusions on fatigue performance with respect to various analytic methods that assess the relationship between different approaches to life prediction, stress reduction, and a rationale of the occurrence of failure.

The most commonly used FEA technique is the Finite Element Analysis (FEA) method in combination with S-N approach, which may or may not consider the mean stress corrections. Chunduru, Kim and Mirman 2011[17] Experiments demonstrated that static structural FEA of an AAR Type E coupler knuckle can identify the pulling lug region as the critical location with maximum stress of 295.6 MPa under 411.3 KN applied load. The corresponding fatigue life S-N curve based approach with zero based loading (R=0) and Goodman correction predicted life of original design coupler knuckle to be 77,700 cycles. The most important fatigue result from this work was the achievement of coupler knuckle design optimization using Response Surface Methodology (RSM) to change the geometry of knuckle’s internal void. The optimized designs had reduced peak stress (down to 186.14 MPa) and an associated increase in predicted fatigue life of 2.4 - 8.3 times over original design, showing the significant impact of geometry refinement on coupler knuckle life.

$$S = \frac{S_a}{1-(\frac{S_m}{S_u})} \text{----------------------[17]}$$

$$S_a = \frac{1}{2}(S_{max} - S_{min}) \text{ ----------------------[17]}$$

$$S_m = \frac{1}{2}(S_{max} + S_{min})$$ ----------------------[17]

$$S_{max} = \max(\sigma_t + \sigma_r)$$ ----------------------[17]

$$S_{max} = \max(\sigma_t - \sigma_r)$$ ----------------------[17]

Where, S_a isalternating stress calculated using, S_m is mean stressS_u, is the ultimate strength of the material, σ_t and σ_r are tangential, radial stress respectively.

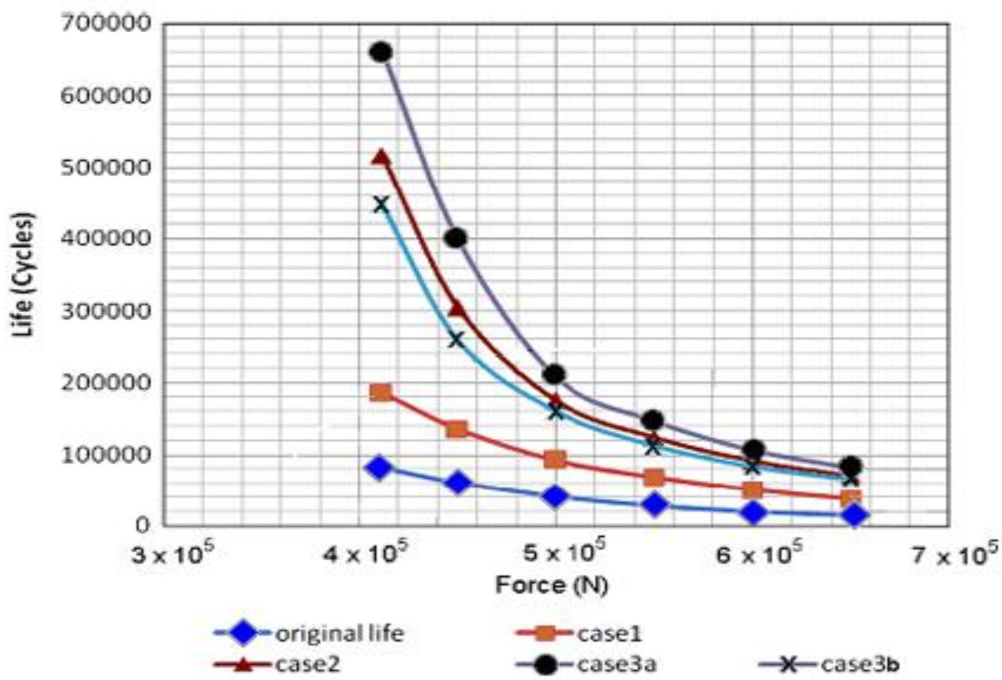

Figure 4: Comparison Plot[17]

Given the complex, multi-axial state of stress in couplers, research has progressed beyond uniaxial S-N methods. Mohammadi et al. 2019[12] conducted a comprehensive study on a draw-hook coupler, employing critical plane approaches to account for multi-axial fatigue. Their methodology involved comparing several models, including Fatemi-Socie (a shear-based model) and Smith-Watson-Topper (SWT, a normal stress-based model), under different connection types. A key fatigue finding was that for the draw-hook coupler, where normal stresses are dominant, the SWT critical plane approach provided the most accurate life predictions when validated against experimental tests. Their results also confirmed that the coupler's fatigue life in a symmetric connection (Type I) was significantly longer than in an asymmetric connection (Type II), linking structural configuration directly to fatigue performance and underscoring the necessity of using appropriate multi-axial criteria.

To address the limitations of the S-N method in regions of high stress concentration, researchers have adopted the Local Stress-Strain (LSS) approach for crack initiation life prediction. Li and Sun (2020) applied this method to a No. 17 coupler knuckle, using the Morrow equation to model the strain-life relationship of Grade E steel. A critical aspect of their methodology was the incorporation of a mixed load spectrum derived from the longitudinal forces on 20 couplers in a 20,000-ton train, accounting for the random position of a coupler within the consist. The central fatigue finding was the extreme sensitivity of life to the fatigue notch factor (K_f), which represents casting defects. Their calculations showed that the service life decreased dramatically from 6.3 years to 0.7 years as K_f increased from 1.5 to 3.0.

2.7. Strength and Limitations

The strengths and limitations of recent studies on railway couplers are important for understanding the strengths and limitations of the methodologies and studies. Many studies integrated experimental and numerical studies well, it means the strength of the study is integrated the NDT and FEA in the study to identify the failure points of the draw-hook coupler. Studies [7] integrated the optical microscope and scanning electron microscope techniques; by using this technique, the researchers can focus on the microstructure characteristics of the brittle fracture of grade E cast steel knuckle.

Another strength is real data. Ren et al. 2022[4] used empirical load spectra from actual operation to generate a realistic scenario for the remaining life of heavy couplers under dynamic loading. The approach based on real data makes the study more applicable to real life. Furthermore, Zou, Luo, and Ma 2018 [8] believed that simulating the runtime behavior of couplers and buffers was very important and it was necessary to be accurate; it would improve the safety of heavy-haul trains. In addition, there is obvious attention for material property. The mechanical behavior of materials is characterized in the study of Li and Sun 2020[8]. Their local stress-strain method is a deep understanding of the material behavior under the operation; it provides essential data for fatigue life prediction.

Of course, there are also some limitations. One obvious shortcoming is that there is a lack of experimental validation. For example, Fomin et al. 2020[14] believed that their results were based on the simulation and analytical models; there was no experimental validation, which limits the application of the results.

Lastly, the narrow focus on certain components is another shortcoming. Some researchers focus mainly on knuckles and in some cases knuckle pins, while there has been no research on the coupler head. This hinders the understanding of the overall coupler system behavior. For example, Some studies [7][10] focused on knuckle without considering the coupler head. The coupler head is also very much important for the overall coupler behavior and safety of the railway coupler. Overcoming this shortcoming may lead to better understanding of the coupler behavior and improve the safety of the rail traffic.

2.8. Challenges

2.8.1. Variability in Loading Conditions

The variability of loading conditions is another challenge [15]. How to deal with this challenge is one of the basic question to be answered, maybe a variety of different modes of operation such as shunting and real train haulage have their own natures. However, the majority of the analysis still relies on statistical distributions to model interacting forces and it may not be able to reflect the actual variation of the world. The Study used statistical distributions constructed based on the past data, so they would not include the extreme world events that are indeed needed to check the coupler lifetime.

2.8.2. Complex Interactions

A Complex interaction between different components such as coupler, knuckle and draft gear are one of the challenges. Zou, Luo, Ma 2018[18] tried to model the dynamics of the coupler but not able to reflect the complex interactions between them. The study showed the importance of accurately simulating the coupler behavior. However, the simplifications in the model would lead to gaps in the understanding of the interactions between different components under different conditions and would lead to flawed predictions of the coupler behavior.

2.9. Type of coupler used

In the railway system, various types of couplers are used for connecting the railcars and safely and efficiently transporting the cargo. This review checks the types of couplers referred to the literature and compare their designs, materials and their operations. The AAR Type E coupler used by Chunduru, Kim, and Mirman 2011[17] is a knuckle type coupler used by freight trains. The coupler has a robust design that can safely connect and move under the dynamic forces experienced by trains. Made of Grade E steel, the coupler is designed to carry a significant amount of load, but it is known to experience fatigue failures at stress concentrations at the pulling lug and cage-hole.

W. Wang et al. 2010[13] studied the coupler No. 17 and other applications in the railway. As can be seen in Fig. 4, the coupler No. 17 is characterized by the structural integrity in the traction actions. According to the results, the cracks originate from the corner junction of the yoke rear and the frame body. Thus, the stress distribution should be attentively analyzed. Hua, Wang and Li 2017[10] studied the coupler type 17 which is used in heavy freight trains. As we know, the coupler No. 17 is used widely in the railway. The hook tongue of the coupler is made of forged Grade E Steel (25MnNiCrMoA) material, which has good mechanical performance, the component of coupler is very important for the whole device, and its performance will affect the service life of the coupler. The aim of this study is to analyze the stress distribution and the formation of fatigue cracks. A good design is required in the case of high stress.

Draw-Hook Coupler and Its Finite Element Analysis Mohammadi et al. 2019[12] studied the draw-hook coupler which plays a very important role in transferring the loads from wagons to the locomotives and vice versa. The coupler is manufactured in compliance with International Union of Railways (UIC) standards using cast steel. In this work, mechanical properties affecting the performance of coupler have been illustrated. Conceptual Couplers for Reduction of Longitudinal Dynamic Loads Fomin et al. 2020[14] Studied the coupler design, which is an innovative development aimed at eliminating some of the disadvantages of conventional couplers. The coupler body is made of steel grade 09G2S. The authors focus on the material and design aspects of coupler improvement.

2.10. Coupler Optimization and Material Improvements

Mohammadi et al. Carried out a failure analysis of railway draw-hook couplers, the complex loading conditions, and the failure mechanisms. The study provided important ideas on the performance of such couplers and their reliability that have enabled us to come up with safer and more reliable rail transportation systems. Sharma & Associates, Studied the stress levels of finite element by the physical tests. They have explored the opportunities of better knuckle fatigue life and the application of more tensile strength material as well as the design modification in the critically stressed areas. The results have shown that the material and specific design changes are possible to improve the fatigue life to a considerable degree, which indicates the possibility to optimize the coupler performance within the current limits of geometry and weight.

2.11. Summery

This comprehensive literature review examined the way researchers are attempting to determine why and how the railway coupler heads fail, how they manage the stress, and how they endure before they failure. Some of the papers that reviewed are a combination of experiments, computer simulations, and numerical models that address the challenging loads and failure modes that these components encounter. The key conclusions of these researches may assist us, the future engineers, in designing less unsafe and more efficient coupler designs. With such insights, the operators of the trains, as well as coupler manufacturers, will be able to design better robust couplers.

Chapter Three

Material and Method

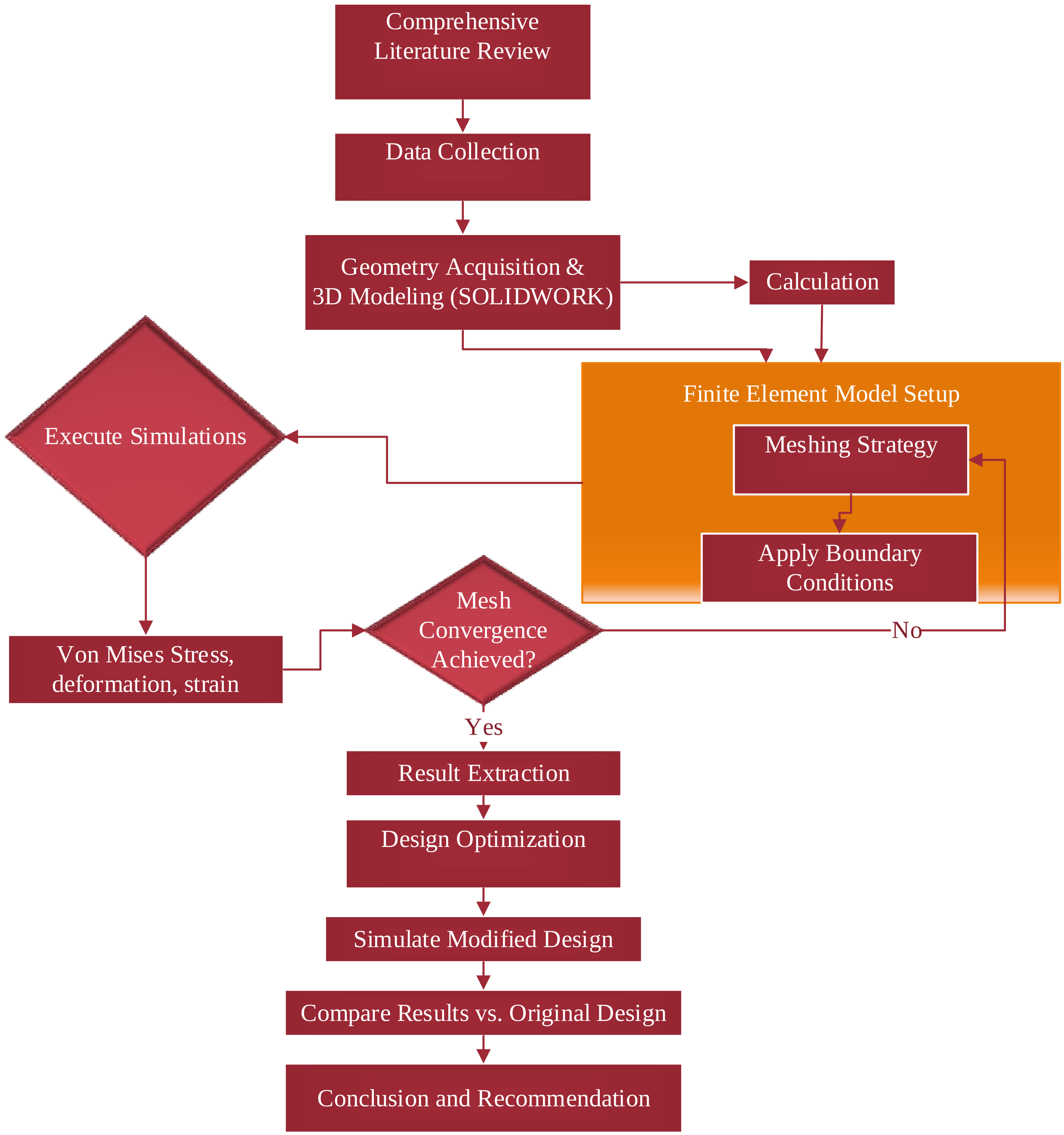

Figure 5: Methodology

3.1. Data Collection

3.1.1. Preliminary analysis

The railway network connecting Ethiopia and Djibouti uses a type of coupler from AAR standards. This coupler provides a means for linking wagons in the train. The assembly allows forces in the longitudinal direction to pass between wagons and also allows movement in Longitudinal and lateral directions. The safety of trains requires that this assembly maintains integrity during operation. The work examining failure patterns uses maintenance data from the Ethio-Djibouti Railway in 2024 and uses examination of parts that failed. This analysis examines main elements in the coupler and describes failure that occurs in these elements.

A. **The coupler head:** The coupler head provides the main structure that connects to the draft gear and connects to the yoke. This element carries the main load and allows transfer of all the forces between wagons. Cracks form in the region of the knuckle pinhole. Figure 6 shows this failure. The data from 2024 indicates 246 cases of failure in total. The coupler head accounts for 85 of these cases.

Figure 6: Cracked coupler head

A. The knuckle pin: The knuckle pin provides a cylindrical part that allows the knuckle to rotate. This rotation allows the knuckle to move between open and closed positions. The pin holds the knuckle in place within the coupler head. Failure of the pin can cause the knuckle to separate from the assembly. This separation results in immediate separation of wagons in the train. The data shows that knuckle pin failure accounts for 130 of the 246 reported failures.

Figure 7: Cracked knuckle pin

B. Knuckle: The component that allows rotation and connects with the similar component of the adjacent joining device, and this produces the connection between wagons. The component, which is held by a pin in the head of the joining device, undergoes high levels of force during the process of joining and during work. There are 246 reports of failure that involve this component.

Figure 8: cracked Knuckle

C. Lock Assembly: The mechanism inside is the assembly that locks and this includes a lock, a device that lifts the lock, and devices that provide force. This element is linked to three out of the 246 reports of failure.

Figure 9: Coupler Lock Assemblies

D. **Knuckle Thrower:** is a component that position and eject the knuckle during the uncoupling process. It is a part that is involved in four failures out of 246 reports.

Figure 10: Knuckle Thrower

The data set contains 246 failure cases in 2024, and the most common failure problems are coupler head cracks and knuckle pin cracks with 85 (34.5%) or 85/246 that means 85 coupler failure out of the total 246 failure case in 2024 covers 34.5% and similarly for the pin 130 (52.9%) in number, respectively. The numbers are almost the same, and it means that the problem is rising and not only appearing on one side of coupler. Concerns are expressed about the suitable material and design of the coupler heads to resist the repeated cyclic loading. In the similar way, the greater quantity on side 1 compares to side 2. However, the number of failure on side 1 and side 2 for coupler head was almost similar.

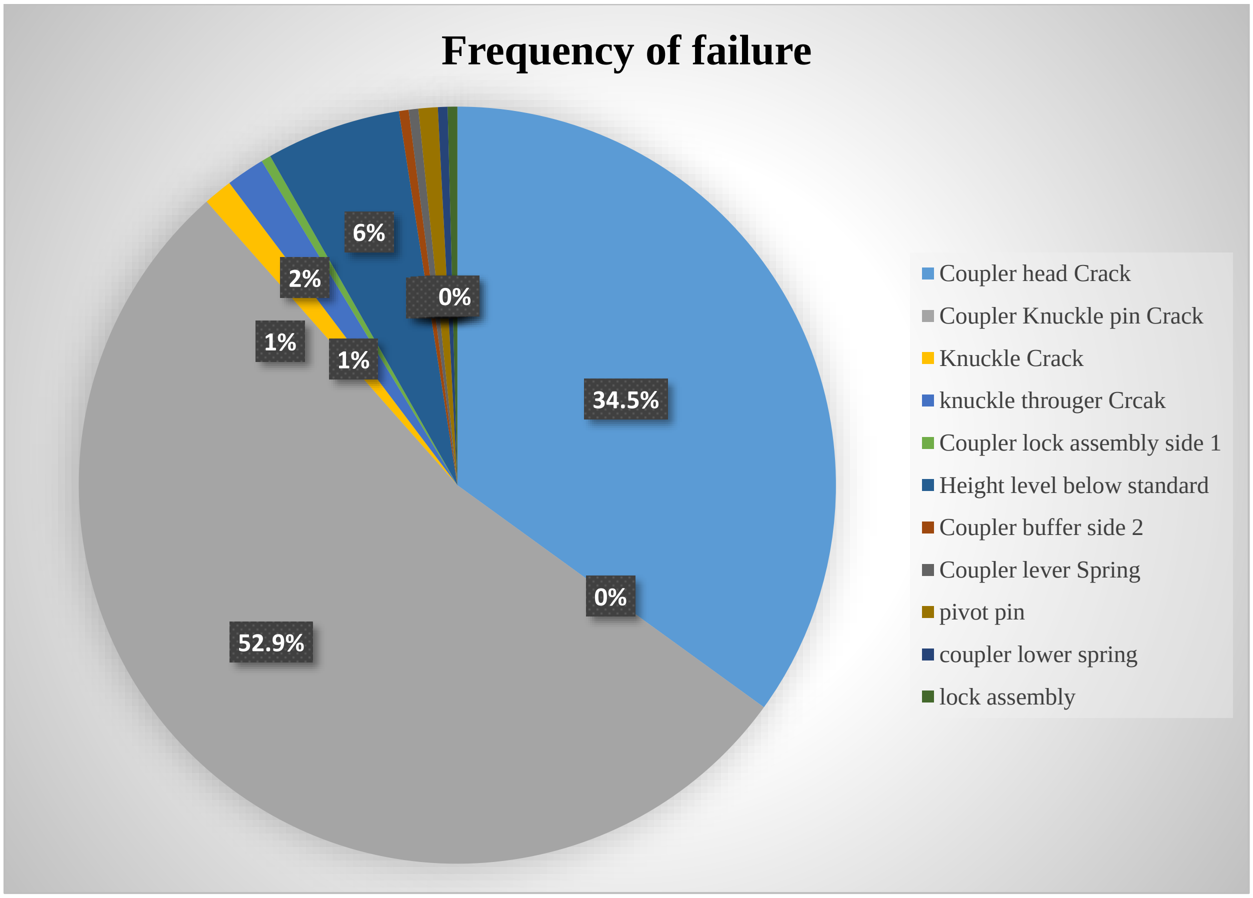

Figure 11: Failure statistics of coupler failure

In addition to the great failures, we have these knuckle cracks and knuckle through cracks. These kind of failures do not happen a lot. Other failure or problems for coupler like, the height is lower than the standard, coupler buffer, spring trouble, etc. these are not the common as above big problem (coupler head and knuckle pin crack)

Table 6: Summary of Coupler Failure Data (Ethio-Djibouti Railway, 2024)

Type of Failure	Number of Failures	Percentage (%)
Coupler Head Cracks	85	34.5%
Knuckle Pin Cracks	130	52.9%
Other Defects	31	12.6%

3.1.2. Technical parameters

Other operational parameter that was collected for the study is tractive force (7200 kW), axle load (245.25 kN max), and train speed (65 km/h). All the data was mined from the specification of railway engineering so that it will be best to model the realistic condition for loading in the ABAQUS. In addition, the material test record for the use of material grade E was used for the data collection.

Table 7: Operational Parameters for Load Modeling

Parameter	Value	Unit
Model	HXD1C	-
Maximum Axle Load	245.25	kN
Tractive Force	~400	kN
Train Speed	65	km/h
Number of Wagons	53	–
Brake Coefficient	0.6–0.8	ϑp
Adhesion Coefficient	0.25–0.35	φk

Table 8: Wagon Technical Parameters

Parameter	Value	Unit	Standard
Type	CW4	-	AAR M-1002
Load Capacity	70	t	EDRA Spec. 2021
Tare Weight	24.8	t	EDRA Spec. 2021

Table 9: Operational Load Conditions

Parameter	Value	Measurement Method
Maximum Train Length	53 wagons	Dispatch Records
Typical Axle Load	245.25 kN	
Average Daily Cycles	4	Maintenance Logs

3.2. Material study

3.2.1. Chemical Composition Test

To establish the grade of the material used in the coupler head in the Ethiopian-Djibouti Railway freight wagons and to establish that the component under test could be that of Grade E cast steel, based on AAR specification, a chemical composition analysis was conducted on a sample of the coupler. Given that accurate elemental analysis was required, the sample was taken to Ethiopian Conformity Assessment Enterprise (ECAE) which appears to be an accredited national testing laboratory in order to have the accurate elemental analysis through spectrometric test procedure. Moreover, this test may provide precise quantitative values of the major and minor alloying elements available in the steel, and thus might allow a direct comparison with the standard chemical requirements of an AAR M -201 Grade E cast steel. This analysis was done in two basic objectives:

- To establish coupler material appears in accordance with the Grade E specification that might be typically employed to manufacturers to assemble railway couplers in terms of the basic chemical compositions, carbon, manganese, silicon, phosphorus, sulfur and other residual elements.
- To establish the model of mechanical and fatigue behavior that could be simulated in the finite element analysis, FEA appears founded on representative material properties, further enhancing the validity of the simulation.

The following subsection may provide and compare the results of the spectrometric test with the AAR, M, 201 Grade, E standard ranges. The complete test outcome appears included in the appendix C.

Table 10: Standard chemical composition of grade E steel[23][20]

Chemical Composition	Grade A, B, B+	Grade C, D, and E
Carbon, maximum percentage	0.32	0.32
Manganese, maximum percentage	0.9	1.85
Phosphorus, maximum percentage	0.04	0.04
Sulfur, maximum percentage	0.04	0.04
Silicon, maximum percentage	1.5	1.5

Table 11: Mechanical Properties (the Association of American Railroads) AAR Grade E Steel Casting According to ASTM A370.

Elements	**Weight %**
Tensile Strength(MPa)	827
Yield Point(MPa)	689
Elongation%	14
Reduction of area, %	30
Younges modulus(MPa)	2×10^{5}
Poision Ratio	0.3
Density(Kg/$\boldsymbol{mm^{53}}$)	7.83×10^{-6}

Table 12: Chemical Composition of (the Association of American Railroads) AAR Grade E Steel Material Samples from Indode rolling stock Depot (Ethio Djibouti railway share company)

Element	**Weight %**
Carbon, maximum percentage 0.32	0.355
Manganese, maximum percentage 1.85	0.551
Phosphorus, maximum percentage 0.04	0.0055
Sulfur, maximum percentage 0.04	0.0076
Silicon, maximum percentage 1.5	0.231
Chromium	0.967
Molybdenum	0.0058
Nickel	0.0352
Almunium	0.0118
Copper	0.0275
Iron	97.9

The mechanical behavior of railway couplers is highly dependent on the properties of the component steels. In the case of Ethio-Djibouti Railway couplers, the current material is Grade E steel with a good combination of strength and ductility. Cast Grade E steel has tensile strength (806–850 MPa) and yield strength (655–755 MPa) sufficient for the static loads, but the microstructure is damaged by defects such as shrinkage porosity and large dendrites resulting in low fatigue resistance under cyclic operational loads. Forged versions of Grade E steel such as 25MnNiCrMoA have better toughness (impact energy: 40 J at 40oC) and finer grain structure and are worthy candidates for a new coupler material. The tables below summarize the relevant mechanical, fatigue and microstructural properties of the forged and cast steels based on standard testing and other literature. These properties will be used as input in the ABAQUS simulations to model the stress distribution and crack initiation and propagation in the coupler assembly. The aim of the analysis is to compare the behavior of the cast and forged versions of Grade E steel and find material based solutions to the recurring coupler failures.

Table 13: Material property [[4], [8] and [10]]

Property	**Cast Grade E Steel (Ren et al. 2022; Li and Sun 2020)**	**Forged Grade E Steel 25MnNiCrMoA (Hua et al. 2017)**	**Unit**
Tensile Strength (σ_k)	806–850	950	MPa
Yield Strength (σ_γ)	655–755	850	MPa
Young's Modulus (E)	**207**	**210**	**GPa**
Elongation (δ)	12.2–18	15	%
Poisson's Ratio (ν)	**0.28**	**0.30**	–
Impact Energy (A_{kv})	25 (at 20°C)	40 at -40°C)	J

3.3. Load calculation

One of the major type of force or load, which act on the coupler, is longitudinal force. In addition, this force have two main type, which are a compressive force and a tractive (tensile) force. Tractive force comes in the same direction of the train's travel but the compressive force comes in the opposite direction. Acceleration, deceleration of the train and variable braking action by pneumatic brakes are the main cause of huge longitudinal forces. These longitudinal loads affect a lot especially during the process of train acceleration, deceleration, and shunting operation.

The force that acts on the coupler knuckle to pull the wagons of a locomotive is the force that is acting on the coupler knuckle of train coupling assembly. The total force produced by the engine is not going to act on the knuckle, in use a portion of that force is used to overcome the friction at the wheels of the locomotive. Therefore, to get it simply moving as operating weight on the rail and the remainder of the thrust force is then available to pull the weight of the wagons. This force is called as draw bar pull force. The Specification includes.

- Power:
- RPM
- Gear ratio
- Wheel Diameter

- Coefficient of friction
- Gross Vehicle Weight

Step1: Rolling resistance (RR) of the locomotive by multiplying the gross vehicle weight (GWV) of the locomotive using coefficient of friction (COF).

Gross Vehicle Weight calculated from the axle load

$$\text{Axle load} = \frac{\text{Total wight of locomotive}}{\text{Number of axle}}$$

$$\text{Total wight of locomotive} \; = \text{Axle load. Number of axle}$$

$$= 245.25 * 6$$

$$=1471.5KN$$

So

$$RR = GWV * COF \text{----------------------}[17]$$

$$= 1471.5 * 0.002$$

$$=2.943KN$$

Step2: Vehicle torque (VT) using the between horsepower, RPM and Torque.

$$VT = \frac{HP*33000}{2\pi*RPM} \text{----------------------}[17]$$

$$= \frac{9655 * 33000}{2\pi * 1720}$$

$$= 29482.1KN$$

Step 3: Output torque (OT) using calculated vehicle torque (VT) and Gear Reduction Ratio (GRR).

$$OT = VT * \; GRR \text{----------------------}[17]$$

$$OT = 29482.1 * \; 6.24$$

OT = 183923.1KJ

Step 4: Forward force output (FFO) by using output torque and radius of drive wheel (R).

$$FFO = \frac{OT}{R}$$ ---------------------[17]

$$FFO = \frac{183923.1}{1250/2}$$

$$FFO = 294.3KN$$

Step 5: Drawbar pull force (DP) by using forward force output and rolling resistance. DP ¼FFO RR

$$DP = FFO - RR$$ ---------------------[17]

$$DP = 294.3KN - 2.943KN$$

$$DP = 291.36KN$$

The force on the coupler at maximum is equal to 291.36 KN. During its structural analysis in the tensile forces and compressive force, the coupler head is tested.

- Under a pneumatic brake emergency braking of any speed with a non-uniform train, it is 2.5MN, and with a uniform train, it is 2.0MN.
- At full service braking to stopping of any motion speed, and at controlled braking of a motion speed of 15km/h and lower, is 2.0MN on a non-uniform train and 1.5MN on a uniform train.

3.4. Modeling

In SOLIDWORKS, it was designed a completely 3D model that included all the important dimensions, shapes and surface of Type 17 coupler. This was an important modeling step because it formed the geometrical basis of all the FEA that would do afterwards. The model was designed to the exact specifications retrieved in technical diagrams and measurements made in the field to make it a real representation. The coupler head and knuckle pin hole areas were given special attention since field data indicated that they were the areas of primary failure. The last model in

Figure 12, was exported STEP format since it is so easy to use with ABAQUS and does not lose its geometry information when exported.

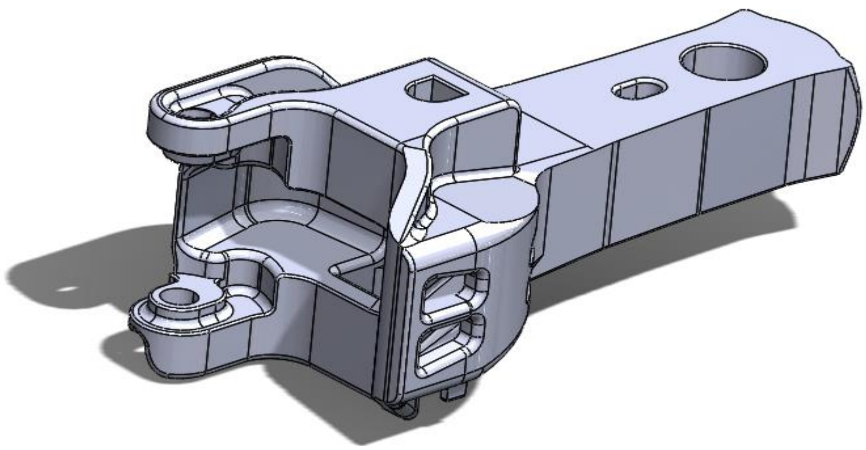

Figure 12: 3D modelling of coupler using Solid work (type 17 standard coupler)

3.5. Finite Element Analysis (FEA) in ABAQUS

3.5.1. Meshing

An excellent meshing option defines the accuracy and efficiency of simulation. In this research, we applied various meshing techniques in the first strength run and the subsequent crack analysis, which were customized to the special requirements of the respective simulation.

3.5.1.1. Meshes for Initial Analysis

For the initial tensile and compressive loads, a tetrahedron mesh in the entire structure was implemented. This kind of element is particularly excellent when meshing complicated and complex shapes like the coupler head as it can readily manner to curved surfaces and irregularities without a considerable amount of manual coloring. The tetrahedral mesh automatically generated simplifies the preparation process of the simulation and therefore it is efficient. This type of mesh is all over the entire body of a coupler as showed in Figure 13.

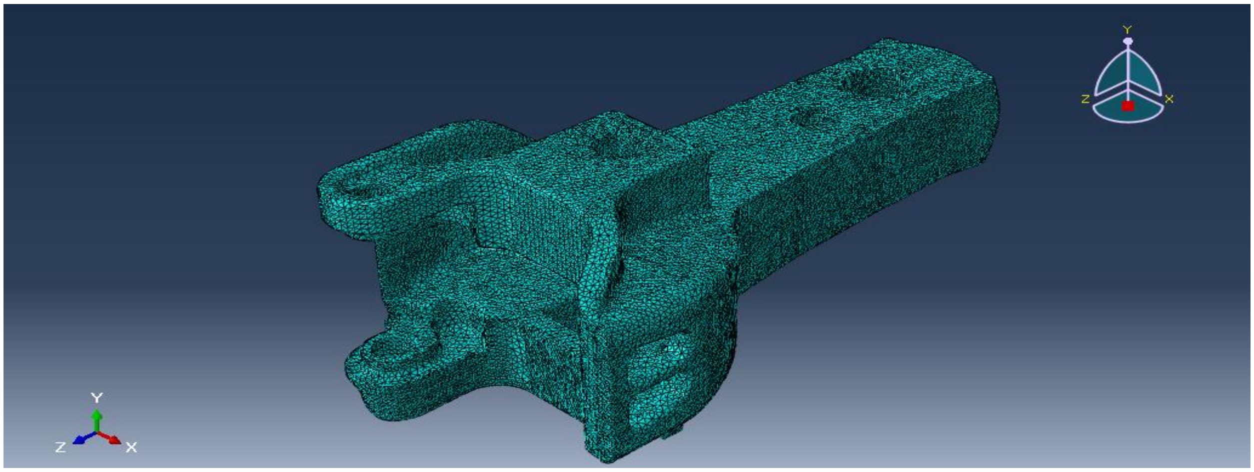

Figure 13: meshing for initial strength analysis

3.5.1.2. Meshes for Crack Analysis

In order to capture the stress singularity at the crack tip a more sophisticated and special meshing technique was required. A basic tetrahedral mesh was not sufficiently refined to produce reliable results for the stress intensity factors or crack characteristics. So initially, a model partition was created only for the crack region therefore commonly marked as contour region as shown in Figure 14(a). The partitioned contour region allowed for the application of a special meshing technique for the region of interest only. A highly refined hex mesh was constructed in that particular region as shown in Figure 14(b). The bottom picture of Figure 14(c) shows a close up view of the contour region. The refined mesh and application of special elements that accept a singularity parameter allows the simulation to model the significant gradient in stress that occurs at the crack tip. The contour region was meshed with the seed that represented the elemental size of 0.15mm.

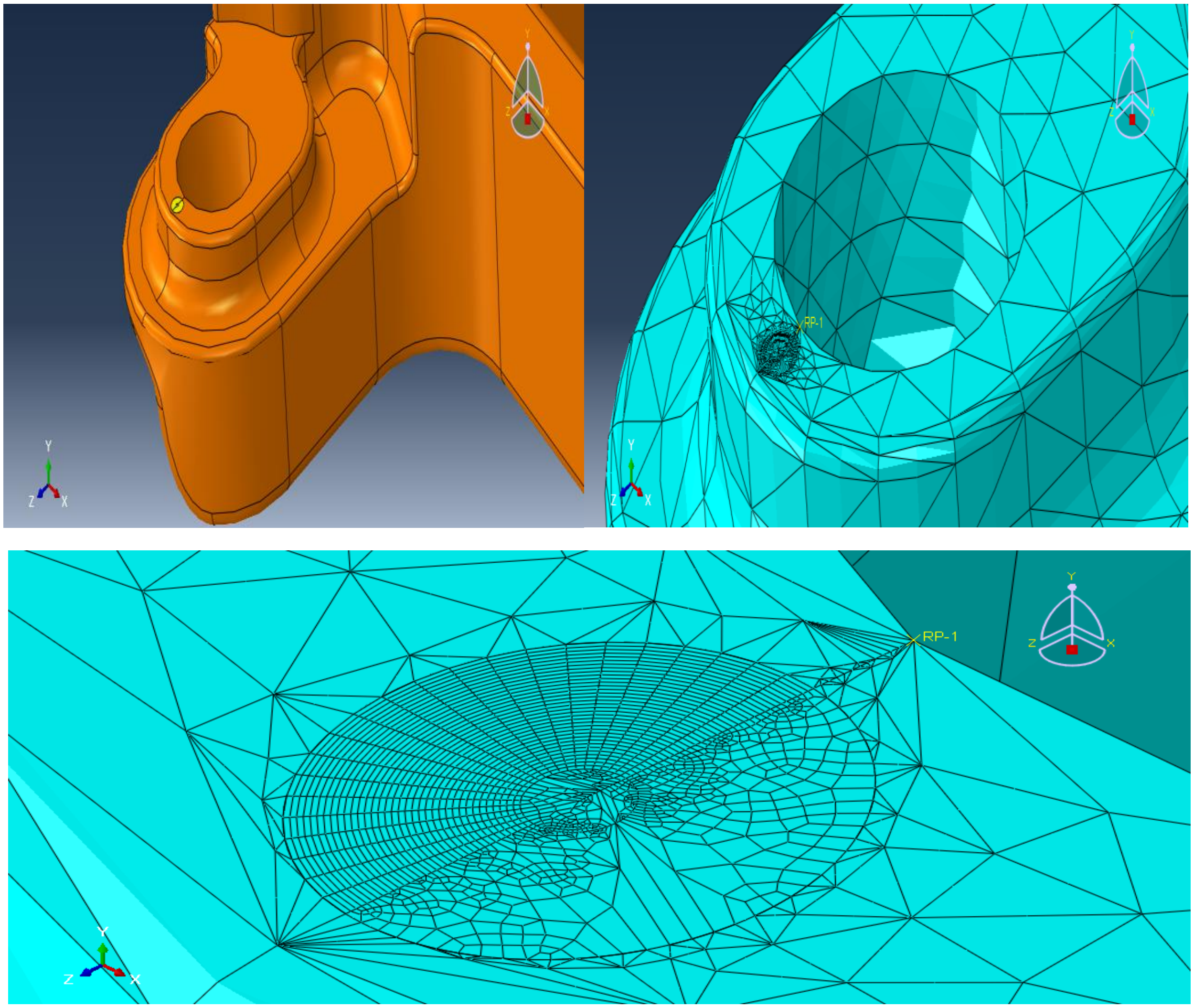

Figure 14: Partition of the couture region from the body and control Meshi

3.6. Loading

Loading is a major step to FEA in order to capture the reality of simulation real-world condition and situations. A boundary condition and loading conditions for the three conditions namely tensile loading, compressive loading and crack analysis was presented below.

3.6.1. Tensile Loading

Tensile Condition Tensile condition represents the condition when longitudinal hauling is applied on the coupler therefore the force that pulls the coupler. On the coupler head, a tensile force of 291.36kN was applied on the coupler head. In order to model the mechanism that holds the coupler in a fixed position, an encastered support boundary was applied on the coupler. The encastered support is indicated in Figure 15, which is at the support hole in the coupler head. The resultant tensile force and encastered support allows the simulation to compute the stresses correctly especially around the knuckle pinhole of the coupler head.

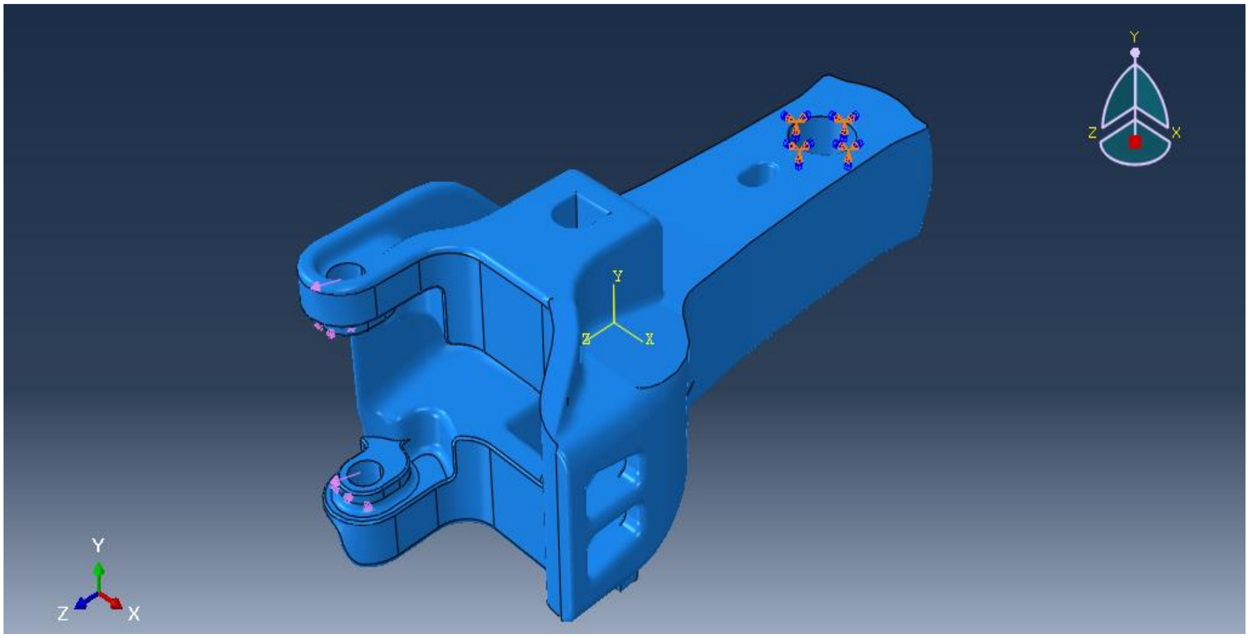

Figure 15: Tensile loading and boundary condition

3.6.2. Compressive Loading

In the compressive loading scenario, which represents the impact on coupler during emergency break, different boundary conditions and loading were applied. According to reference, 2.5 MN compressive force was used for non-uniform train on emergency break was converted to pressure (19.1 MPa) by finding the area on which the force is applied. Area was measured by SolidWorks software as shown in Figure 16 and it is 6242.55 mm2. As shown in Figure 16, 19.1 MP compressive force was applied on the area where coupler head would be impacted on. The boundary conditions for the compressive scenario would be to restrain the movement of the coupler from the opposite end, applying the force from the rest of the train in opposition to it.

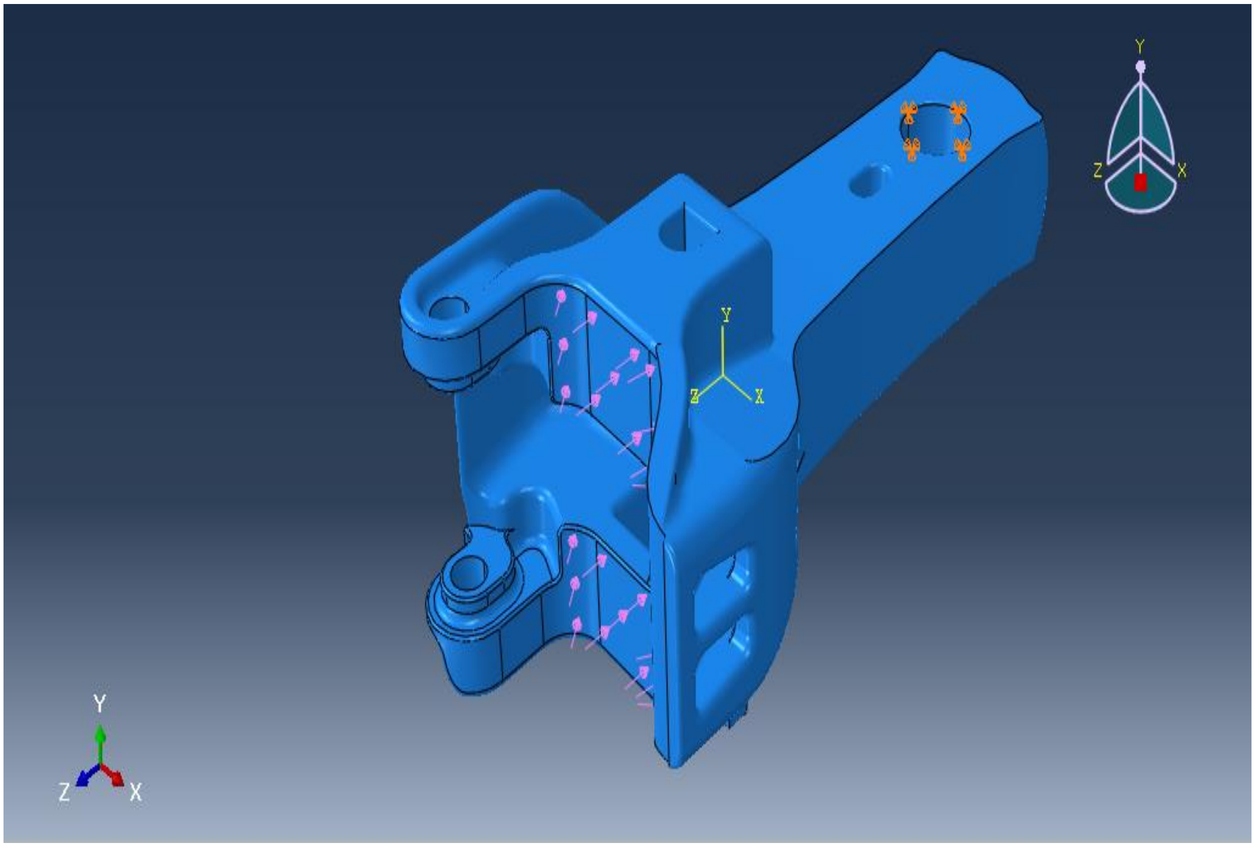

Figure 16: Compressive loading and boundary condition

3.6.3. Tensile loading after the crack was introduced

In the crack analysis, a tensile load 291.36 KN was applied on a coupler head with a pre-existing crack as in the above tensile loading. In crack measurement, different sizes of cracks were measured but on this study, an average of crack size, which was characterized by a front length of 7.5 mm and a depth of 19 mm, was used. The applied crack was on the pinhole of the coupler head as shown in figure (17). The boundary conditions were same with the tensile loading, a fixed support on the coupler head support hole. In addition, a displacement support was used on the pinhole's face. The displacement support was used to mimic the behavior of the crack on the material and that is why it was implemented to make the simulation accurate in the range of stress intensity around the crack tip.

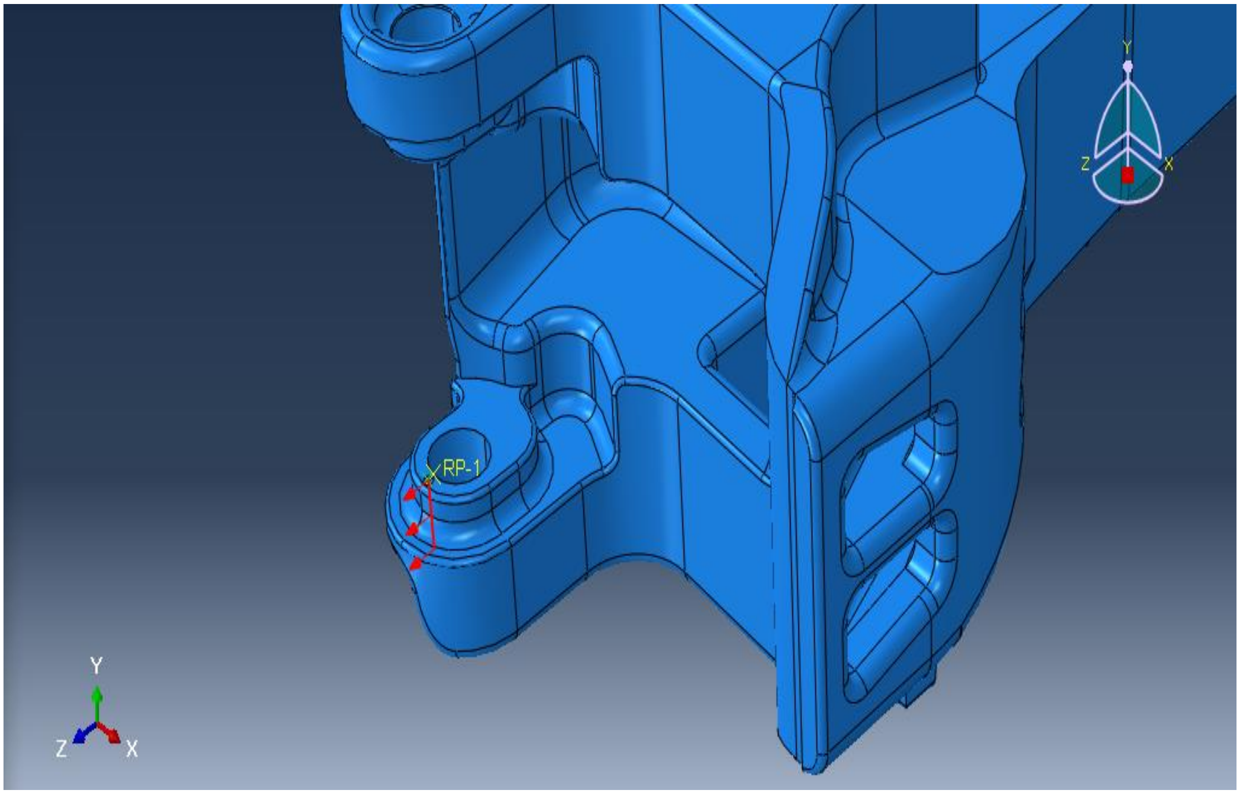

Figure 17: Introduced crack on the couture region

3.7. Mesh Convergence

In order to be sure that simulation results are accurate, a mesh convergence study was performed for both tensile and compressive loading situations. It includes a process of improving the mesh (more elements), therefore adding more elements and observing the changes in the key output. The aim is to continue adding more elements until a certain point where the difference in stress is so insignificant and this means that the solution is converged. In Figure 18, von Mises stress increases with the element count. There were big variations in the values of stress with the maximum of 319.146 MPa at first. The values started to be constant with the addition of elements and finally reached 281.172 MPa at the last refinement. The stabilization of the values means that the mesh is thick enough such that we have a valid converged solution to the compressive loading analysis.

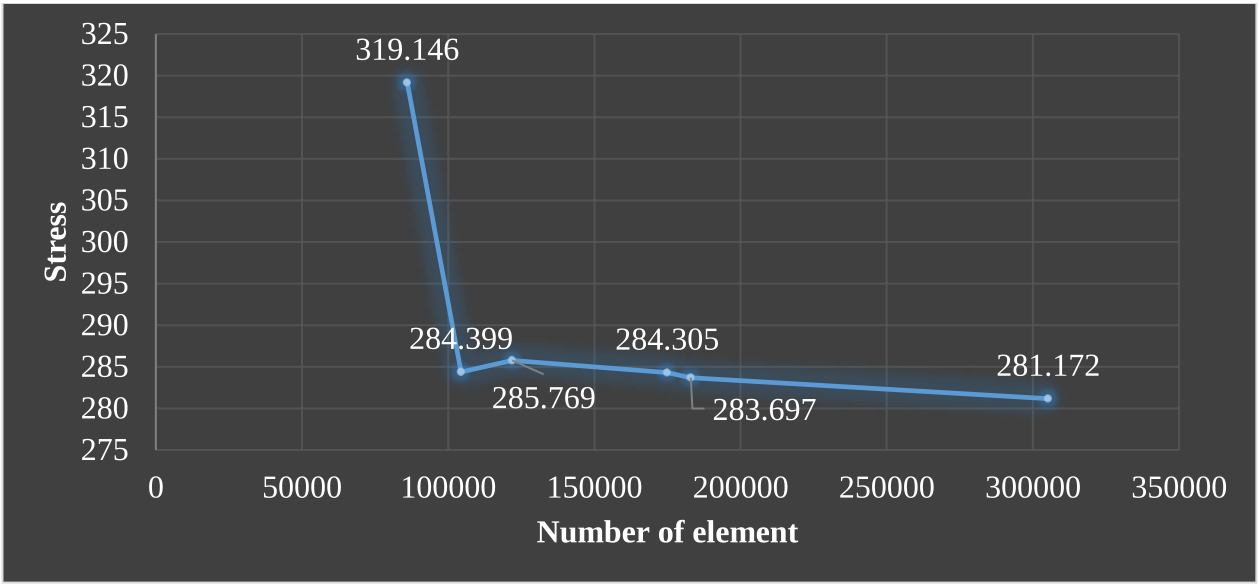

Figure 18: Compressive Loading Convergence

In a related one plotted in tensile loading case, von Mises stress against number of elements. Figure 19, obtained the initial stress of 76.87 MPa with relatively small number of elements. Then through refined mesh, the stress value kept changing as more elements add, but as the number of elements increase, the values tend to level off. Finally, when the number of elements reached the maximum the value stabilized at 70.81 MPa. The leveling off the curve means that the solution has reached its convergence (hence the correctness of the final stress value). Similarly, a mesh convergence test was done for the modified geometry as shown in figure 20

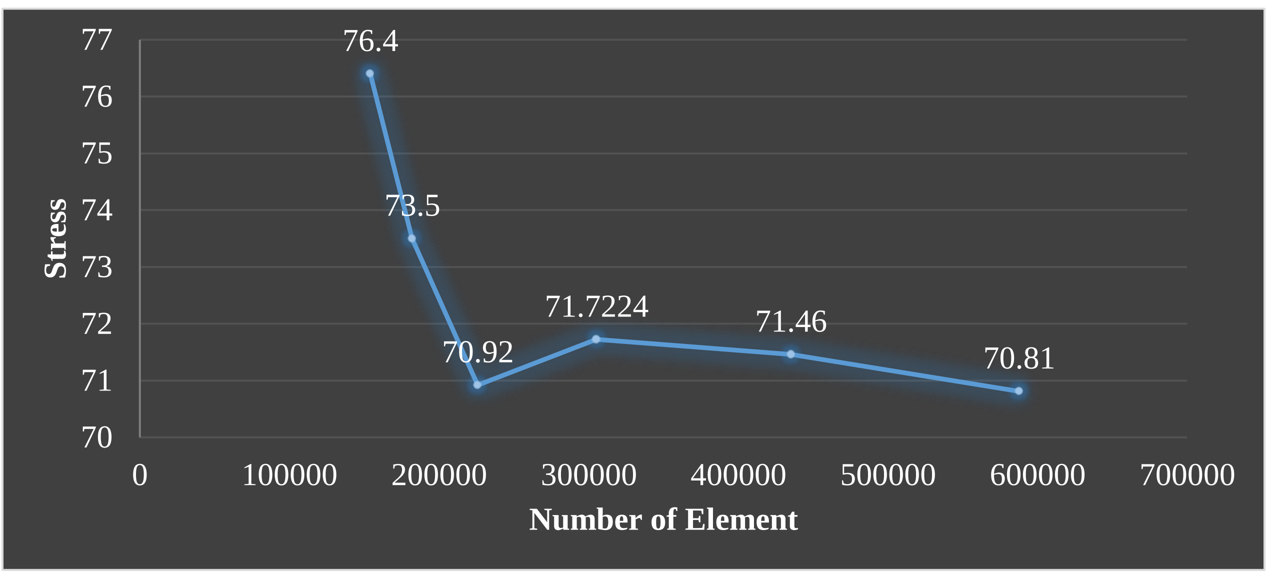

Figure 19: Tensile Loading Convergence

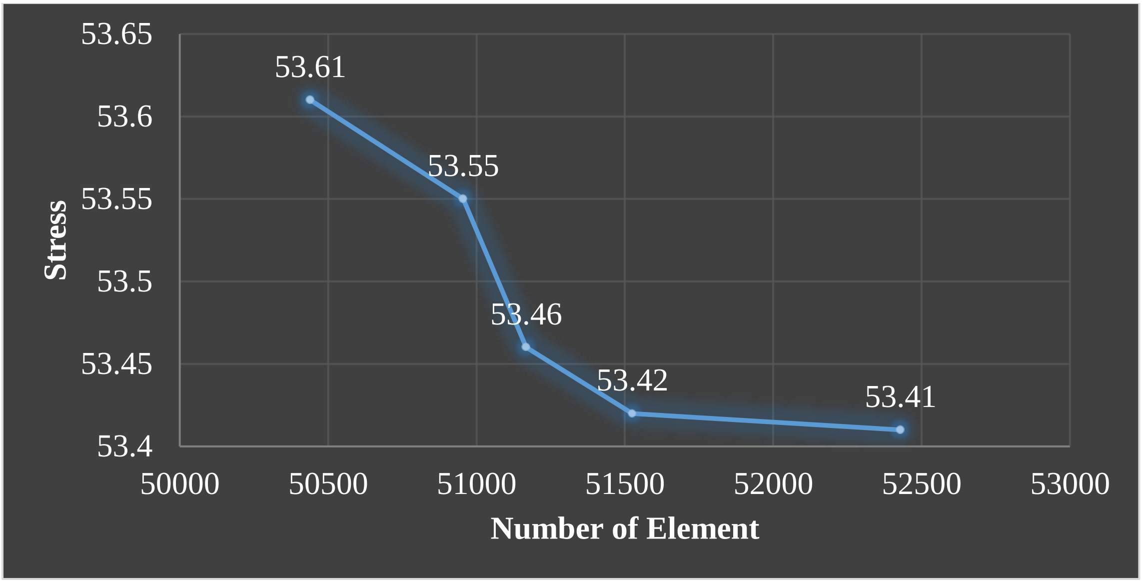

Figure 20: Modified Geometry Convergence

3.8. Fatigue analysis

Introduction Considering the purpose of determining the life cycle of the coupler head a fatigue analysis has been applied using the FE- Safe software. The input data for the analysis has been created from the ABAQUS output results files in ODB format, which includes static stress solutions for each loading scenario. The material properties have been set into the FE- Safe by defining an S-N curve data set for the Grade E steel. The dataset has been created based on the material ultimate tensile strength of 855 MPa and other parameters by using the software steel model to calculate the endurance limit and high cycle fatigue behavior. The fatigue analysis has been based on the Stress-Life (S-N) methodology. One of the most important elements of the configuration is the implementation of the Goodman mean stress correction theory. The aim of the analysis has been determined the fatigue life over the whole component and the results have been presented as LOGLife values which is the base 10 logarithm of life in cycles. In the model including the initial crack, same SN approach has been used including the Goodman correction.

3.9. Geometry Modification

The study on the geometric modification was initiated through analysis of factors that cause localization of stress. This analysis used finite-element analysis and evaluation of relevant literature. Results show that changes in geometry, particularly in holes with circular shape and junctions, produce high stress values. These findings established categories of possible changes that include changes in materials, changes in processes for manufacturing, controls in operations, and changes in geometry.

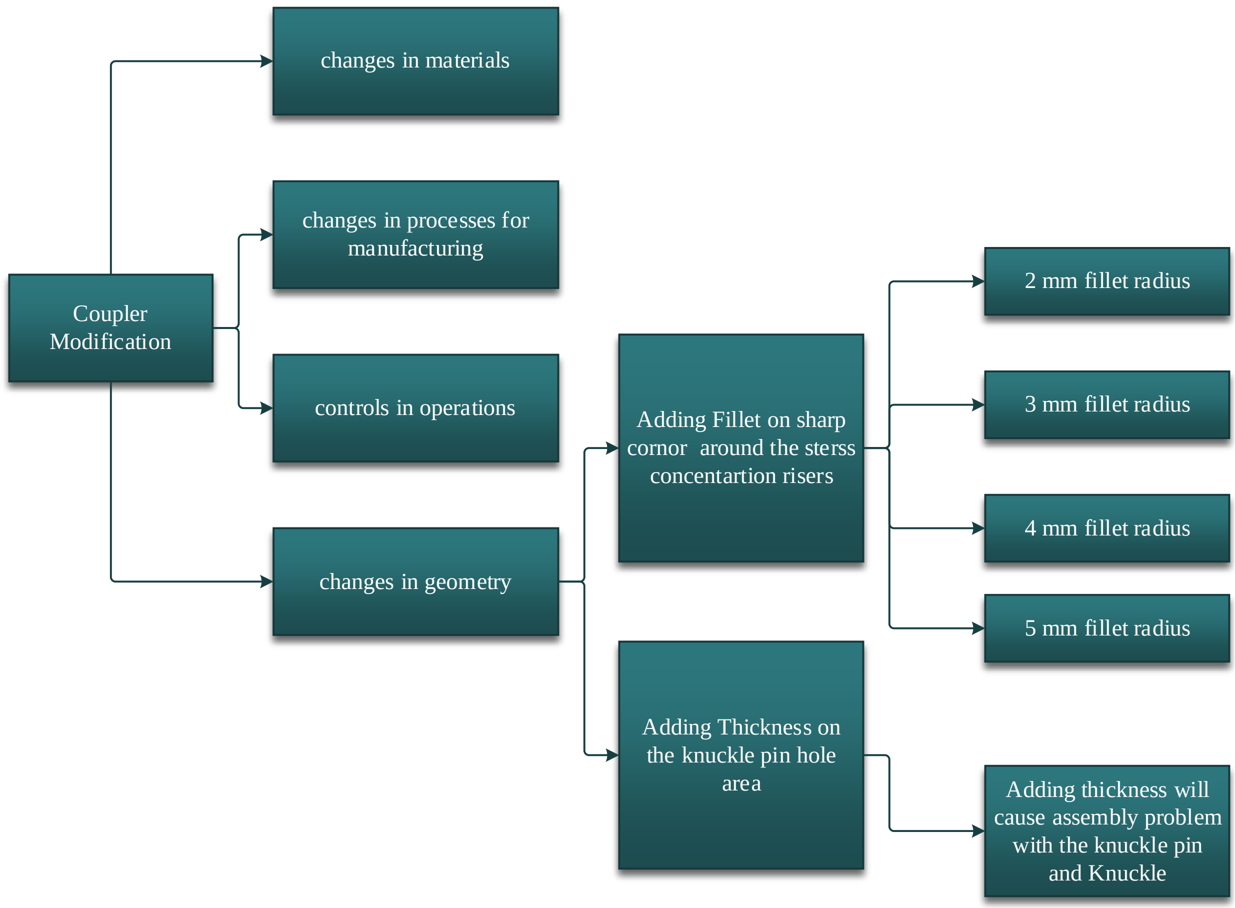

Figure 21: Geometric modification

Approaches that focus on materials may reduce negative effects but fail to address causes of the issue. These material changes may increase strength of the component or resistance to failure but retain design features producing localized high stress. Implementation of such changes also involves high costs. Strategies for improving manufacturing similarly received no consideration. Such techniques require significant capital spending on equipment and training of individuals and require that the process undergo approval again following implementation. Similarly, Strategies relating to operations, including strategies for maintenance, remained outside the scope of this investigation. Underlying shortcomings in engineering design are not addressed by operational controls such as limits on load or speed and inspections with high frequency. These measures reduce productivity in operations and show continuous increases in cost. These measures therefore function as administrative controls but not as changes in engineering design. They fail to provide solutions with long-term durability or to improve operating durability that the coupler demonstrates.

Data provide support for this approach and show that changes in the form of elements in the coupler, including changes that reduce sudden changes in form, produce lower levels of stress in similar designs for couplers. As an example, Chunduru, Kim, and Mirman 2011[17] found that changes in form at points in the knuckle where pulling occurs and allow Type E couplers from AAR to reduce stress by between 10 and 18 %. Similarly, Hua, Wang, and Li 2017[10] found that Type E couplers reduce stress by removing edges that show changes on S surfaces. These findings indicate that resistance to loading that occurs multiple times increases without changes in properties of materials.

As a result, changes in form provide the approach that is most balanced for combining usefulness that is immediate, costs for implementation that are minimal, and findings from data that show reduction in areas where stress concentrates in couplers that are already in use in the system. The approach addresses the main source where stress concentrates by changing the physical form, provides improvements in performance that can be predicted, does not create problems for compatibility with systems for manufacturing and operating that are current, and provides returns in economic terms that are considerable across the period of time that the system operates. Filing radii and chamfers at internal corners and transitions proves beneficial because it creates smooth stress distribution, meaning that it will not accumulate force at sharp edges. The first FEA, which has been run on the shape and the result, is shown, is that the sharp cornered shape around the knuckle pinhole is actually the main stress concentration area since the result is shown in chapter four. The corners are like stress raisers and the local stress is very high at that point compared to the average of the component. Therefore, that spot is the actual weak spot. The main modification that will be applied to reduce the stress concentration is adding the fillet radius on the coupler head knuckle pinhole as in the figure 22. Adding the fillet radius as in the above figure is an effective way to reduce the stress concentration. Because it creates a smooth transition and it spreads the load over a larger area.

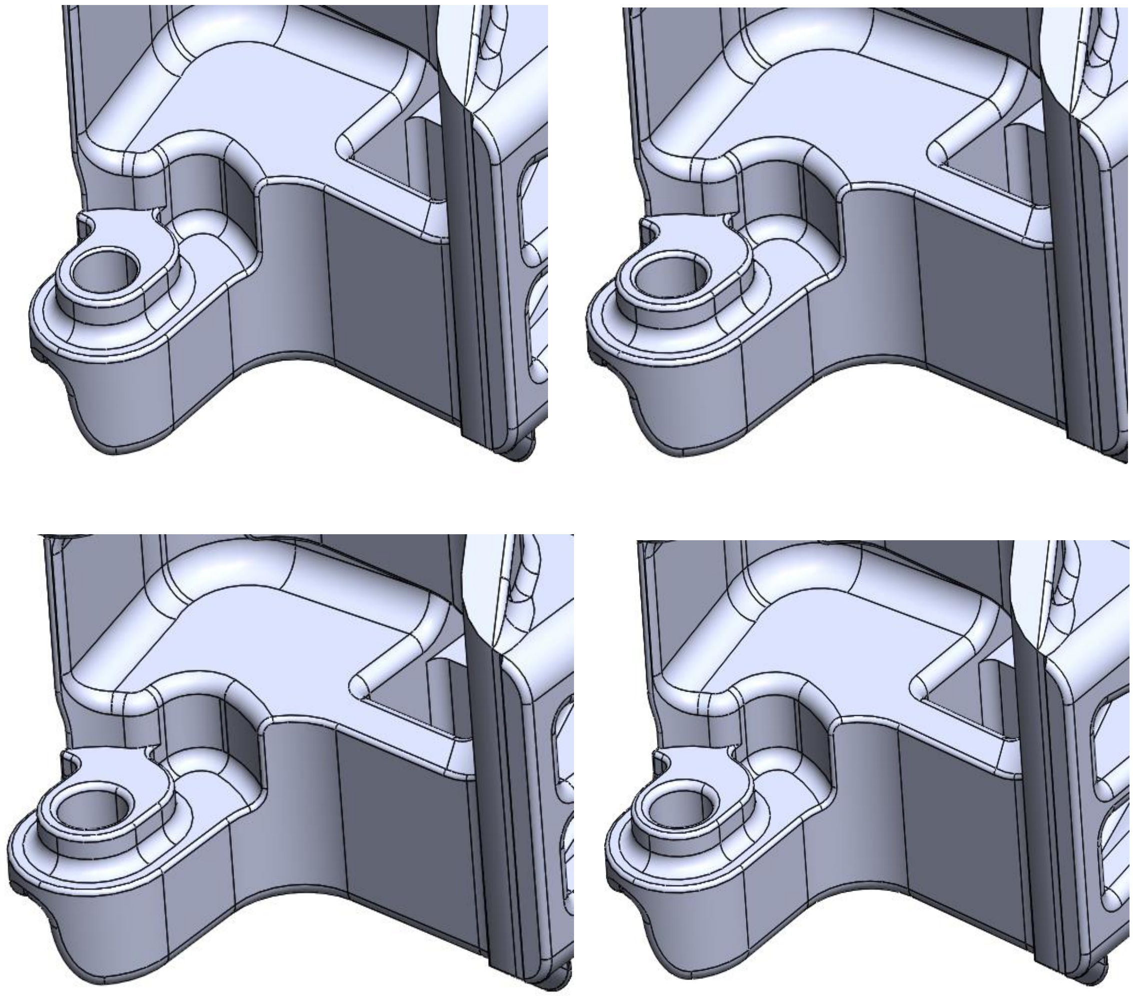

Figure 22: Modified Geometry with different fillet radius on the pinhole region

Chapter Four

Result and Discussion

4.1. Results

4.1.1. Stress, strain, Deformation and LOGLife under Critical Loads

Considering the purpose of determining the life cycle of the coupler head by implementing, the above loading and boundary conditions, which are shown in the previous chapter, the following Finite Element Analysis results have been achieved. The analysis has been implemented for the tensile critical load scenario, which is used in everyday hauling, and compressive critical load scenario, which is used in emergency breaking.

4.1.1.1.Tensile Loading Results

Due to the tensile loading during the hauling, the maximum von Mises stress of 70.8 MP was observed around the knuckle pinhole after the mesh had been fine-tuned, when the component was analyzed under tensile load as showed in Figure 23. This may be below the yield strength of Grade E steel (655 MPa), but it showed where the stress build up to. The von Mises stress map is essentially a map that indicates where the areas of the component are most at risk of failure, and as we can see from the map, the knuckle pinhole is the weak spot. The maximum displacement was found to be around 0.0106 mm, which occurred at the knuckle pinhole of the coupler head, and the maximum principal strain was about 0.000324 mm, which was centered at the edges of the pinhole of the coupler head, as illustrated in Figure 24 and 25 respectively. Furthermore, the LOGLife fatigue estimation predicted the logarithmic life of estimation over 10^5.713 cycles at the zones highlighted in Figure 26.

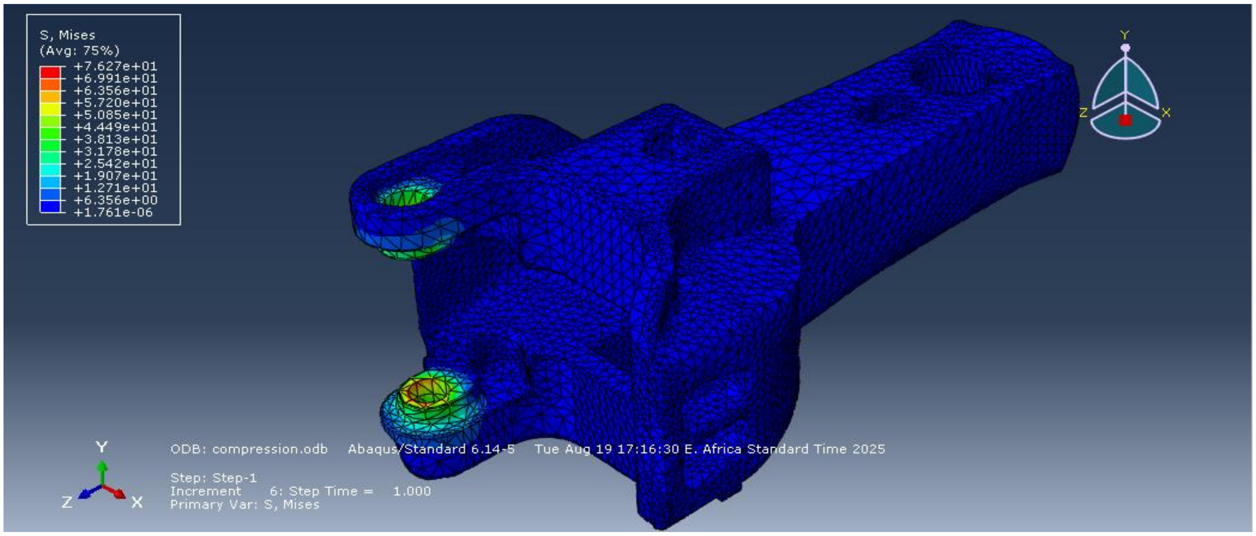

Figure 23: von Mises stress (in MPa) when the coupler was subjected to tensile loading

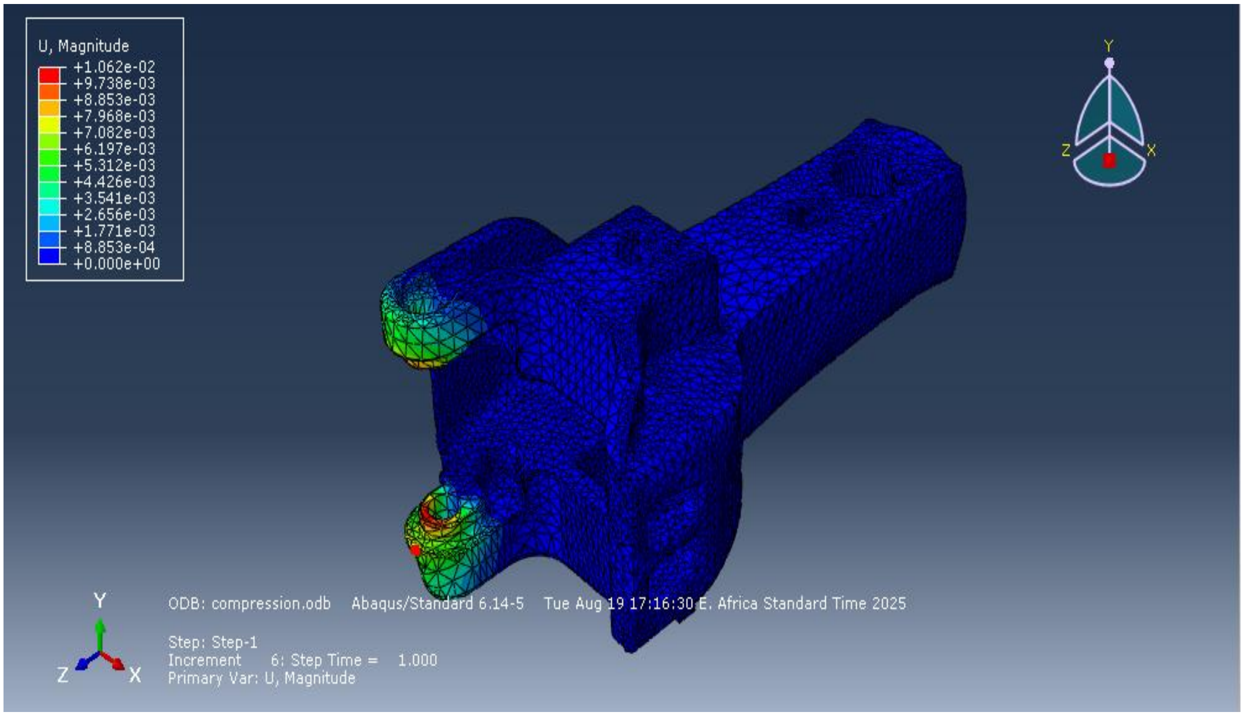

Figure 24: Deformation (in mm) due to tensile loading

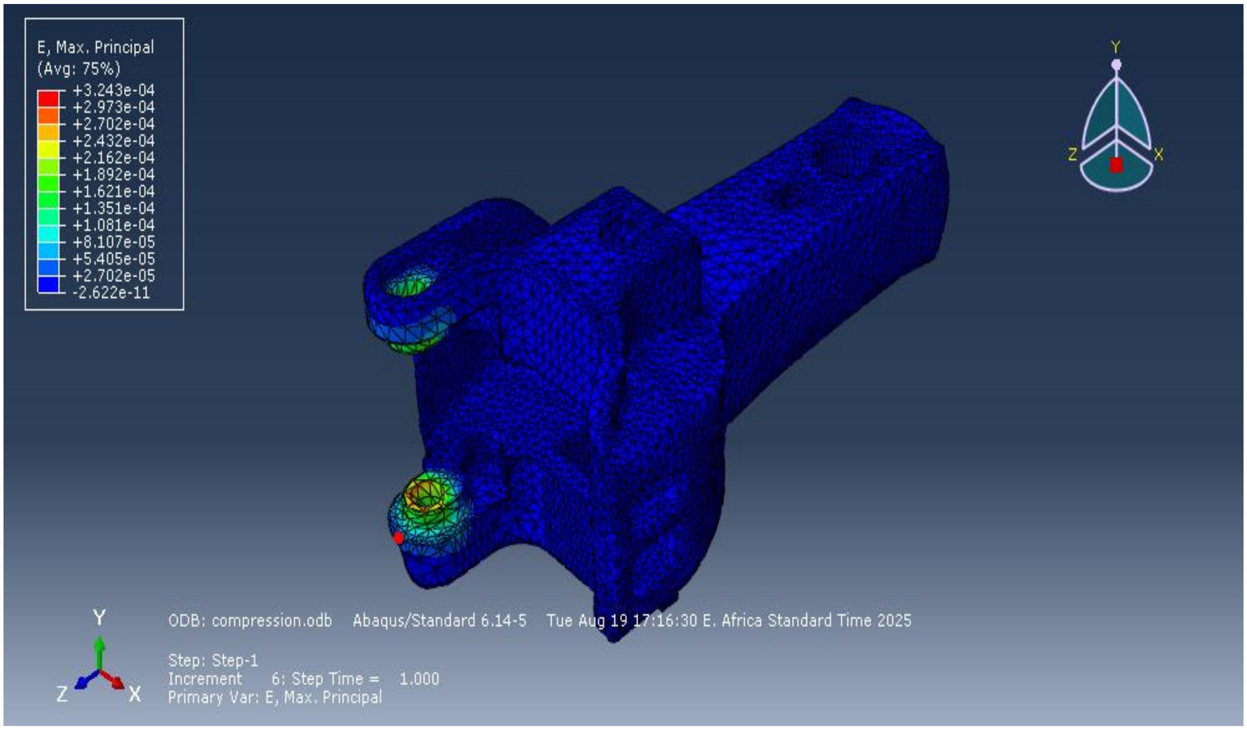

Figure 25: Maximum principal strain (in mm) due to tensile loading

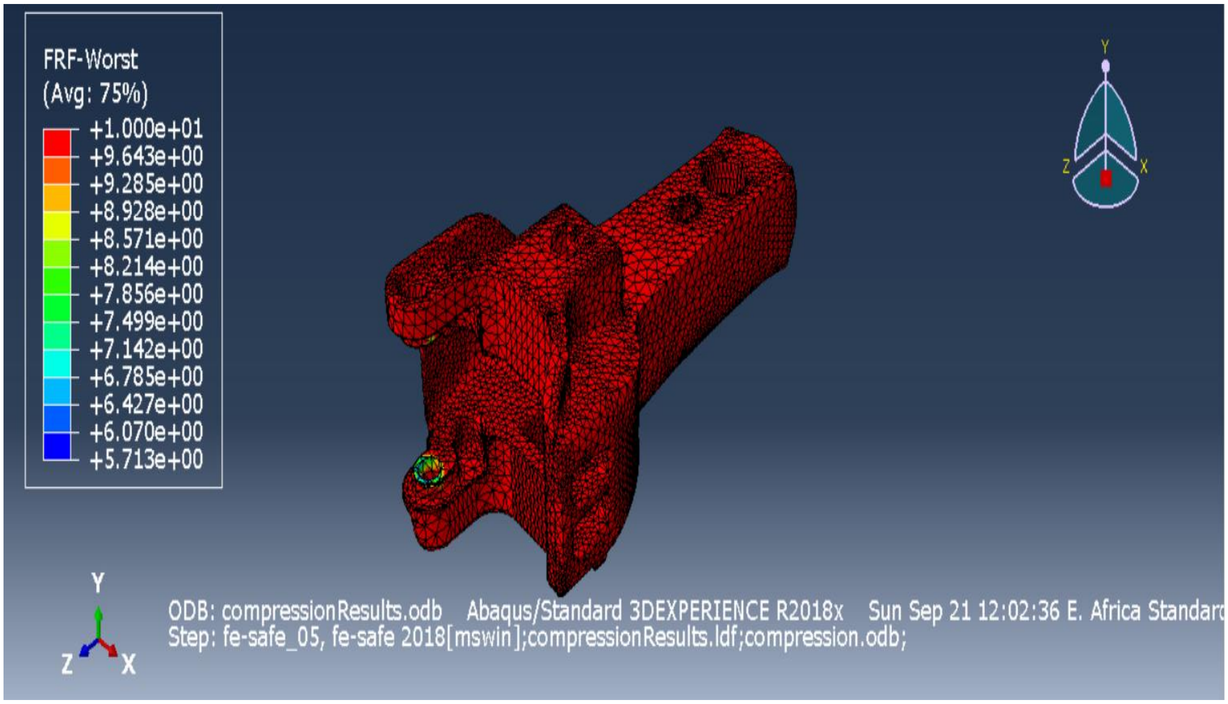

Figure 26: LOGLife of coupler when subjected to tensile loading

4.1.1.2.Compressive Loading Results

When the compressive loading which experienced during the emergency breaking, the pattern of the stress distribution is quite different from tensile loading. The main stress hotspots in the simulation are at the points of contact in the region, on the face of the coupler, where the compressive force is exerted. The maximum von Mises stress measured 281.172 MPa as illustrated in Figure 27. The deformation at the compression reached its peak at around 0.328 mm on the face of the coupler and its internal components as illustrated in in Figure 28. Strain analysis showed in figure 29, that the maximum principal strain was around 0.000747 mm, which occurred at the points of compression.

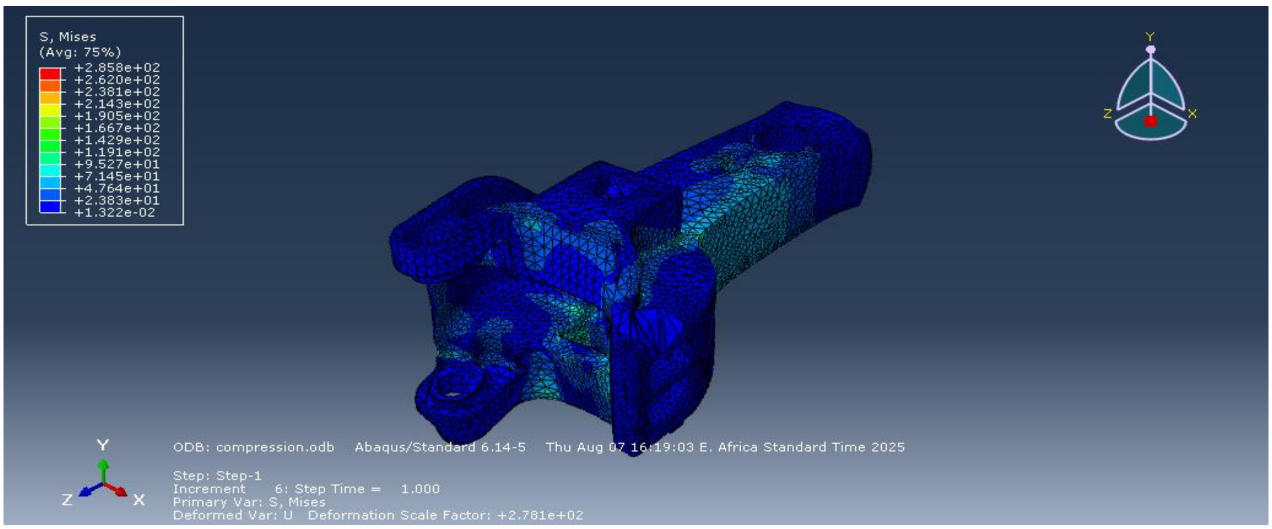

Figure 27: von Mises stress (in MPa) when the coupler was subjected to Compressive loading with different number of element

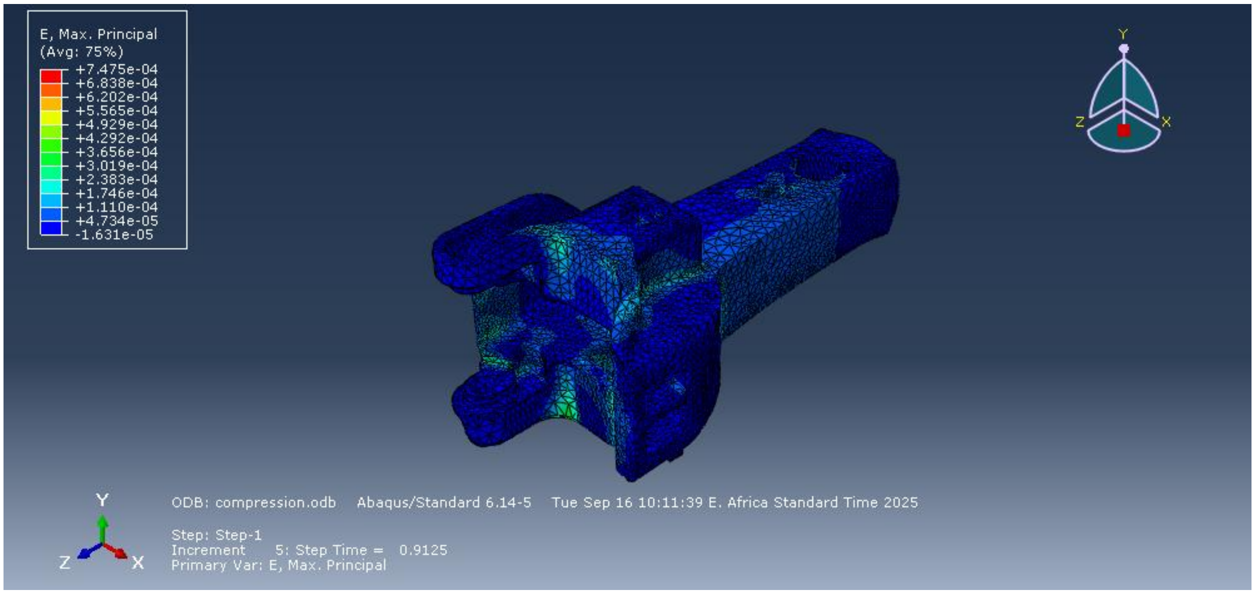

Figure 28: Maximum principal strain (in mm) due to tensile loading

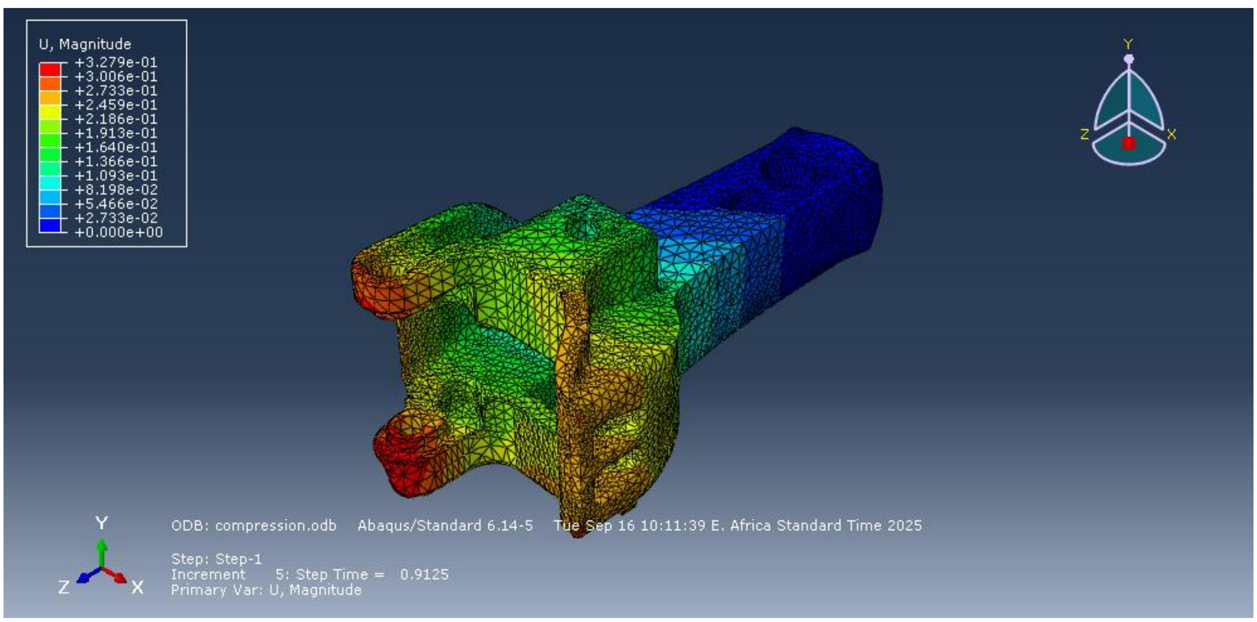

Figure 29: Deformation (in mm) due to tensile loading

4.1.2. Crack Analysis Results

With the same boundary condition and application of loading but with the introduction of pre-existing crack dimensioned 7.5mm by 19mm at the region of interest from field observation, it can be seen that the stress distribution is significantly modified. The crack study provides the most pertinent information to assess the integrity of the coupler when a pre-existing flaw is present. The simulation under the same tensile loading of 291.36 KN as the initial case showed an increased concentration of stress proximal to the crack tip. As shown in Figures 30, the von Mises stress at the crack tip reached the maximum value with stress intensifying the stress concentration around the crack, which is certainly guaranteed to cause failure. The deformation also increased to the maximum of about 2.21 mm proximal to the crack tip, enhancing the localized distortion and promoting failure propagation as showed in Figure 31. The strain intensified to the maximum principle value of about 0.0116, which localized at the edge of the crack as presented in Figure 32. In addition, the LOGLife also decreased dramatically to the range lower than 100 cycles, which means the material would fail fatigue rapidly at the presence of the crack. The region where the crack would propagate would be indicated as showed in Figure 33.

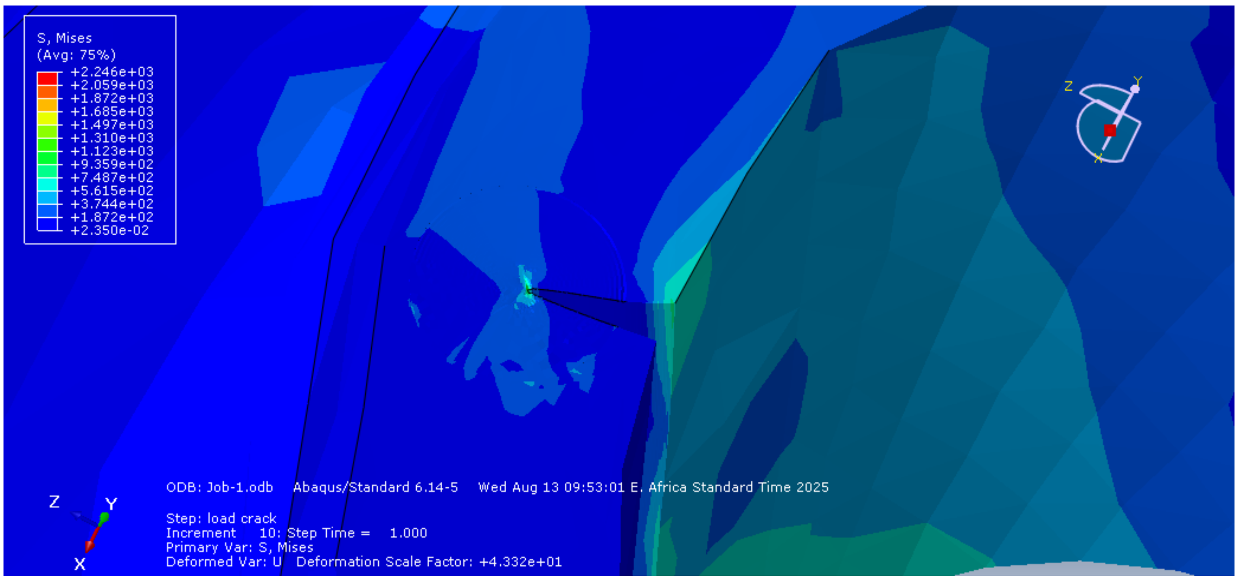

Figure 30: von Mises stress (in MPa) around the couture region

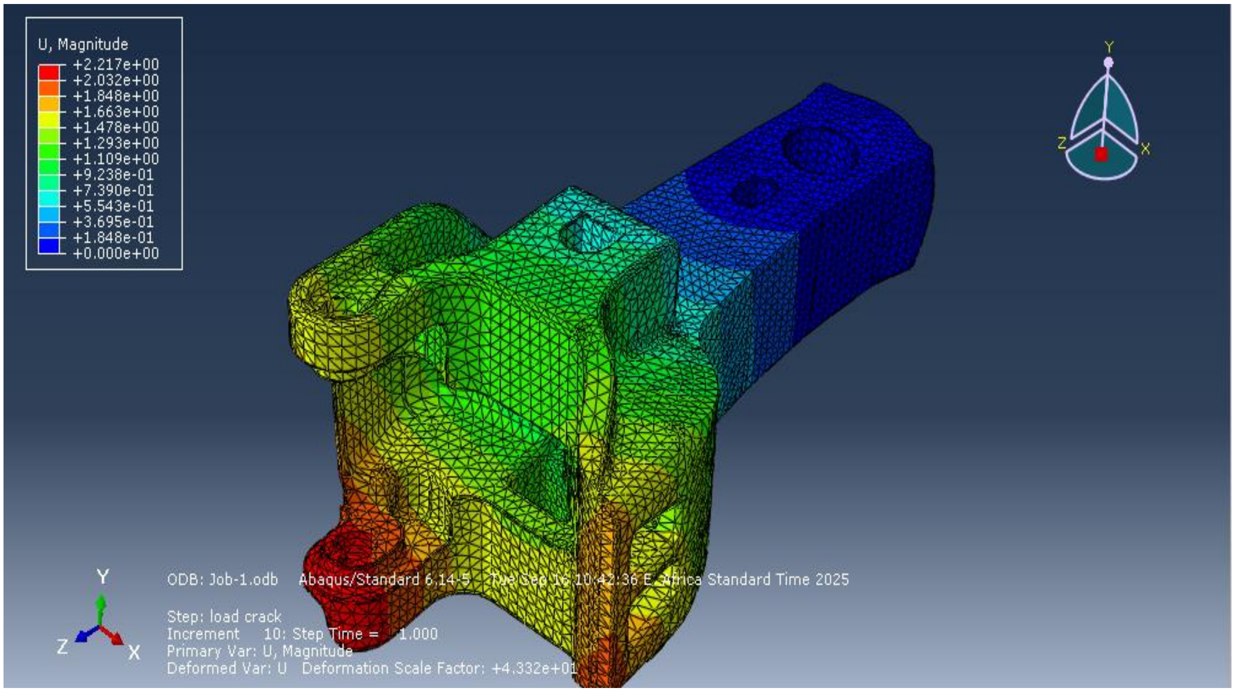

Figure 31: Deformation of cracked coupler (in mm) due to tensile loading

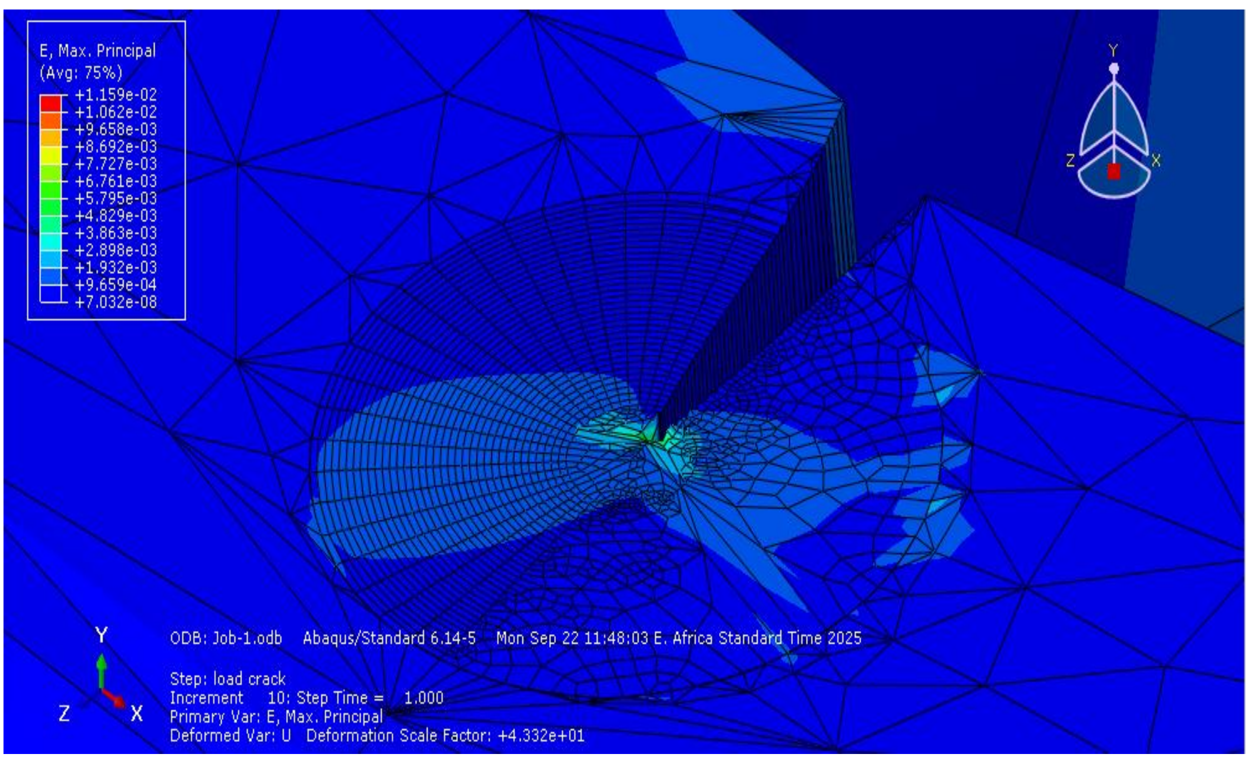

Figure 32: Maximum principal strain (in mm) of cracked coupler on tensile loading

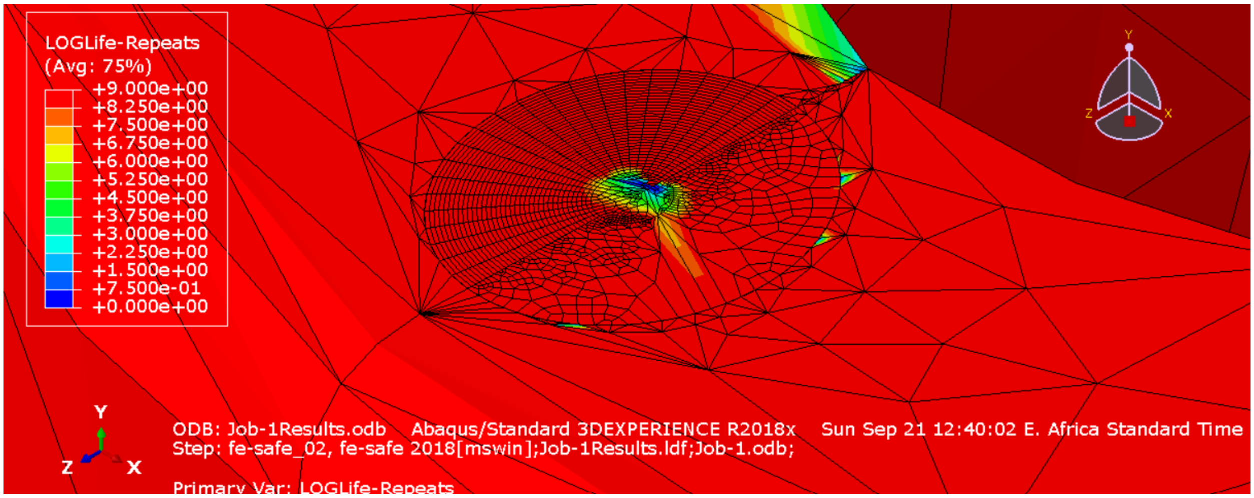

Figure 33: LOGLife of cracked coupler when subjected to tensile loading

4.1.3. Results on Geometric Modifications

Introduction of fillet radius at the sharp internal corner of knuckle pinhole, which means the geometry of the coupler, is modified at the region of interest. The comparative FEA under tensile loading of the same value of 291.36KN shown in figure 34 that the peak value of von Mises stress at the critical point would be decreased. The maximum von Mises stress of the simulated modified geometry was decreased to about 53.41Mpa, which is at fillet radius of 5 mm. In addition, the maximum deformation is about 0.0227mm. The distribution of stress around the pinhole filleted would be smoother as showed in Figure 35. Moreover, the strain would intensify to the maximum principle value of about 0.000226, which would distribute uniformly with the geometric change as shown in Figure 36. What is more, the LOGLife would increase to more than 10^6 cycles as shown in Figure 37.

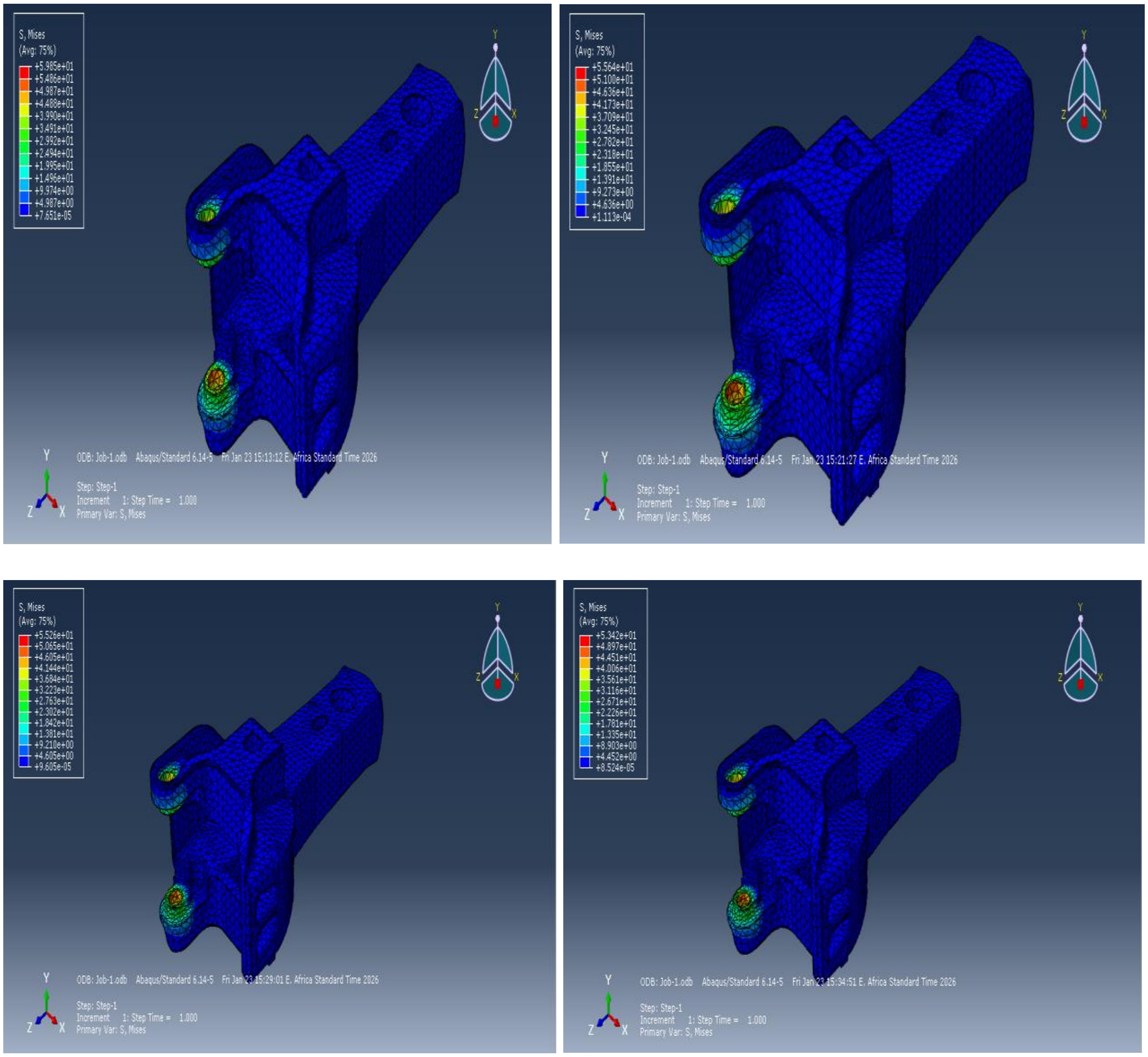

Figure 34: Modified Geometry von misses stress (in MPa) result at different fillet Radius

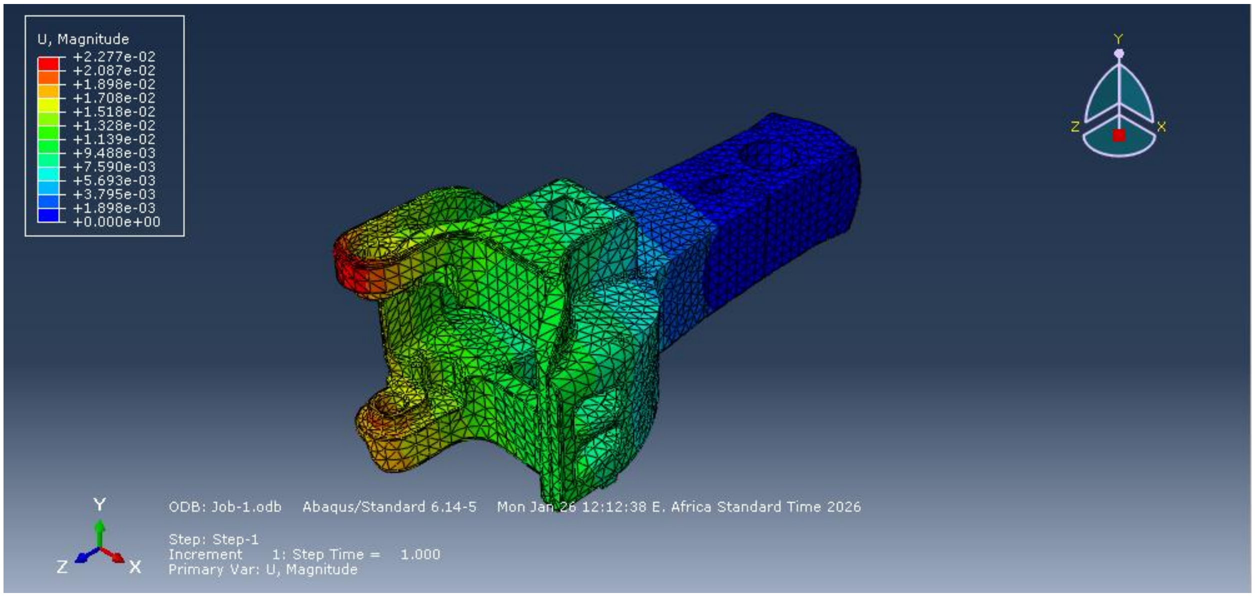

Figure 35: Deformation of Modified coupler (in mm) due to tensile loading

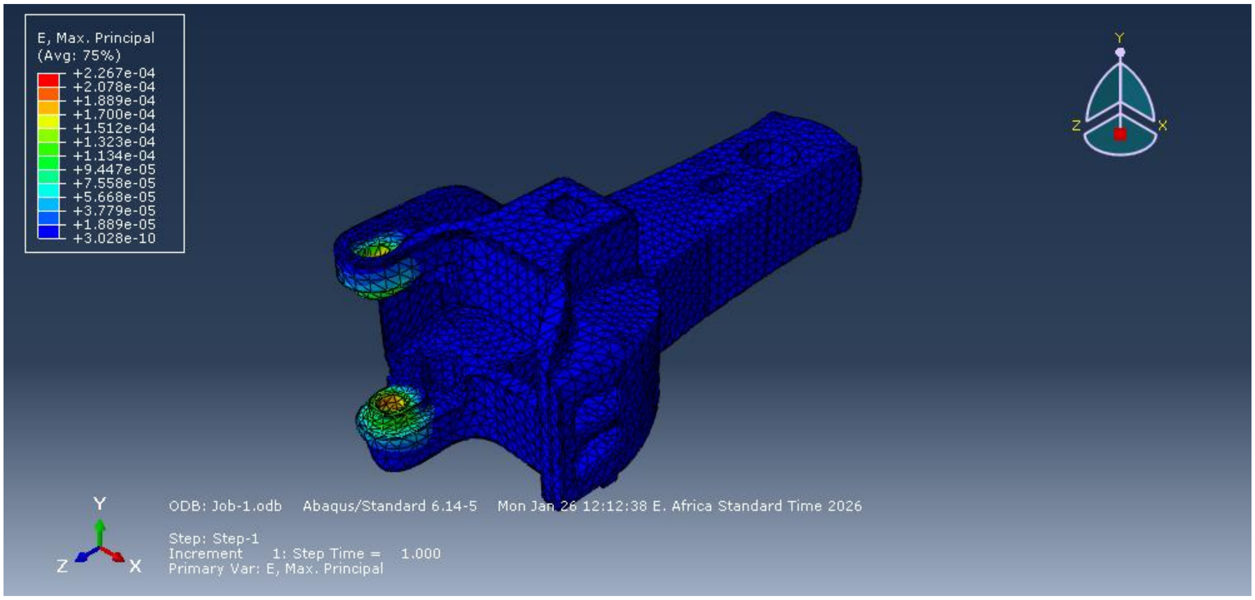

Figure 36: Maximum principal strain of Modified coupler (in mm) due to tensile loading

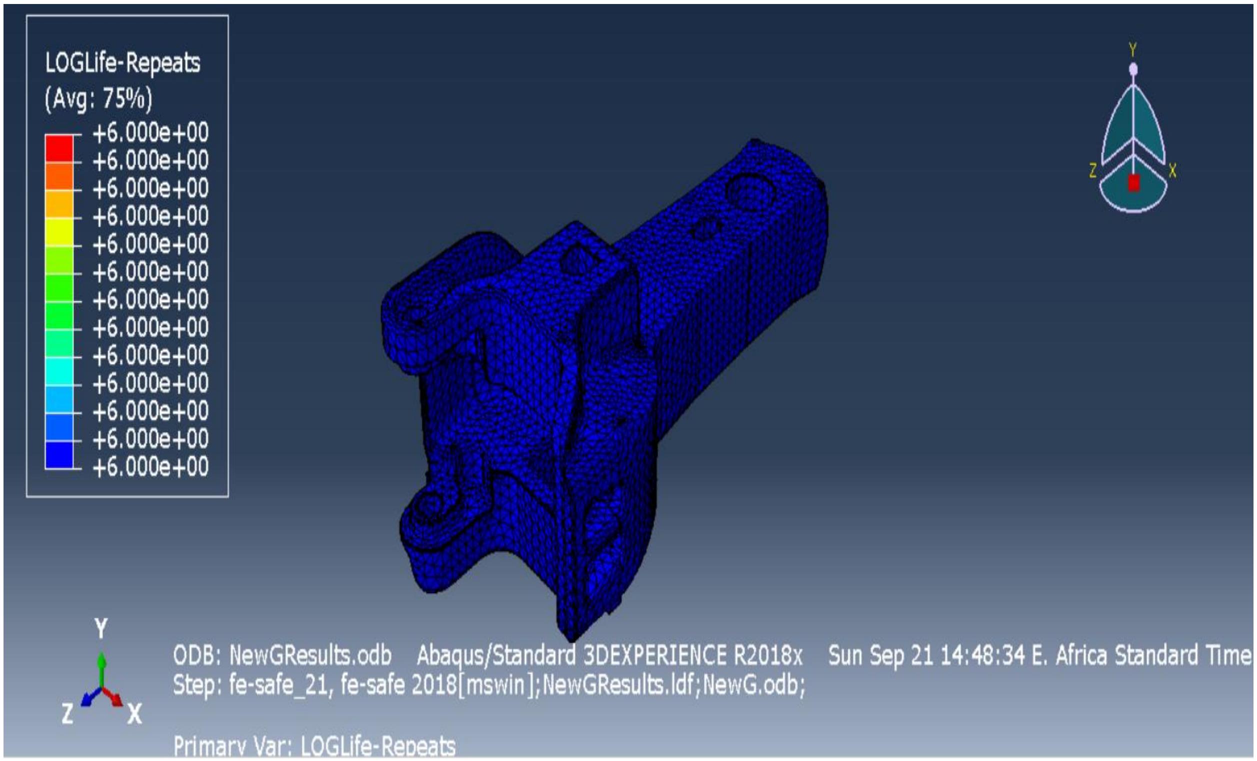

Figure 37: LOGLife of Modified coupler when subjected to tensile loading

Table 14: Result summery

Analysis Cases	Max. von Mises Stress (MPa)	Max. Deformation (mm)	Max. Principal Strain (mm)	Life Cycles
Tensile Loading	70.81	0.0106	0.000324	> 10^5.713 (~ 516,000)
Compressive Loading	281.17	0.328	0.000747	
Tensile Loading With Crack	2,246.00	2.21	0.0116	< 10^0 (< 1)
Tensile Loading on Modified Geometry	53.41	0.0227	0.000226	> 10^6 (> 1,000,000)

4.2. Discussion

4.2.1. The FEA Analysis Result and its implication to Preliminary Failure analysis

A preliminary statistical failure analysis, which was done, based on the maintenance record was the foundation of this research. From the above failure analysis, we can see that the failure pinhole causes 34.5 percentage of all failures. The result of FEA also prove the empirical finding, which gives us the computational validation we wanted. When the tensile-load simulation was carry out, the maximum von Mises stress was 70.8MPa and it was concentrated at the pinhole. The good agreement between the result of failures in the real world that we actually had and the one that the model predicted shows that the FEA has the right real model simulation of the problem. That is, the statistical observation that recorded from the maintenance record has taken a firmer engineering principle that the pinhole geometry is a significant stress concentrator and therefore the apparent initial crack initiation point.

4.2.2. Implications of Stress Results in the Context of Material Strength

An exhaustive study comparing the computed stresses with the material characteristic of Grade E steel must be made in order to understand the failure modes. Tensile Load (70.8 MPa) in Relation to Material Strength the 70.8 MPa is well below the yield strength (σ_γ = 655-755 MPa) and ultimate tensile strength (σ_k = 806-850 MPa) of Grade E steel. However, the significance of 70.8 MPa is that it is the amplitude of a cyclic load. In high cycle fatigue, it is possible to fail at a stress well below the yield strength if the component is subjected to a cyclic load. Finite Element Analysis (FEA) has proven that the tensile operational load due to geometric concentration is high enough to initiate the micro-cracks over numerous loading cycles and cause the failures that we have recorded from the preliminary failure analysis of the component. The result of both deformation (0.0106 mm) and Strain (0.000324) is low, which means that the component is still elastic under this tensile load. However, the LOGLife result of 10^5.713 cycles (~516,000 cycles) is the significant result, which explains the Limited life span of the coupler.

Although the compressive stress 281.2 MPa is greater than tensile loading stress, since it impact for the failure is less because of a wide surface contact and volume. It does not cause yielding but it represents the lower limit of the stress cycle, when braking events. The sum of tensile (70.8 MPa) and compressive (281.2 MPa) stresses results in a considerable range of stress ($\Delta\sigma$ = ~352

MPa). The resulting high stress range is one of the reasons for fatigue damage, which greatly reduces the service life of the component.

After simulation of cracked coupler, the computed stress distribution was amplified which exceeds the yield strength of the material by 3.4 and the ultimate tensile strength of the material by 2.8 times. This situation is not possible since the material would start yielding and plastic deformation well before this. It shows that when the first micro-crack is initiated either by fatigue or a casting related defect, the mechanics change from the strength of the bulk material to the stress intensity at the terminus of the crack. This explains the catastrophic nature of the failures we have seen in practice

The stress is concentrated and that leads to high strain (0.0116) and deformation (2.21mm) at the tip of the crack. At the instant that LOGLife goes below one cycle, it is an instant failure. That is why field failures are so catastrophic and sudden, the coupler behaves as expected until the crack reaches a critical state and then it fails under the normal load application. From the information on deformation, it is evident that the failure is not gradual, but sudden and brittle, and the crack tip starts to break.

4.2.3. FEA Result Effect on Geometric Modification

The results of the analysis also have shown a great reduction in the concentration of stresses in the critical knuckle pinhole area, was found 53.41Mpa. The results were found a valid confirmation of the effectiveness of geometric modifications (especially the fillet) as a means of internal stresses distribution. In contrary, the geometric modification is an effective solution to the problem of concentration of root of the stress. In addition to this, the LOGLife was found to last longer than 106 cycles that means an important increment of magnitude in the duration of fatigue. The relative small change in the deformation pattern (0.0227mm) and the reduced value of the strain (0.000226) represents that the stress is more uniformly distributed and the concentration of stress is reduced. Once again the results of the research proves that the very source of the stress concentration can be removed or eliminated by the way of the geometric optimization in order to interfere with the process of crack initiation and avoid the conditions leading to the final failure.

4.2.4. Material test and its implication

The chemical analysis demonstrates that the composition of the in-service coupler may largely conform to the AAR-M 201 Grade E Steel, with manganese (0.551%), phosphorus (0.0055%), sulfur (0.0076%), and silicon (0.231%) appear to lie within the specified values. However, the actual carbon content could be 0.355, which might slightly exceed the maximum of 0.32 that is allowed. Moreover, the molecular metallurgical examination of the impact of each elemental deviation on tensile strength, hardness and impact toughness may be examined only within the boundaries of the current numerical analysis. Nevertheless, even small changes in composition could slightly alter material behavior in cyclic loading. Thus, the total elemental profile may support the stress deformation by the finite-element simulation that measured tensile and compressive stress of 70.8 and 281.2 respectively.

Furthermore, both values were significantly lower than the yield point. However, minor changes in elemental ratios might have subtle influences on material behavior and could help crack nucleation in cyclic loading states. Additionally, these could be experimentally tested by additional experiments outside the context of this thesis. Given that the relevant question has been addressed here, the identification and reduction of geometrical stress concentrations through the Finite Element Analysis might clearly show that the knuckle pinhole was the locus of failure. In light of the compositional variability of the observed nature, the carbon, which may be one of the main determinants of strength and ductility, could suggest a probable contributory factor. However, the data might also highlight that the in-service characteristics of the coupler and their interaction with the observed stress concentrations need specific material research to be thoroughly characterized.

4.3. Validation

4.3.1. Input Data Verification

The research was based on established engineering principles and backed up by an extensive literature review. Formulas used for drawbar pull computation are standard in railway engineering. Material properties for grade E steel such as yield strength, Young's modulus and poison's ratio were extracted from primary sources such as peer-reviewed publications (e.g. [4], [8]), It is ensured that the model has input data reflects the material actual behavior. All the operational parameters such as maximum axle load, tractive force, and train speed and brake coefficients were extracted directly from the official specifications and dispatches of Ethio-Djibouti Railway.

4.3.2. Real-time Validation

The most important thing that had to be done in order to validate it qualitatively was that the simulation predictions should narrow down to what the field data did. The finite element model that knuckle pinhole area is the point that has the highest concentration of stress when applied with normal tensile loads only. And, incidentally, that hit was nailed, the maintenance log data validated it, the second most frequently occurring type of failure, failures accounting for 85 (34.5%) of the total number of failures, were in the coupler heads (which are obviously connected with the stress field of the pinholes).

4.3.3. Result Validation

A progressive mesh refinement was carried out and the peak von Mises stress was monitored. Convergence of the solution was only confirmed when a minimal variation in the stress results from successive mesh refinements was observed. In other words, in the tensile example, the stress reached a stable value of approximately 70.81 MPa subsequent to initial variations. The above procedure has proven that the results obtained from the present study indeed represent approximations of the continuous mathematical solution regardless of the mesh size, i.e. the numerical dependability of the results has been validated.

4.3.4. Validation for Proposed Solution

The Modified model was applied to the same tensile load (291.36 kN) and meshing procedure used for the initial model. The success of the geometry modification was validated by a direct comparative FEA. The Modified model was applied the same tensile load and subjected to the same analytical protocol. The results provided quantitative, multi-dimensional evidence of improvement:

- The value of the maximum von Mises stress was improved from 70.8 MPa to 53.41 MPa.
- The Fatigue Life was improved from $10^{5.713}$ to more than 10^{6} cycles
- Reduction in the maximum principal strain.

Chapter Five

Conclusion and Recommendation

5.1. Conclusion

This study analyzed premature failure of rail couplers on Ethio-Djibouti Railway in a systematic way by combining field data analysis and FEA model. The problem was diagnosed well by FEA model and an effective solution was engineered. This work has identified the most prevalent failure mode for coupler head crack (70.5%) and knuckle pin crack (52.9%) mechanisms are not random events, but results of predictable stress raisers in the coupler assembly caused by high cycle fatigue nature of railway service operations. The chemical analysis demonstrated that the material of in-service coupler appears, in general, to comply with the significant Grade E specification, notwithstanding the fact that the carbon percentage was slightly higher than the maximum possible. Moreover, this observation may suggest that although the identified geometry concentration of stress appears to be the main dominant factor in the overall failure, material composition might be a secondary contributory factor.

By calculating Stress, Deformation, and Fatigue Life using FEA analysis, a multi-dimensional understanding of the failure mechanism was achieved. The results have proven that the pinhole at the knuckle was the most critical zone of stress concentration (70.8 MP of von Mises stress under tensile loading and 281.2 MPa under compressive loading). The joint analysis of deformation and strain pattern on the component under tensile and compressive loading gave us a general idea of the component's elastic response to the two different loading conditions. The calculated fatigue life prediction of loading ~516,000 cycles of loading to the original coupler provided a durability baseline before yield and matched the observed field failure rate caused by high-cycle fatigue. The most important results from the analysis of crack. The introduction of a pre-existing flaw caused a catastrophic shift in the behavior of the structure, the stress field intensified the stress concentration around the crack and the strain localized to 0.0116 at the tip of the crack. The predicted fatigue life collapsed to less than 1 cycles.

Finally, the geometric change (implementation of fillet radius at the critical knuckle pinhole) as a very beneficial counterexample was added. The subsequent comparative FEA yielded reduction of the maximum stress (53.41 MPa) by 24.57 %, more advantageous stress distribution, but most of all multiplying the expected fatigue life by double (LOGLife > 1,000,000 cycles).

In summary, this research presents a comprehensive analysis of the failure of couplers, starting with the collection of empirical data and ending with the verification by computations and a practical engineered solution. It shows that the use of failure analysis and complex FEA is a strong method for solving complicated industrial problems, which in turn demonstrates a clear path for the Ethio-Djibouti Railway to increase its operational reliability, safety and economic efficiency.

5.2. Recommendation

Based on the basic idea and result of the study, there are some Recommendation to solve or improve the freight wagon coupler challenges for railway company's. A big priority and enhance maintenance system by implementing regular, planed inspections focused on the knuckle pinhole region to identify and remove cracked couplers from service before they fail catastrophically. Because the study implemented after the appearance of the crack, the coupler is no longer fit to carry, the loads give service for the operation.

And procurement specification of Grade E steel must be Considered in such a way that it could have a higher tolerance of carbon content hence guaranteeing it appears contained within a range of below 0.32 interval, and thus may prevent unintended nature and conduct regular chemical tests for the adherence to material specification. Furthermore, chemical tests might indicate adherence before components are deployed into service.

Besides that, this is a long term plan to this coupler head design with fillet radius at the key corner because it has been known that it will reduce the stress concentration which is the main cause of the failure and increase the fatigue life and hour of the coupler. With the corrections made, corrected, and implemented, railway would become safer; reduce down time and save a ton of money in the end.

5.3. Future Work

Similar work in the future should consider more than just a simple stress evaluation should consider the evolution in the future, prospectively, include fracture mechanics. In addition, it will be better if an experimental study necessary to obtain the basic information on the constituent of material properties should be included. The mechanical tests such as tensile, fatigue and fracture toughness evaluations should be included in the experimental study. Beside of the experimental study a Linear Elastic Fracture Mechanics (LEFM) approach was recommended to model the process of crack initiation and propagation through the calculated Stress Intensity Factor (SIF) in critical locations.

6. Reference

[1] O. P. Yadav and N. S. Vyas, "The influence of AAR coupler features on estimation of in-train forces," *Railw. Eng. Sci.*, vol. 31, no. 3, pp. 233–251, 2023, doi: 10.1007/s40534-022-00297-8.

[2] S. Wagner, C. Cole, and M. Spiryagin, "A review on design and testing methodologies of modern freight train draft gear system," *Railw. Eng. Sci.*, vol. 29, no. 2, pp. 127–151, 2021, doi: 10.1007/s40534-021-00237-y.

[3] "Railway coupling - Wikipedia." https://en.wikipedia.org/wiki/Railway_coupling (accessed Aug. 12, 2024).

[4] X. Ren *et al.*, "Fracture mechanics based residual life prediction of railway heavy coupler with measured load spectrum," *Int. J. Fract.*, vol. 234, no. 1–2, pp. 313–327, 2022, doi: 10.1007/s10704-022-00627-1.

[5] G. Allegri, "A unified formulation for fatigue crack onset and growth via cohesive zone modelling," *J. Mech. Phys. Solids*, vol. 138, p. 103900, 2020, doi: 10.1016/j.jmps.2020.103900.

[6] Y. Zhong *et al.*, "An improved cohesive zone model for interface mixed-mode fractures of railway slab tracks," *Appl. Sci.*, vol. 11, no. 1, pp. 1–25, 2021, doi: 10.3390/app11010456.

[7] J. Huang, L. Xia, Y. Zhang, and S. Li, "Investigation on brittle fracture mechanism of a grade E cast steel knuckle," *Case Stud. Eng. Fail. Anal.*, vol. 2, no. 1, pp. 15–24, 2014, doi: 10.1016/j.csefa.2013.12.007.

[8] C. Li and S. G. Sun, "Crack growth life estimation for No. 17 coupler knuckle in China Datong-Qinhuangdao railway freight trains," *IOP Conf. Ser. Mater. Sci. Eng.*, vol. 770, no. 1, 2020, doi: 10.1088/1757-899X/770/1/012008.

[9] R. Rafiee and S. Sotoudeh, "A cohesive zone model for predicting the initiation of Mode II delamination in composites under cyclic loading," *J. Reinf. Plast. Compos.*, vol. 40, no. 5–6, pp. 179–192, 2021, doi: 10.1177/0731684420949660.

[10] G. Hua, Y. Wang, and W. Li, "Contact analysis of Type17 coupler based on finite element

method," *Eng. Fail. Anal.*, vol. 77, pp. 23–30, 2017, doi: 10.1016/j.engfailanal.2017.02.015.

[11] Q. Fu, S. Yi, B. Chen, T. Q. Bui, X. Hu, and W. Yao, "A crack-tip element for modelling arbitrary crack propagations," *Theor. Appl. Fract. Mech.*, vol. 105, p. 102422, 2020, doi: 10.1016/j.tafmec.2019.102422.

[12] M. Mohammadi, A. Rahmatfam, M. Zehsaz, and S. Hassanifard, "Failure analysis study of railway draw-hook coupler," *J. Cent. South Univ.*, vol. 26, no. 4, pp. 916–924, 2019, doi: 10.1007/s11771-019-4060-4.

[13] W. Wang, R. Guo, M. Wang, and Z. Yu, "Crack propagation simulation and residual life analysis of coupler yoke," *Proc. - 2010 2nd Int. Conf. Model. Simulation, Vis. Methods, WMSVM 2010*, pp. 66–69, 2010, doi: 10.1109/WMSVM.2010.47.

[14] O. Fomin, A. Lovska, O. Kovtun, and V. Nerubatskyi, "Defining patterns in the longitudinal load on a train equipped with the new conceptual couplers," *Eastern-European J. Enterp. Technol.*, vol. 104, no. 7, pp. 33–40, 2020, doi: 10.15587/1729-4061.2020.198660.

[15] E. S. Oganyan *et al.*, "Loading simulation and lifetime evaluation of automatic coupler in extreme environment," *Procedia Struct. Integr.*, vol. 20, no. 2018, pp. 42–47, 2019, doi: 10.1016/j.prostr.2019.12.113.

[16] R. Zou, S. Luo, and W. Ma, "Simulation analysis on the coupler behaviour and its influence on the braking safety of locomotive," *Veh. Syst. Dyn.*, vol. 56, no. 11, pp. 1747–1767, 2018, doi: 10.1080/00423114.2018.1435893.

[17] S. P. Chunduru, M. J. Kim, and C. Mirman, "Failure analysis of railroad couplers of AAR type E," *Eng. Fail. Anal.*, vol. 18, no. 1, pp. 374–385, 2011, doi: 10.1016/j.engfailanal.2010.09.016.

[18] C. Cole, M. Spiryagin, Q. Wu, and Y. Q. Sun, "Modelling , simulation and applications of longitudinal train dynamics," *Veh. Syst. Dyn.*, vol. 0, no. 0, pp. 1–74, 2017, doi: 10.1080/00423114.2017.1330484.

[19] B. Krishna, K. Roy, U. Rakshit, B. Malakar, B. K. Roy, and B. Krishna, "ScienceDirect

Study Study on on Longitudinal Longitudinal Forces Forces of of a a Freight Freight Train Train for for Different Different Types Types of of Wagon Connectors Study on Longitudinal Forces of a Freight Train for Different Types of Study of a ,” *IFAC-PapersOnLine*, vol. 51, no. 1, pp. 283–288, 2018, doi: 10.1016/j.ifacol.2018.05.074.

[20] M. Nuramin, R. S. B. Utomo, and D. W. Karmiadji, “Simulation and Experimental Validation of Stress Analysis for Train Coupler,” vol. 32, no. 4, pp. 1–12, 2025.

[21] H. Wang, X. Liu, X. Wang, and Y. Wang, “Numerical method for estimating fatigue crack initiation size using elastic–plastic fracture mechanics method,” *Appl. Math. Model.*, vol. 73, pp. 365–377, 2019, doi: 10.1016/j.apm.2019.04.010.

[22] I. Sharma & Associates, “Enhancing the Safety Of Coupler Knuckles,” no. September, 2023.

[23] “AAR M-201 Steel Casting Specifications | PDF | Heat Treating | Annealing (Metallurgy).” https://www.scribd.com/doc/56712436/AAR-M201-Specification?v=0.780 (accessed Jan. 23, 2026).

Appendix A

Table 15: Coupler failure history of Ethio Djibouti Railway Share Company in 2024

Cause of Coupler Failure		Frequency of failure
Coupler head Crack	Side 1	42
	Side 2	43
	Total	85
Coupler Knuckle pin Crack	Side 1	74
	Side 2	56
	Total	130
Knuckle Crack	Side 1	3
	Side 2	0
	Total	3
knuckle thrower Crack	Side 1	2
	Side 2	2
	Total	4
Coupler lock assembly side 1		1
Height level below standard		14
Coupler buffer side 2		1
Coupler lever Spring		1
pivot pin		2
coupler lower spring		1
lock assembly		1

Appendix B

Table 16: Locomotive specification

Technical data description	Value
Tractive power of locomotive at wheel rim (continuous system)	7200 kW
Electric braking power of locomotive at wheel rim (continuous system)	7200kW
Axle Load	Without bob weight : 23 t With bob weight : 25 t
Maximum operating speed	120 km/h
Power factor (λ)	≥0.98
Locomotive efficiency	≥ 0.85
Current system	25kV/50Hz
Starting tractive effort	570kN with 25t axle load 520kN with 23t axle load
Continuous tractive force of locomotive	400kN with 25t axle load 370kN with 23t axle load
Maximum regenerative braking force (at coupler)	400kN with 25t axle load 370kN with 23t axle load
Continuous speed	65 km/h with 25t axle load 70 km/h with 23t axle load

Appendix C

ECAE ኢተምድ

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Ethiopia Conformity Assessment Enterprise

ቁጥር (No.) 2|8|16-2|10332/26

ቀን (Date) 22 JAN 2026

To: Elias Asega Assefa

Addis Ababa

On you letter dated January 20, 2026 you have requested for the analysis on Grade E Steel.

Accordingly, the analysis is completed as per your request and hence you find the report attached here with.

Regards,

Solomon Mulubirhan
Customer Service Manager

THE FEDERAL DEMOCRATIC REPUBLIC OF ETHIOPIA
Ethiopian Conformity Assessment Enterprise

Enc: 2 Page of test reports MTR/4900/18

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ወደ ላቀ ብቃት የሚያደርስ!
Moving you forward!

ECAE	የኢትዮጵያ የተስማሚነት ምዘና ድርጅት Ethiopian Conformity Assessment Enterprise	Document No. TLD/F7.08-1	
		Copy No. -	Rev No. 3
Title	TEST REPORT የፍተሻ ሪፖርት	Page No. 1 of 2	Effective Date 25 oct 22

Name and address of client:	Elias Asega Assefa, Addis Ababa	Test Report No:	MTR/4900/18
Tel:	+251-935-48-36-98	Test Order No:	--
Fax:	--	Reported date:	22/01/2026
E-mail:	--	Date of sampling	Not specified
Date sample Received:	20/01/2026	Place of sampling	Not specified
Client Sample code: (Brand)	--	Sampled and submitted by	Client
Type of sample:	Grade E steel	Date tested:	22/01/2026
Laboratory Designation Number: 18132019		Method Specification:	-

S/N	Characteristics tested	Test Method / Specification	Standard Requirements			Test result	Comment
			Min	Nom	Max		
1.	Chemical composition (%)	Spectrometric/-	-	-	-	One -page chemical composition result are attached at the back of this test report	-

Remark

1 This test report relates only to the specific sample product which has been tested by ECAE testing laboratory.

Test report authorized by, Name Liyew Wudie, Position Analyst IV, Sign.

የኢትዮጵያ የተስማሚነት ምዘና ድርጅት
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Ethiopian Conformity Assessment Enterprise

ISO/IEC 17025:2017 Accredited Testing Laboratory

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BOLE SUBCITY, WOREDA 6, ADDIS ABABA, ETHIOPIA

Sample Name: Grade D

10132013

	C Conc. [%]	Si Conc. [%]	Mn Conc. [%]	P Conc. [%]	S Conc. [%]	Cr Conc. [%]	Mo Conc. [%]	Ni Conc. [%]	Al Conc. [%]	Co Conc. [%]	Cu Conc. [%]	Nb Conc. [%]	Ti Conc. [%]
1	0.361	0.233	0.563	0.0051	0.0073	0.970	0.0045	0.0352	0.0119	0.0080	0.0276	0.0011	0.0040
2	0.355	0.229	0.552	0.0049	0.0076	0.957	0.0051	0.0348	0.0118	0.0072	0.0275	0.0010	0.0034
3	0.349	0.229	0.548	0.0065	0.0078	0.975	0.0078	0.0355	0.0117	0.0091	0.0275	0.0019	0.0041
<x>	0.355	0.231	0.551	0.0055	0.0076	0.967	0.0058	0.0352	0.0118	0.0081	0.0275	0.0013	0.0039

	V Conc. [%]	W Conc. [%]	Pb Conc. [%]	Sn Conc. [%]	As Conc. [%]	Zr Conc. [%]	Bi Conc. [%]	Ca Conc. [%]	Ce Conc. [%]	Sb Conc. [%]	Se Conc. [%]	Te Conc. [%]	Ta Conc. [%]
1	0.0120	<0.0050	0.0030	0.0024	<0.00100	0.0014	<0.00100	0.0027	0.0023	0.0111	<0.0020	0.0044	0.0146
2	0.0120	<0.0050	0.0024	0.0022	<0.00100	0.0015	<0.00100	0.0022	0.0021	0.0095	<0.0020	0.0042	0.0086
3	0.0124	<0.0050	0.0031	0.0023	<0.00100	0.0015	<0.00100	0.0019	0.0036	0.0072	<0.0020	0.0037	0.0322
<x>	0.0121	<0.0050	0.0028	0.0023	<0.00100	0.0014	<0.00100	0.0023	0.0026	0.0093	<0.0020	0.0041	0.0185

	B Conc. [%]	Zn Conc. [%]	La Conc. [%]	N Conc. [%]	Fe Conc. [%]
1	0.0022	0.0010	0.0010	0.0011	97.7
2	0.0021	0.0011	0.0011	0.0015	97.7
3	0.0023	0.0015	0.0013	0.0017	97.7
<x>	0.0022	0.0012	0.0011	0.0014	97.7

Figure 38: Ethiopian Conformity Assessment (ECAE) Material Test Result and letter

Appendix D

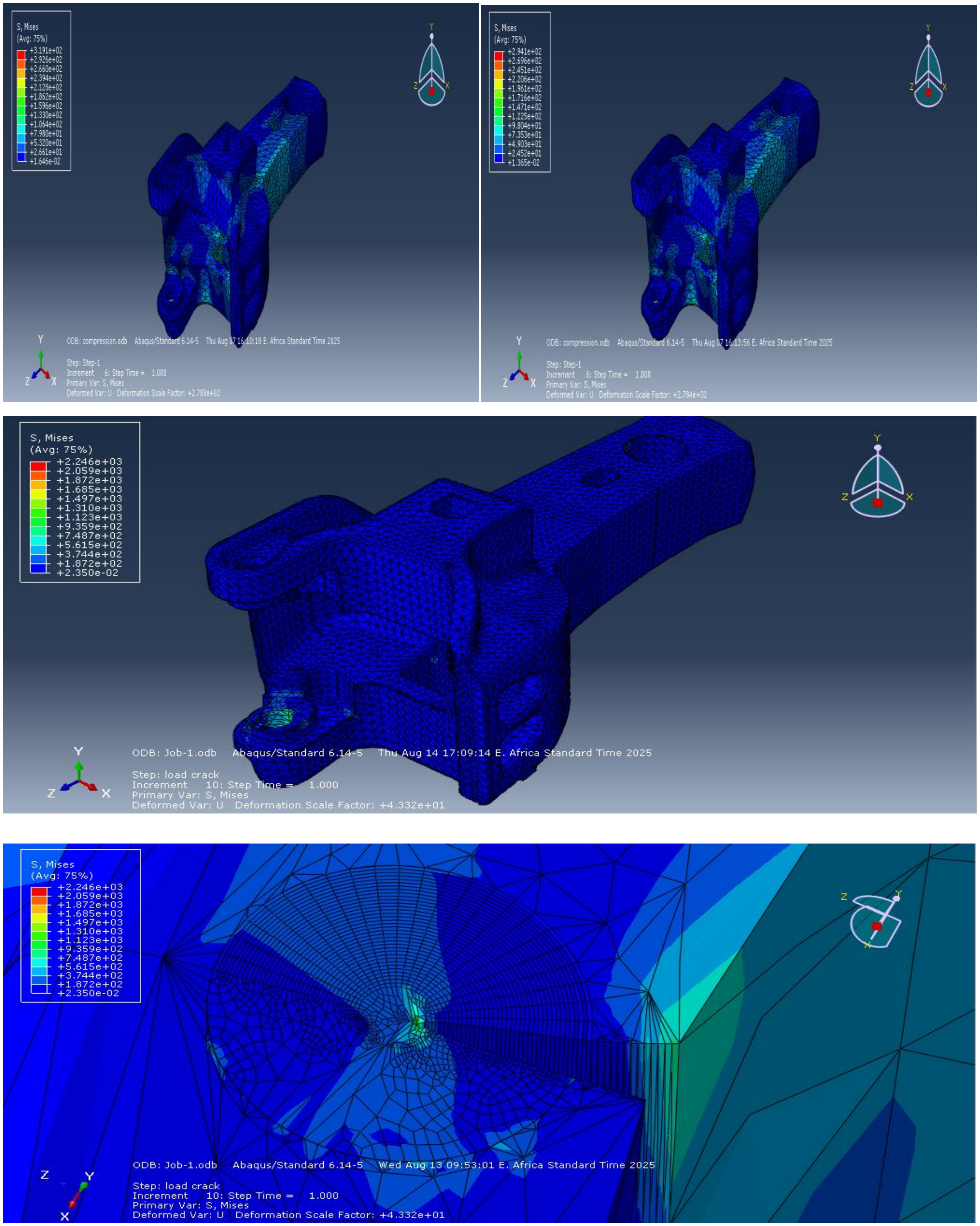

Figure 39: ABACUS results of vonmises stress

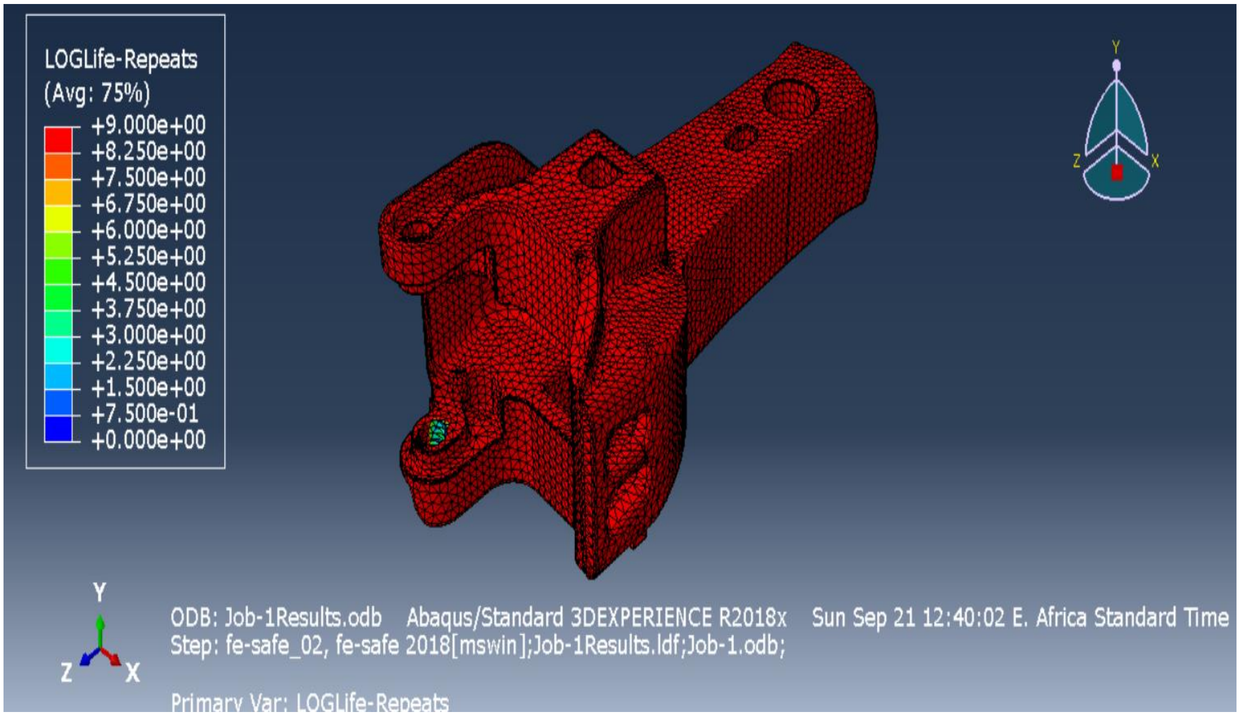

Figure 40: ABACUS LOGLife result