



**ADDIS ABABA UNIVERSITY**  
**ADDIS ABABA INSTITUTE OF TECHNOLOGY**  
**SCHOOL OF MECHANICAL AND INDUSTRIAL ENGINEERING**  
**GRADUATE PROGRAM IN RAILWAY ENGINEERING**

**Strength and fatigue analysis of composite bogie frame**

**BY: Khadir Daher**

A Thesis submitted to the School of Mechanical and Industrial Engineering in partial fulfillment of the requirements for the Degree of Masters of Science in Mechanical Engineering

**(Railway stream)**

**ADVISOR: Mr. Tolossa Deberie**

June, 2017

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**WEAR RATE ANALYSIS OF OVERHEAD LINE CONTACT WIRE BY CONSIDERING  
CURRENT EFFECT USING ANSYS.**

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## **DECLARATION**

I, the undersigned, declare that this thesis is my original work and has not been presented for a degree in this or any other universities, and all sources of materials used for the thesis work have been fully acknowledged.

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This thesis has been submitted for examination with my approval as a university advisor.

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**ABSTRACT**

The bogie frame accommodates various bogie equipment and is generally fabricated by welding together two cross beam into H-shaped frame, compound side beams were developed using press welding. This research paper presents the fatigue strength analysis for the composite bogie frame of AALRT. The bogie frame of a railway is an important structural member for the support of vehicle loading. In general, more than 25 years' durability is necessary. The core objective of this proposal is to analyse strength and fatigue of bogie frame. The problem has been formulated by using composite bogie frame. For this purpose, a bogie frame has been modeled using solid works software and imported to ANSYS work bench 2016 for analysis. In the analysis of the research a three-dimensional finite element model of the bogie frame has been used to investigate the effect of the applied loading force at the frame surface area.

The fatigue life has been analyzed for using carbon/epoxy and structure steel. While the material using for AALRT is structure steel. The total deformation of the carbon/epoxy  $2.1101e-6$ Max, the equivalent stress 225.39Max and the total deformation of the structure steel 0.74025Max, the equivalent stress 209.55Max.

The results show the carbon/epoxy composite bogie frame had a good fatigue performance in comparison with conventional metal bogie frame and is considering as the best effective way to reduce the weight of railway vehicle.

**KEYWORDS:** Bogie frame, fatigue, strength, composite and ANSYS:

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**NOMENCLATURE**

AALRT	Addis Ababa light rail transit
$\sigma_a$	Applied Stress
$\sigma_{\text{mean}}$	Mean stress
$\sigma_{\text{max}}$	Max stress
$\sigma_{\text{min}}$	Min stress
$\Delta\sigma$	Stress range
R	Ratio of minimum to maximum stress
$S_e$	Endurance Limit
$M_v$	The mass of car in running order
P1, P2	the mass of passengers at exceptional loads and normal service load cases respectively
C	The wheel loads of the relevant bogie expressed as a%
$m_1$	Effective car body mass
$m^+$	the bogie mass
$n_b$	Number of bogie

# Chapter One

## Introduction

### 1.1 Background

Transport represents one of the most important human activities worldwide. It is an indispensable component of the economy and plays a major role in spatial relations between locations. Transport is important because it enables trade between people, to overcome space, which is shaped by a variety of human and physical constraints such as distance, time, administrative divisions and topography.

Rail transport is where a train runs along a set of two parallel steel rails, known as a railway or railroad and one of the most important transportation modes to transport passengers and goods from one place to another place.

The history of the growth, decline and restoration to use of rail transport can be divided up into several discrete periods defined by the principal means of motive power used. The first trains were single wagons pushed or pulled by people or animals, and were used to move goods, such as coal. Steam trains were the first type of trains. They use coal in a fire box to boil water until it turns to steam. The steam is forced through powerful pistons to give the engine the power to drive the wheels. At first, steam engines moved mainly goods, but were soon used to carry passengers as well. Steam engines are still in use all over the world, although most have been replaced by diesel or electric trains. Diesel locomotives were first introduced in Australia in the 1930's. They were a powerful addition to the railways. Diesel fuel powers an engine which drives a generator to make electricity. The electricity powers traction motors that turn the wheels. Electric trains are faster, quieter, and simpler to run than the diesel train. Electric trains are also better for the environment as they do not discharge exhaust fumes. Diesel locomotives are used to transport enormous quantities of materials over huge distances. They are also more efficient and smoother than steam trains, and carry much heavier loads [6].

Electric trains were first introduced in the late 1870's. The main advantage of electric traction is a higher power-to-weight ratio than forms of traction such as diesel or steam that generate

power on board. Electricity enables faster acceleration and higher tractive effort on steep gradients. On locomotives equipped with regenerative brakes, descending gradients require very little use of air brakes as the locomotive's traction motors become generators sending current back into the supply system and/or on-board resistors, which convert the excess energy to heat. Other advantages include the lack of exhaust fumes at point of use, less noise and lower maintenance requirements of the traction units. Given sufficient traffic density, electric trains produce fewer carbon emissions than diesel trains, especially in countries where electricity comes primarily from non-fossil sources. However, the track is expensive and there are problems moving the trains from one track to another [5].

Rail transportation has been the most demanded transportation offering better safety, speed and comfort.

With the rapid increasing of passenger flow of subway vehicle, the duration of metro has become more important for assessment of service life. Especially, the safety of bogie frame is considerably influenced by the fatigue strength that is the ability of withstanding irregular loads under condition of fatigue crack development. The bogie of a railway vehicle sustains the weight of the car body, controls the wheel sets on straight and curved track, and absorbs the vibrations [1]. The bogie frame is subjected to a combination of vertical, longitudinal, lateral and other particular forces (roll, yaw, etc.) throughout its operational lifetime. The bogie frame is not only a support for components but it is also a structural and guidance element in itself, and so exhaustive investigations of the durability of this structure must be performed [7].

The bogie of a railway vehicle sustains the weight of the car body, controls the wheel sets on straight and curved track, and absorbs the vibrations [2]. The weight of the bogie makes up approximately 37% of the total vehicle weight. Therefore, reducing the weight of the components making up the bogie system is essential for lightweight railway vehicle design. In particular, a bogie frame, which accounts for approximately 20% of the bogie weight, is intended to support heavy static and dynamic loads. This is why it is common to produce bogie frames with composite material in the case of solid steel. They have to be equipped with suspension and damping systems to safeguard the comfort of passengers and to absorb vibrations due to the unevenness of the railway track on which the vehicles run [3].

In this research, the main objective is to analyse fatigue and strength of bogie frame using finite element method find out the fatigue strength of the weak parts in the bogie frame. The reason

why it is necessary to consider the fatigue characteristic carefully is that fatigue is a microscopic fracture caused by the initiation and propagation. Therefore the goal of this research is to change the existant material into composite material by making analysis the fatigue strength assessment of key components in the bogie frame with satisfying the fatigue life of the bogie frame.

## 1.2 Types of bogie of AALRT

### 1.2.1 Motor bogie frame

Bogie is structure of bolster, full side bearing, outter-side axle box and fixed axle wheelset, and is mounted underneath module Mc at both end of car. It mainly includes frame, wheelset, primary suspension, secondary suspension, traction assembly, driving unit, brake unit and auxiliary devices [23].

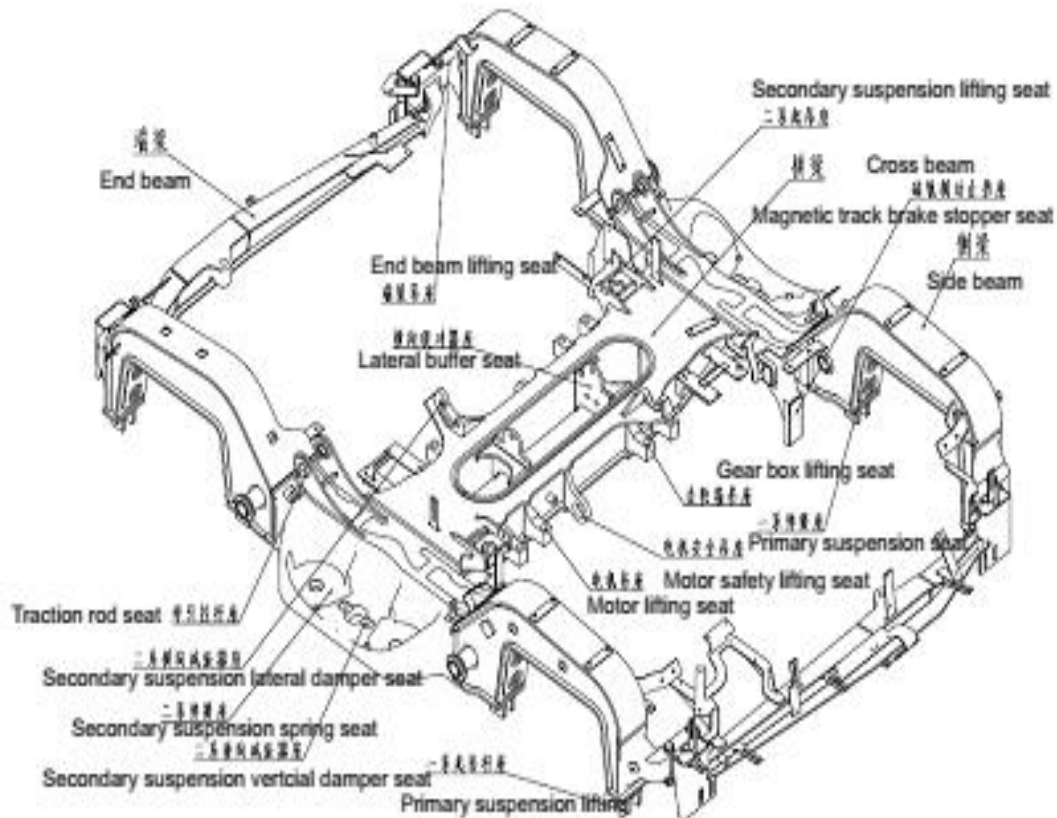
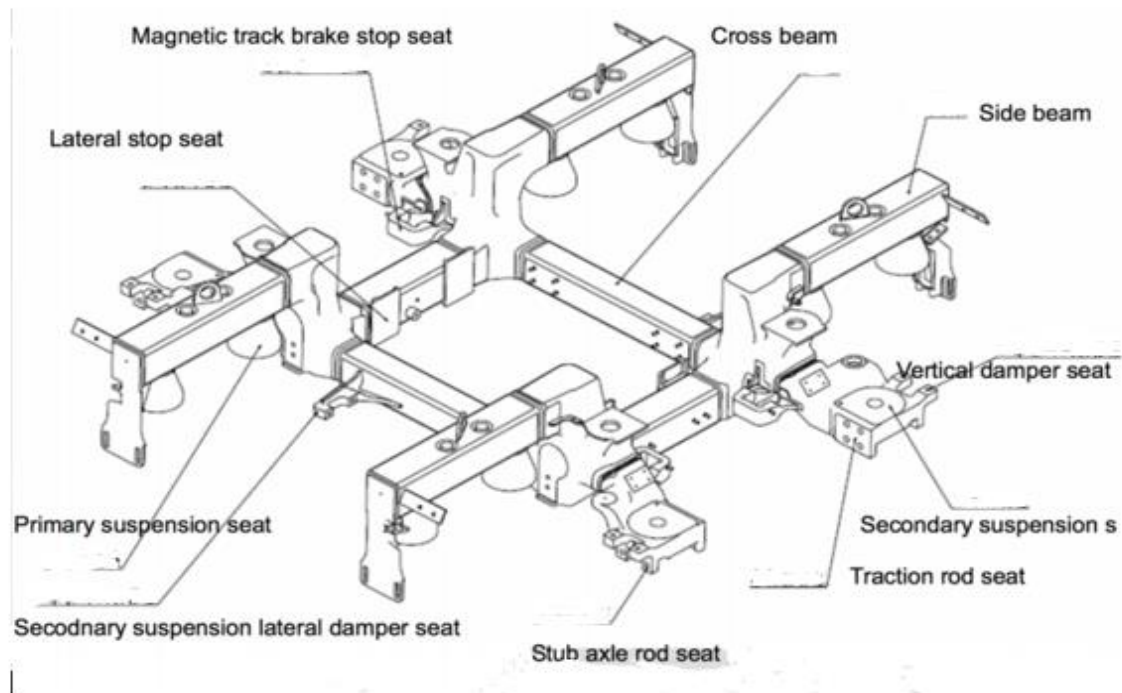


Figure 1.1: Power bogie [23].

### 1.2.2 Trailer bogie

Bogie is structure of inner-side axle box and independently rotated wheelset, and is mounted underneath Tp module in middle of car. It is mainly consisted of frame, independently rotated wheelset, primary suspension, secondary suspension, traction assembly, brake unit and auxiliary devices [23].



**Figure 1.2: Unpowered bogie [23].**

### 1.3 General Description about Bogie Frame

The bogie frame is an important and integral member of bogie in ICF rail coach. The bogie in coach construction plays a vital part since factors like safety; speed and comfort mainly depend on the bogie on which the coach body is loosely mounted. The main purpose of the bogie frame is to withstand and/or transfer vertical loads of the superstructure with payload, lateral forces caused due to negotiating the curves and interaction between rail and wheel and longitudinal force due to drafting of the coach by the engine. The conventional bogie frame is made of heavy plate sections fabricated to form “H” type frames consisting of two side frames, two transoms, two headstocks and four longitudinal. The Fiat bogie frame consists of two side frames connected by means of two circular cross section. The material used is mild

steel, (IS 2062, fe410wc) and the frames are fabricated by employing CO2 welding techniques.

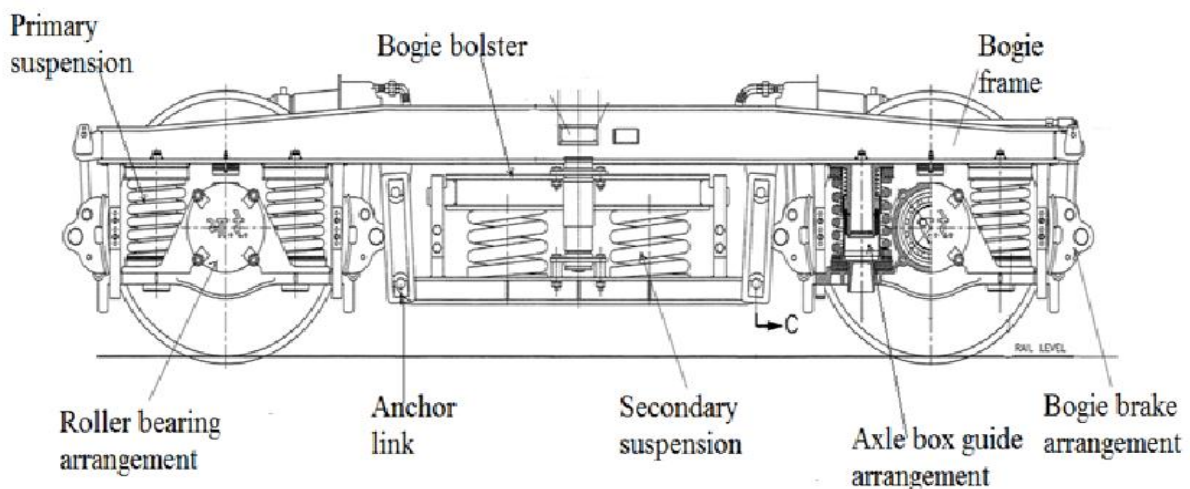
It supports the bogie bolster, wheel arrangement, primary, secondary suspension and it provides pivoting action while accepting the curves. It bears entire load of the coach and transmit to the wheel through side bearers the tractive effect which is transmitted through centre pivot pin both static and dynamic loads while running [4].

#### 1.4 Functions of Bogie Frame

- The main purpose of the bogie frame is to withstand and/or transfer vertical loads of the superstructure with payload, lateral forces caused due to negotiating the curves and interaction between rail and wheel and longitudinal force due to drafting of the coach by the engine.
- To have flexibility in the wheelbase, two bogies are provided per coach, which are pivoted at two points by members called centre pivot.
- Bogie frame have sections for holding bolster, break arrangement, axle box guide and many other parts which are welded to the frame.

#### 1.5 Location of Body Frame

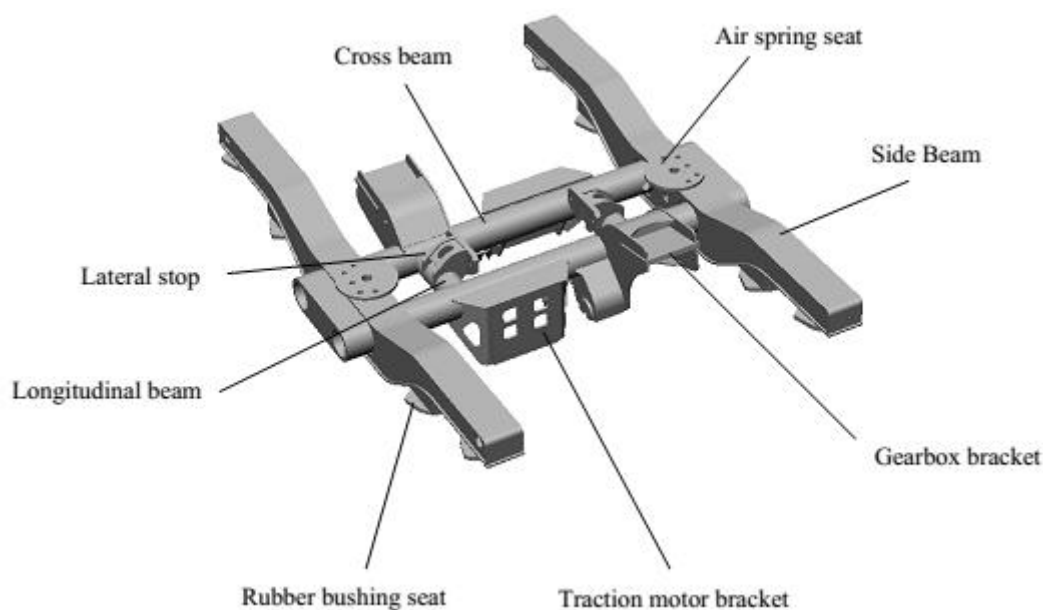
Body frame is located in as shown in the Figure 1 below in a bogie. Each coach under frame requires two bogie one for the front chassis and another for the back chassis of a coach3. Bogie frame consists of many sections for accommodating many parts of the bogie as shown in Figure 1 [4].



**Figure 1.3:** bogie of rail [4]

### 1.6 Bogie Frame Structure

The bogie frame is adopted by welded structure, **Figure 1.2** demonstrates that the main framework architecture is H-shaped in the horizontal plane, which is composed of two box-shaped side sills, the overall composition of the box beam welding, by the central concave belly of the fish box structure composed of a spring seat side beam welding, basic brake mounts, anti-roll torsion bar seat, etc., the cavity has a thickness of 10 mm stiffener plate [9]. Box beam structure for the central opening, the transverse beam welding has ended with stopper seat, traction rod seat, motor bracket, gearbox bracket and secondary lateral damper seat and so on [8].



**Figure 1.4: The structure of bogie frame [8]**

### 1.7 Problem statement

While many parts may work well initially, they often fail in service due to fatigue failure caused by repeated cyclic loading. In practice, loads significantly below static limits can cause failure, if the load is repeated sufficient times. Thus, train accident cause damage to infrastructure and rolling stock as well as service disruption, and may cause casualties and harm the environment. As one of the Statistical analyses were conducted to examine the effects of accident cause, type of track, and derailment speed. The analysis showed that broken rails or welds were the leading derailment cause on main, yard, and siding tracks [40]. Derailment are the most common type of train accident, but the important parameters affecting derailmennt are train speed, loinding problem and broken wheels. Characterizing the

capability of a material to survive many cycles a component may experience during its lifetime is the aim of fatigue analysis. Bogie frame exhibits the repeated cyclic loading as a result of the suspension properties and causes in sever damages. Thus, composite materials are common material in order to resist the cyclic load.

## **1.8 The Objective of the Research**

### **1.8.1 General Objective**

The major objective of this research is to make analysis on the strength and fatigue of composite bogie frame for Addis Ababa LRT.

### **1.8.2 Specific Objective**

- Model a bogie frame using solid works software.
- Strength and fatigue analysis of the bogie frame.
- Determine the important forces acting on the bogie frame and modeling the bogie frame.
- Simulate bogie frame of the train using Finite Element Method.

## **1.9 Scope and Limitation of the Research**

The scope of this study is to analys thestrength and the fatigue of bogie frame of addis ababa LRT. Material selection will be done based on strength and light weight. The analysis will be done on composite bogie frame (carbon/epoxy). Bogie are one of the man parts of of train wich not only carry static loads due to the body weight but also dynamic loads due to the rail surface roughness and imperfect wheels. But the dynamic analysis will not be carried out in this research. This research is limited on static analysis and fatigue.

## **1.10 Research Methodology**

This research proposes the methods to analysis strengths and fatigue of composite bogie frame of Addis Ababa LRT passenger train.

The method includes the following task to achieve the objectives of the research:

- The research method used in this research is purely quantitative.
- Literature Reviewing: This includes reading related books, research paper, articles and software tools etc.
- Using conventional method to model stresses in a bogie frame of a rail carriage.
- Using ANSYS software to simulate the bogie frame.

After deciding the method, the next step is collecting data to analyze strength and fatigue of composite bogie frame. In quantitative research the form of data collected is quantitative data. In this research, the data are divided into primary data and secondary data.

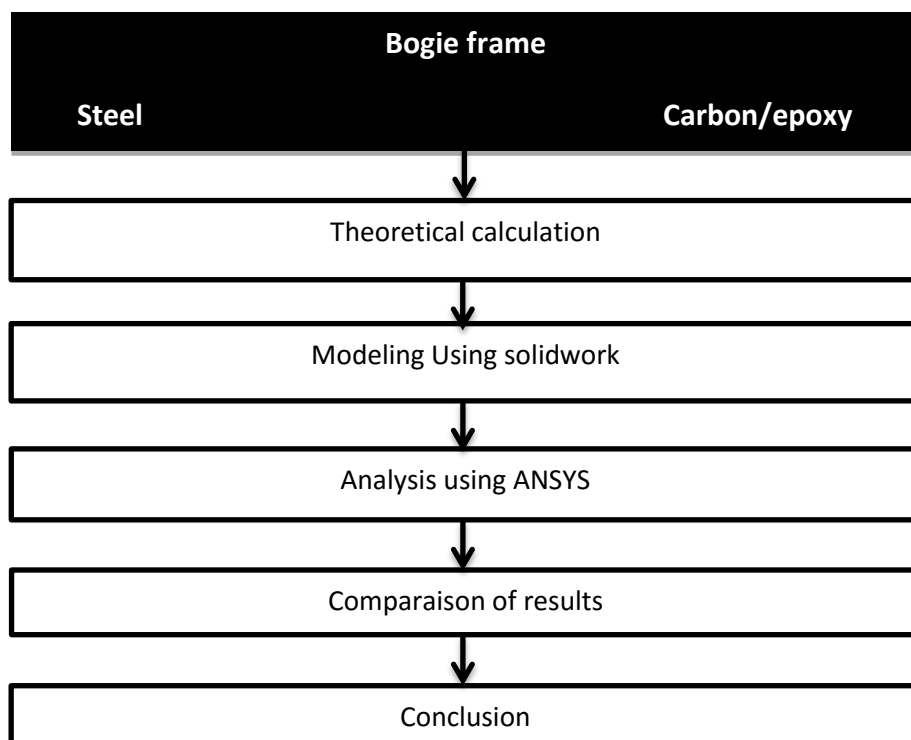
➤ **Primary Data**

The primary data is data which are collected in the field based on the existing and reality condition.

➤ **Secondary Data**

The secondary data is a data which is collected to support the primary data and as comparison to other studies. The secondary data in this research are obtained from the institution or organizations associated with the research object.

For the purpose of this research, and in order to achieve the objectives listed in the sub topic of specific objective of the research the data will be collected through secondary data collection method.



**Figure 1.5: Work flow of study methodology**

### 1.11 Significance of the research

This research will have the following significance:

- Analysis the fatigue strength factor parametres with FEM approach.
- Compared composite material and the material using by LRT.
- Give clear understanding for inspectionn of railway of bogie frame.
- Improve the safety of operation by improving the damage of the bogie frame caused of the fatigue
- Safes importing cost and time of utilization by mannufacturing the composite of bogie frame units locally by improved fatigue and strength results analysis new findings that have significant impact on the development of durable and good faillure resistance.

The research outcomes will have significant importance for the ERC especially, the safety of bogie frame is considerably influenced by the fatigue strength that is ability of withstanding irregular loads under condition of fatigue crack development. Furthermore, the research gives significant insight for local manufacturing of the composite bogie frame for Ethiopian Railway Cooperation (ERC) from the developed design methodology to reduce the purchasing and investment cost.

### 1.12 Organization of the research

This research is organized into five chapters.

**Chapter one** introduced about background of LRT and bogie frame, the situation of Addis Ababa LRT.

**Chapter two** summarizes the efforts of previous studies related to the current study.

**Chapter three** makes a selection of materials for bogie frame.

**Chapter four** presents the model and analysis strength and fatigue of bogie frame comparing with composite bogie frame.

**Chapter five** discusses the results of simulation.

**Chapter six** conclusion, recommendation and future work.

## Chapter Two

### Literature review

#### 2.1 Introduction

The bogie frame is the main load bearing components and power transmission components of the vehicle, when the vehicle is in motion the process, not only to the bogie frame to withstand loads, but also need to pass a variety of forces between the body and the wheel. Due to the fatigue test costs are expensive, the fatigue strength assessment of key components in the bogie frame using finite element model can find out the fatigue strength of the weak parts, can reduce the risk of fatigue testing prototypes, shorten development cycles, reduce trial costs. Therefore, one can conclude that bogie is one of the most important components in wagon frame. There are several standards for strength evaluation of the conventional bogie frame such as JIS E 4207, UIC 615-4 and EN 13749.

#### 2.2 Previous Related Worked Papers

The bogie of a railway vehicle sustains the weight of the car body, controls the wheel sets on straight and curved track, and absorbs the vibrations [9]. The weight of the bogie makes up approximately 37% of the total vehicle weight. Therefore, reducing the weight of the components making up the bogie system is essential for lightweight railway vehicle design. In particular, a bogie frame, which accounts for approximately 20% of the bogie weight, is intended to support heavy static and dynamic loads, such as the vertical load by the body of the vehicle, braking and accelerating load, twisting load induced by track twisting, and traction load. This is why it is common to produce bogie frames with solid steel (especially a freight bogie) or welded structures. Such bogie frames are rigid and heavy, weighing from 1 to 2 tons. They have to be equipped with suspension and damping systems to safeguard the comfort of passengers and to absorb vibrations due to the unevenness of the railway track on which the vehicles run.

**Jung Seok Kim and Hyuk Jin Yoon [12]**, studied the structural safety of a composite bogie frame was evaluated using the static test and the finite element analysis. In order to achieve these goals, the material properties such as the in-plane, the out-of plane and the fatigue limits were evaluated. Through the structural safety evaluation using the Goodman diagram, it was clear that the composite bogie frame was within the safe region. And, the maximum stress occurred at the strain gauge located on the joint region between that side beams and the cross

beam. In addition, the overall stress distributions of the bogie frame were evaluated using the finite element analysis. The limitation of the study regarding this study they have not considering the fatigue strength analysis of composite bogie frame.

**K.W. Jeon, K.B. Shin and J.S. Kim [11]**, presented the bogie of railway vehicle is the primary structures, which support the weight of carbody and passengers, and under the repeated external loading between rail and wheel. Therefore, in order to have enough strength and stiffness against the external loading, bogie frame were made of solid steel or welded structures based on metal materials such as SM490A. In this study, the fatigue life and strength of a composite bogie frame for urban subway train were evaluated. The fatigue test of a GEP224 glass fiber/epoxy 4-hareness satin woven composite material applied to bogie frame was performed to obtain S-N curves under tension-compression loading condition. The Goodman diagrams of a composite material were obtained by fatigue test. Then, the fatigue life and strength of bogie frame were evaluated by Goodman diagrams according to the JIS E 4207. The limitation due to this study is, has not included the methodology to analyse the composite bogie frame.

**Wei Tang\*, Wenjing Wang and Yao Wang, Qiang Li [8]**, studied the equivalent stress at key positions of Bogie Frame for DMUs Exported to Tunisia is obtained by using simulation analysis. The evaluation of static strength and fatigue strength is checked referring to UIC specification and Goodman sketch for welding materials. In addition, the modal analysis of the frame is made, and the vibrational modal of frame in given frequency domain is predetermined to evaluate the dynamical behavior of the frame in order to meet the dynamical design requirements. The results show that the key points of the calculated frame of the equivalent stress are less than allowable stress, and thus it could provide a theoretical foundation for the optimized design of frame structure and safety of industrial production. ANSYS software is used to calculate the inherent frequency and vibration shape of bogie frame, and the results reveal that the torsional stiffness of the bogie frame is small. Trains benefits from the low torsional stiffness to come over lines with vertical irregularity, and bogie frame can avoid other excitation frequency. The limitation of this study is, has not included dynamic loads by vibration of motors.

Composite materials are becoming more important in the construction of railway structures. Composite materials consist of a combination of materials that are mixed together to achieve specific structural properties. The individual materials do not dissolve or merge completely in

the composite, but they act together as one. Normally, the components can be physically identified as they interface with one another. The properties of the composite material are superior to the properties of the individual materials from which it is constructed.

**Jung-Seok Kim, Hyuk-Jin Yoon, Sung-Hoon Lee, Woo-Geon Lee, Kwang-Bok Shin [10]**, in order to replace a conventional steel bogie to a composite one, in this study, the glass/epoxy composite bogie frames with two different shapes have been designed to be applied to the bogie of urban subway trains. The durability of the composite bogie frames was evaluated using a Goodman diagram and finite element analysis under different loading conditions. From the analysis results, the two types of composites met the static structural safety requirements under ten different loading conditions. The maximum Tsai-Wu failure indexes of the two composite bogie frames were 0.48 and 0.57, and the values occurred under the twisting load. In the durability evaluation using Goodman diagrams, it was clear that the two models would be safe under the fatigue loading conditions. The critical point was the side beam bottom area for the bogie frames with side beam height of 50mm, while the joint center area revealed higher mean stress and stress amplitude values in the bogie frames with side beam height of 150mm. By adopting composite bogie frame which give less deflection and less induced stress value, the safety and operation with higher speed can be insured in addition to reduction of weight.

**Woo-Geun Lee, Jung-Seok Kim, Hyuk-Jin Yoon [13]**, have studied the failure strength and modes of Tjoints used in a composite bogie frame has been evaluated under a bending load. The bending load is corresponding to a traction load applied to the cross beams of the composite bogie frame. The composite bogie frame is composed of two side beams and two cross beams. In order to make the composite bogie frame, first, the two cross beams and the two side beams were assembled by adhesively bonded method. Then, GEP224 glass/epoxy prepregs were laid up on the surface of the assembled structure to form the skin. In this study, two types of T-joints were fabricated and tested. The first one is a T-joint in which a cross beam and a side beam are connected using only adhesive bonding method. The second one is a T-joint in which a cross beam and a side beam are assembled using adhesive bonding and skin layup. The failure loads for the adhesive only joints and the joint with the adhesive bonding and skin layup were measured through the bending test. From the test result, it was clear that the joint with the adhesive bonding and skin layup had a safety margin of 2.86 taking into account the traction load of 23.8kN. The limitation as to my study is could not address about adhesive composite joints with in the given title.

**Jung-Seok Kim and Woo-Geun Lee [14]**, have studied in order to replace the conventional steel bogie with a composite bogie, a composite side beam made of glass/epoxy was designed and manufactured to be used in the bogie frame of an urban subway train. Although the side beam manufactured by the autoclave curing method had better structural properties, the side beam manufactured by the RTM revealed the good structural properties and a little higher deflection. The strain distribution along the longitudinal direction showed three peaks and two valleys due to the variation of the cross sectional area of the composite side beam. The evaluation of fatigue strength using the Goodman diagram showed that the side beam met the structural safety. The results of this study can be used as the basic data to develop the whole composite bogie frame. Especially, the investigation for the different manufacturing method can be used as good decisionmaking data in the commercialization phase. Through the parametric study for the different design parameters, it was known that the variation of the side beam height appeared to be strongest effect to deflection. The limitation of the study with regard to this study/perspective is, they have not considered completely the shape of the bogie frame during the study.

**Jungwon Seoa, Hyunmoo Hur, Hyunkyu Jun, Seokjin Kwon, Donghyeong Lee [15]**, have studied The objective of this paper is to estimate the structural integrity of the bogie frame of an electric railcar. Strength analysis has been performed by finite element analysis. From this analysis, stress concentration areas were investigated. To evaluate the loading conditions, dynamic stress was measured by strain gauge. It has been found that the stress and strain due to the applied loads were multi-axial conditions according to the location of the strain gauge. Fatigue strength evaluations of the bogie frame were performed to investigate the effect of a multi-axial load through the employment of a critical plane approach. The limitation of the study with regard to this study is, they have not considered the case of composite bogie frame.

**Fan-Song LI, Ping-Bo WU, Yi-Zhao NIE, Ye SONG [16]**, have studied the fatigue strength of a railway vehicle bogie frame evaluated by endurance limit approach and cumulative damage approach. The differences between the two approaches are studied, and the conclusions are shown below.

(1) The Haigh-Goodman and Smith-Goodman diagram are identical when considering the same safety factor, while Haigh-Goodman provided in JIS standard is conservative relative to that in UIC standard due to adopting different safety factor.

(2) The transverse load recommended in UIC norm are not conservative when evaluate the fatigue strength of bogie frame.

(3) The elementary S-N curve are too conservative to reflect real situation, and the Haibach modified S-N curve are recommended when using cumulative damage approach because its advantage.

The loads of the bogie frame were calculated by UIC 615, which contain vertical loads, transverse loads, longitudinal loads from car body, and dynamic loads by vibration of motors or gearboxes. The limitation due to this study is, has not included the fatigue strength of a railway vehicle composite bogie frame.

**Jishan Li, Jinhai Wang, Xi Li, Jianwei Yang and Haitao Wang [17];** have discussed a problem for safety of bogie frame of subway vehicle under overload situation has been discussed. Firstly, the structure of bogie frame and service condition are introduced to explain the reason caused fatigue failure. Then, the testing points are selected in terms of the structure of bogie frame, the characteristics of processing technique, load transfer path and the operation situation of subway vehicle. This paper aims to develop a fatigue analysis process based on experiment data. Section 2 describes the experiment method of stress acquisition of bogie frame during running in details to prepare for the follow-up work. Section 3 proposes the process for fatigue analysis using nominal stress method combined with rainflow counting method and Miner damage rule applied to calculate complex product that is bogie frame. Section 4 gives the result of analysis and concludes the advantages and disadvantages of the process during the study. The limitation of the study is only to mantain the guidance of bogie frame.

#### **Summary of the reviewed literatures:**

Nowadays, most of the literatures listed in this thesis focus only the strength and fatigue analysis of composite bogie frame In addition, description, methods, results of the literatures are discussed and the limitations and strengths of the research (validation of the results) were analyzed. In this thesis analysis of bogie frame will be done due to the fatigue strenght and known the bogie is one of the most important railway vehicle part, while the bogie frame is the main bearing structure in vehicle system. Due to its importance, many scholars have been studied the fatigue strength.

Nevertheless the objectives of the above-mentioned study differ from the objective of this project. The fatigue life of a member or of a structural detail subjected to repeated cyclic loadings is defined as the number of stress cycles it can stand before failure. Depending upon the member or structural detail geometry, its fabrication or the material used, four main parameters can influence the fatigue strength:

- the stress difference, or as most often called stress range,
- the structural detail geometry,
- the material characteristics,
- the environment.

In this paper, the main focus is on the bogie frame analysis, in which the main idea is to use a composite material of the bogie frame instead of steel material. Although, in order to replace the conventional steel bogie with a composite bogie, the structural safety of a composite bogie frame was evaluated using the static and the finite element analysis. Therefore, a composite bogie frame has many benefits for conventional bogie frame based on metal material.

## Chapter Three

### Selection of bogie frame material

#### 3.1 Mechanical Properties

Mechanical properties describe the behavior of material in terms of deformation and resistance to deformation under specific mechanical loading condition. These properties are significant as they describe the load bearing capacity of structure. Elastic modulus, strength, hardness, toughness, ductility, malleability are some of the common mechanical properties of engineering materials.

Every material shows a unique behavior when it is subjected to loading.

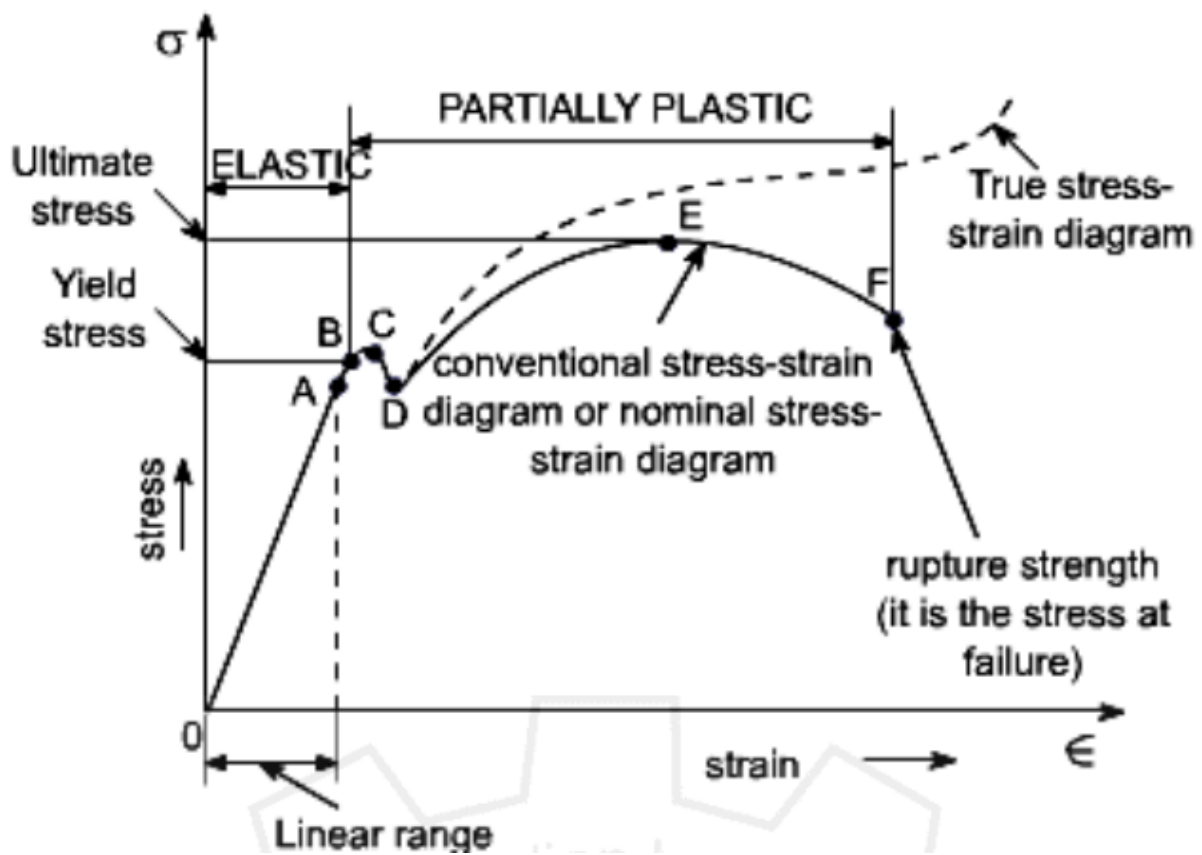
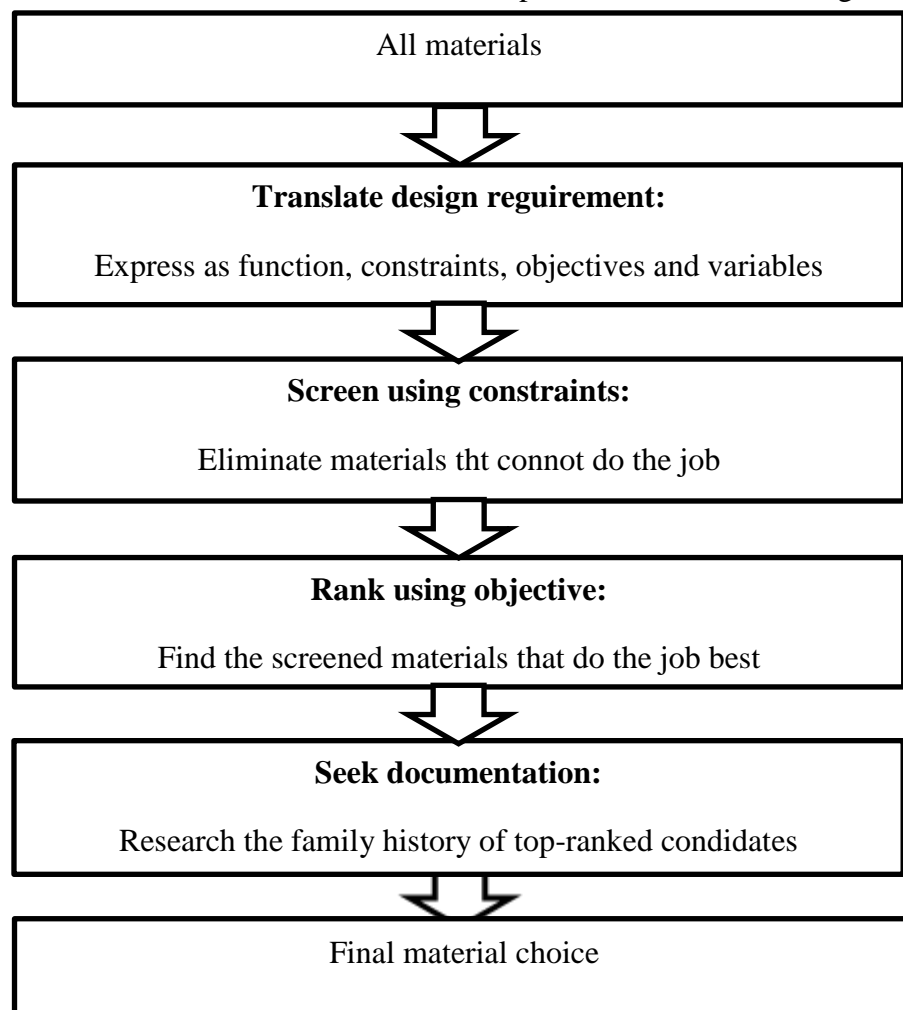


Figure 3.1: Stress-strain curve for carbon-steel [38].

### 3.2 Materials Selection Process

The engineering process involves three different steps: selecting a suitable material, specifying a shape or design for the engineering problem, and determining the necessary manufacturing processes to create the design [1]. The engineering process thus begins with the material selection process. The material selection process begins with identifying the desired attributes of the engineering problem, such as looking at the density, strength, or cost of the material for example. When looking at an engineering problem, certain design demands are required in order to fit the goals of the problem, such as a high strength material at low cost. After these attributes and demands are determined, the criterion will be compared with real life materials in order to find the best possible match. In order to keep an open mind, all materials are originally viewed as possible options for the engineering problem, which in this case is the robot frame. An overview of the materials selection process can be seen in Figure 3.2 on the left. An overview of the materials selection process can be seen in Figure.



**Figure 3.2: Material selection procedure [37]**

### 3.3 Current materials used to manufacture bogie frame

#### 3.3.1 Steels

Steels are materials which contain by mass more iron than any other single element, having a carbon content generally less than 2 % and containing other elements. A limited number of chromium steels may contain more than 2 % of carbon, but 2 % is the usual dividing line between steel and cast iron [25].

Iron and steel form the critical elements of structure for the vast majority of vehicles, and are low-cost materials with an extensive experience base and familiarity to the industry. The past several years have seen steady increases in the use of high-strength steels (HSS), many versions of which are referred to as high-strength, low-alloy (HSLA) steels. These materials plus their associated advanced design and fabrication techniques (as well as improved design and fabrication using traditional steels) formed the basis of the American Iron and Steel Institute (AISI) Ultralight Steel Auto Body (ULSAB) series of studies and demonstration projects.

Steels are classified on the basis of chemical composition into;

- (a) Unalloyed steels; and
- (b) Alloy steels.

##### 3.3.1.1 Rules for classification

The following rules are observed for classifying steels as unalloyed or alloyed:

- (a) Classification is based on the specified cast analysis;
- (b) When a minimum value or range is specified for an element, the minimum value is taken for classification;
- (c) When only a maximum value is specified for manganese, the maximum value is taken for classification; and
- (d) When a maximum value is specified for elements other than manganese, a value of 0.7 times the maximum value is taken for classification.

##### 3.3.1.2 Unalloyed steels

Unalloyed steels are those steels in which the percentage of each element is less than its limiting value. Depending on their carbon content, unalloyed steels are subdivided into:

- (a) Low carbon steels which contain less than 0.30 % carbon;

- (b) Medium carbon steels which contain from 0.30 % to 0.60 % carbon; and  
 (c) High carbon steels which contain more than 0.60 % carbon.

Unalloyed steels are also subdivided into:

- (a) Plain carbon steels which contain a specified mean manganese content of less than 1 %;  
 (b) High manganese carbon steels which contain a specified mean manganese content of more than or equal to 1 %; and  
 (c) Free cutting steels which contain a specified minimum sulphur content of 0.070 % and/or bismuth, lead, phosphorus, tellurium or selenium.

### 3.3.1.3 Alloy steels

Alloy steels are those steels in which the percentage of each element is equal to or greater than its limiting value. Depending on the total alloy content, alloy steels are subdivided into:

- (a) Low alloy steels which have a total alloy content less than 5 %; and  
 (b) High alloy steels which have a total alloy content greater than or equal to 5 %.

Some of the stainless steel grades suggested for rail vehicle are as follows:

Duplex austenitic-ferritic stainless steel the most commonly used duplex grade is 0.02% C – 22% Cr – 5.5% Ni – 3% Mo – 0.15% alloy, whose standard European designation is X2CrNiMoN22-5-3 / 1.4462.

**Table 3.1:** Specific Strength of Stainless Steels, 6061 Aluminum and High Strength Steel

Property	Duplex Stainless Steel	Austenitic Stainless Steel			Aluminum		High Strength Steel HSLA
		Annealed	C850(2)	C1000(3)	T4(4)	T6(5)	
Density : $\rho\left(\frac{g}{cm^3}\right)$	7.8	7.9	7.9	7.9	2.7	2.7	7.83
Yield Stress : $\sigma\left(\frac{N}{mm^2}\right)$	640	370	600	880	130	275	410
Specific Strength (N/mm <sup>2</sup> /g/cm <sup>3</sup> )	82	46.8	76	111.4	48.1	100	52.4

### 3.3.2 Aluminum

Aluminum is the world's most abundant metal and is the third most common element comprising 8% of the earth's crust, the versatility of aluminium makes it the most widely used metal after steel.

Adequate formability is one of the requirements for aluminum sheets to produce complex stampings at acceptable economical rates. This involves appreciation of the interaction of the crystallographic texture, sheet thickness and stamping die or lubricant parameters. In addition, the aluminum alloys chosen for exterior panels must have the ability of age hardening to provide suitable strength for dent resistance during the oven paint baking.

Aluminum castings have been applied to various automobile parts for a long period. As a key trend, the material for engine blocks, which is one of the heavier parts, is being switched from cast iron to aluminum resulting in significant weight reduction. Aluminum castings find the most widespread use in automobile.

As an example a modular assembly carries the electromagnets which provide levitation and guidance of the vehicles; moreover, the linear motors used for traction are integrated into the same mechanical structure. These modular bogies for Maglev vehicles are made of aluminum, which helps to reduce the overall vehicle weight. The weight of an urban Maglev vehicle is a critical issue. When minimizing the weight of the bogie structure, life cycle requirements have to be taken into consideration at the same time. It is required to know the operating load history to be an input to fatigue analysis [24].

#### Aluminum Properties

- High strength/weight ratio
- No fatigue limit (vibration = trouble!)
- Widely variable toughness
- Most alloys resistant to air, humidity, solvents
- Acids and bases very bad!
- Inexpensive and easy to work

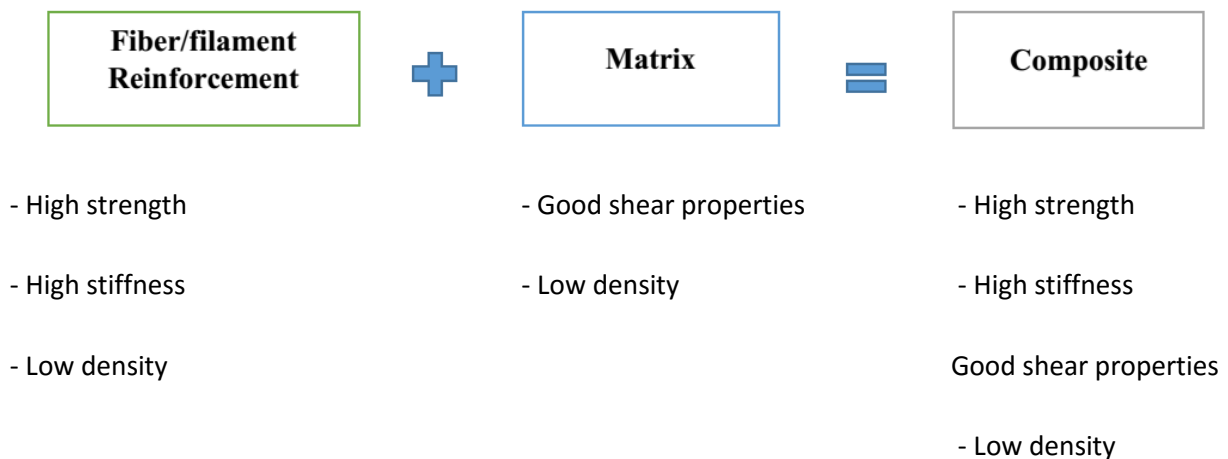
The bogie structure applied for maglev vehicles are made of aluminium. The lighter aluminium bogie structures help to reduce the overall vehicle weight.

### 3.3.3 Composite materials

Composite materials are engineering materials made from two or more constituent materials that remain separate and distinct on a macroscopic level while forming a single component. There are two categories of constituent materials: matrix and reinforcement [26].

The primary functions of the matrix materials are to transfer stresses between the reinforcing material and to protect them from mechanical and/or environmental damage and whereas the presence of fibers/particles in a composite improves its mechanical properties such as strength, stiffness etc [27].

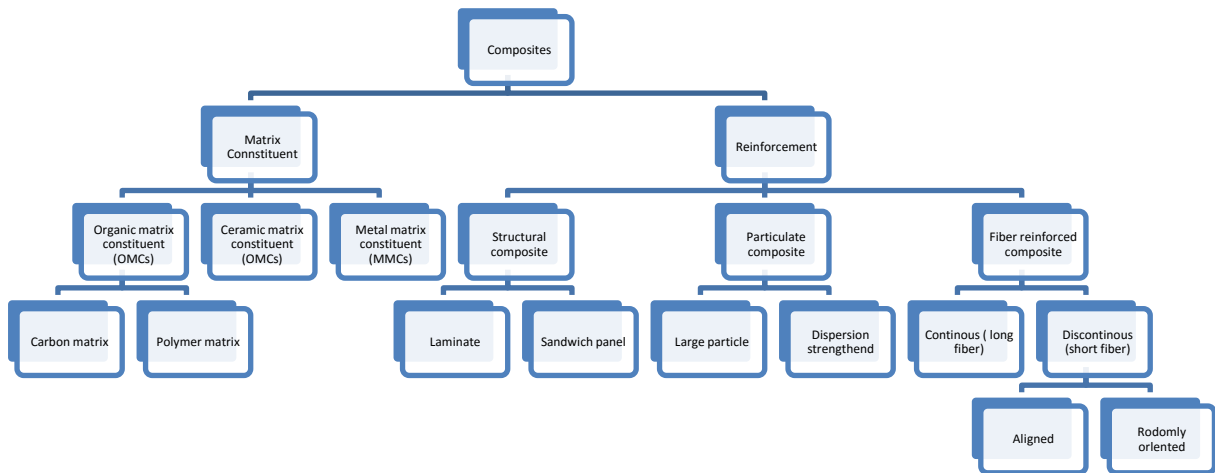
The matrix material surrounds and supports the reinforcement or the fiber materials by maintaining their relative positions. The reinforcing material impart their special mechanical and physical properties to enhance the matrix properties [30]. In general terms composite are explained as the following:



**Figure 3.3: component of a composite.**

### 3.3.3.1 Classification of composite materials

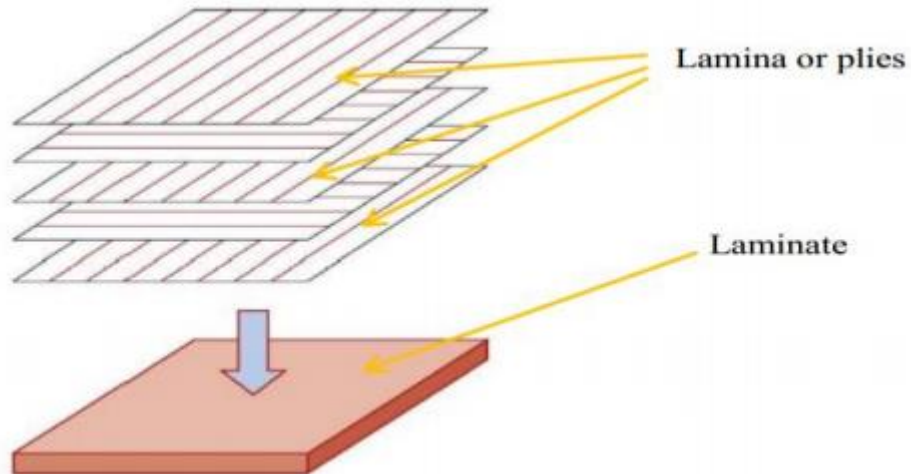
According to [20, 53] Composite materials are commonly classified as depicted in the following figure.



**Figure 3.4: Classification of composite materials [28, 35, and 36].**

### Laminar Composites

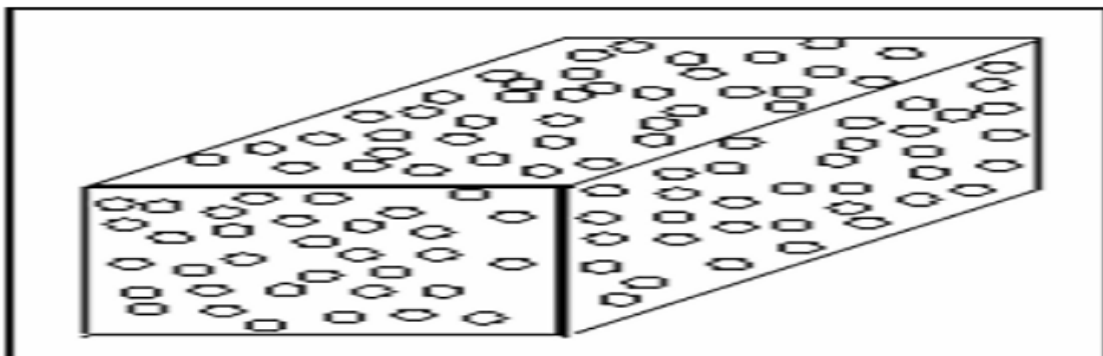
There are many types of laminate composites from these clad and sandwich laminates have many areas of application, although they are well known by following the rule of mixture from the modulus and strength point of view. Powder metallurgical processes such like; roll bonding, hot pressing, diffusion bonding, brazing and etc. can be employed for the fabrication of different alloys of sheet, foil, powder or sprayed materials. It is not possible to achieve high strength materials unlike the fiber version. But sheets and foils can be made isotropic in two dimensions more easily than fibers. The main functional types of metal-metal laminates that do not possess high strength or stiffness are single layered ones that endow the composites with special properties, apart from being cost effective. They are usually made by pre-coating or cladding methods [35].



**Figure 3.5: laminate composite [33].**

### Particulate Composites

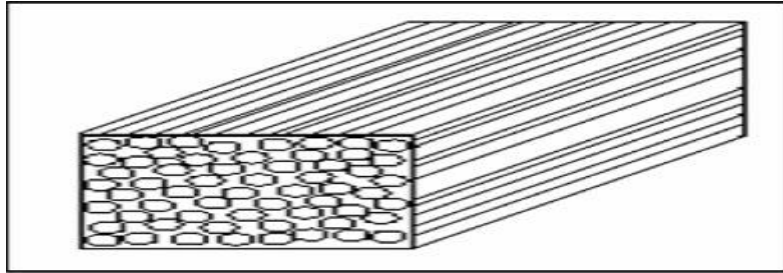
Particles usually reinforce a composite equally in all directions called isotropic composite. Plastics, cements and metals are examples of particles. Particles used to strengthen a matrix don't do so in the same way as fibers. For one thing, particles are not directional like fibers. Spread at random throughout a matrix, particles tend to reinforce in all directions equally. The difference between particulate composite and dispersion strengthened ones is, thus, obvious. The mechanism used to strengthen each of them is also different. The dispersed in the dispersion-strengthened materials reinforces the matrix alloy by arresting motion of dislocations and needs large forces to fracture the restriction created by dispersion. In particulate composites, the particles strengthen the system by the hydrostatic coercion of fillers in matrices and by their hardness relative to the matrix [33].



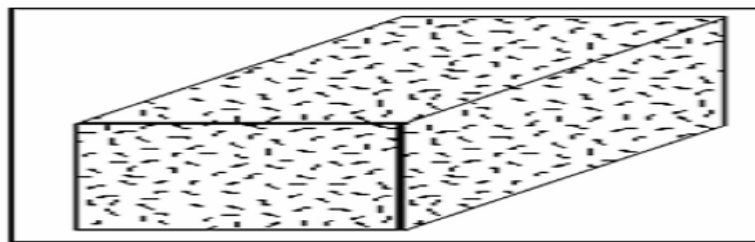
**Figure 3.6: Particulate Composite [35].**

### Fiber reinforced composites (FRP)

Fibers are the important class of reinforcements, as they satisfy the desired conditions and transfer strength to the matrix constituent influencing and enhancing their properties as desired. Glass fibers are the earliest known fibers used to reinforce materials. Ceramic and metal fibers were subsequently found out and put to extensive use, to render composites stiffer more resistant to heat [29].



**Figure 3.7: Long- fiber reinforced composites [35]**



**Figure 3.8: Short-fiber reinforced composites [35].**

### Carbon fibers

The properties of carbon fibers are equal to steel, but with lower density. As mentioned in Table 3.2 below, carbon fibers high stiffness and strength, and the fibers have also good thermal stability and when combined into a matrix is the fatigue resistance excellent [31, 32].

Most of the time carbon fibers are combined with a polymer matrix, and which is called CFRP or carbon fiber reinforced plastics. It is possible to receive a high performance material with a weight reduction of more than 50 compared to high strength steel by using CFRP. The strength and stiffness of CFRP is as high as for high strength and stiffer steel and the density is 40 per cent lower than aluminum. The fatigue and creep resistance of CFRP are also good, and by using laminate orientation the material can be designed to be tougher and more damage tolerant than metals [34].

Table below shows advantages and disadvantages of some common fibers.

**Table 3.2:** Advantages and disadvantages of reinforced fibers [31].

Fiber	Avantageous	disadvantageous
E-glass	<ul style="list-style-type: none"> <li>• High strength</li> </ul>	<ul style="list-style-type: none"> <li>• Low stifness</li> </ul>
	<ul style="list-style-type: none"> <li>• Low cost</li> </ul>	<ul style="list-style-type: none"> <li>• Short fatigue life</li> </ul>
		<ul style="list-style-type: none"> <li>• High Temperature Sensitivity</li> </ul>
Amide (kelvar)	<ul style="list-style-type: none"> <li>• High tensile strength</li> </ul>	<ul style="list-style-type: none"> <li>• Low compressive strength</li> </ul>
	<ul style="list-style-type: none"> <li>• Low density</li> </ul>	<ul style="list-style-type: none"> <li>• High moisture absorption</li> </ul>
Boron	<ul style="list-style-type: none"> <li>• High stiffness</li> </ul>	<ul style="list-style-type: none"> <li>• High cost</li> </ul>
	<ul style="list-style-type: none"> <li>• High compressive strength</li> </ul>	
Carbon (AS4, T300, c6000)	<ul style="list-style-type: none"> <li>• High strength</li> </ul>	<ul style="list-style-type: none"> <li>• Moderately high cost</li> </ul>
	<ul style="list-style-type: none"> <li>• High stiffness</li> </ul>	
Graphite (GY-70, pitch)	<ul style="list-style-type: none"> <li>• Very high stiffness</li> </ul>	<ul style="list-style-type: none"> <li>• Low strength</li> </ul>
		<ul style="list-style-type: none"> <li>• High cost</li> </ul>
Ceramic (Silicon carbide, amumina)	<ul style="list-style-type: none"> <li>• High stiffness</li> </ul>	<ul style="list-style-type: none"> <li>• Low strength</li> </ul>
	<ul style="list-style-type: none"> <li>• High use temperature</li> </ul>	<ul style="list-style-type: none"> <li>• High cost</li> </ul>

✓ **FR-4 Fiberglass-Epoxy Composite**

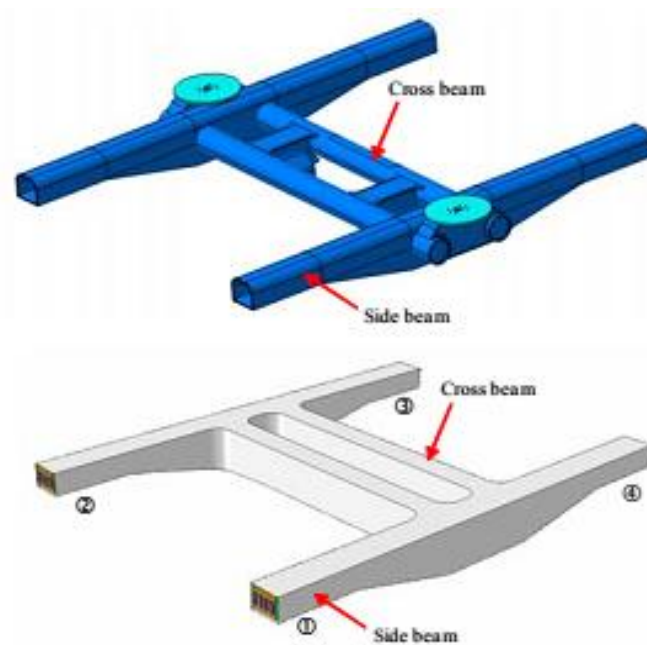
- Circuit board material; inexpensive
- Machining dust is hazardous
- Strong, but somewhat brittle

✓ **Carbon Fiber**

- Very expensive
- Sheets, tubes available w/o custom tooling
- Very strong, but a bit brittle

### 3.3.3.2 Composite bogie frame

The conventional bogie frame of a urban subway train is manufactured as a welded steel box format (like a hollow tube) to reduce the weight (Fig. 1(a)). The SM490A steel is usually used as the base material of the bogie frame. In case of the composite bogie frame, its external shape is similar to the conventional one as in Fig. 1(b). It also has two side beams and two cross beams. It is 2970 mm long and 2170 mm wide. In order to meet the structural requirements, the inside of the side beams of the proposed composite bogie frame was filled with the following structural parts; composite chords, ribs, and foam cores. The glass/epoxy preregs were stacked up on the inner structural part to form the skin, as seen in Fig. 1(b) [10].



**Figure 3.9: The conventional steel bogie frame and the composite bogie frame [10].**

## Chapter Four

### Static and Fatigue Analysis

#### 4.1 Fatigue Analysis

##### 4.1.1 Metal Fatigue

Fatigue is the weakening of a material caused by repeatedly applied loads. It is the progressive and localized structural damage that occurs when a material is subjected to cyclic loading. The nominal maximum stress values that cause such damage may be much less than the strength of the material typically quoted as the ultimate tensile stress limit, or the yield stress limit.

Fatigue occurs when a material is subjected to repeat loading and unloading. If the loads are above a certain threshold, microscopic cracks will begin to form at the stress concentrators such as the surface, persistent slip bands (PSBs); and grain interfaces. Eventually a crack will reach a critical size, the crack will propagate suddenly, and the structure will fracture. The shape of the structure will significantly affect the fatigue life, square holes or sharp corners will lead to elevated local stresses where fatigue cracks can initiate. Round holes and smooth transitions or fillets will therefore increase the fatigue strength of the structure.

A common cause of structural fracture, fatigue failure occurs because of cyclic loading. In essence, fatigue damage progresses in two stages; the crack initiation stage, in which one or more small cracks begin to form in the material, and the crack growth stage. In the crack growth stage, the initial crack propagates until it results in the failure of the structural material. Avoiding fatigue failure is a fundamental principle in the design of structures that are exposed to cyclic loading and vibration. Fatigue can be classified as one of two types depending on the number of load cycles prior to failure. High-cycle fatigue failure results after millions of load cycles. Failures resulting from a lower number of load cycles, thousands or less, are low-cycle fatigue failures. In low-cycle fatigue, the deformations due to load are mainly plastic, whereas high cycle fatigue deformations are elastic.

Fatigue, or metal fatigue, is the failure of a component as a result of cyclic stress, or the initiation and subsequent growth of crack or growth from a pre-existing defect until it reaches critical size. The failure occurs in three phases: crack initiation, crack propagation, and catastrophic over load failure. The part can fail even though stresses are not those high. Over

time, fatigue cracks can start and then grow large enough to cause sudden failure. Due to the fatigue test costs are expensive, the fatigue strength assessment of key components in the bogie frame using finite element model can find out the fatigue strength of the weak parts, can reduce the risk of fatigue testing prototypes, shorten development cycles, reduce trial costs.

The top three causes of fatigue failure are:

- Design/manufacturing defect
  - Badly designed product or manufacturing/production
- Material defect/ variance
  - Material test properties not well understood
- Usage outside the design envelope
  - Operational dynamics, loads etc...not wellknown
  - Customer abuse/misuse

Fatigue, or metal fatigue, is the failure of a component as a result of cyclic stress. The failure occurs in three phases: crack initiation, crack propagation, and catastrophic overload failure. The duration of each of these three phases depends on many factors including fundamental raw material characteristics, magnitude and orientation of applied stresses, processing history, etc. Fatigue failures often result from applied stress levels significantly below those necessary to cause static failure [18].

Fatigue failures are typically characterized as either low-cycle (<1,000 cycles) or high-cycle (>1,000 cycles). The threshold value dividing low- and high-cycle fatigue is somewhat arbitrary, but is generally based on the raw material's behavior at the microstructural level in response to the applied stresses. Low cycle failures typically involve significant plastic deformation. An example would be reversed 90° bending of a paperclip. Gross plastic deformation will take place on the first bend, but failure will not occur until approximately 20 cycles. Plastic deformation does play a role in high cycle fatigue; however, the plastic deformation is much localized and not necessarily discernable by a macroscopic evaluation of the component. In summary, while a valve spring designer may consider a failure at 10,000 cycles very short life, the failure can still be the result of high-cycle fatigue because the material response at the microstructural level is the same as in a 10,000,000-cycle failure under lower applied stresses [18].

Most metals with a body centered cubic crystal structure have a characteristic response to cyclic stresses. These materials have a threshold stress limit below which fatigue cracks will not initiate. This threshold stress value is often referred to as the endurance limit. In steels, the life associated with this behavior is generally accepted to be  $2 * 10^6$  cycles. In other words, if a given stress state does not induce a fatigue failure within the first  $2 * 10^6$  cycles, future failure of the component is considered unlikely. For spring applications, a more realistic threshold life value would be  $2 * 10^6$  cycles. Metals with a face center cubic crystal structure (e.g. aluminum, austenitic stain less steels, copper, etc.) do not typically have an endurance limit. For these materials, fatigue life continues to increase as stress levels decrease; however, a threshold limit is not typically reached below which infinite life can be expected [18].

**Endurance Limit:** Certain materials have a fatigue limit or endurance limit which represents a stress level below which the material does not fail and can be cycled indefinitely. If the applied stress level is below the endurance limit of the material, the structure is said to have an infinite life. This is characteristic of steel and titanium in benign environmental conditions. Many non-ferrous metals and alloys, such as aluminum, magnesium and copper alloys, do not exhibit well-defined endurance limit. Steels typically show an endurance limit, = 40% of yield; this is typically associated with the presence of a solute (carbon, nitrogen) that pins dislocations and prevents dislocation motion at small displacements or strains (which is apparent in an upper yield point). The highest value of the stress amplitudes in a symmetrical cycle of mechanical load variation, or the maximum stress of an asymmetrical cycle, to which a material can be subjected for an unlimited number of cycles without failure. The value of the amplitude or the maximum stress in a cycle that, when repeated for a specific number of cycles, causes fatigue failure or produces macroscopic cracks is called the fatigue strength.

**Avoiding fatigue failure:** There are two fundamental ways to prolong fatigue life: improve the design or improve the mechanical properties of a material, *i.e.*, use a more fatigue resistant material, employ better manufacturing methods, or add thermal and mechanical treatments. From an economics point of view, it is usually more beneficial to improve structural design than to upgrade material, because material costs are recurring, while making the design improvements requires only a single initial investment. With respect to improving the design, fatigue analysis results can identify any existing problem areas and suggest likely strategies for improvement.

**Fatigue strength:** The stress, at which a body under cyclic loading fails after certain numbers of load cycles, is called the fatigue strength of the body for that number of cycle.

#### 4.1.2 S-N-curves

The S-N diagram also called Wohler curve is the plot of the fatigue strength of a test specimen against the number of load cycles. The fatigue strength values are plotted in linear scale along the Y axis and the number of loading cycles are plotted along X axis in logarithmic scale of the S-N curve. After the S-N diagram for a particular specimen is available, you can find the fatigue strength for any particular number of loading cycles.

The cyclic variation of mean stress produced by cyclic loading conditions affects the life of a structure. To evaluate their fatigue life, material samples are typically exercised to failure by cyclically loading them to produce a constantly varying mean stress. The amplitude of this mean stress is then recorded along with the number of cycles to failure. From numerous tests covering a range of mean stress amplitudes, a stress-life diagram relating stress amplitude ( $S_a$ ) to number of cycles to failure ( $N$ ) can be produced for any given material. This S-N diagram is an important and standard way of presenting fatigue data. Another equivalent type of S-N diagram can be produced by plotting stress ratio with respect to the number of cycles to failure [19].

One basic idea behind fatigue testing is constant amplitude loading, that is, fatigue loading in which the applied cyclic load is sinusoidal shaped and of constant amplitude and frequency. The load cycle is the smallest repeating period of the resulting mean stress history. For local stresses,  $\sigma_a$  is stress amplitude and  $\sigma_m$  is mean stress.  $\sigma_{max}$  is maximum stress, and  $\sigma_{min}$  is minimum stress. The load cycle is noted mathematically as  $\sigma_m \pm \sigma_a$ . Tensile stresses have positive values, and negative values are compressive stresses. According to this notation and considering the sign convention, the following equations for maximum, mean, and minimum stress can be expressed.

The stress range is the algebraic difference between the maximum and minimum stress in a cycle:

$$\Delta\sigma = \sigma_{max} - \sigma_{min} \dots\dots\dots(4.1)$$

The stress amplitude is one-half the stress range:

$$\sigma_a = \frac{\Delta\sigma}{2} = \frac{\sigma_{max} - \sigma_{min}}{2} \dots\dots\dots(4.2)$$

The mean stress is the algebraic mean of the the maximum and minimum stress in the cycle:

$$\sigma_m = \frac{\sigma_{max} + \sigma_{min}}{2} \dots\dots\dots(4.3)$$

Two ratios that are often defined for the representation of mean stress are the stress ratio R and the amplitude ratio A:

$$R = \frac{\sigma_{min}}{\sigma_{max}} \dots\dots\dots(4.4)$$

$$A = \frac{\sigma_a}{\sigma_m} = \frac{1-R}{1+R} \dots\dots\dots(4.5)$$

For fully-reversed loading conditions, R is equal to -1. For static loading, R is equal to 1. For a case where the mean stress is tensile and equal to the stress amplitude, R is equal to 0. A stress cycle of R = 0.1 is often used in aircraft component testing, and corresponds to a tension-tension cycle in which the minimum stress is equal to 0.1 times the maximum stress.

#### 4.2 Types of Cyclic Loading

There are essentially four classes of fatigue loading, with the ANSYS Fatigue Module currently supporting the first three:

- Constant amplitude, proportional loading
- Constant amplitude, non-proportional loading
- Non-constant amplitude, proportional loading
- Non-constant amplitude, non-proportional loading

In these descriptions, the amplitude identifier is readily understood: Is the loading a variant of a sine wave with a single load ratio, or does the loading vary, perhaps erratically, with the load ratio changing with time? The second identifier, proportionality, describes whether the changing load causes the principal stress axes to change. If the principal stress axes do not change, then it is proportional loading. If the principal stress axes do change, then the cycles cannot be counted simply and it is non-proportional loading [20].

#### 4.2.1 Constant amplitude, proportional loading

- Loading is of constant amplitude because only one set of FE stress results along with a loading ratio is required to calculate the alternating and mean values.
- Is the classic, “back of the envelope” calculation describing whether the load has a constant maximum value or continually varies with time.
- The loading ratio is defined as the ratio of the second load to the first load ( $LR = L2/L1$ ).
- Loading is proportional since only one set of FE results are needed (principal stress axes do not change over time).
- Since loading is proportional, looking at a single set of FE results can identify critical fatigue locations.
- Since there are only two loadings, no cycle counting or cumulative damage calculations need to be done.

#### 4.2.2 Constant amplitude, non-proportional loading

- Looks at exactly two load cases that need not be related by a scale factor.
- The loading is of constant amplitude but nonproportional since principal stress or strain axes are free to change between the two load sets.
- This happens under conditions where changing the direction or magnitude of loads causes a change in the relative stress distribution in the model. This may be important in situations with non linear contact, compression-only surfaces, or bolt loads.
- This type of fatigue loading can describe common fatigue loadings such as :
  - Alternating between two distinct load cases (like a bending load and torsional load).
  - Applying an alternating load superimposed on a static load.
- No cycle counting needs to be done.
- But since the loading is non-proportional, the critical fatigue location may occur at a spatial location that is not easily identifiable by looking at either of the base loading stress states.
- Fatigue tools located under a solution branch are inherently applied to that single branch and thus can only handle proportional loading.

### 4.2.3 Non-constant amplitude, proportional loading

- Instead of using a single load ratio to calculate alternating and mean values, the load ratio varies over time.
- Think of this as coupling an FE analysis with strain-gauge results collected over a given time interval.
- Since loading is proportional, the critical fatigue location can be found by looking at a single set of FE results.
- However, the fatigue loading which causes the maximum damage cannot easily be seen.
- Thus, cumulative damage calculations (including cycle counting such as Rainflow and damage summation such as Miner's rule) need to be done to determine the total amount of fatigue damage and which cycle combinations cause that damage.
- Cycle counting is a means to reduce a complex load history into a number of events, which can be compared to the available constant amplitude test data.
- The ANSYS Fatigue Module uses a "quick counting" technique to substantially reduce runtime and memory.
- In quick counting, alternating and mean stresses are sorted into bins before partial damage is calculated.
- Without quick counting, data is not sorted into bins until after partial damages are found.
- The accuracy of quick counting is usually very good if a proper number of bins are used when counting.
- Bin size defines how many divisions the cycle counting history should be organized into :
  - Strictly speaking, bin size specifies the number of divisions of the rainflow matrix.
  - A larger bin size has greater precision but will take longer to solve and use more memory.
- For Stress Life, another available option when conducting a variable amplitude fatigue analysis is the ability to set the value used for infinite life.
- In constant amplitude loading, if the alternating stress is lower than the lowest alternating stress on the fatigue curve, the fatigue tool will use the life at the last point.

- This provides for an added level of safety because many materials do not exhibit an endurance limit.

#### 4.2.4 Non-constant amplitude, non-proportional loading

- Most general case and is similar to Constant Amplitude, non-proportional loading, but in this loading class there are more than 2 different stress cases involved that have no relation to one another.
- Not only is the spatial location of critical fatigue life unknown, but also unknown is what combination of loads cause the most damage.
- Thus, more advanced cycle counting is required such as path independent peak methods or multiaxial critical plane methods.
- Currently the ANSYS Fatigue Module does not support this type of fatigue loading.

### 4.3 Modeling and fatigue analysis

#### 4.3.1 Material modeling

##### 4.3.1.1 Bogie frame material

The AALRT bogie frame is designed and calculated in compliance with UIC615-4, EN13749 and VDV152 European railway standards. These European Standards cover a wide variety of different bogie types, According to EN 13749 STD the AALRT Bogie will be categorized to bogie category B-IV which is bogies for light rail vehicles and trams [21].

Frame: steel UNI EN 10025 S355J2G3C

- According to the thickness of the frame, yield strength will be 335Mpa.
- Axle box: EN-AC-AI-Si-7Mg0.6

A bogie is a chassis or framework carrying wheels, attached to a vehicle, thus serving as a modular subassembly of wheels and axles. Bogies take various forms in various modes of transport. A bogie may remain normally attached or be quickly detachable; it may contain a suspension within it. The purpose is to improve ride quality by absorbing vibration and minimizing the impact of centrifugal forces when the train runs on curves at high speed. Bogie is formed of several parts: two wheel and axis, two side beams, crossings, cushions, suspension system and levering of brake.

Bogie is structure of bolster, full side bearing, outer-side axle box and fixed axle wheelset, and is mounted underneath module Mc at both end of car. It mainly includes frame, wheelset,

primary suspension, secondary suspension, traction assembly, driving unit, brake unit and auxiliary devices.

#### 4.3.2 Dimension

**Table 4.1:** Main Technical Parameters of the bogie. [22]

Item	Motor bogie	Trailer bogie
Type	CW12	CW13
Maximum operating speed	70km/h	
Maximum test speed	80km/h	
Rail Gauge	1,435mm	
Car body mass (actual)	44,000kg	
distance between the back of the wheel flange	1380 <sup>0</sup> <sub>.2</sub> mm	1377.7 <sup>+2</sup> <sub>.1</sub> mm
Wheel base	1900mm	1800mm
Axle load	10.5t	11.5t
Wheel diameter (new/worn)	660mm/580mm	
Bogie mass	≤6t	≤4t

**Table 4.2:** Main Technical Parameters of the bogie. [22]

Axle distance	2560mm
Wheel diameter (new / worn out )	915 / 845mm
Distance between wheels	1600mm
Brake disk diameter	640mm
<b>Bogie:</b>	
Width	3190mm
Height	949mm
Length	3534mm
Mass	3803 kg

**Table 4.3:** Vehicle weight [23].

Load	Carbody weight	Passenger weight	Total weight
Empty vehicle (t)	44	0	44
Rated passenger capacity (t)	44	15.24	59.24
Overload capacity (t)	44	19.02	63.02

Note: Take 60 kg as average weight of each passenger; tare weight of vehicles  $\leq 44t$ .

**Table 4.4:** symbols of Accelerations which are used in load cases. [21]

Acceleration ( $m/s^2$ )	Symbol	
	Vehicle body	Bogie (primary spring)
Vertical	$a_{zc}$	$a_{zb}$
Transversal (dynamic)	$a_{yc}$	$a_{yb}$
Centrifugal (quasi static)	$a_{ycc}$	$a_{zcb}$
Longitudinal	$a_{xc}$	$a_{xb}$

**Table 4.5:** symbols of Masses which are used in load cases. [21]

Mass (Kg)	Symbol
Vehicle in running order	$M_v$
Vehicle body	$m_1$
Bogie mass without any secondary spring masses (if present)	$m^+$
Bogie primary spring mass	$m_2$
Exceptional payload	$P_1$
Normal service payload	$P_2$

**Table 4.6:** symbols of forces which are used in load cases. [21]

Force (N)	Position	Symbol		
		Static	Quasi-static	Dynamic
Vertical	Load applied to bogie	$F_z$		
	Force on sideframe 1 or sidebearer 1	$F_{z1}$	$F_{z1qs}$	$F_{z1d}$
	Force on sideframe 2 or sidebearer 2	$F_{z2}$	$F_{z2qs}$	$F_{z2d}$
	Force on centre pivot	$F_{zp}$	$F_{zpq}$	$F_{zpd}$
	Force at (vehicle body) c of g	$F_{zc}$		
Transverse	Force applied to bogie	$F_y$		
	Force on axle 1	$F_{y1}$	$F_{y1qs}$	$F_{y1d}$
	Force on axle 2	$F_{y2}$	$F_{y2qs}$	$F_{y2d}$
	Force at( vehicle body) c of g	$F_{yc}$		
	Force due to wind	$F_{w1}$		
Longitudinal	Force at each wheel	$F_{x1}$		
	Force at (vehicle body) c of g	$F_{xc}$		
	Force at (vehicle bogie) c of g	$F_x$		

**Table 4.7:** Acceleration values for exceptional loads. [21]

Load case	Vehicle body masses					Bogie mass			
	$a_{zc}$ ( $m/s^2$ )	$a_{yc}$ ( $m/s^2$ )	$a_{yc}$ ( $m/s^2$ )	$a_{xc}$ ( $m/s^2$ )	$q$ ( $N/m^2$ )	$a_{zb}$ ( $m/s^2$ )	$a_{yb}$ ( $m/s^2$ )	$a_{ycb}$ ( $m/s^2$ )	$a_{xb}$ ( $m/s^2$ )
switches	3.2	2.2	—	Emergency braking rate	600 <sup>a</sup>	30	16	—	Emergency braking rate
Running through curves	1.6	1.3	2.0	Emergency braking rate	600 <sup>a</sup>	12	6.5	2	Emergency braking rate

<sup>a</sup> wind speed of 105 Km/h

**Table 4.8:** Acceleration values for normal service loads. [21]

Load case	Vehicle body masses					Bogie masses			
	$a_{zc}$ ( $m/s^2$ )	$a_{yc}$ ( $m/s^2$ )	$a_{yc}$ ( $m/s^2$ )	$a_{xc}$ ( $m/s^2$ )	$q$ ( $N/m^2$ )	$a_{zb}$ ( $m/s^2$ )	$a_{yb}$ ( $m/s^2$ )	$a_{ycb}$ ( $m/s^2$ )	$a_{xb}$ ( $m/s^2$ )
switches	2.4	1.6	—	—	200 <sup>a</sup>	25	12	—	—
Straight track	1.2	0.9	—	Service braking rate	—	8.5	4.5	—	Service braking rate
Running through curves	1.2	0.9	1.0	Service braking rate	—	8.5	4.5	1.0	Service braking rate

<sup>a</sup> wind speed of 60km/h

### 4.3.3 Acceptance of the design

#### 1. Condition

##### ➤ Load Case Combination for Static Calculation

The forces to apply for the static calculation with exceptional loads are

- vertical forces coming from sprung masses
- transversal forces coming from each axle
- longitudinal forces (longitudinal exceptional forces are caused from exceptional vertical loads and curve riding)
- forces of a potential collision
- track twist

#### a) Load cases of the bogie frame

- For exceptional loads the effective car body mass  $m_1$  including passengers, corresponding to a particular bogie is:

$$m_1 = (m_v + p_1) - n_b m^+ \dots \dots \dots (4.6)$$

$$P_1 = \text{mass of passengers} = \text{number of passengers} * \text{average mass} \dots \dots \dots (4.7)$$

$$P_1 = 317 * 60\text{Kg} = 19,020\text{Kg}$$

$$m_v = 44\,000\text{ Kg}$$

$$m_1 = (44\,000 + 19,020) - (3 * 3803)$$

$$m_1 = 51\,611\text{ Kg}$$

Where:

$m_v$  is the mass of car in running order;

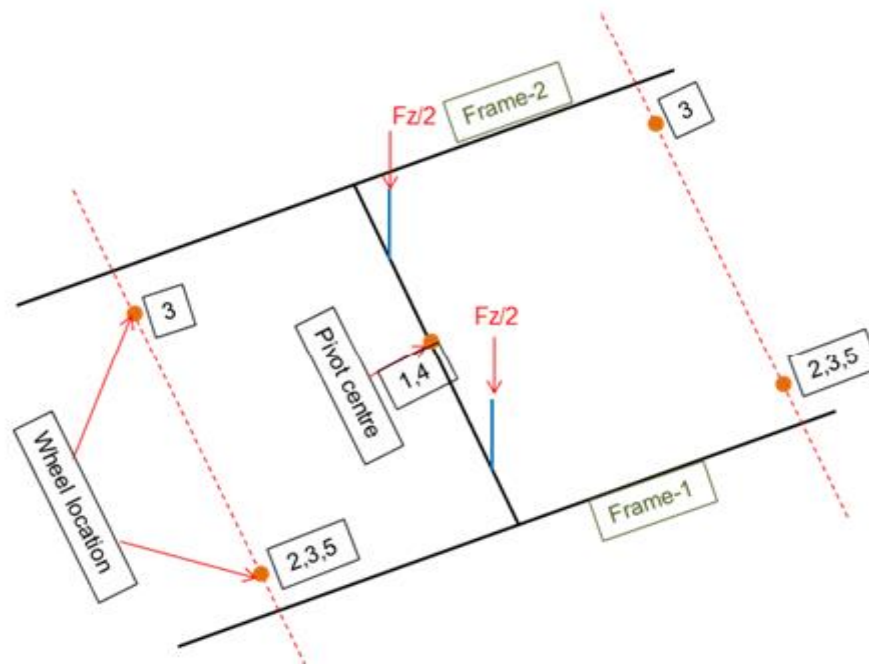
$P_1$ , is the mass of passengers;

$m^+$  is the bogie mass;

$n_b$  Number of bogies.

### ❖ Vertical Load

As discussed above, vertical load acts on four locations (load carriers) of the bogie frame. The magnitude of vertical load is determined by the following formula, and vertical proof load is 1.4 times of vertical crush load due to 1g of vertical acceleration of car body due to track induced forces. Boundary condition is shown in the diagram below [39].



**Figure 4.1: Schematic representation of Vertical load case [39].**

$$Fz_{max} = \frac{k \cdot g (Mv + P1 - 3m^+)}{3} \dots \dots \dots (4.8)$$

$$Fz_{max} = \frac{1.4 \cdot 9.81 (44\,000 + 19\,020 - 3 \cdot 3803)}{3}$$

$$Fz_{max} = 236.28 \cdot 10^3 N$$

Since the total vertical load is shared for two side frame so that force shared by each frame is calculated as follows:

$$Fz1 = Fz2 = \frac{Fz_{max}}{2} = \frac{236.28 \cdot 10^3 N}{2} = 118.14 \cdot 10^3 N$$

Here, the factor K depends on the exceptional load case and this factor is equal to 1.4 (track induced forces).

### ❖ Lateral Load

The lateral load will be shared by both secondary suspension and lateral stopper. Sharing of load between the secondary suspension and lateral stopper depends on the clearance between the lateral stopper & bolster and the stiffness of the secondary spring. The detail calculation is shown below [39].

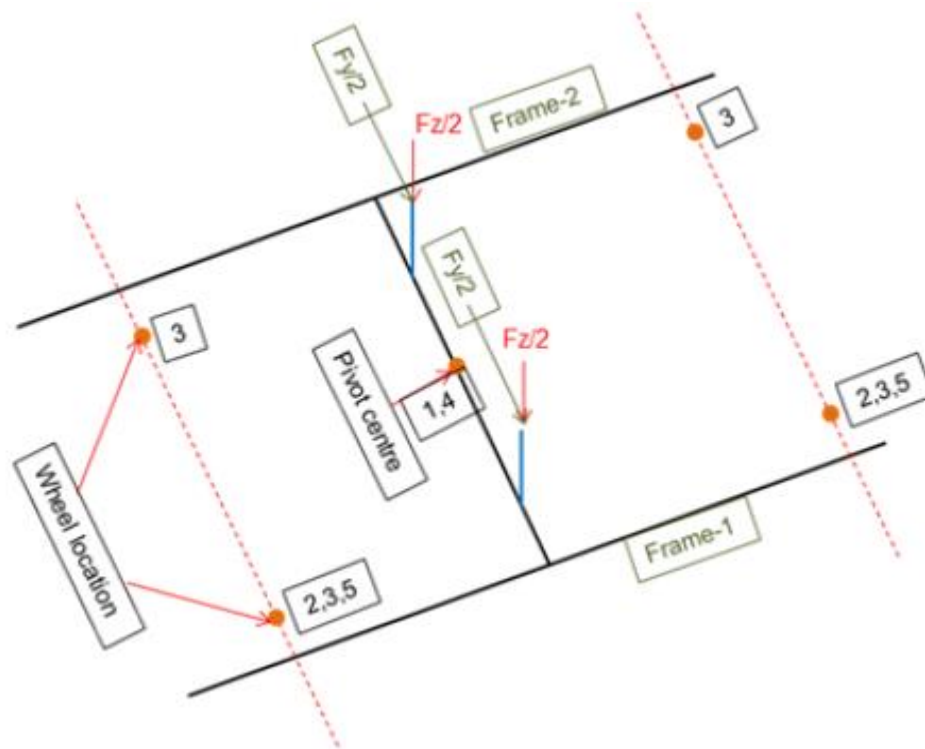


Figure 4.2: Schematic representation of lateral load case [39].

a) Load due to vehicle weight.

$$F_{y_{max}} = 2 * \left( F_{y_{tr \ min}} + \frac{Mv + P_1 * g}{3 * n_a} \right) \dots \dots \dots (4.9)$$

Where

$n_a$  = Number of axles

$F_{y_{tr \ min}} = 10^4$  = transverse force resistance of unloaded track [21].

$$F_{y_{max}} = 2 * \left( 10000 + \frac{44\ 000 + 19020}{3 * 6} * 9.81 \right)$$

$$F_{y_{max}} = 88.69 * 10^3 \text{ N}$$

these force is supported for two side frames

b) Forces applied on anti-roll systems for Exceptional loads case

Case 1 Switch:

$$a_{yb} = 16 \text{ m/s}^2$$

Centrifugal (quasi-static):  $a_{ycb}=0$

$$F_{yb} = (a_{yb} + a_{ycb})m^+ \dots\dots\dots(4.10)$$

$$F_{yb} = (16 + 0) * 3803$$

$$F_{yb} = 60\ 848 \text{ N}$$

Case 2 running through curve:  $a_{yb}= 6.5 \text{ m/s}^2$

Centrifugal (quasi-static):  $a_{ycb}=2 \text{ m/s}^2$

$$F_{yb} = (a_{yb} + a_{ycb})m^+ \dots\dots\dots(4.11)$$

$$F_{yb} = (6.5 + 2) * 3803$$

$$F_{yb} = 32\ 325.5 \text{ N}$$

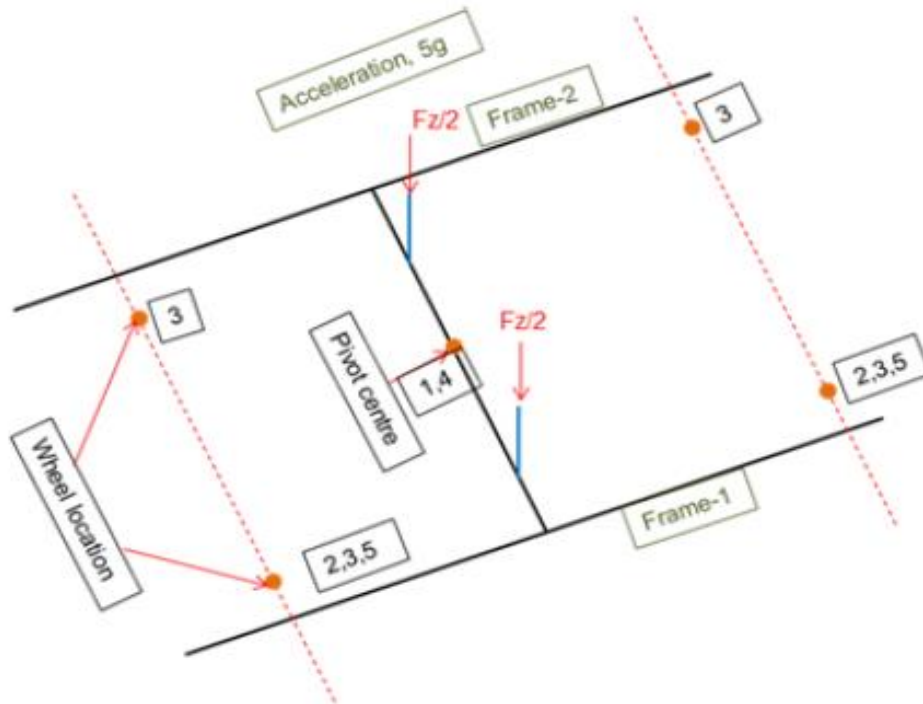
Total transverse force on bogie C of G

$$F_y = 88.69 * 10^3 \text{ N} + 60\ 848 \text{ N} + 32\ 325.5 \text{ N}$$

$$F_y = 181.86 * 10^3 \text{ N}$$

### ❖ Longitudinal load

This load is caused due to the impact of the car body which induced a longitudinal acceleration of 3g and 5g for shunting locomotives applicable at the center of the gravity of the bogie. The mass of the motor and the axle assembly is considered as lumped mass and is imposed on the mass elements in the FEA. This body force may be applied as a longitudinal acceleration of 5g [39].



**Figure 4.3: Schematic representation of longitudinal load case [39].**

a) Loads in connection between bogie and car body (collision conditions)

$$F_{xb} = m^+ 5g \dots \dots \dots (4.12)$$

From table:

$$\text{bogie mass } m^+ = 3803 \text{ kg}$$

$$F_{xb} = m^+ 5g$$

$$F_{xb} = 3803 * 5 * 9.81$$

$$F_{xb} = 186.54 * 10^3 \text{ N}$$

b) Longitudinal force (applied at the center of gravity)

$$F_{Xb} = m^+ a_{xb} \dots\dots\dots(4.13)$$

From the standard:

$$\text{bogie mass} = m^+ = 3803\text{kg}$$

➤ Exceptional Loads resulting from masses attached to the axle box

Vertical acceleration:  $a_{xb} = 50\text{m/s}^2$

$$F_{Xb} = 3803 * 50$$

$$F_{Xb} = 190.2 * 10^3\text{N}$$

c) Exceptional Loads resulting from braking

The loads resulting from braking is 1.3 times those produced during emergency braking

Average deceleration of Emergency Braking is  $a_{xb} = 1.5 \text{ m/s}^2$

$$F_{Xb} = 1.3 m^+ a_{xb} \dots\dots\dots(4.14)$$

$$F_{Xb} = 1.3 * 3803 * 1.5$$

$$F_{Xb} = 7415.85 \text{ N}$$

d) Exceptional Loads resulting from traction motors

The exceptional loads may be taken as 1.3 times those produced during starting: Average

Acceleration on for Start-Up:  $a_{xb} = 1 \text{ m/s}^2$

$$F_{Xb} = 1.3 m^+ a_{xb} \dots\dots\dots(4.15)$$

$$F_{Xb} = 1.3 * 3803 * 1$$

$$F_{Xb} = 4.944 * 10^3\text{N}$$

e) Forces applied on anti-roll systems for Exceptional loads case

Case 1                  Switch

Emergency braking rate (an assumption) =  $1.5 \text{ m/s}^2$

$$F_{Xb} = m^+ a_{xb} \dots\dots\dots(4.16)$$

$$F_{Xb} = 3803 * 1.5$$

$$F_{Xb} = 5.705 * 10^3\text{N}$$

Case 2 running through curve:

$$a_{xb} = \text{Emergency braking rate} = 1.5 \text{ m/s}^2$$

$$F_{xb} = 3803 * 1.5$$

$$F_{xb} = 5.705 * 10^3 \text{ N}$$

f) Transverse force due to wind (applied at center of pressure of body side)

$$F_w = A_w q \dots \dots \dots (4.17)$$

Take an assumption:

Tramcar Length= 28400mm and Tramcar height= 3742mm

$$A_w = L * H \dots \dots \dots (4.18)$$

$$A_w = 28400 * 3742$$

$$A_w = 106.3 * 10^6 \text{ mm}^2$$

Therefore transverse force due to wind can be calculated as

$$F_w = A_w q$$

Wind pressure  $q = 600 \text{ N/m}^2$  take an assumption

$$F_w = 106.3 * 600$$

$$F_w = 63.8 * 10^3 \text{ N}$$

By assuming 50 % the wind load which is applied on the body has transferred to the bogie longitudinally.

Total longitudinal force

$$F_x = 186.54 * 10^3 \text{ N} + 190.2 * 10^3 \text{ N} + 7.416 * 10^3 \text{ N} + 4.944 * 10^3 \text{ N} + 5.705 * 10^3 \text{ N} \\ + 31.9 * 10^3 \text{ N}$$

$$F_x = 426.71 * 10^3 \text{ N}$$

### ❖ Track Twist load

This load case corresponds to a derailment of the vehicle in operational life, in normal condition ( $k=1$ ). The twist is equal to 0.5% of the bogie wheelbase [39].

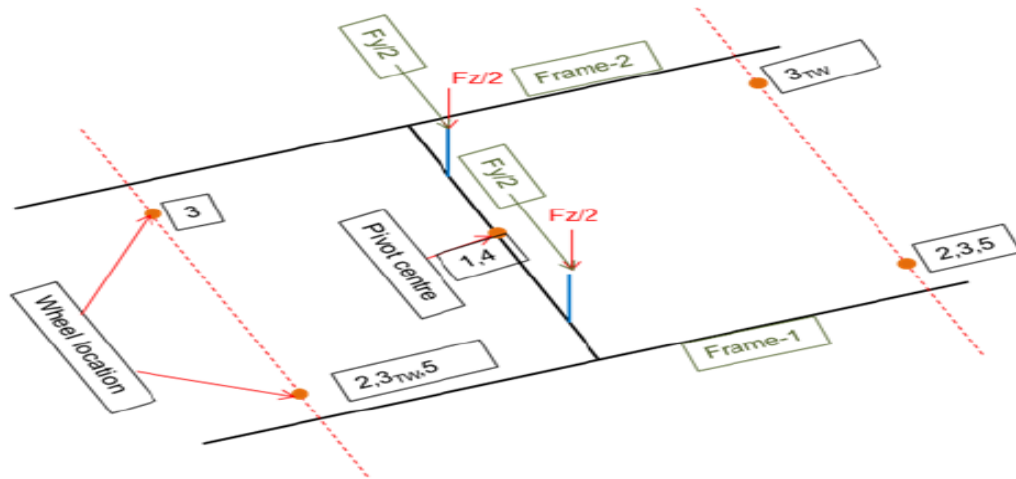


Figure 4.4: Schematic representation of Twist load case [39].

$$Twist = 0.005 * 3190 = 15.95mm$$

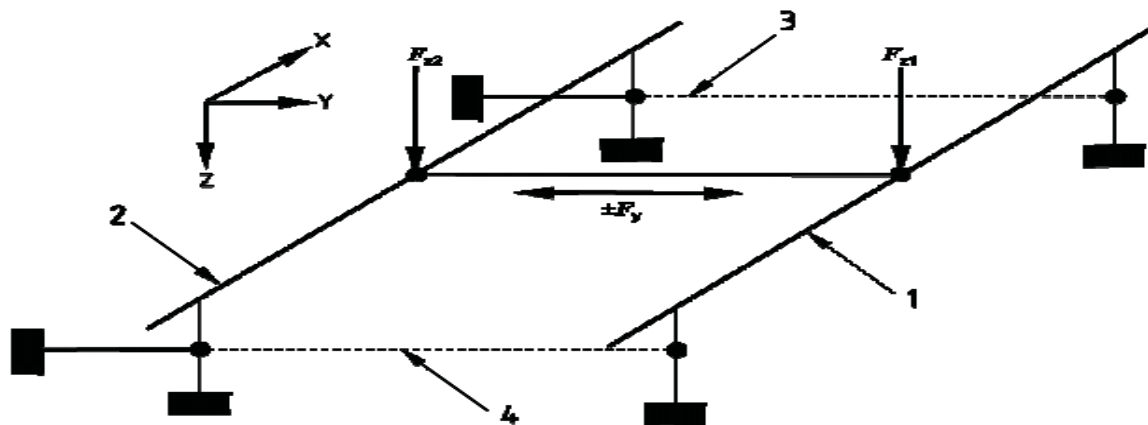
$$Dwz = \frac{Twist}{2} = \frac{15.95}{2} = 7.975mm$$

This load is induced by a track twist of 1% and is applied at the level of the wheel on the bogie fitted with its suspension.

### ❖ Wheel unloading

With the vehicle empty (under vertical load only), considering a complete unloading of one wheel with the vertical displacement of the wheel being limited to rail height is considered one exceptional load case.

- ✚ Total vertical force  $FZ = 236.28 * 10^3 N$
- ✚ Total longitudinal force  $F_x = 426.71 * 10^3 N$
- ✚ Total lateral force  $F_y = 186.86 * 10^3 N$



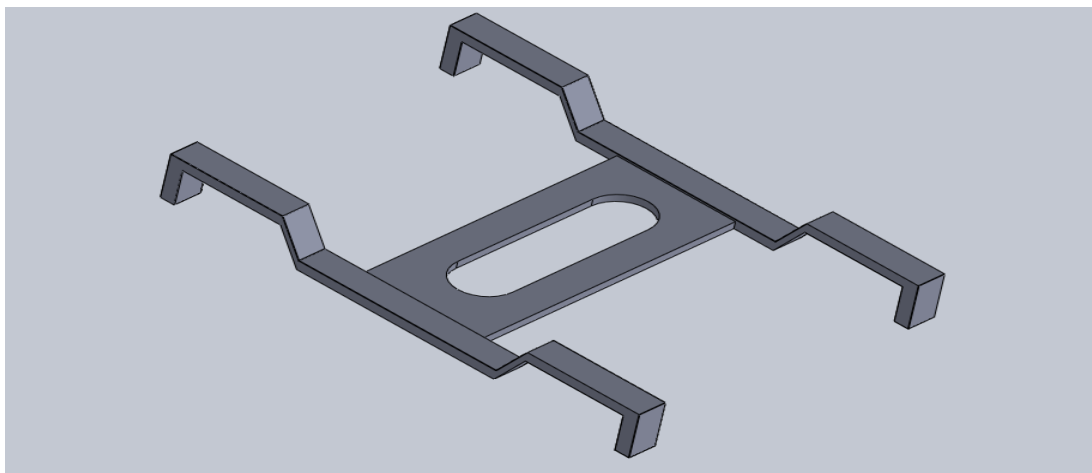
Key:-

1. Side Beam 1
2. Side Beam 2
3. Axle 1
4. Axle 2

**Figure 4.5:** Side frame bogie loading arrangement [21].

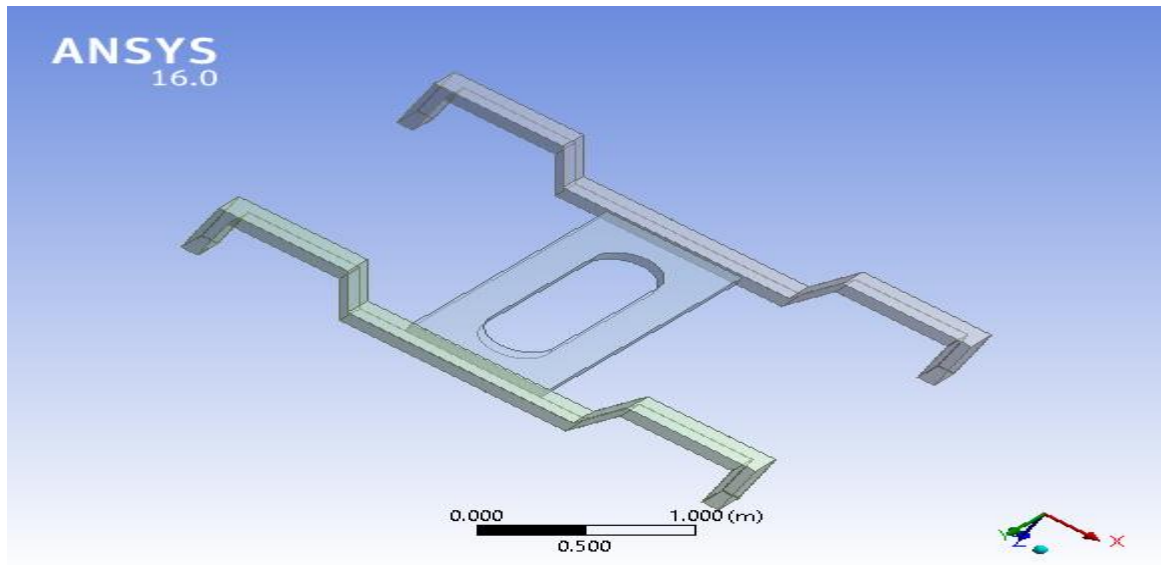
#### 4.3.4 Geometrical model

- First, the 3-D model of the bogie frame was modeled in solid works.
- The model is imported to ANSYS work bench.
- Meshing has performed with fine and refinement.
- Material used is Carbon/epoxy sheet (table 3.9) and structure steel (table 3.10).
- Dimensions are taken from AA l.r.t.

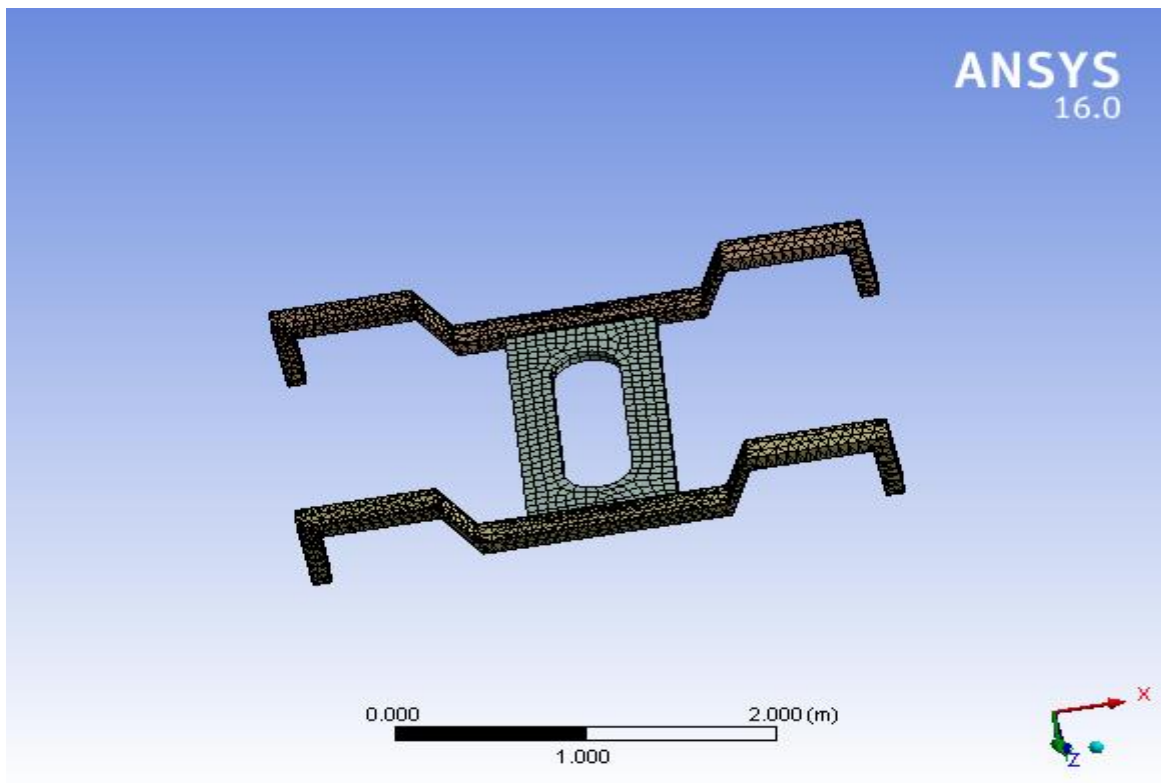


**Fig 4.6:** 3D Model of bogie frame

#### 4.3.4 Modeling the bogie frame using ANSYS



**Fig. 4.7: Static structure analysis the Geometry of the bogie frame**

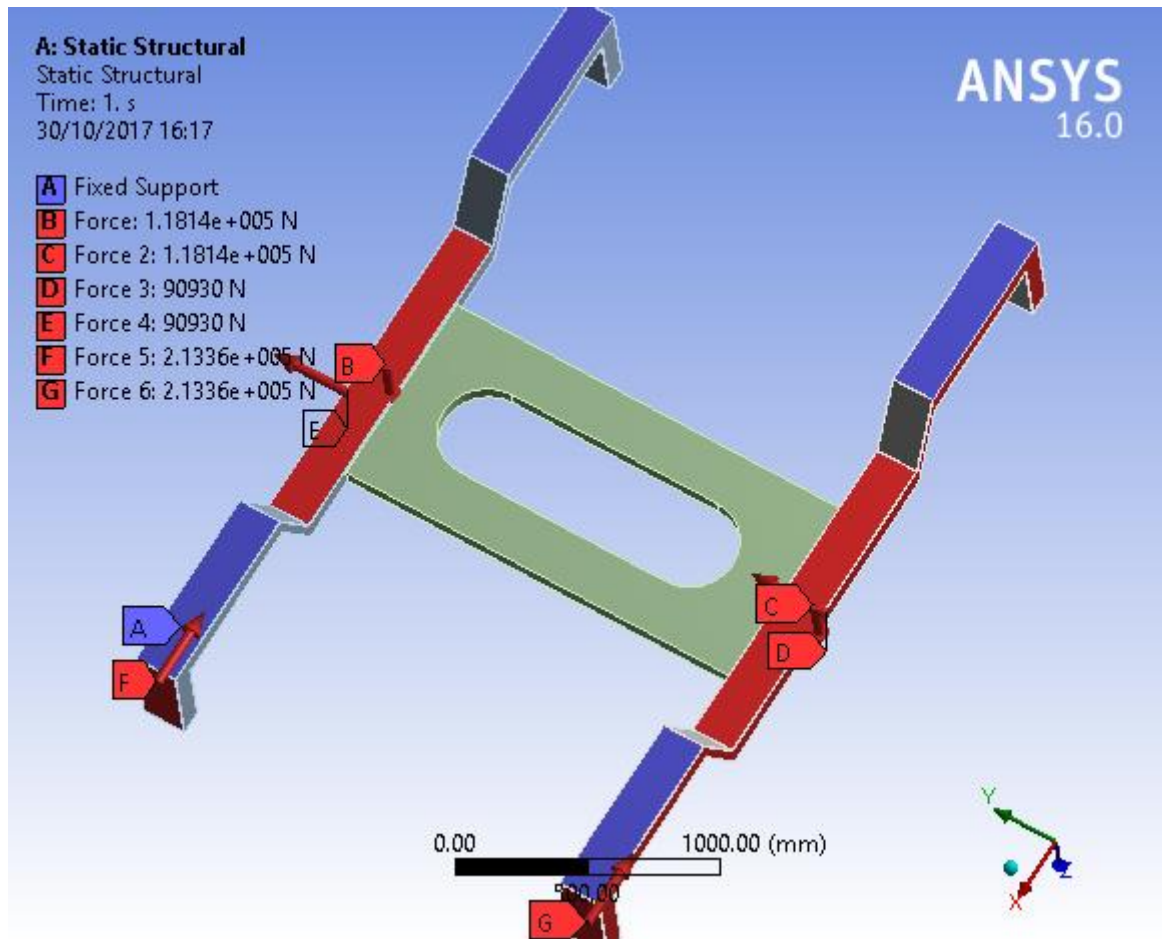


**Fig. 4.8: Static structure analysis mesh of the bogie frame**

## Boundary condition

The analyzed bogie frame has been subjected to the following:

- The bogie frame is fixed at the four ends of the side frame.
- Loads are applied equally at the two side frames.
- Loads B and C (in fig 4.9) are equal and to be applied simultaneously.



**Fig. 4.9: The applied forces and fixed support on the frame**

**Table 4.9:** Material Properties (Carbon/epoxy sheet)

Density	1.5 gcm <sup>-3</sup>
Poisson's ratio	0.24
Young's modulus	7E10 MPa
Tensile yield strength	0.00621 MPa
Compressive yield strength	0.00585 MPa
Tensile ultimate strength	600 MPa
Compressive ultimate strength	570 MPa

**Table 4.10:** Material Property (structure steel)

Density	7850Kgm <sup>-3</sup>
Poisson's ratio	0.3
Elastic modulus	2E+05Mpa
Endurance limit	86.2Mpa

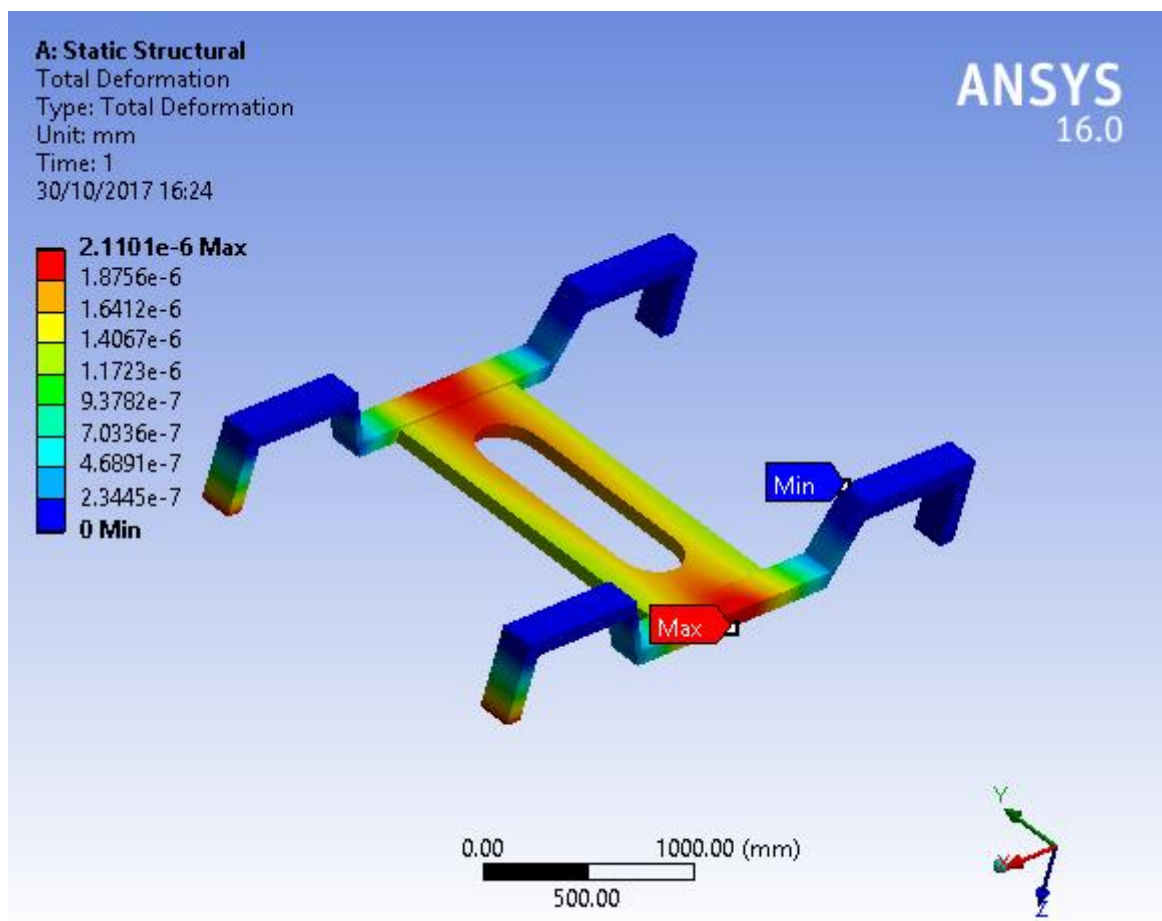
## Chapter Five

### Result and Discussion

#### 5.1 Result

##### 5.1.1 ANSYS Results

- ❖ Static analysis results for the bogie frame



**Fig. 5.1:** Static structure analysis deformation results of carbon/epoxy

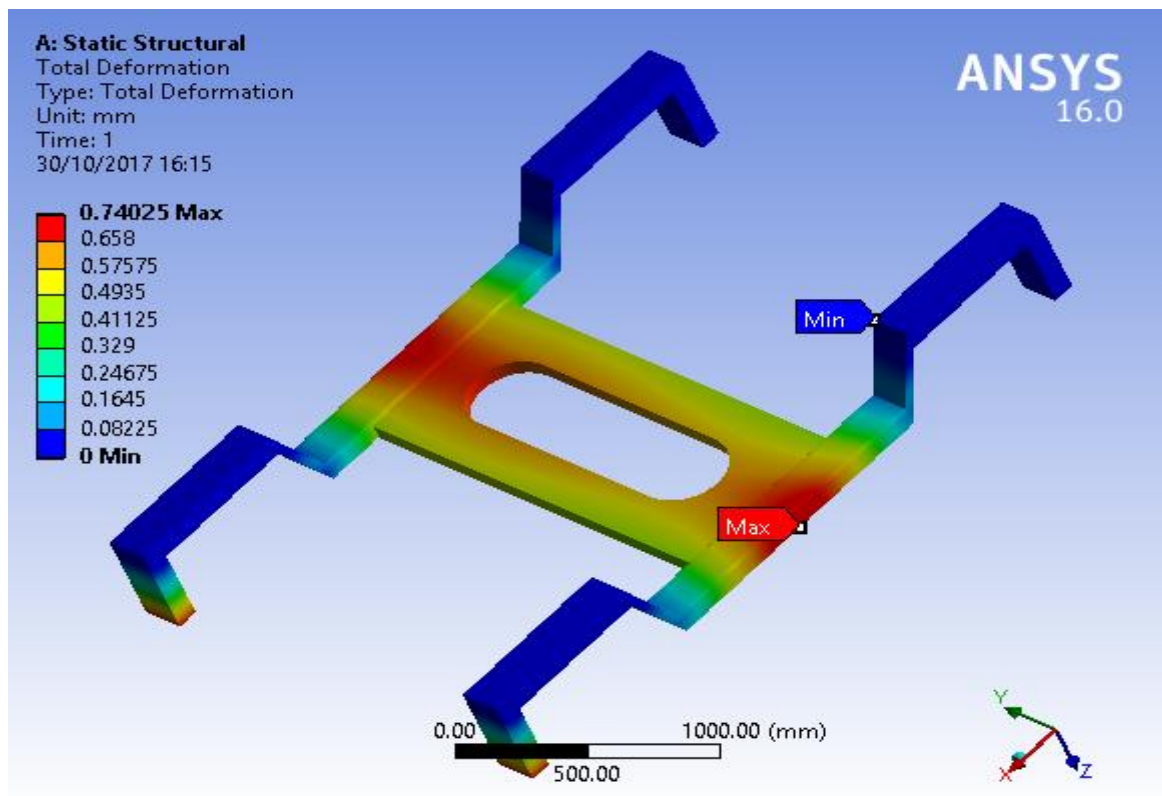


Fig. 5.2: Static structure analysis deformation results of structure steel

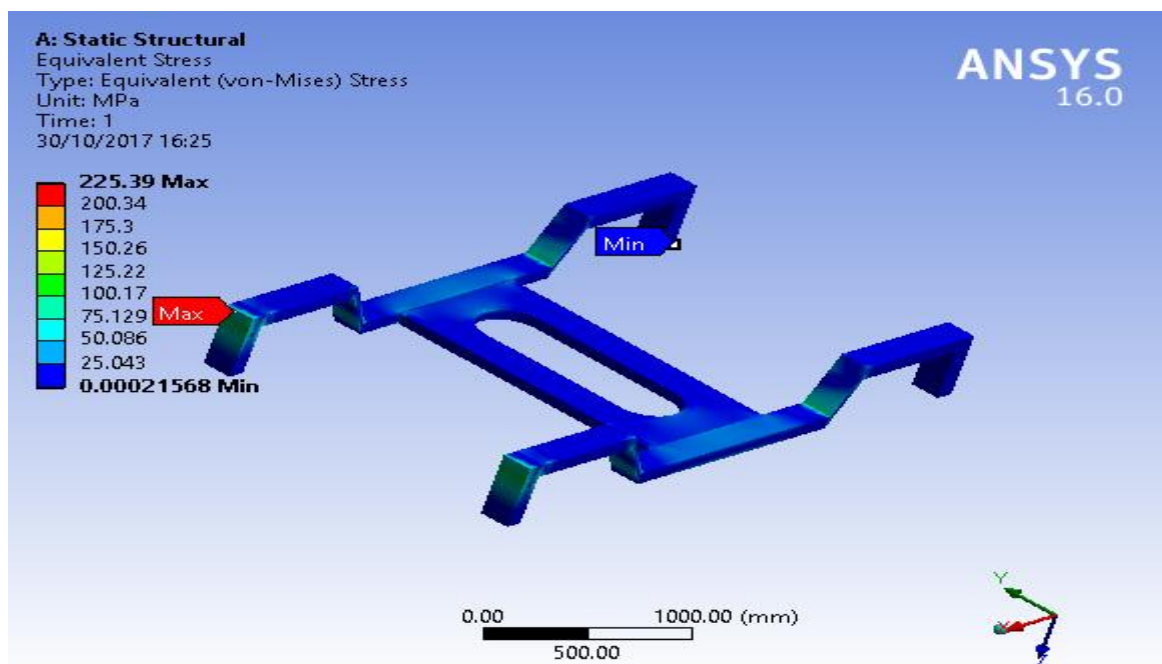
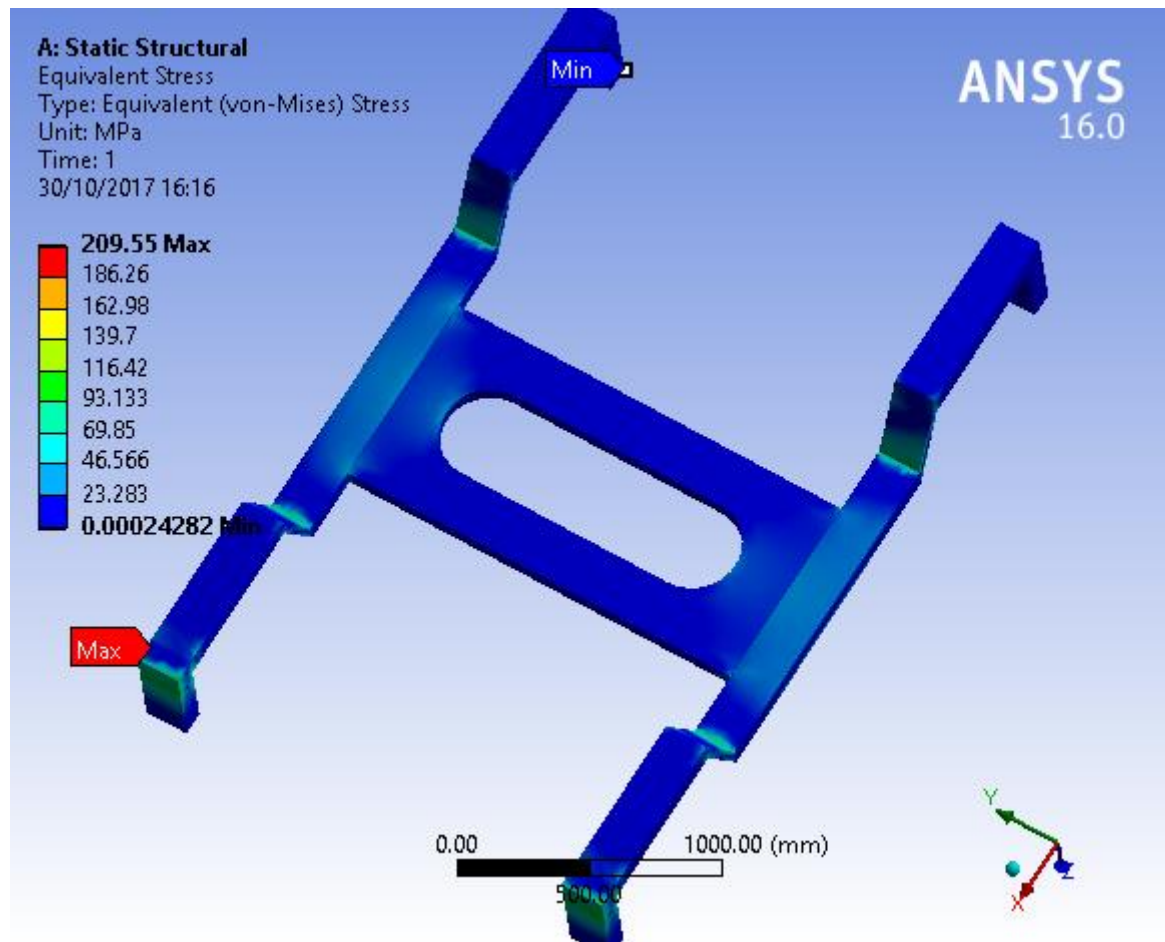


Fig. 5.3: Static structure analysis Equivalent (von-Mises) Stress results of carbon/epoxy



**Fig. 5.4:** Static structure analysis Equivalent (von-Mises) Stress results of structure steel

**Table 5.1:** summarized results of equivalent stress and total deformation

Type	Total deformation	Equivalent (von-Mises) Stress
<b>Carbon/epoxy</b>		
<b>Max</b>	2.1101e-6	225.39
<b>Min</b>	0	0.00021568
<b>Structure steel</b>		
<b>Max</b>	0.74025	209.55
<b>Min</b>	0	0.00024282

### 5.1.2 Discussion

From ansys workbench analysis, it has been obtained the results of different parameters such as deformation results, Equivalent (von-Mises) Stress results. The static structure analysis shows that the total deformation of the material carbon/epoxy is 0 up to  $2.1101e-6$ Max and the total deformation of structure steel which is used by Addis Ababa LRT train is 0.74025Max. The static analysis equivalent (von-Mises) Stress of the carbon/epoxy is 0.00021568Min up to 225.39Max and for structure steel is 209.55Max. The comparison of the two different results shows that the carbon/epoxy material is the better one for Addis Ababa LRT train.

## Chapter Six

### CONCLUSION, RECOMMENDATION

#### 6.1 Conclusion

In this study, in order to replace the conventional steel bogie with a composite bogie, a composite material made of carbon/epoxy was designed and manufactured to be used in the bogie frame of Addis Ababa l.r.t.

The FE model has been developed to analyze the equivalent stress and deformation in the bogie frame with the use of forces applied to the bogie frame model which have been obtained by static strength and fatigue strength of bogie frame solution. To analyze the above mentioned activities of the system, a static Analysis have been carried out using ANSYS workbench. The bogie frame has modeled in solid works and imported to ANSYS work bench by using actual data from Addis Ababa l.r.t.

The result shows that all the stress amplitudes are less than fatigue limit, which means that the bogie frame meets the requirements of fatigue strength. Therefore, a composite bogie frame has many benefits for conventional bogie frame.

## 6.2 Recommendation

The bogie frame in railway rolling stock is intended to support heavy static and dynamic loads, such as the vertical load exerted by the body of the vehicle, braking and accelerating loads, twisting loads induced by track twisting and traction loads. It accounts for approximately 20% of the overall bogie weight.

The lightweight bogie system reduces wear on the rails and wheels, which consequently require less maintenance. Reducing the axle load is also a key factor for a railway industry that aspires to develop high-speed and high-capacity trains. On the bases of the results the research recommends giving a special attention of the composite material.

## 6.3 Future work

In this study a simple static strength for fatigue analysis model has been used and therefore, the bogie of Addis Ababa l.r.t is subjected to much more load variation than passenger trains due to passenger weight difference between the full weight condition during rush hour and the tare weight condition.

- Future research areas related to the current research are listed below:
- Identify and improve the life of crack initiation and propagation of carbon/epoxy composite bogie frame.
- Conduct the experiment of the carbon/epoxy by developing a better fatigue strength.
- Effect of increasing speed on fatigue life of the composite bogie frame.

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Appendix

