ADDIS ABABA UNIVERSITY

ADDIS ABABA INSTITUTE OF TECHNOLOGY

AFRICAN RAILWAY CENTER OF EXCELLENCE

STRENGETHENING OF PRE-STRESSED GIRDER OF RAILWAY BRIDGE USING CARBON FIBER REIN-FORCED POLYMER

A Thesis in Railway Engineering (Civil Infrastructure)

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A Thesis

Submitted in partial fulfilment of the requirements for the Degree of Master of Science in railway Engineering

(Civil Infrastructure)

APPROVAL

The undersigned have examined the thesis entitled **''Strengthening of pre-stressed girder of railway bridge using carbon fiber reinforced polymer (a case study of Addis Ababa light railway transit)''** presented by Awet Tekle, a candidate for the degree of **Master of science in Railway Engineering (Civil Infrastructure)** and herby certify what it is worthy of acceptance.

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UNDERTAKING

I certify that the research work titled ‘‘Strengthening of pre-stressed girders of railway bridges using carbon fiber reinforced polymers (a case study of Addis Ababa light railway transit)’’ is my own work. The work has not been presented elsewhere for assessment. Where material has been used from other sources, it has been properly acknowledged or referred to.

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ABSTRACT

The use of composites to strengthen and renew infrastructure is widely accepted around the world. Traditional methods of strengthening structures are expensive, time-consuming, and labour-intensive. Carbon fiber reinforced polymers (CFRP) are in use nowadays because they are light and strong materials that are also corrosion-resistant. Carbon Fibre Reinforced Polymers (CFRP) plates are regarded as a suitable alternative to strengthen girders due to their high tensile strength and good modulus of elasticity. In this study, prestressed concrete girders were loaded with a static load and reinforced with carbon fiber reinforced polymers (CFRP) sheets. The carbon fiber reinforced polymer (CFRP) plates and sheets used in this study were adhered to the tensile sections of pre-stressed concrete girders with epoxy adhesive. The results, obtained from ANSYS numerical analysis, showed that using carbon fiber reinforced polymer (CFRP) plates with epoxy adhesive increases the load carrying capacity of a prestressed girder bridge by 11.4%, 22.36%, and 27.63% when it is strengthened with one layer, two layers, and three layers of carbon fiber reinforced polymers (CFRP), respectively.

Key words: Strengthening; steel–concrete; ANSYS and composite.

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NOTATION

∅	Diameter
ρ	Density Of Concrete
υ_c	Poisson's Ratio,
$\alpha/^0c$	Thermal Expansion:
E_s	Young's Modulus
σ_{tt}	Yield Strength,
E_{st}	Tangent Modulus.
ε_0	Initial Strain
G_F	Energy Fracture
$F_{c,}$ cyl	Cylindrical compressive strength
$F_{c,}$ cube	Cubic compressive strength
σ_{ct}	Tensile Strength Of Concrete
υ_s	Poisson's Ratio Of Steel
p_s	Density Of Steel
σ_{st}	Tensile Strength Of Steel
(α_s), /c	Thermal Expansion Of Steel
D	Wheel Diameter
v	Vehicle Speed
∅	Impact Factor
P_{st}	Static Wheel Load
P_d	Design Wheel Load
b_f	CFRP Strip Width
ρ_{cf}	Density Of CFRP
υ_{cf}	Poison's Ratio Of CFRP
σ_v	Equivalent (Von-Mises) Stress
σ_b	Bending Stress
σ_s	Shear Stress

ACRONYMS

CFRP	Carbon Fiber Reinforced Polymers
FRP	Fibre Reinforced Polymer
PS	Pre-Stress
AALRT	Addis Ababa Light Rail Transit
FE	Finite Element
CAD	Computer Aid Design
PSG	Prestressed Concrete Girder
RC	Reinforced Concrete
UHPFRC	Ultra-High Performance Fiber Reinforced Concrete
EB	Externally Bonded
NSM	Near Surface Mounted
ERC	Ethiopian Railway Corporation
CFRP	Carbon Fiber Reinforced Polymers
FRP	Fibre Reinforced Polymer
PS	Pre-Stress
AALRT	Addis Ababa Light Rail Transit
FE	Finite Element
CAD	Computer Aid Design
PSG	Prestressed Concrete Girder
RC	Reinforced Concrete
PSCBGRB	Prestressed Concrete Box Girder Railway bridge

CHAPTER 1 INTRODUCTION

1.1 Background

Beam bridges (also referred to as Girder Bridges) are the most common superstructure component of the bridge which lie on abutments or piers. In its simplest form, a girder bridge is just supported at each end by piers (or abutments).

The excessive load and its self-weight subjected, the reinforced concrete beam or/and prestressed concrete beam to excessive deflection and crack. Reinforced concrete structures are periodically updated and enhanced in performance throughout their service life. Changes in their application, for example, the Indian railway has set a goal of increasing axle load [1][2], new design standards, deterioration due to exposure to an adverse condition results in rusting in the steel environment, and natural disasters such as earthquakes, tsunamis, and floods are all major contributors of the Excessive deflection and failure.

In such circumstances there are two possible remedies: replacement or retrofitting. Complete structural replacement might come with a number of drawbacks, including significant labor and material cost, negative environmental impact and inconvenience due to interruption of the function of the structure e.g., traffic problems. When possible, it is often better to repair or upgrade the structure by retrofitting.

There are different techniques to strength the girder of bridge however in the last decade, the development of strong epoxy glue has led to a technique which has great potential for strengthening of structure. The strengthening technique involves fibre reinforced polymer (FRP) plates to the surface of the concrete. The plates then act coherent with the concrete and help to carry the loads and significantly decrease the deformation.

FRP can be convenient compared to steel for a number of reasons. These materials have higher ultimate strength and lower density than steel. The installation is easy and temporary support until the adhesive gains its strength is not required due to the low weight. They can be simply cut to length on site and may be molded on site into intricate forms. Composite materials are becoming increasingly popular in the bridge industry for strengthening purposes. These materials, particularly CFRP, offer several advantages such as resistance to corrosion, a high strength to weight ratio, and almost unlimited delivery length, thus eliminating the need for joints [7].

Nowadays, Carbon Fibre Reinforced Polymer (CFRP) composite plates are broadly being used to strengthen concrete structures. Distinctive physical specifications of such plates such as high tensile strength and module of elasticity have made them an excellent choice for strengthening. The tensile strength, for example, is over ten times as that of steel [5]. Furthermore, strengthening the structure with CFRP significantly increases the structure's load carrying capacity. In the past few year, there has been significant growth in the usage of CFRP laminates for strengthening and repair structures.

In this research, strengthening of the pre-stressed box girder of the bridge using CFRP subjected to static loadings were carried out to determine the load rating capacity when it strengthened withe CFRP. Static analysis were conducted on eight models with different layer thickness, width strip and spacing. And the Results from static simulation revealed that the load carrying capacity of the prestressed girder box is significantly increased. Though the result was satisfactory but the research didn't account the lateral and longitudinal force. Thus, future work should account such loads.

1.2 Statement of The Problem

Many reinforced and pre-stressed concrete bridges are constructed annually around the globe; however, structures show failures due to load increment, age, and environmental impacts. Thus, there is a need to strengthen such structures rather than replace them with new ones.

Almost all damaged and newly installed reinforced pre-stressed bridges are regularly repaired and strengthened using the traditional method; however, the result is unsatisfactory. The majority of the damage is caused by faulty construction, frequent loading, natural hazards, unexpected impacts on structural parts, deterioration of the structure, which causes structures to fail before their expected age, natural hazards, and so on, as stated above. In recent decades, engineers have introduced composite materials for strengthening beams, columns, and slabs. During the operation phase, carbon fiber reinforced polymers (CFRP) will provide solutions for repairing and rehabilitating pre-stressed girders as well as upgrading their load-carrying capacity.

The following are some of the most typical issues:

- Chloride attack, corrosion, and deterioration
- Fatigue damage accumulation
- Accidental damage, such as an over height vehicle impact,
- Initial design flaws, construction defects, and lack of proper maintenance
- due to design age or overloading on bridges.
- Change the axle load, like what they did in India.

Due to the above reasons, the bridge structure may fail. If the bridge fails, the economy of the country will be adversely affected as a result of blocking the rail route. In addition, it may lead to disastrous accidents, which could lead to the destruction of wealth and the loss of irreplaceable lives. A timely strengthening method using an effective strengthening method is therefore unquestionable.

1.3 Research Objective

1.3.1 Main Objectives

The overall target of this research is to investigate the behavior of pre-stressed box girders retrofitted with one, two, and three layers of CFRP with different strip widths and thicknesses.

1.3.2 Specific Objectives

1. Research goals include evaluating the practicality and efficiency as well as analysing the deflection and stress capacity of Ps girders enhanced with CFRP.

2. To determine what impact CFRP has on the load rating capacity of a pre-stressed girder when one, two, or three layers of CFRP with varied thicknesses and widths are used to maintain an existing pre-stressed box girder. railway bridge of the Addis Ababa light railway transit system

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1.4 Scope and Limitations of the Thesis

The research was limited to strengthening the pre-stressed girder bridge using CFRP under static loading, considering only the design wheel load. In this regard, the study aims to develop maintenance techniques using carbon fiber-reinforced polymers. The scope of this project was limited to the preparation of a model using AutoCAD 2018 and the analysis of the model using an ANSYS work bench on one of the already built pre-stressed girders of the Addis-Ababa railway bridge. Although this study considered double track, it did not cover the dynamic analysis of bridges. The bridge was regarded to have linear behavior, while the pre-stressed concrete was assumed to have elastic behavior. Thus, in this thesis, different strengthening techniques adopted in different countries could be discussed, but the girder would be strengthened only by CFRP. And policies, strategies, and a plan of maintenance would not be included. Furthermore, experimental analysis was not carried out, but validation would be carried out by comparing the experimental result, which was done by Richard, with the numerical FE result.

1.5 Organization of The Thesis

This thesis is organized into five chapters as follows:

- Chapter 1 A brief background, problem statement, objective, scope, and limitations of the research are found in this chapter.
- A Chapter 2 Literature Review on the behavior of prestressed concrete girders (PSG), bridge failure and cause of failure, strengthening methods, and the work on fiber-reinforced polymers that has been done so far by various researchers will be presented.
- Chapter 3 describes the strengthening formulation, finite element modelling, and methodology used. The validation of FEM, geometrical shape, and dimensions of the prestressed girder bridge and CFRP were discussed in this chapter.
- Chapter 4 presents the analysis results and discussion. This part contains the numerical analysis results of the studied pre-stressed girder. The behavior of the pre-stressed girder when laminated using CFRP is discussed.
- Chapter 5: Conclusion and recommendations In the final chapter, the research thesis has been concluded, and further research areas have been suggested.

CHAPTER 2 Literature review

2.1 Introduction

Pre-stressed and reinforced concrete (RC) bridges may require strengthening for a variety of reasons. Deterioration due to environmental or physical loading, extreme loading, accidents, or simply increasing vehicle loads may result in the need to strengthen the bridge girder structurally [8]. Defects in design, details, building, maintenance, and use of weak materials, as well as poor consideration of external events, were identified as the leading causes of bridge failures. Deficiency in design refers to mistakes, oversights, omissions, or conceptual flaws that may have occurred during the bridge's design process. Several natural hazards, such as flood, scour, wind, earthquake, landslide, debris flow, and storm surge, are unavoidable and are among the root causes of many bridge failures. Therefore, proper maintenance of the bridge is the only solution to upgrading its strength. This chapter covers the basic definition of the bridge and the type of the bridge, the type of railway bridge, the type of girder bridge, the form of the pre-stressed box girder of the bridge, the type of loading, bridge damage, maintenance, rehabilitation, and repair techniques, fiber reinforced polymers, maintenance techniques, efficiency, and percentage of the strengthening.

2.2 Structure and Bridge Types

2.2.1 Introduction

A bridge is a structure that spans an obstruction, such as a river, valley, or canyon. Its function is to allow access over the obstruction. Bridges are built primarily to cross barriers in communication. Due to their strategic placement, attractive qualities, and significance to the nation's transportation infrastructure, bridges are essential parts of the rail network. Thus, bridges act as a vital link between the development of transportation infrastructure and the economy.

Figure 2. 1 Railway bridge at "Meskel-Square, Addis Ababa.

2.2.2 Type of Railway Bridge

There are different types of bridges. One can categorize the railway bridge based on the type of material used; others can be categorized based on the span length of the bridge; and others may be categorized based on structural form as well as their functionality and the type of stress imposed on them. Further, bridges may be classified by how the forces of tension, compression, bending, torsion, and shear are distributed through their structure. Most bridges will employ all of the principal forces to some degree, but only a few will predominate. The separation of forces may be quite clear [9], [10].

2.2.2.1 Bridge Classification

This [10] researcher is classified the railway bridge as follow in accordance with the length of superstructure as:

1. Super major bridge: - where, the bridge length is more than 500 m.
2. Major bridge: - where, the bridge length is between 100 m and 500 m.
3. Medium bridge: - where, the bridge length is between 20 m and 100 m.
4. Minor bridge: - where, the bridge length is 20 m or lower.

2.2.2.2 According to Structural Form

According to the structural form, the bridge is categorized as an arch bridge, box girder, t-girder, or suspension bridge. Their basic definition is cited below.

1. **Arch bridge**

Arch bridges are defined by researchers [9], [10], and [11] as spans with abutments at either end. The abutments on either side are forced by the weight of the bridges.

2. **Beam**

Beam bridges are horizontal beams supported at each end by substructure units and can be either simply supported when the beams only connect across a single span or continuous when the beams are connected across two or more spans. There are different forms of beams, such as T-shaped, I-shaped, and box-shaped beams [9], [10].

3. **Truss**

A truss bridge is a bridge whose load-bearing superstructure is composed of a truss. This truss is a structure of connected elements forming triangular units, [9], [10].

4. **Cantilever**

Cantilever bridges are built using cantilevers- horizontal beams supported on only one end. Most cantilever bridges use a pair of continuous spans that extend from opposite sides of the supporting piers to meet at the center of the obstacle the bridge crosses, [9][10].

5. **Suspension**

These type of bridge are suspended from cables. In modern bridges, the cable hangs from towers that are attached to caissons or cofferdams. The caissons or cofferdams are implanted deep into the bed of the lake, river or sea, [9], [10].

6. **Cable-stayed**

Cable stayed bridges, like suspension bridges are held up by cables. However, in a cable stayed bridge, less cable is required and the towers holding the cables are proportionately higher, [9], [10].

2.2.2.3 Based on Stress Induced

Based on the stress induced, bridge can be classified as pre-tension and post-tension. But it can be named generally as prestressed concrete bridge.

- **Prestressed concrete bridge**

Prestressing is a means of inducing known stresses in a structure or member before the full or live load is applied. These stresses are induced by tensioning the strands, wire, or rods, which are then anchored to the member being stressed by mechanical, hydraulic, electrical, thermal, or chemical means [12]. Pre-stress is suitable for long-span bridges because it decreases significantly the depth of the girder and increases the durability and serviceability of the structure [13].

Pre-stress has many advantages as it enhances the flexural, torsion, and shear strengths of the structure [14]. And it significantly decreases the depth of the beam or girder of the bridge or slab in the building. It also decreases the dead load as the depth of the girder or slab is low [13]. The use of high-strength concrete and steel in pre-stressed members results in lighter and slenderer members than is possible with RC members. In fully pre-stressed members, the member is free from tensile stresses under working loads, so the whole section is effective. It has some disadvantages. The first one is that the availability of experienced workers is limited. The equipment cost is very high. The availability of well-trained engineers is limited. Pre-stressed sections are brittle. Pre-stressed concrete sections are less fire-resistant.

The two type of prestressing concrete system are pre-tensioning and post-tensioning.

1. pre-tensioning concrete system

In pre-tensioning system the tension is applied to the tendon before casting of the concrete. The stage of pre-tensioning is depicted below [14].

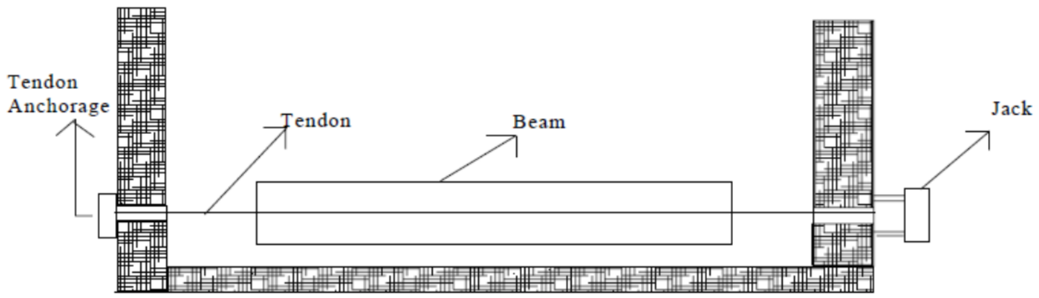

Figure 2. 2 Pre- tensioning of tendon

A. First the wires or strands are stressed;

B. Second the concrete is cast around the stressed wires/strands;

c. and in 3rd stage, the pre-stressed is transferred from the external anchorages to the concrete, once it attains adequate strength.

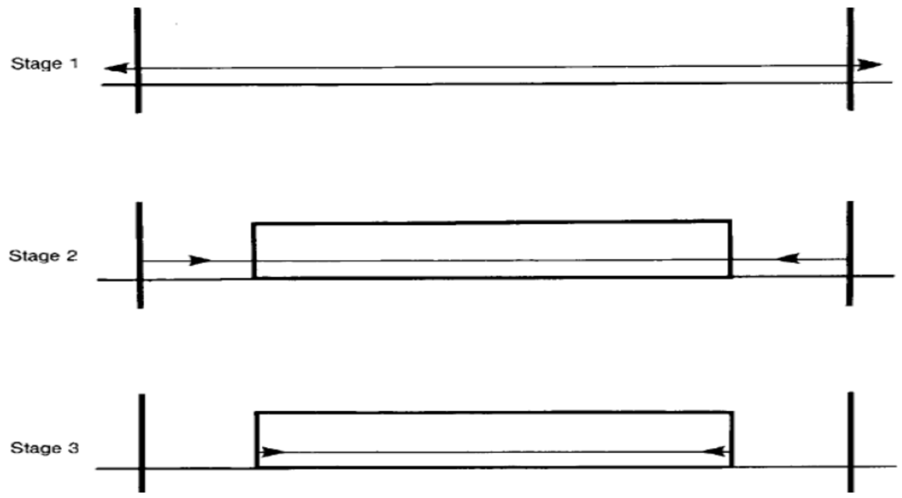

Figure 2. 3 Stage of Pre-Tensioning

In the case of pre-stressing, concrete is placed after the steel is tensioned. The Construction sequence for pre-tensioned concrete beam or girder is depicted below.

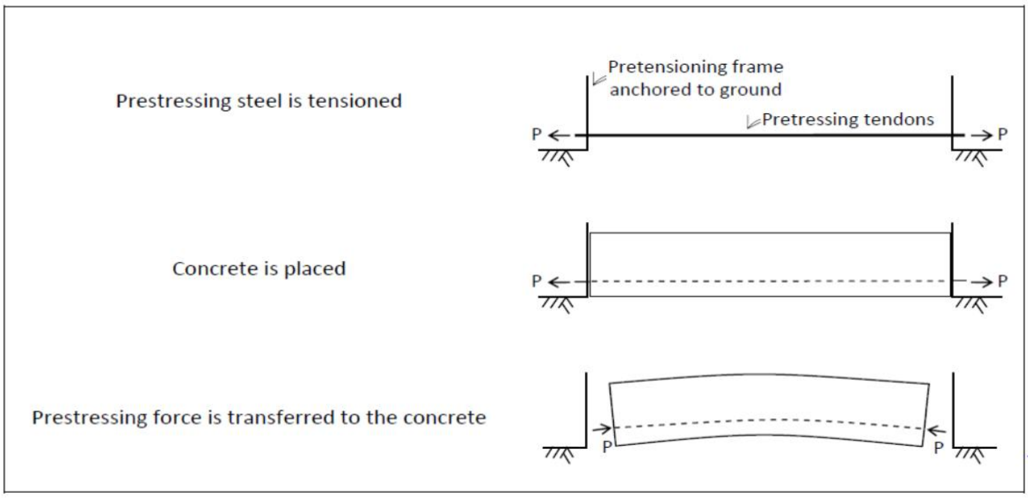

Figure 2. 4 Construction Sequence for Pre-Tensioned Concrete Beam

2. post-tensioning concrete

In this scenario; First the concrete is hardening and then tendons are tensioning [14]. In short the stage of post tensioning is summarized as follow:

A. The strands or tendons are fed through the ducts.
B. then the tendons are tensioned.
C. And at last tendons are anchored to the concrete.

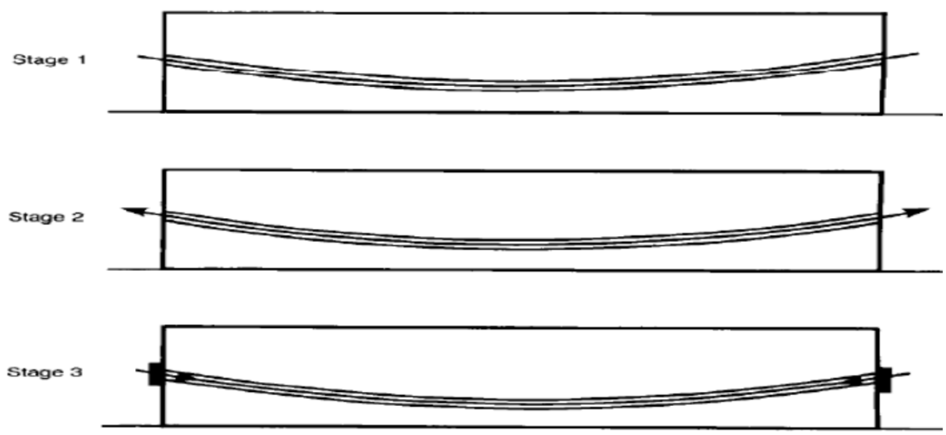

Figure 2. 5 Stage of Post Tensioning.

2.3 Type of Girder Bridge

1. T-girder

The T-beam construction consists of a transversely reinforced slab deck that spans across the longitudinal support girders. These require more complicated formwork, particularly for skewed bridges, compared to the other superstructure forms. T-beam bridges are generally more economical for spans of 12 to 18 m. Prestressed concrete T-beams with depths from 1.75 to 2.6m are applicable for spans from 16.5 to 27.6m for railway bridges. The girder stem thickness usually varies from 35 to 55 cm and is controlled by the required horizontal spacing of the positive moment reinforcement. The optimal lateral spacing of longitudinal girders is typically between 1.8 and 3.0 m for a minimum cost of formwork and structural materials. However, where vertical supports for the formwork are difficult and expensive, girder spacing can be increased accordingly [15]. The T-girder has a big disadvantage because it has no bottom flange with which to deal with tensile forces, and it isn't appropriate for curved structures or skews.

2. Box-girder

The box girder is the most flexible bridge deck form. It can cover a range of spans from 25 m up to the largest non-suspended concrete decks built, of the order of 300 m. Single box girders may also carry decks up to 30 m wide. For the longer-span beams, beyond about 50 m, they are practically the only feasible deck section.

The advantages of the box form are principally its high structural efficiency, which minimizes the prestress force required to resist a given bending moment, and its great torsional strength, with the capacity this gives to re-center eccentric live loads, minimizing the prestress required to carry them. One of the main disadvantages of box decks is that they are difficult to cast in situ due to the inaccessibility of the bottom slab and the need to extract the internal shutter. Either the box has to be designed so that the entire cross section may be cast in one continuous pour, or the cross section has to be cast in stages [16]. For a box section deck of constant depth, it is likely to lie between 30 m and 45 m, while if the deck is provided with a haunch, the most economical span will lie between 40 m and 60 m [16]. Precast, pre-stressed box girder sections are frequently used for simple spans of over 30 m and are particularly suitable for widening bridges to control defections [15].

This study shall focus only on the design of prestressed concrete precast pre-tensioning slabs and post-tensioning box-girder railway bridges. First, the box-girder has more advantages: it is more flexible, suitable on curves with high structural efficiency, has great torsional strength, and is most economical for longer spans, whereas prestressed concrete slab girders are very valuable for bridge decks where the supports are skew or for irregularly shaped decks. They also have more flexibility, are more economical for short spans, and are more suitable on curves than prestressed T-girder bridges.

2.3.1 Form of Prestressed Box-Girder Railway Bridge

Bridge designers have a variety of options available when considering the advantages of precast and cast in situ in concrete construction.

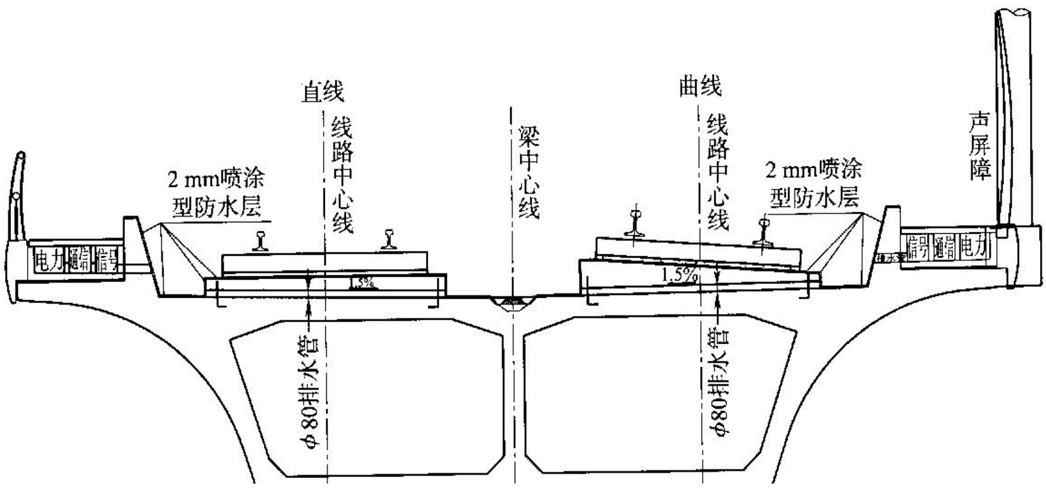

Figure 2. 6 Form of Boxed Girder Bridge

A box section deck consists of side cantilevers, the top and bottom slabs of the box itself, and the webs. For a good design, there must be a rational balance between the overall width of the deck and the width of the box. Box sections suffer from a certain blandness of appearance; the observer does not know whether the box is made of an assemblage of thin plates or is solid concrete [16], [1]. Box girders can be constructed as single cell, double cell, or multicellular; they may be monolithically constructed with the deck, called closed box girders, or the deck can be separately constructed afterwards, called open box girders; they can be rectangular, trapezoidal, or circular; the girder web can be vertical or inclined, which reduces the width of the bottom flange [15]. Boxes may be rectangular or trapezoidal, with the bottom flange narrower than the top. Rectangular box sections are easier to build and are virtually essential for the longest spans due to the great depth of the girders. However, they have the disadvantages that their appearance is somewhat severe and that their bottom slabs may be wider than necessary [16]. The trapezoidal cross section is frequently economical as well as good-looking. In general, the width of the top of the box is determined by the need to provide points of support to the top slab at suitable intervals. The cross-section area of the bottom slab is logically determined at mid-span by the need to provide a bottom modulus sufficient to control the range of bending stresses under the variation of live load bending moments. For a box of rectangular cross section with a span/depth ratio deeper than about 1/20, the area of the bottom slab is generally greater than necessary, resulting in redundant weight. Choosing a trapezoidal cross section allows the weight of the bottom slab to be reduced. Close to the piers, the area of the bottom slab is determined by the need to limit the maximum bending stress on the bottom fiber and to provide an adequate ultimate moment of resistance. If the narrow bottom slab defined by mid-span criteria is inadequate, it is simple to thicken it locally. For a very wide deck that has a deep span/depth ratio, this logic may give rise to webs that are inclined at a very flat angle. The designer should be aware of the difficulties in casting such webs and make suitable allowances in specifying the concrete and in detailing the reinforcement. Also, an important consideration in the design of box-section decks is the distortion of the cross-section under the effect of eccentric live loads. The effect of this distortion is reduced in a trapezoidal cross section. Boxes may have a single cell or multiple cells. It was explained how important it is for economics to minimize the number of webs. Furthermore, it is more difficult to build multi-cell boxes, and it is worthwhile extending the single-cell box as far as possible before adding internal webs [16].

Once the span of a box section deck exceeds about 45 m, it becomes relevant to consider varying the depth of the beam. This is not an automatic decision, as it depends on the method of construction. Clearly, this decision also has an aesthetic component. The depth may be varied continuously along the length of the beam, adopting a circular, parabolic, elliptical, or Islamic profile. These attributes depend on the quality of the conceptual design. Economy in this context is not simply saving money; it is a concept of rationality and frugality. It is fundamental to engineering design that the designer is constantly planning how he can save materials and how he can make the construction process simpler, even if many of these design decisions in isolation would not register on the overall balance sheet of a project [15]. Therefore, my design shall focus only on the analysis and design of precast prestressed concrete. Rectangular Box-Girders, which are easier to build and are virtually essential for the longest spans due to the great depth of the girders, and Voided Slab Bridges, which are very valuable for bridge decks where the supports are skew or for irregularly shaped decks where the columns do not define organized spans or when the deck weight starts to become excessive, are also suitable in torsion fields.

2.4 Bridge Loading Type

- **Longitudinal force**

The force usually due to acceleration and breaking of trains and thermal expansion or contraction of the rail along the direction parallel to the rails act on the track structure [17].

- **Lateral force**

The forces in lateral direction act on the track structure usually comes from the lateral wheel force due to friction between the rail and wheel especially when a train goes around corners. It also comes from the buckling reaction force of the rail which is usually caused by a high longitudinal force in the rail [18].

- **Vertical force**

This is the force acting perpendicular to the track structure. These force are commonly from static load of the wheel and the self-weight of all the track structures are considered as vertical load [19].

2.5 Bridge Damage

Knowing the cause of the bridge damage is vital to draw a suitable method of maintenance. In the world there are many rail-way bridge damage, however the cause is more or less the same. This researcher [20] has developed a bridge damage factor recognition. The model for automatically recognizing damage factor from the text taken from the bridge inspection report. Thus, the authors collected 1188 inspection report on bridges across general national highways in Korea. And a research carried out in Britain [21] reported that the most common attributed to structural failure is flooding. In Uk and Ireland there are over 10,000 such structure which have been affected by flooding. The researcher has concluded that the main cause of failure of bridges is undermining of the abutments or piers by scour.

To identify the cause of the damage for masonry bridge; this [22] researcher has recommended a multi-level assessment utilising the potential of various in situ non-destructive testing procedures. In its report the main cause of the bridge damage is: the presence of the internal voids, flaws, layering condition, mapping of non-homogeneity, moisture content, etc. and [23] researcher has cited in his report that the main cause of the damage of steel bridge is deterioration and that is largely depend on the loading history that is directly related with fatigue. In other way fire has an imperative effect to the strength of the bridge and it may cause a substantial damage of the structure, a [24] has evaluated the fire damage on a prestressed concrete railway bridge. Fire exposition caused the formation of internal cracks in prestressed beam and this valuably affect the stability of the structure. and this researcher [25] has retrofitted the girder of the bridge using CFRP Strips to the corrosion damage. The research reported that if the girder of the bridge has a corrosion damage, the behaviour of the concrete member is substantial and that include in reduction of the steel reinforced area.

There are three primary cause of damage to prestressed concrete bridge girders, two of which are accidental or unintended:

1) Accidental impact damage due to over-height vehicles, primarily at the bottom areas [3]. This mode of damage is not unique to prestressed girders, but the emergency decisions to be made and the repair processes may be special and unique for prestressed concrete (Figure 1.1).

2) Unintended construction-related damage during deck removal processes, primarily at the top area of the beam. This mode of damage has frequently occurred in prestressed bridge girders (Figure 1.2).

3) Long-term corrosion and deterioration of prestressed girders, primarily at the beam end areas adjacent to expansion joints, as well as overall deterioration. This long-term mode of damage typically results from exposure to salts leaking through expansion joints (Figure 1.3). [2], [4]

Figure 2. 7 Accidental Impact Damage Due to Over-Height Vehicles

Figure 2. 8 Unintended Construction-Related Damage

Figure 2. 9 Corrosion and Deterioration of Prestressed Girders

2.6 Maintenance, Rehabilitation and Repair of the Bridge

2.6.1 Maintenance

Maintenance is a work carried out on a regular basis to keep a structure or piece of machinery in a good operational condition. However, to achieve good and reliable maintenance one have to choose a proper method of maintenance, [10], [11].

The researcher [10] cites that, bridge maintenance is one of the most important tasks since it affects the structure's lifespan, overall cost, and most importantly, safety. But it received less attention in the previous few years. For many years, many bridge owners and designers, in particular, believed that reinforced concrete did not deteriorate and that achieving a 120-year life with little or no Maintenance. This has been proven false in practice, since some bridges have needed significant upkeep, strengthening, and even early replacement due to degradation. The idea of "functional obsolescence," where structures need regular maintenance and upgrades throughout their lifespan until they need to be replaced, has become common practice. If no repairs or preventative measures are taken, it is projected that many concrete bridges would continue to show signs of degradation. Numerous variables can significantly impair the lifetime of bridges, necessitating maintenance and repairs at a relatively early age. It is difficult to plan and construct bridges without flaws that could shorten their lifespan. But there should be things that may be done to preserve and enhance a bridge's toughness throughout its useful life. Dealing with maintenance, rehabilitation and repair are the words which are used repeatedly. Therefore, it's needed to discuss in brief about Rehabilitation and Repair of Bridge.

2.6.2 Rehabilitation and Repair

Rehabilitation is the full restoration of a bridge structure's most damaged components with the goal of regaining and greatly extending the bridge's original functionality whereas repair is the activity often to isolated or a piece of one element of a structure that are required to restore functionality or serviceability owing to distress from things like vehicle collision damage, documented scour, or significant localized deterioration.

There are different approach of beam or/and girder maintenance, however I will only focus on fiber reinforced polymers. Many researchers have conducted experiments to show that fiber reinforced polymers can be used to strengthen reinforced concrete. For years, the most commonly investigated material for external reinforcement has been fiber-reinforced polymer (FRP), and FRP external bonding is now the most widely used strengthening technology. High strength, excellent strength/weight ratio, high resilience to fatigue and corrosion, and ease of manufacture are all advantages of FRP [6], [26]. Since ancient times, fibers have been employed as reinforcement. Horsehair was once used in mortar and straw was once used in mud bricks. Asbestos fibers were employed in concrete in the early 1900s.

This [1] researcher used a CFRP to strengthened the shear capacity of the girder of a railway bridge in Örnsköldsvik, Sweden. The result showed that the strain of the steel is decreased by 10% when the girder has inserted CFRP bar.

This [2] researcher has also presented that the composite structure strengthening using Carbon fiber reinforced polymer has increased the ultimate load carrying capacity and plastic stiffness.

This [3] researcher strengthened some component of the bridge that had been damaged and cracked because the bridge was operated for 16 years, primary they would try to close the crack, however the crack was appeared again in that vicinity. Thus, they use pre-stressed CFRP plate for composite box girder to improve the mechanical performance of components in service stage, prevent peeling damage, reduce strain lag phenomenon.

This [4] researcher try to address the deficiency of the common bridge girder in united states. The author discussed with various strengthening method and concluded that, the most suitable strengthening method is using FRP, this is so because FRP laminate doesn’t need to remove concrete parts or drill into the section. Another advantage is that it provides a protection for the patch of concrete and reinforcing steel from an aggressive of water and salts and thus corrosion and deterioration.

2.6.3 Repair Procedure

The main steps in a typical repair procedure can be summarized in eight steps according [27] this author:

1. inspection and monitoring;
2. decision on choosing a repair material;
3. decision on choosing the repair method;

4. surface preparation;
5. application of repair material;
6. anchorage system.

2.6.3.1 Inspection and Monitoring

To assess the severity of the damage, the cause, and the prognosis, this may be done periodically or based on usage, or it may be prompted by reports of damage or excessive loading [4]. It is important to ascertain the structure's current load carrying capacity. Any structural issues should be identified, along with their root causes. It's important to comprehend the state of the concrete substrate. In addition, it is important to specify the dimensions of the structural members as they currently are, the location, size, and causes of cracks and spalls, the level of any steel reinforcement corrosion, the presence of any active corrosion, the type and location of the steel reinforcement that is already there, the concrete's in-place compressive strength, and the soundness of the concrete, particularly the concrete cover in all areas where the strengthening material will be bonded to the concrete. Then, a choice is taken regarding the necessary course of action for the bridge, which may include repair, demolition, or leaving alone and continuing to monitor [4], [10], [27]. The decision-making authorities will weigh the price and dependability of repair work against demolition or replacement.

2.6.3.2 Choosing A Repair Material

An appropriate repair material has to be chosen considering the availability and durability of the material, ease of handling on site, cost-effectiveness, type and condition of the structural element, and the targeted enhancement in the structure. for instance; Retrofitting of flexural concrete elements is traditionally accomplished by externally bonding steel plates to concrete. Although this technique has proved to be effective in increasing strength and stiffness of reinforced concrete elements, it has disadvantages of being susceptible to corrosion and difficult to install [6]. The Common materials used for the repair of PRC bridge girders are fiber reinforced composite and steel, in addition to other materials such as ultra-high performance fiber reinforced concrete (UHPFRC), Aluminium alloy, Ferro cement, and shotcrete.

2.6.3.3 Choosing Repairing Method of Railway Bridge

After the appropriate material is chosen, the next decision is to choose a proper way for the application of the material to the damaged girder [28]. There are several factors affecting this decision, including:

- whether the repair technique is commercially available
- girder type (box girder or I-girder): The shape of the girder cross section is important in the choice of the repair technique. For example, for rectangular beams, the most common way of repair is fully wrapping of the member. For T-beams, however, this solution is impractical due to the presence of the flange.
- dominant repair limit state
- severity of the damage that it can repair
- fatigue performance
- whether strengthening is needed beyond undamaged capacity
- whether the method can be combined with strand splicing.
- speed of mobilization and constructability
- whether specialized labour is required
- whether proprietary tools are required
- whether lift equipment is required
- how much is the closure below the Railway bridge?
- time for typical repair, environmental impact of repair process, and durability
- The resulting change in the size of the element that is being repaired as it affects the overall aesthetics of the element and might enforce additional labour cost and disruption of the structure’s service. This is controlled by the thickness of the strengthening material used.
- cost and aesthetics.

Methods for the application of the repair material to the damaged girder include: Externally Bonded (EB) techniques, Near Surface Mounted (NSM) techniques, and Embedded reinforcement. And we will discuss typically about EB and NSM later.

2.6.3.4 Surface Preparation

Surface preparation, that is cleaning and roughening the surfaces of composites is a critical step in the repair process which can elevate bond strength. If the surface isn’t prepared properly and that can result in de-bonding. Sandblasting, water jetting, grinding, brushing, air pressure, rounding of corners, pressure washing the concrete surface, surface patching, and nylon peel-ply techniques are commonly used to avoid de-bonding.

2.6.3.5 Application of The Repair Material

The next one is the application of the repair material. Depending on the repair approach being used (externally bonded (EB) technique, near surface mounted (NSM) method, or as embedded reinforcement), the repair material should be applied in different ways and configurations. In general, there are two ways to strengthen flexural strength of the structure with FRP: externally bonded EB systems and near-surface-mounted NSM systems [29].

- Near surface strengthening method (NSM)

NSM is a technique in which the concrete's top layer is cut to a specific size and then filled with steel bars or FRB rods using epoxy to create a bond with the concrete. Some drawbacks of this technology include difficulty in applying it to existing structures and concrete cover separation.

- Externally bonded strengthening method

Applying the externally bonded technique (EB) involves roughening and cleaning the surface that needs strengthening, completely combining the adhesive components, and then brushing on epoxy. Placing FRP laminates has numerous benefits over utilizing steel plates, including a high strength to weight ratio, resistance to corrosion from the environment, low maintenance requirements, ease of handling, and greater longevity, [29].

2.6.3.6 Anchorage System

For cases of excessive shear stress, an anchorage system will be highly recommended to delay the deboning of the strengthened structure. A proper anchorage system might allow the use of a strengthening plan that otherwise would not meet design code provisions, allowing the repair material to continue carrying load even after deboning occurs and thereby increasing its contribution. Different anchorage systems have been introduced so far depending on the strengthening method that they are used for. Some examples include: additional horizontal strips of the repair material, embedment of the repair material into the beam flange through pre-cut grooves with adhesive bonding, various mechanical anchorage systems involving bolts and plates, and fan-shaped textile-based anchors.

2.6.4 Strengthening Technique

Reinforced concrete is strengthened in order to perform higher design loads, restore strength that has been lost due to deterioration, fix structural flaws, or improve ductility. Externally bonded steel plates, steel or concrete jackets, external post-tensioning reinforcement, and fiber-reinforced polymers (composite material) can all be used to strengthen flexural and shear strength of the structure. different researchers have been carried out different strengthening techniques to improve the strength of the bridge structures. Researchers [30] for example have used a post installed shear connector suitable for post installation to strengthening existing steel-concrete structure with no, or insufficient, shear connection. External bonded composite method is one of the most practical and more sophisticated way of strengthening bridge structure component as in the case of [31], the girder of the bridge is strengthened using a plate of carbon fiber reinforced polymer. There are many researchers who has been used FRP for strengthening the bridge components. The advantage of FRP is paramount in increasing load caring capacity of the bridge. Furthermore, it decreases the deformation, shear stress and the von-misses stress. The detail description of the FRP and its type is entailed below.

2.7 Fiber Reinforced Polymer and Matrix

Fiber reinforced polymers have been adopted for reinforcing for different structural elements in various discipline in this century. The researched carried out in the past of the two decades have presented FRP as alternative over the traditional method of strengthening for different structural members. Nowadays, FRP is gaining more importance as demand light weight material with high strength [32]. There is various type of fibers which are available for composite materials and they are basically classified as natural and synthetic fiber. New research revealed that when two fibers are combined together and blended with matrix material to form composite they give unprecedented material property. The role of the matrix in fibre-reinforced composite is to transfer stress between the fibers, to provide a barrier against an adverse environment and to protect the fiber from mechanical abrasion [33]; And it maintains the position and orientation of the strengthening material. The binding agent or matrix in the composite is very important. There are four major of matrices; these are polymeric, metallic, ceramic and carbon. Most of the composites used in the industry today are based on polymer matrices. Polymer resins have been divided broadly into two categories: thermosetting and thermoplastics.

- **Thermosetting**

Thermoset is a hard and stiff cross linked material that doesn't soften or become mouldable when heated, like elastomers and thermoplastics do. The most commonly used thermoset polymers are epoxy resins

- **Thermoplastic**

This type of polymers require heat to make them functional. It retains their shape after cooling. In addition, these polymers may be reheated and reformed, often without significant changes in their properties.

Some of the natural and synthetic fibers are depicted below.

❖ **Advantage of fiber reinforced polymers**

This [29] researcher has put those advantages

1. Lightweight.
2. Performed High Strength and stiffness to Weight ratio.
3. Resist environmental influences such as corrosion.
4. Easy to Shape, handle and transporting high workability.
5. Low heat conductivity.
6. More durability.

All over the world, FRP applied for a wide range of strengthening such as strengthening slabs using FRP strips, strengthening beams in shear and flexure, strengthening columns using FRP tubes and adhesive bonded FRP wraps. The figure below has shown the application of the FRP in different structural members.

Figure 2. 10 FRP strengthening for structural members.

Disadvantage of fiber reinforced polymers composite material.

1. FRP composites are brittle material (its failure is brittle not ductile).
2. High manufacturing costs.
3. Materials require refrigerated transport and storage and have limited shelf lives.
4. Materials must be completely cleaned for all contamination before repair.
5. Composites must be dried before repair because all resin matrices and some fibers absorb moisture.
6. Repair at the original cure temperature requires tooling and pressure.

2.7.1 Natural Fiber

Natural fiber have been used to reinforce materials for over 3000 years [33]. Natural fiber are extensively available in nature [34], [32], [35]. It is more preferable type of the fiber as it is easily degrading and doesn't pollute the environment [36], [37] and moreover it has high-strength and specific stiffness and low cost per unit volume [38], [39], [40].

Figure 2. 11 Natural fiber

2.7.2 Synthetic Fiber

Fibers that are made by chemical synthesis are called synthetic fiber. These synthetic fibers are further classified as organic and inorganic based on their content [32]. It is believed that the strength and stiffness of the fiber materials are much higher than that of the matrix material. As per [32], he classified the synthetic fiber in to four; those are: Glass fiber, carbon fiber, graphene fiber and basalt fiber. But, this thesis will only discuss about the carbon fiber reinforced polymers.

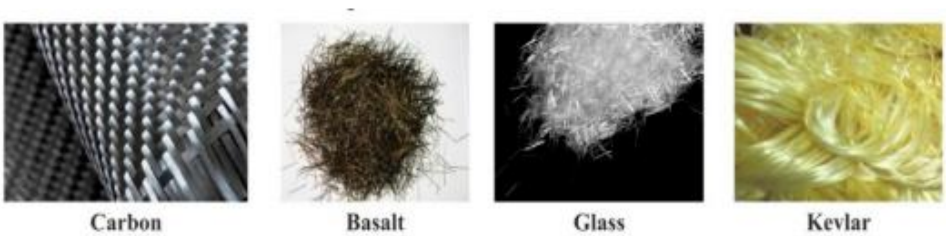

Figure 2. 12 Synthetic Fiber

2.7.3 Carbon Fiber

There are different types of the FRP as mentioned in 2.7.2 however carbon fiber reinforced polymers are highly appreciable method of strengthening in most of girder of the bridge. In most literature the CFRP in the form of sheets and strips are used. CFRP in the form of sheet used for strengthening of beams and columns. Sheet CFRP strengthening these elements by providing confining pressure. The physical properties of carbon fiber reinforced composite materials based on this research [33] depend considerably on the nature of the matrix, the fiber alignment, the volume fraction of the fiber and matrix, and on the molding condition. This research used a sheet form of CFRP as it provides confinement and ease application. This type of fiber has various application in aerospace; automobile; sports as well as in different civil structure. the use of advanced composite materials for bridge application began to slowly emerge in the late of 1970s and early 1980s. their high strength-to-weight ratio [41], combined to resistance to corrosion, has played a significant role in creating interest in these material for bridge repair and rehabilitation [31]. This is preferable whenever more stiffness is required, in such case the GFRP is replaced by CFRP. CFRP along with Epoxy resin work as system together and the fiber provide high load carrying capacity, High tensile strength, and rigidity, whereas the resin protects and transfer the load to fiber and also acts as binder. Epoxy resins are the most common matrix in structural repair applications due to their characteristics such as good adhesive properties, low shrinkage during curing, and resistance to environmental degradation [28]. More over based on this researcher [42] the growth of the carbon fiber market has an impact on different industries where energy efficiency can be increased and other properties, such as good electrical conductivity are not yet exploited. CFRP has many advantage in wide area of disciplines.

2.8 Efficiency and Percentage of Strengthening

Different researchers have been rating the significance of the CFRP in load rating of the beams of the bridges. This [42] researcher has reported single layer of CFRP layer has got an increment of 13% in ultimate loading capacity of the beam. Two layers and three layers however showed an increment of 26 and 32% respectively. Moreover, the deflection reduction when 1layer, 2 layers and 3 layers CFRP applied to the bottom surface of the beam are 13.6%, 23.9% and 27.6%. and other researchers [43] has reported that 10% increment on loading capacity of the beam and this [44] researcher, has carried out a research on the efficiency and percentage of load carrying capacity of the beam subjected to blast loading and he reported that the CFRP reduces deflection due to explosion. However, by increasing the number of layers of CFRP, the rate of reduction in deflection decreased. This is likely to be due to the bond strength capacity between the CFRP and the concrete face.

CHAPTER 3 FINITE ELEMENT MODELLING AND STRENGTHENING

3.1 Introduction

This chapter includes research methodology used, geometric dimension of pre-stressed box girder of railway bridge, finite element modelling of pre-stressed girder bridge, validation of A9 type of pre-stressed concrete sleeper and modelling and strengthening of the pre-stressed concrete girder of the bridge.

The study area was in common cross-section E-W of the railway network of E-W and N-S of AA-LRT. One pre-stressed box girder of the non-ballasted railway bride that was already built in AA-LRT having length of 25m and breadth of 4.5m was used. The bridge is double truck railway bridge and its main purpose is to give an access for passenger train traffic. The bridge is simple supported beam and it was designed and built by china railway group limited in 2015.

3.2 Research Methodology

The research area of the thesis was in Addis Ababa Light Railway Transit particularly for strengthening of the pre-stressed box girder of railway bridge.

Over the study of strengthening concept, the numerical analysis was done using ANSYS software. The dimension of the pre-stressed girder bridge and the Material properties of the bridge was obtained from AA-LRT whereas the property of the CFRP was obtained from industrial manufacturer and literature review. 3-D model of the structure has been modelled using Auto-Cad. The structure has been imported in ANSYS software and proper material property has been assigned in space claim in engineering data of the ANSYS software. Proper mesh has been done and finally validation has been carried out prior to main work. Until failure, the pre-stressed steel reinforcement has been modelled as an ideal elastoplastic material, and the CFRP has been modelled as a linear elastic material. In this thesis one of Addis Ababa's already-built railway bridges has been used. Modelling the strengthened and un-strengthened pre-stressed girder of the bridge and analysing the ultimate load capacity along with the von-mises stress, deflection, and shear stress of the pre-stressed girder of the bridge using ANSYS software has been carried out. In this thesis technical papers, journals and publication had been reviewed from library and internet on related topics.

The detailed methodology was shown in figure 3.1 below.

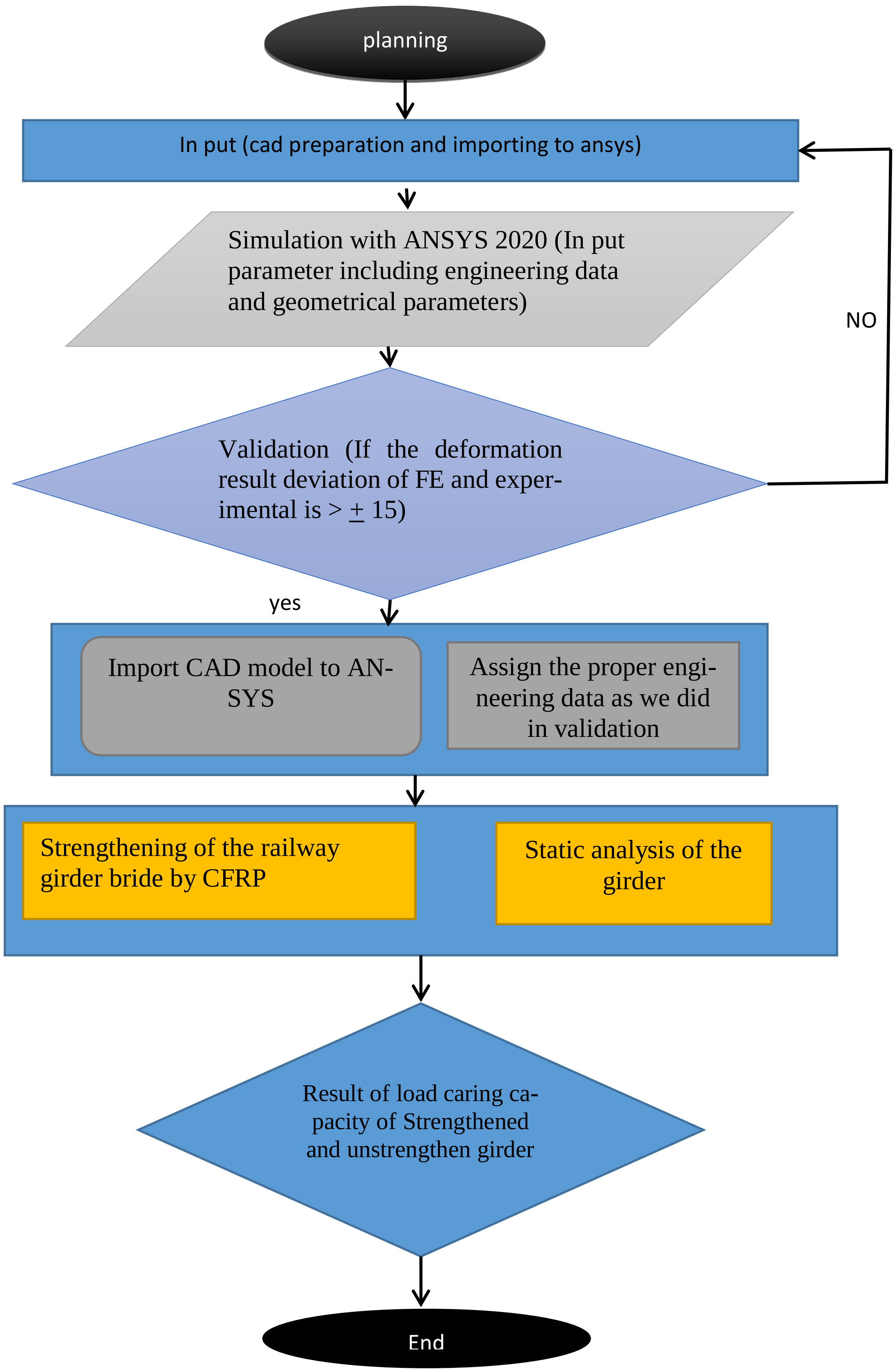

Figure 3. 1 The Detailed Methodology

3.3 Finite Element Modelling

The choice of the structural modelling is vital; this is because it enables us to predict the real bridge response. In fact, the level of detail in the model increase the accuracy of the result. Therefore, the detail properties of the material and good knowledge of the software have a large weight. Thus, to investigate and analysis the behaviour of the prestressed girder of the bridge, a finite element model was developed using ANSYS 2020 software package under static loadings before and after strengthening of the girder of the bridge.

3.4 Modelling The Geometry

It is important to limit the number of elements due to the constraints of the computational time. So if the geometry is symmetrical in geometry, symmetrical in loading, symmetrical in the orientation of the material and symmetrical in the output of the result, one can use the concept of the symmetry and the geometry of the structure can be taken as half and/or Quarter. The dimension and material property of the pre-stressed girder of the railway bridge is explained in section 3.8

3.5 Validation of the FEM

Validation is used to insure if the model represents the reality at a given confidence. This include modelling of the structure at a reasonable state of representing the structure on ground. The validation criteria are uniquely defined set of consideration to decide with agreement of the model prediction and the test result is reasonable enough to consider the model to be valid. There for the main objective of this section is to assess the quality of the FE model by comparing the results of the FE and experimental result. Upon validation with the test result, the analysis of the software could be proceeding as follow. In case of the FEM validation, only a static structural analysis was conducted. The input materials such as concrete and prestressed steel outlined in the following section.

3.5.1 Concrete and Prestressing Wires Materials

3.5.1.1 Concrete Material

The railway sleepers are made of concrete material. the concrete property of C52 are depicted as shown in the table below.

Table 3. 1 Concrete Material Property [45]

Density P_c (kg/m^3)	Poisson's ratio: υ_c	$F_{c,}$ cyl (Mpa)	$F_{c,}$ cube (Mpa)	Young's modulus $E_{c,}$(Mpa)	Compres-sive Strength, σ_{cc} (Mpa)	Tensile strength. σ_{ct} (Mpa)	GF (N/m)
2400	0.2	55	67	34,400	52	2.85	154

3.5.1.2 Pre-Stressing Steel Wire Material

The property of the steel wire material is depicted here below in Table 3.2, [45]

Table 3. 2 Property of Pre-Stressed Steel Wire

Diame-ter, ∅ (mm)	Density, ρ_c (g/cm^3)	Pois-son's Ratio, v_c (MPa)	Thermal expansion: α (/°C)	Young's modulus: E_s(GPa)	yield Strength, σ_{tt} (Mpa)	Tangent modulus. E_{st} (Mpa)	Initial strain ε_0 (mm/m)
7	7.8	0.3	$1.1*10^{-5}$	200	1750	20000	5

According to [45] the FE and Validation of static full-scale test is next discussion here below

3.6 Static Full-Scale Test Done by Rikard

The hydraulic jack used by Rikard was mounted in a set-up as shown in the figure below 3.2.

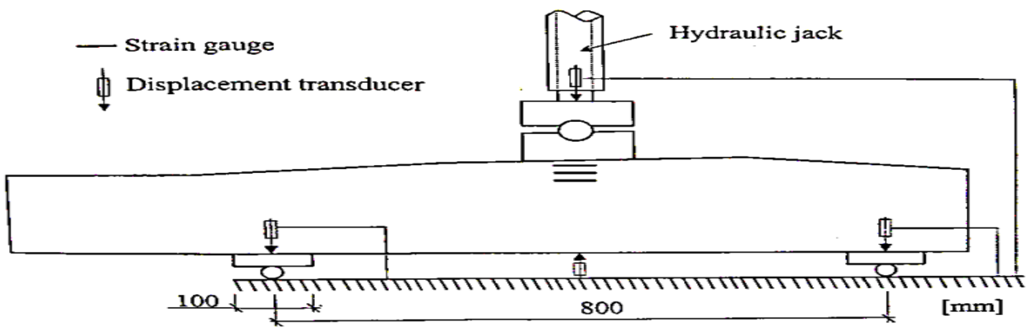

Figure 3. 2 Test set-up used in the Test Done by Rikard, 2000

As in [45] the static test is carried out using a hydraulic jack; six sleepers of type A9P were cut at the middle perpendicular to the line of the sleepers. And each half-sleeper was subjected to a bending moment that produce the same principal deflections as if it placed on track system. The support condition in this case is fixed where sleeper is tied on the ground on four locations as shown in figure 3.3 and the load is applied to the rail seat area varying from 0 to 237.5 KN.

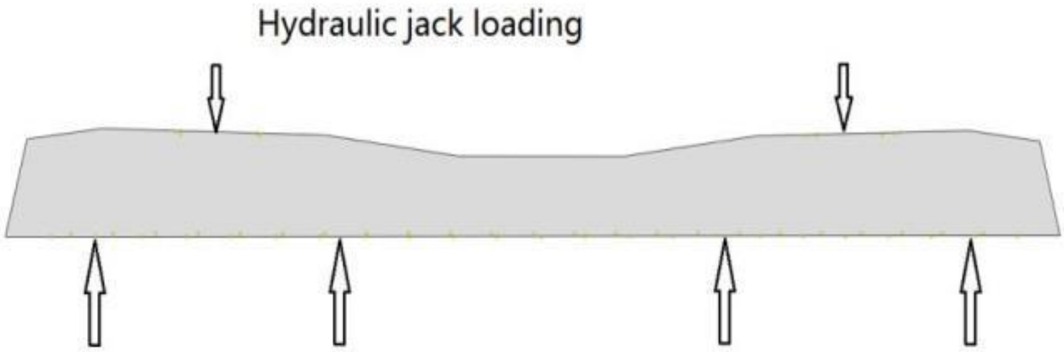

Figure 3. 3 Support Condition

The support condition is fixed both in vertical direction at four points of the bottom of sleeper like those in the test as in the figure above.

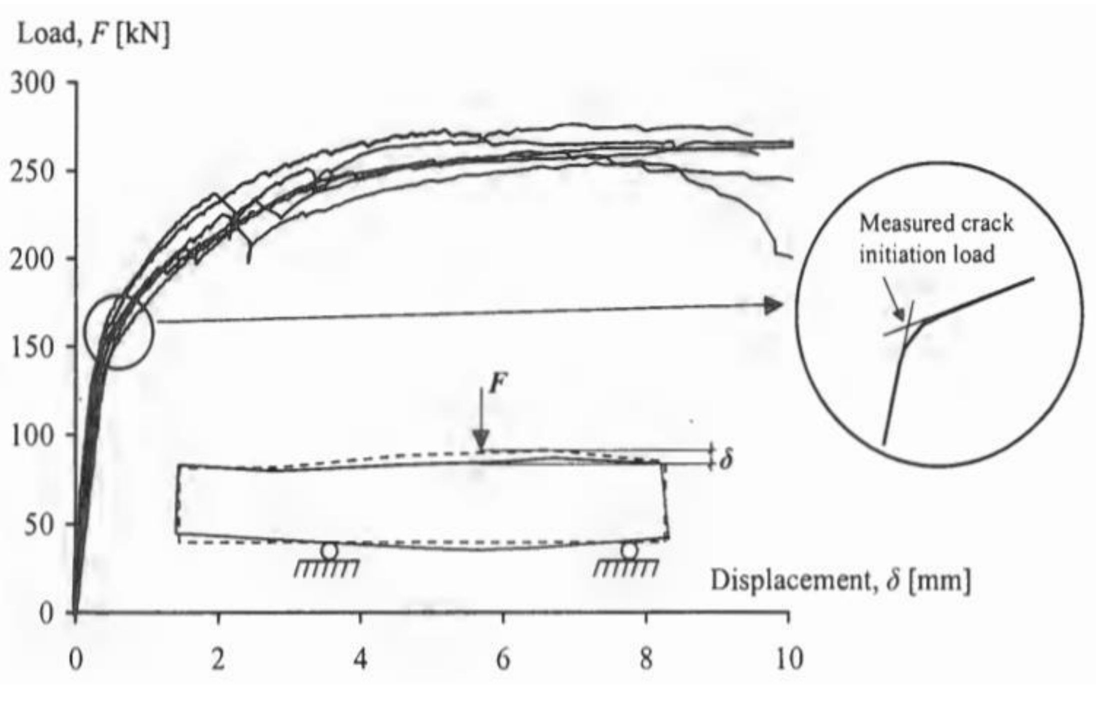

Figure 3. 4 The Load-Vertical Displacement Relation for the Six Tested Half-Sleepers [45].

3.7 Sleeper Modelling and Validation

3.7.1 Element Type

Different of element types exists for both steel and concrete materials because the aim and required output might vary from model to model. The following briefs the elements used in modelling prestressed concrete sleeper. These recommended elements are based on the commercially available in ANSYS software. The element type for this model is shown in Table 3.3 below.

Table 3. 3 Element Types for Working Model

Material type	ANSYS
Concrete	Solid65
Steel reinforcement and pre-stressed tendon	Link180

3.7.1.1 Ansys Solid65 Element

A Solid65 element was used to model the concrete. This element has eight nodes with three degrees of freedom at each node translations in the nodal x, y, and z directions. The element is capable of plastic deformation, cracking in three orthogonal directions, and crushing [46].

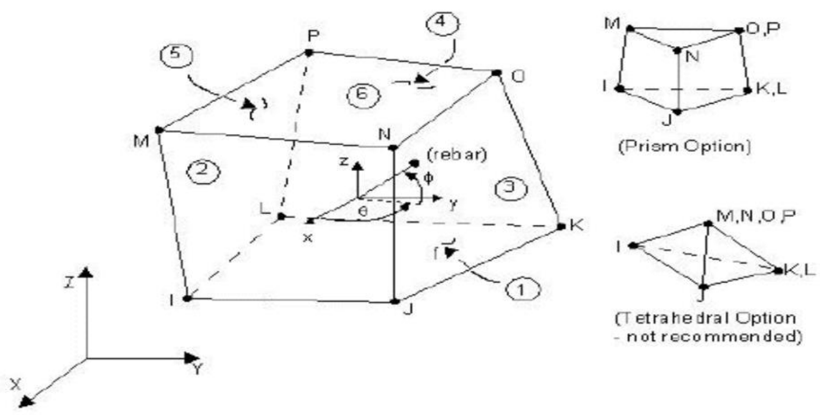

Figure 3. 5 SOLID65 Three-dimensional Element [46]

3.7.1.2 ANSYS LINK180 Element

A Link180 element was used to model steel reinforcement [46]. This element is a 3D spar element and it has two nodes with three degrees of freedom translations in the nodal x, y, and z directions. This element is capable of plastic deformation.

LINK180 requires users to input ‘’real constants’’ to define reinforcement geometry, material behaviour, and prestressing strain. However, the perfect bonding between concrete and prestressing wires has to be assumed [47]. An advantage of using LINK180 is that, it is possible to specify an initial strain for the element. This is useful for defining the initial prestressing force. LINK 180 further allows a change in cross-sectional area as a function of axial elongation. By default, the cross-sectional area changes such that the volume of the element is preserved, even after deformation. The default is suitable for elasto-plastic applications. LINK 180 offers compression-and-tension, tension-only, and compression-only options [47].

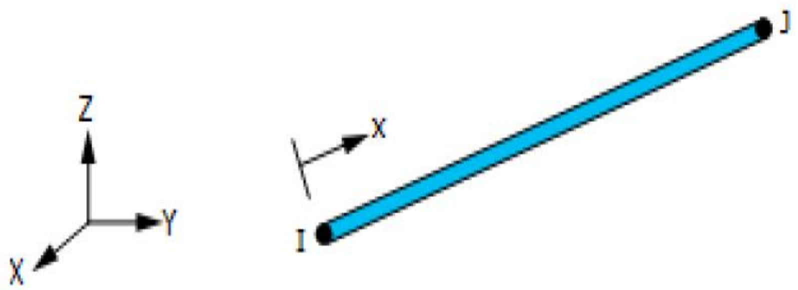

Figure 3. 6 LINK180 Bar Element Displayed with Local and Global Axis [45]

Pre-stress loss of the steel

The pre-stressed loss is the sum of the loss due to elastic deformation, loss due to concrete creep, loss due to shrinkage of concrete, and loss due to relaxation of steel[60], [61].

1. Loss due to elastic deformation can be calculated as:

   $\text{Loss} = \text{ modular ratio } \times \text{fco}$

where f_{co}= stress at the bottom of concrete level of tendon

$modular\ ratio = ES/EC$ and $fco\ =\ Po/A\ +\ Po\ e2/I$

P_0= initial stress, A= area of concrete, e=eccentricity and I= moment of inertia.

2. Loss due to creep of concrete is calculated as follow:

   $Loss = Ø\ x\ m\ x\ fco$, where Ø= 1.4 for transfer after 28 days

3. Loss due to shrinkage of concrete

   $Loss = Es\ x\ €cr$

   where cr= $300*10^{-6}$ shrinkage strain for pre-tensioning

4. Loss due to relaxation of Steel

   $Loss = 5\%\ of\ initial\ stress$

   Thus, the total loss is the sum of the four losses.

3.7.2 Static Modelling of Sleeper Type A9p

In this section, a finite element model for sleeper is discussed and a model is established using the finite Element package ANSYS 20, that is a numerical tool used to model and simulate mechanics behaviour and response of sleeper. In this case, the concrete sleeper is modelled as three dimensional solid elements, solid 65. And the prestressed wire is embedded as truss element, Link 180 and subjected to an initial prestrain of 5mm/m with fixed support condition. In this case the concrete cross section is simplified as rectangular and the bond slip between concrete and reinforcement is ignored. The material properties have been cited in the above tables. The FE model result is analysed and compared with the Rikard [45]. The longitudinal and cross sectional section of the Rikard are depicted below.

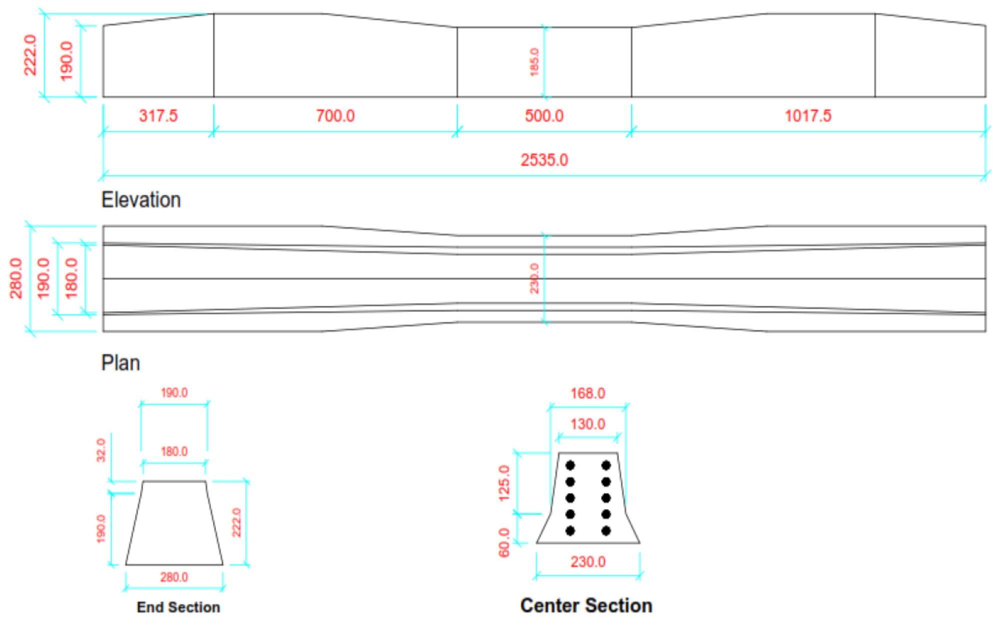

Figure 3. 7 Sketch of Sleeper Type A9P [45]

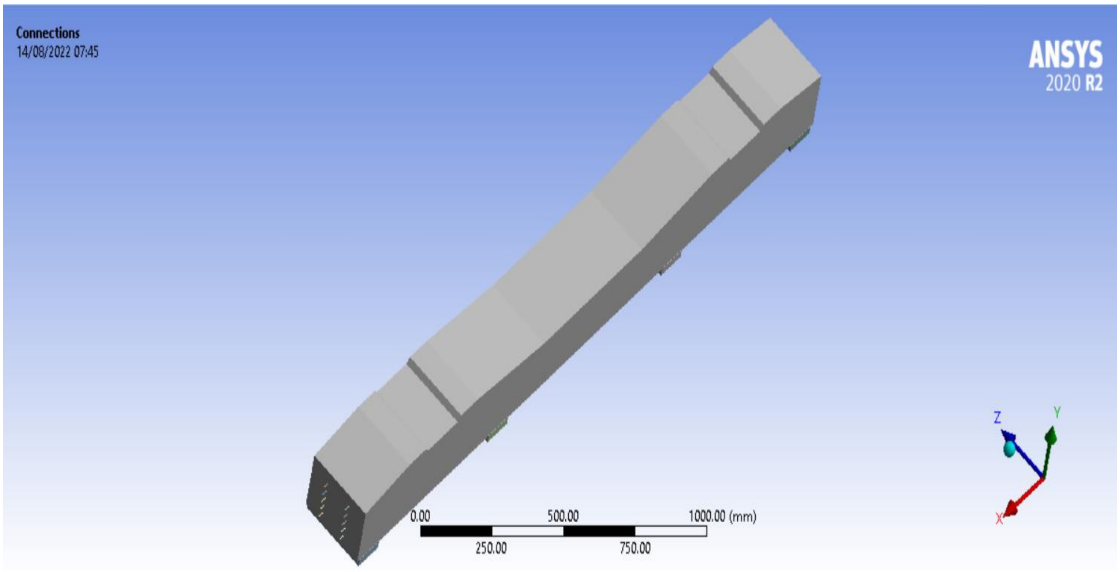

Figure 3. 8 Static Model of the A9P Sleeper

The load applied on rail seat area is varying from 0 to 237.5 KN and this load is the same as the hydraulic jack applied in Rikard. And the model was meshed as shown in figure below and 25mm mesh size was adopted.

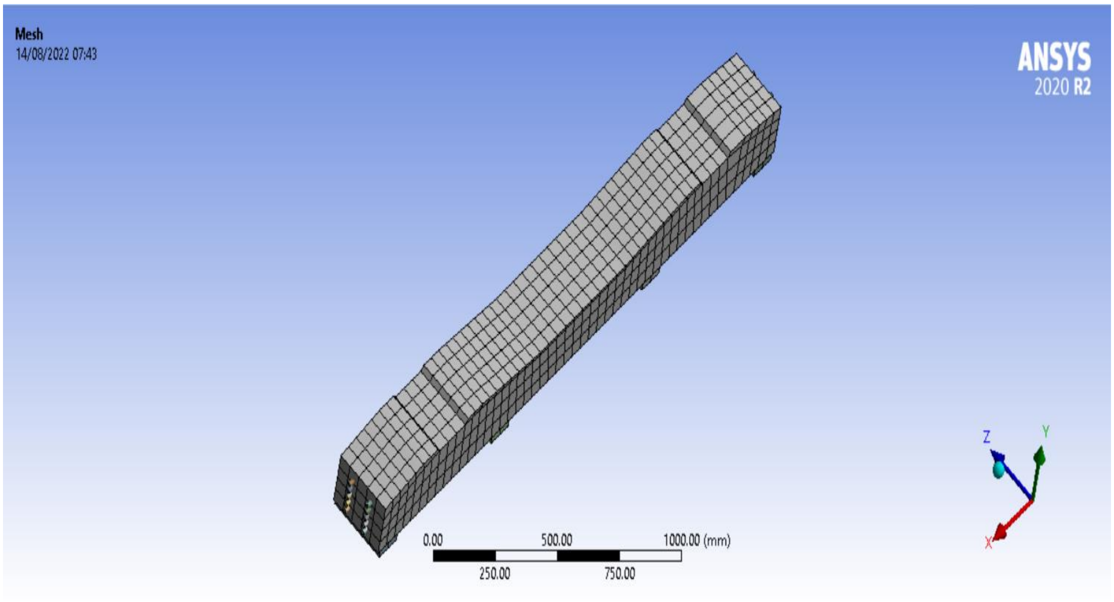

Figure 3. 9 Meshed Model of the Sleeper with Embedded Reinforcement

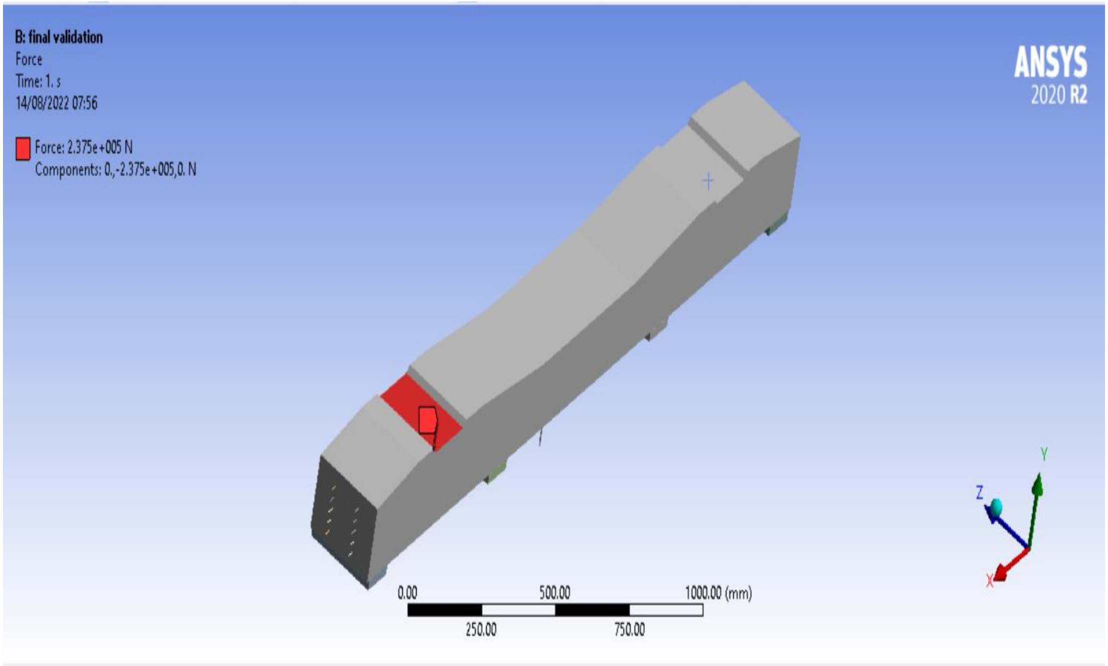

Figure 3. 10 Applied force

3.7.3 Numerical Result

The structural Response, that is the load-vertical displacement relationship, in numerical analysis has to be compared with the experimental result carried out by Rikard to validate the quality of the FE model. In the case of the Rikard's model the concrete was modelled as elastoplastic and brittle cracking material where as in this FEM concrete was modelled as an elastoplastic material. The stress-strain of the Rikard and vertical deformation of the FEM model concrete are depicted below.

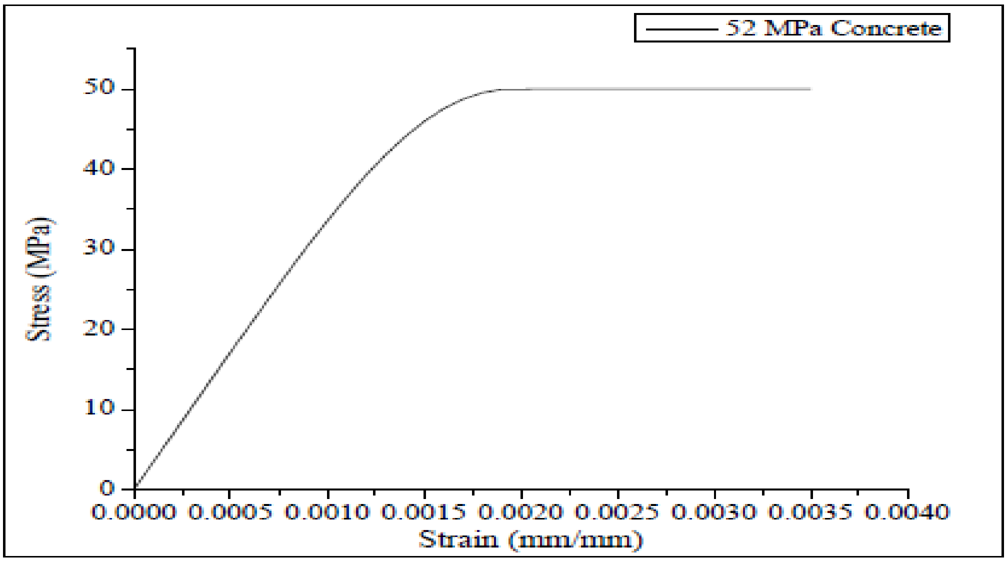

Figure 3. 11 The Stress-Strain Graph for 52 MPa Concrete

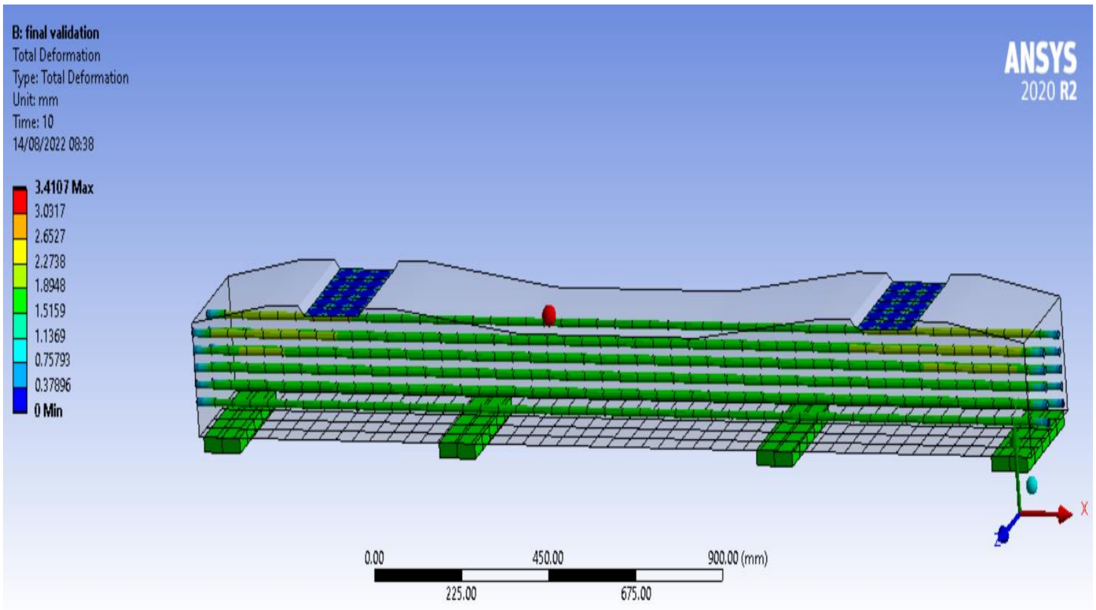

Figure 3. 12 Contour Plot for Vertical Deformation at 237.5 kN

The force –deformation result is shown below and the maximum directional deformation was obtained at 237.5 kN.

Table 3. 4 Force Vs Deformation.

Force(kN)	0	50	150	200	237.5
Deformation(mm)	0.000	0.354	1.083	2.086	3.4107

Table 3. 5 deformation variation in percentage (%).

Force(kN)	Experimental deformation(mm)	FEM deformation (mm)	Percentage of variation
0	0	0	0
50	0.354	0.361	1.95
150	1.083	1.094	1.01
200	2.086	2.100	0.66
237.5	3.410	3.703	8.21

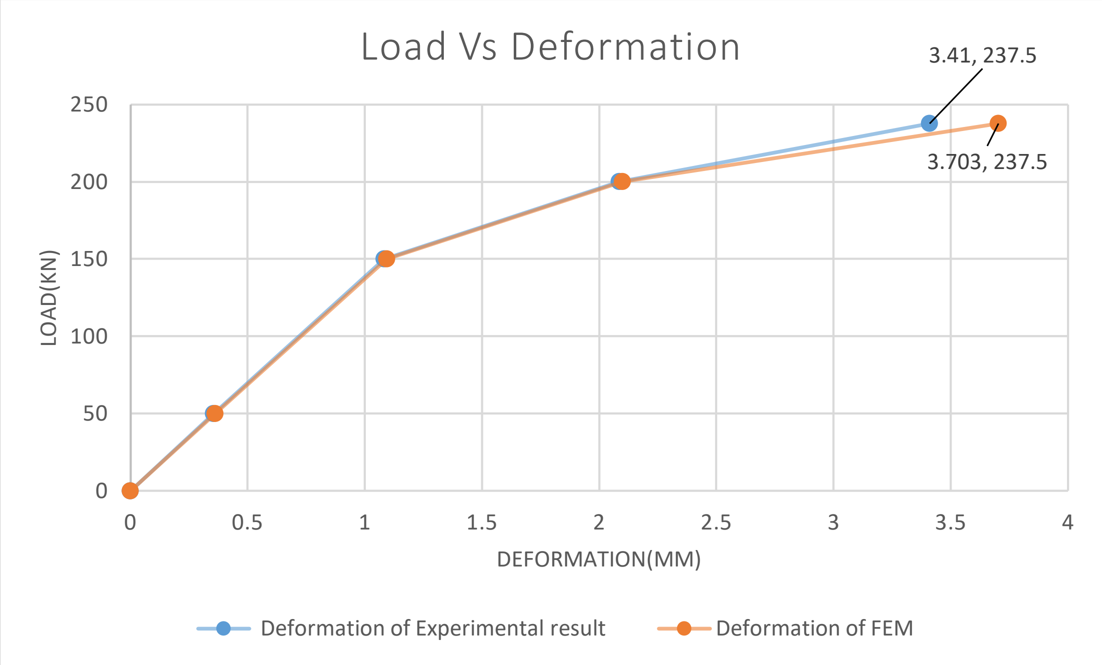

Figure 3. 13 Load Versus Deformation of Experimental and Numerical Result

The directional deformation of the FEM has no more than ± 15 % deviation as compared with Rikard 2000, and this shows that the quality of FE model is good as shown in the table 3.5 above. If the model is validated with respect to the test results, we can proceed to further analysis using this FE-model. Since the static results match with experimental results, ANSYS software can be used to conduct static simulations.

3.8 Geometric Shape and Dimension of Pre-Stressed Girder Bridge of Addis Ababa Light Rail Transit

3.8.1 Girder Cross Section

The geometric shape and dimension of the prestressed girder bridge of Addis Ababa LRT is cited below. In this thesis a simple supported girder of the bridge obtained from AALRT office is used. And a quarter part of the bridge is modelled and analysed. The total length of the bridge is 25m. and the bridge is double truck bridge. As far as the geometric, material property and orientation of material, expected output result as well as loading are symmetric; a quarter part of the bridge has been adopted to minimize the simulation computational time. All the units are here in mm and 1:50 scale is used in modelling of the bridge. Therefore, the final result has to be multiplied by 50.

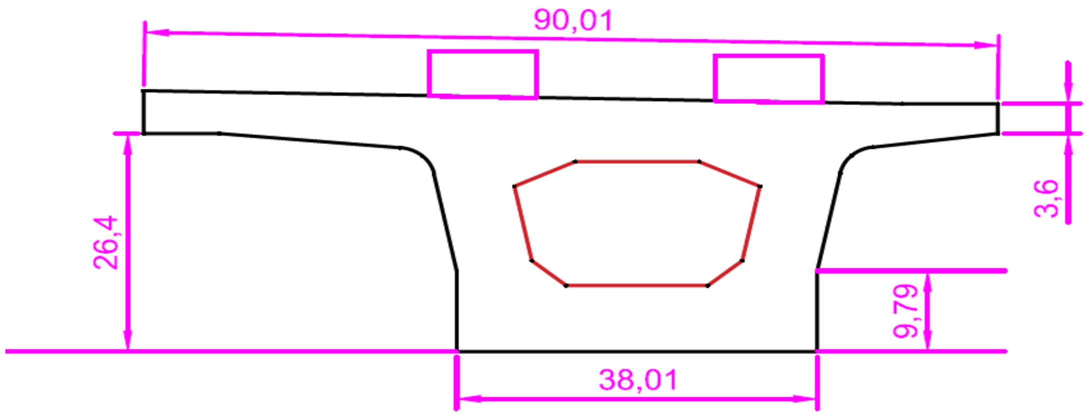

Figure 3. 14 The Cross-Sectional View of the Quarter Bridge 1:50 scale.

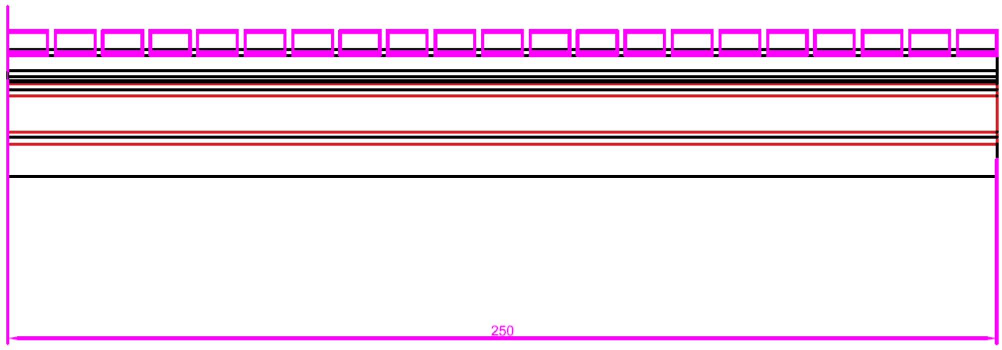

Figure 3. 15 Longitudinal Section of the Quarter Bridge scale of 1:50

3.8.2 Material Property

The general parameters are given as such

Table 3. 6 The General Parameter of the Pre-Stressed Girder Bridge

Parameter	value	Source
Axle load	25 t	AALRT & ERC feasibility study [48]
Sleeper spacing center to center	60 cm	AALRT & ERC feasibility study[48]
Concrete grade	50 Mpa	AALRT & ERC Design Department

3.8.2.1 The Property of Concrete, Steel, Pre-Stressed Wire

According to National Standard of People's Republic of China [49], the concrete strength grade for prestressed concrete structures shall not be less than C30.

When strand, steel wires and heat-treated steel reinforcements are to be used as pre-stressed steel reinforcement and the concrete strength grade may not be less C40.

As reported by ERC design department, the concrete grade C50 was used for pre-stressed girder bridge. The stress-strain relationship is shown in figure 3.15 below.

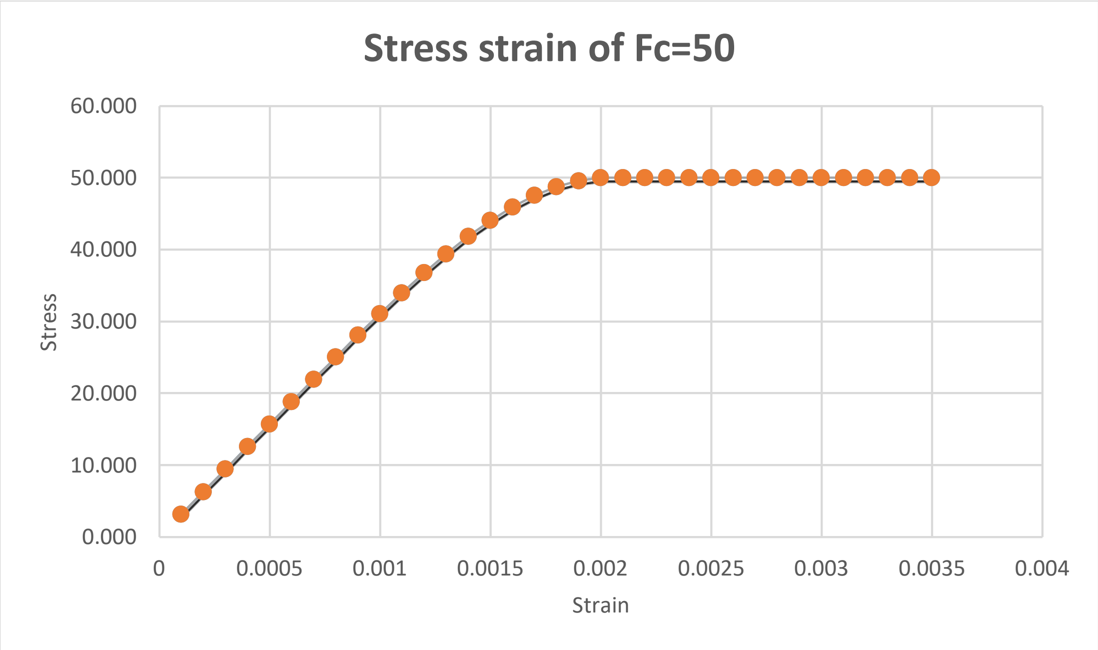

Figure 3. 16 The Compressive Stress-Strain Diagram of Concrete, fc' =50 MPa

The values presented in figure 3.16 depicted the behaviour of concrete and is taken as model inputs in SOLID65 and LINK 180. The allowed value of the controlled stress for stretching shouldn't exceeded the controlled stress for stretching prestressed reinforcement.

The Table 3.7, 3.8 and 3.9 summarizes the properties of concrete, steel and prestressing wires used in Finite Element Analysis correspondingly.

Table 3. 7 Material Properties of Concrete

Density (ρ_c) (kg/m^3)	Poisson's ratio: υ_c	Thermal expansion (α_c), /c	Young's modulus E_c, (Mpa)	Compressive Strength, σ_{cc} (MPa)	Tensile strength. σ_{ct} (MPa)	Strain value
2400	0.2	1.0*10^-5	34,400	50	2.85	0.003

Table 3. 8 Material Properties of Steels

Steel type	Density(p_s) (kg/m^3)	Poisson's ratio: υ_s	Thermal expansion (α_s), /c	Young's modulus, E_s, (MPa)	yield Strength, σ_{tt}(MPa)	Tensile strength. σ_{st} (MPa)
reinforcement HPB235	7800	0.3	1.18*10^-5	2.1*10^5	235	370
reinforcement HRB335	7800	0.3	1.18*10^-5	2*10^5	335	455

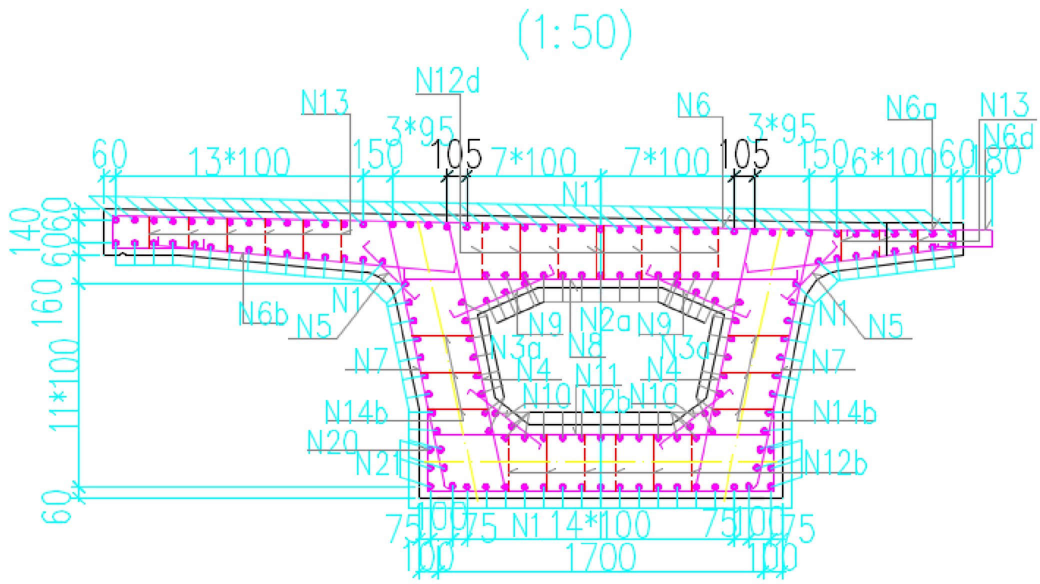

Figure 3. 17 cross sectional view of the pre-stressed girder bridge along with reinforcement

Table 3. 9 Material Properties of Pre Stressed Steel

Steel type	Density(P_s) (kg/m^3)	Poisson's ratio: υ_s	Thermal expansion (α_s), /c	Young's modulus E_s, (MPa)	elongation	Tensile strength. σ_{st} (MPa)	Pre-stress loss
Pre-stressed steel	7800	0.3	$1.18*10^{-5}$	$1.95*10^{5}$	3.5%	1860	5.8%

The distance between adjacent longitudinal and transverse reinforced bars are 10cm and the concrete cover should not be less than 50cm. the vertical spacing of the pre-stressed bars shouldn't be 8 times the diameter of the strand and the prestress loss is 5.8% at mid span.

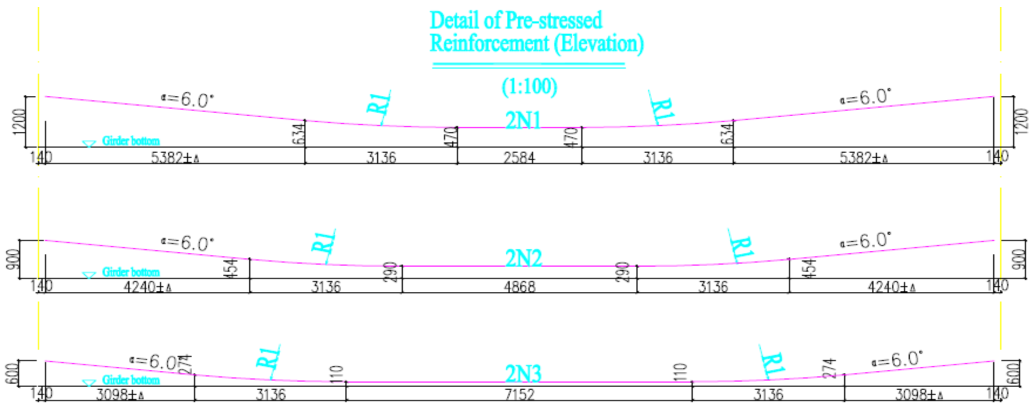

Figure 3. 18 Elevation Prestressed Tendon

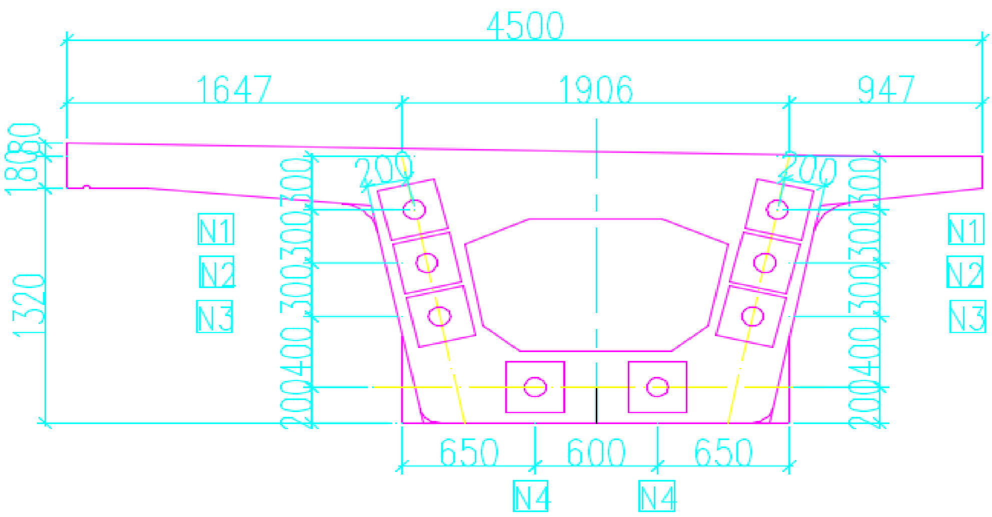

Figure 3. 19 Front View of Prestressed Reinforcement

The quantity of the reinforcement bars of the pre-stressed girder of railway bridge are tabulated in the Table 3.10 below. The cross-sectional view of the PSC –girder is also shown in Figure 3.17

Table 3. 10 Quantity and Cross-Sectional Area of Bars, Rebars and Tendons

Bars, Rebars and Tendons			
N0.	diameter in mm	quantity	length of single piece (M)
N1(longitudinal)	12	98	24.919
N2a(transverse)	12	38	4.314
N2b(transverse)	12	30	4.359
N3a(transverse)	12	32	4.259
N4(transverse)	12	388	1.595
N5(transverse)	16	498	0.526
N6(transverse)	16	249	4.832
N6a(transverse)	16	241	1.97

Bars, Rebars and Tendons			
N0.	diameter in mm	quantity	length of single piece (M)
N6b(transverse)	16	249	1.691
N6d(transverse)	16	241	1.329
N7(transverse)	12	249	4.664
N8(transverse)	12	249	2.194
N9(transverse)	12	498	0.675
N10(transverse)	12	498	0.58
N12b(transverse)	10	42	0.445
N12d(transverse)	10	84	0.429
N13(transverse)	10	1121	0.323
N14b(transverse)	10	36	0.441
N20(transverse)	12	56	0.658
N21(longitudinal)	12	12	1.646
Prestress	15.2	8	24.9

3.8.2.2 Girder Loading

The predominant load in the girder is the vertical load. To have a clear understanding however, there are three track load condition. The vertical load consists of the static axle load, and additional dynamic increases: those are quasi-static, dynamic ride or impact load. So these load has to be super imposed on the static wheel load. Thus, the general method used to determine the design vertical wheel load is empirically express it as a function of the static wheel load as

$$P = \emptyset\, P_s$$

Where; P_d is the design wheel load in kN, Ps is the static wheel load in kN, and Ø is the dimensionless impact factor, that is always greater than one (> 1).

And the dimensionless impact factor is calculated as a function of the vehicle speed and wheel diameter.

$$\emptyset = 1 + 5.21 V/D$$

Where; v is the vehicle speed(km/h), and D is the wheel diameter(mm).

The static wheel load, P_s = Q*0.5g= 125 kN and Ø= 1.434

Therefore; P_d=179.3 kN

The schematic wheel load of AALRT is depicted as below figure.

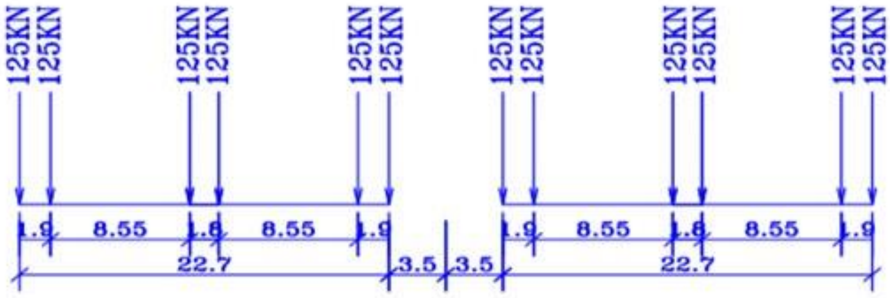

Figure 3. 20 Schematic view of Axle load

3.9 Geometric Shape and Dimension of The CFRP

3.9.1 Over View

Carbon reinforced polymer(CFRP) are composite materials that are rely on the carbon fiber to provide the stiffness and strength while the polymer provides a cohesive matrix to protect and hold the fiber together and provides some toughness. in this thesis the carbon is designed as bonded with concrete as theoretically the resin has high bonding capacity. Carbon fiber reinforced polymer(CFRP) material possess good rigidity, high strength, low density, corrosion resistance, vibration resistance, high ultimate strain, high fatigue resistance and low thermal conductivity.

3.9.2 Material Property and Dimension

For strengthening the ultimate load capacity, commercially available wet lay CFRP of 1000 mm, 1500mm and 500 mm and a thickness of 1.5 mm and 2 mm were used with one, two and three layers. For anchoring the CFRP a longitudinal strip of CFRP has lied on another CFRP.The detailed property of the CFRP is presented below as in Table 3.11

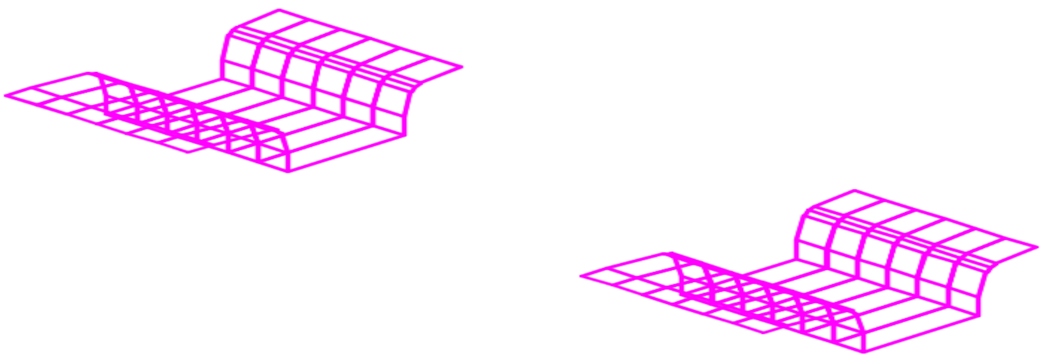

Figure 3. 21 CFRP at 4m from Support and Mid-Span

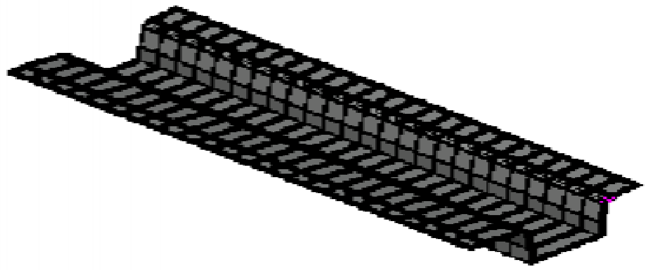

Figure 3. 22 Full Length CFRP

Table 3. 11 Material Property and Dimension of CFRP

Density (ρ_{cf}) (kg/m^3)	Poisson's ratio: υ_{cf}	Thickness of the strip (mm)	Width of the strip, (m)	Spacing of the strip(m)	Young's Modulus E_{cf}, (MPa)	Tensile strength. σ_{cft}, (MPa)	Resin content
1800	0.3	1.5 or 2	0.5 ,1 and 1.5	0.5 and 1	56500	2759.9	35%

3.10 Prestressed Girder Bridge and Carbon Fiber Reinforced Polymer Modelling

3.10.1 Over View

Finite element analysis (FEA) is a powerful tool which can be applied to the design of irregular shaped member, whose geometry causes standard analysis to be difficult or more importantly inaccurate. It provides a tool that can simulate and predict the responses of reinforced and prestressed concrete members. The FEM is a numerical method for approximating solution for the problem that is difficult to solve analytically. This numerical method is done when the problem domain is divided into small elements having a simple geometry.

ANSYS is an advanced linear and non-linear simulation package that has been previously used to solve many complex and real word problem. Model constructions were first done using outcad 2018 and then later imported in ANSYS Workbench.

Using ANSYS 2020, a three-dimensional non-linear finite element model of railway prestressed girder concrete was developed.

3.10.2 Static Analysis in Ansys

Static structural analysis in ANSYS Workbench starts with engineering data and analyses models under static loadings. When entering engineering data, be sure to carefully follow the instructions in Tables 3.7, 3.8, 3.9 and 3.11 to enter the values of the material attributes and their corresponding units.

3.10.3 Pre-Stressed Girder Bridge Geometry

The selected pre-stressed girder is first modelled using a Computer Aided Design(Auto-Cad) And then the pre-stressed girder geometries were saved and imported, to Space claim, ANSYS Workbench. After importing the geometries, a proper cross-sectional area of the line bodies was prepared. The pre-tensioning process was next executed by applying an initial strain corresponding to the prestress. For analysis purposes, since the pre-stressed girder was symmetric, a quarter of it was considered as shown in Figure 3.23 below.

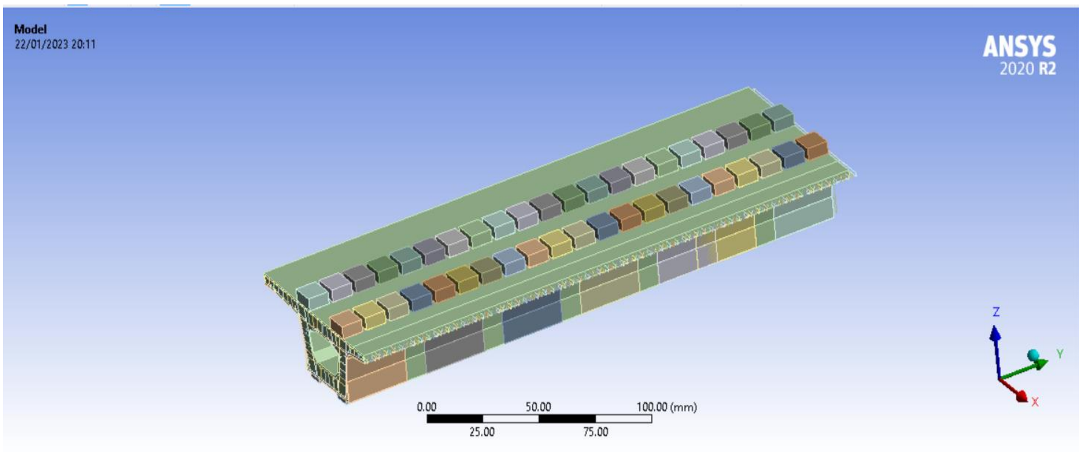

Figure 3. 23 Quarter Part of the Bridge

3.10.4 Meshing

The meshing shown in figure 3.24 was used. Hex dominant method was used for this model and mid-sized nodes set to “Dropped” to force the use of 8-nodes SOLID65 element instead of the default SOLID186. The hex-dominant meshing was preferred as it is both more efficient and accurate therefore producing a better (more uniform) mesh if a size control is placed on one or more edges. Hex meshing reduces element count therefore reducing the running time. The elements are aligned in direction of flow thus reducing the numerical error. The mesh size used was 1.5mm for this model. The number of nodes and elements in this meshed girder are 751158 and 340820 respectively.

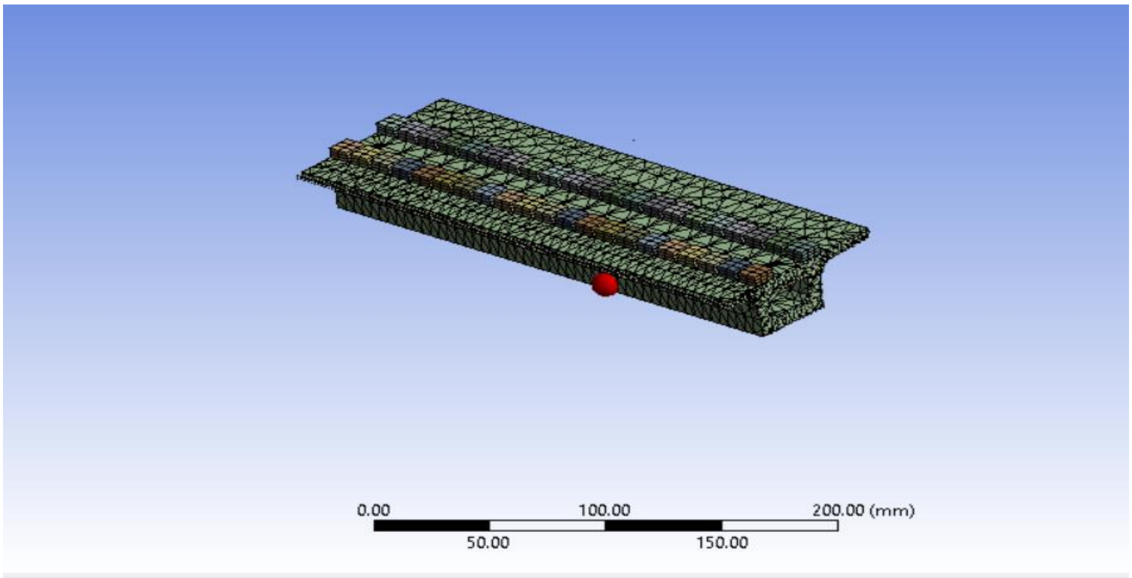

Figure 3. 24 Meshing

3.10.5 Loading and Boundary Conditions

The loading is applied to the pre-stressed girder loaded gradually varying from zero to 500 kN with 25kN load increment to avoid inertia effect. The vertical load is applied on sleeper box based on the schematic loading given by AALRT, refer Figure 3.2 in the previous section. The support of the pre-stressed girder is modelled as a simply supported seated on the stainless steel of 50 mm by 50mm, the stainless steel is fixed into the piers of the girder. External bonded method has been used to strength the pre-stressed girder and CFRPs have been laminated to the surface of the concrete. One, two and three layers of CFRP have been used.

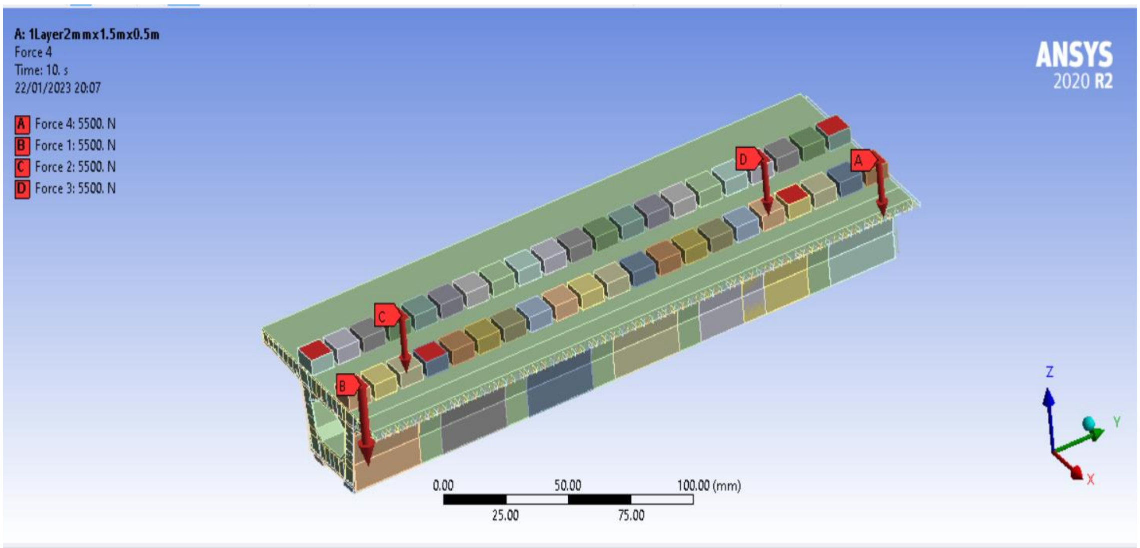

Figure 3. 25 Loading of the Girder

3.10.6 Solutions in Ansys Workbench Static Structural Analysis

A set of solutions are available in ANSYS such as deformation (total or directional) and stresses (equivalent and shear). The pre-stressed girder was modelled and analysed to determine the respective deformations and stresses. The relationship between the three stresses such as equivalent stress, shear stress and bending stress could be reported. For instance, Ivanov [50] in 2014 expressed the normal stress in terms of bending stress and an equivalent stress.

$\sigma v = \sqrt{(\sigma b)^2 + 3(\sigma s)^2}$ …………………………………….. (3-1)

Where:

σv= Equivalent (Von-Mises) stress, σb= bending stress and σs= shear stress

$\sigma b = \sqrt{(\sigma v)^2 - 3(\sigma s)^2}$ ……………………………………. (3-2)

CHAPTER 4 ANALYSIS RESULTS AND DISCUSSION

4.1 Overview

In the preceding chapter, a three-dimensional pre-stressed girder which is currently in use for Ethiopian railway lines is modelled in detail. The geometry, material property, elements used, etc. which are parameters used in modelling are mentioned in the preceding chapter. In this section the analysis results of the girder model are presented. The pre-stressed girder of the bridge is Static analysed to carried out the load rating capacity, equivalent stresses and deflections under static load. The structural response of the girder in terms of Load and deflections for different width and thickness strip of CFRP is also discussed.

4.2 Static Behaviour of Prestressed Girder Bridge

The prestressed girder bridge was analysed using ANSYS Workbench through static structural analysis. In this section, the analysis results of the model are presented and statically analysed to obtain the deformation and stresses for strengthened and non-strengthened girder of the bridge. Steady loading and response conditions are assumed; that is, the loads and the structure's response are assumed to vary slowly with respect to time.

4.2.1 Deformation

The Deformation results, in ANSYS work bench, are generally obtained as either total deformation or directional deformation. In this thesis, the deformation of strengthened girder with one, two and three layers are analysed the deformations of the strengthened and unstrengthened pre-stressed girder of railway bridge are tabulated below.

Table 4. 1 Deformation (in mm) of the pre-stressed girder when strengthened with 0 and 1 layer of CFRP

Load(kN)	0 layer without CFRP	1 layer(thickness*strip width* strip spacing)			
		2mm*0.5m*0	1.5mm*0.5m*0	2mm*1m*1m	2mm*1.5m*0.5m
0	0	0	0	0	0
50	5.0997	4.7584	4.7412	4.25085	4.53165
75	7.6494	7.1375	7.112	6.3765	6.7975
100	10.1994	9.517	9.4825	8.5015	9.0635
125	12.7494	11.896	11.853	10.627	11.329
150	15.2994	14.275	14.2235	12.7525	13.595
175	17.8488	16.6545	16.594	14.878	15.861

Load(kN)	0 layer without CFRP	1 layer(thickness*strip width* strip spacing)			
		2mm*0.5m*0	1.5mm*0.5m*0	2mm*1m*1m	2mm*1.5m*0.5m
200	20.3988	19.0335	18.9645	17.0035	18.1265
225	22.9488	21.413	21.3355	19.129	20.3925
250	25.4988	23.792	23.706	21.2545	22.6585
275	28.0482	26.171	26.0765	23.3795	24.924
300	30.5982	28.5505	28.447	25.505	27.19
325	33.1482	30.9295	30.8175	27.6305	28.323
350	35.6982	33.309	33.1885	29.756	29.456
375	38.2482	35.688	35.559	31.8815	31.7215
400	40.7976	38.067	37.9295	34.007	33.9875
425	43.3476	40.4465	40.3	36.1325	36.2535
450	45.8976	42.8255	42.6705	38.2575	38.519
475	48.4476	45.205	45.0415	40.383	40.785
500	50.997	47.584	47.412	42.5085	43.051

Table 4. 2 Deformation (in mm) of the pre-stressed girder when strengthened with 2 and 3 layers of CFRP

Load(kN)	2 layers		3 layers	
	2mm*1m*0	2mm*1m*4m	2mm*1m*1m	2mm*0.5m*0.5
0	0	0	0	0
50	4.17435	4.25085	4.03925	3.9573
75	6.2615	6.3765	6.059	5.936
100	8.3485	8.5015	8.0785	7.9145
125	10.436	10.627	10.098	9.893
150	12.523	12.7525	12.118	11.872
175	14.6105	14.878	14.1375	13.8505
200	16.6975	17.0035	16.157	15.829
225	18.7845	19.129	18.1765	17.808
250	20.872	21.2545	20.1965	19.7865
275	22.959	23.3795	22.216	21.765
300	25.046	25.505	24.2355	23.7435
325	27.1335	27.6305	26.2555	25.7225
350	29.2205	29.756	28.275	27.701
375	31.308	31.8815	30.2945	29.6795
400	33.395	34.007	32.314	31.6585
425	35.482	36.1325	34.334	33.637
450	37.5695	38.2575	36.3535	35.6155
475	39.6565	40.383	38.373	37.594
500	41.7435	42.5085	40.3925	39.573

4.3 Stress

Stress is defined as the average force per unit area that some particle of a body exerts on an adjacent particle, across an imaginary surface that separates them.

4.3.1 Equivalent (Von-Mises) Stress

Equivalent stress (also called *von Mises stress*) is often used in design work because it allows any arbitrary three-dimensional stress state to be represented as a single positive stress value. Equivalent stress is widely used to represent a material status for ductile material. Engineers use this simple scalar value to determine if the material has yield or failed. In this thesis the Pre-stressed box Girder Railway bridge is neither yielded nor failed. Thus, the sample value of the Equivalent von-mises stress are represented as shown Table 4.3 below.

Table 4. 3 Equivalent Von-Misses Stress of the Strengthened and Unstrengthened

load(kN)	unstrengthened girder	strengthened girder		
		1-layer	2-layers	3-layers
	Equivalent stress (Mpa)	Equivalent stress (Mpa)	Equivalent stress(Mpa)	Equivalent stress(Mpa)
50	384.12	526.93	351.29	332.56
75	576.18	702.58	526.93	498.85
100	768.24	878.22	702.58	665.13
125	960.3	1053.9	878.22	831.41
150	1152.4	1229.5	1053.9	997.69
175	1344.4	1405.2	1229.5	1164
200	1536.5	1580.8	1405.2	1330.3
225	1728.5	1756.4	1580.8	1496.5
250	2112.7	1932.1	1756.4	1662.8

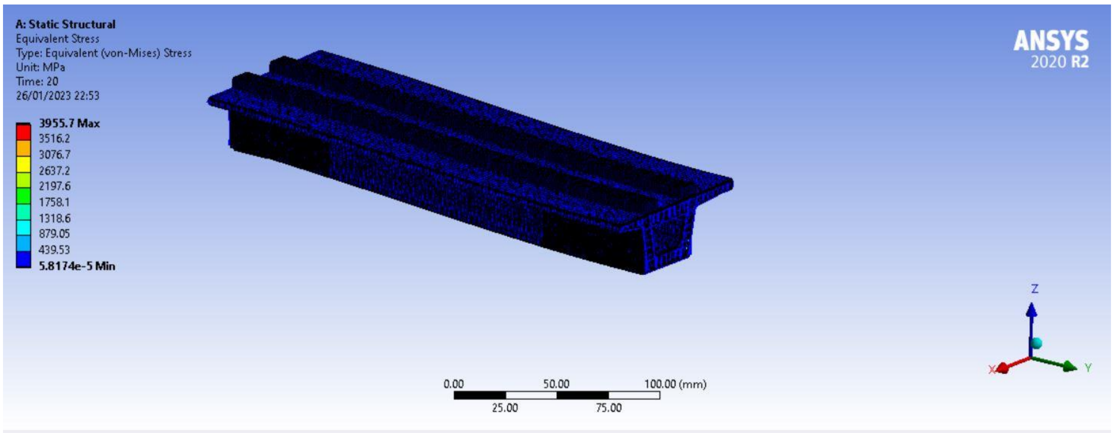

Figure 4. 1 Contour Plot of Von-Mises Stress Along the Length of the Bride

4.3.2 Shear Stress

Shear stress occurs when a load is applied parallel to its area and it equally varies across the cross sectional area. The shear stress of the strengthened and unstrengthened pre-stressed box girder of Railway bridge is shown in appendix C, D, E and F.

4.3.3 Load Carrying Capacity

Load carrying capacity is the maximum ability of the structural member or material to take loading before failure occurred. In this thesis the Load carrying Capacity of the bridge is governing by the Serviceability Limit State, because the Structure Doesn't show any rupture though it Exceeds the Deflection limit. the load carrying capacity of the girder bridge increased averagely by 11.4 %, 22.36 %, and 27.63 % when the pre-stressed girder of the bridge is strengthened with single, double and triple layers of the CFRP. And the most effective Strip and thickness of the CFRP are from one layer, the one it has 2mm thickness, 1.5m width strip and 0.5 m spacing; and from two strip CFRP, the one who has 2mm thickness, 1m strip width without any spacing; and from three layers CFRP the one with 2mm thickness, 0.5m strip width and 0.5 m spacing are more effective.

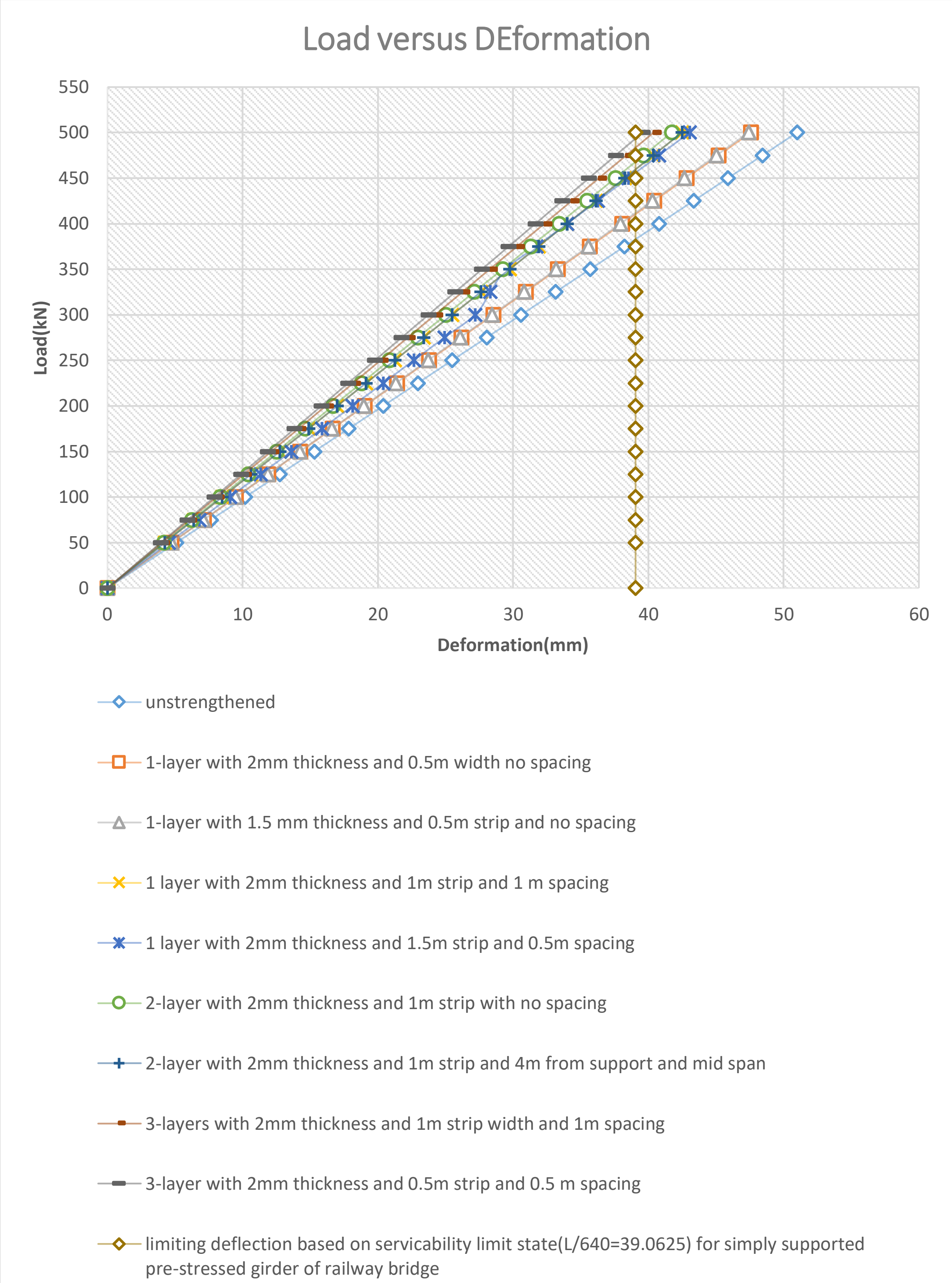

Figure 4. 2 Load versus Deformation

The ultimate load carrying capacity of the box pre-stressed girder bridge when it strengthened with different layers and thickness, strip width and spacing of the strip are depicted as in the Table below.

Table 4. 4 percentage of ultimate load increment of different layers of CFRP

dimension of CFRP	unstrengthened	strengthened						
		1-layer CFRP			2-layers CFRP		3-layers CFRP	
thickness(mm)	0	1.5	2	2	2	2	2	2
strip width(m)	0	0.5	1	1.5	1	1	1	0.5
spacing(m)	0	No	1	0.5	No	1	1	0.5
ultimate load (UL) carrying capacity(kN)	380	410	410	450	470	460	482	488
percentage UL Increment%	0	7.89	7.89	18.42	23.68	21.05	26.84	28.42

CHAPTER 5: CONCLUSION AND RECOMMENDATION

5.1 Conclusion

In this research, strengthening of the pre-stressed girder of the bridge using CFRP subjected to static loadings were carried out to determine the load rating capacity when it strengthened withe CFRP.

Static simulations were conducted on nine models and Results from static simulation revealed that the load carrying capacity of the prestressed girder when it strengthened with single, double and triple layers are 11.4 %, 22.36 %, and 27.63 % respectively.

CFRP plate Strengthened for pre-stressed box girder bridge has an advantage of reliable effect, good technology and good technical economy. It effectively improves the mechanical performance of the components in service stage, prevent peeling damage, reduce the strain lag phenomenon, and can be constructed without interrupting, high material utilization rate light weight, and beautiful appearance.

5.2 Recommendation

The following are recommended areas for future research in regards to prestressed girder of the bridge:

1. This research provides a static model of the prestressed girder of the bridge considering only the wheel load. However, other track components such as rail, rail pads, ballast bed and subgrade affect the girder loading under different loadings and their effect was not examined in this research due to time and resource constraints. Therefore, this research further recommends that future analysis for prestressed girder including all track components as part of railway track system in order to better comprehend the effect of these factors to the prestressed girder of the bridge.
2. Railway track route might be straight or curved or transition between the two. The lack of lateral resistance in curved railway track can produce misalignment problems caused by centrifugal forces. In this research, only the vertical wheel load was considered. The effect of other track loads such lateral and longitudinal loads on prestressed girder were not considered. Therefore, to ensure proper lateral stability of the track is enhanced, future research that includes both lateral and longitudinal loads on girder of the bridge is recommended.

3. Only static simulation was carried out in this research. Thus, a dynamic simulation is recommended in the future work.
4. The pre-cumber effect was not considered in the calculation of deflection of the girder bridge. This lead for the bridge Girder to reach the serviceability limit for deflection at low load level. Thus, to exhaustively assess the serviceability limit analysis of the bridge Girder the pre-cumber effect has to be incorporated in future work.
5. During validation, the numerical and experimental results of unstrengthened pre-stressed structures were compared; however, validation on strengthened pre-stressed structures using CFRP is recommended in future work.

REFERENCE

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APPENDICES

APPENDIX A: NUMERICAL VALIDATION RESULTS

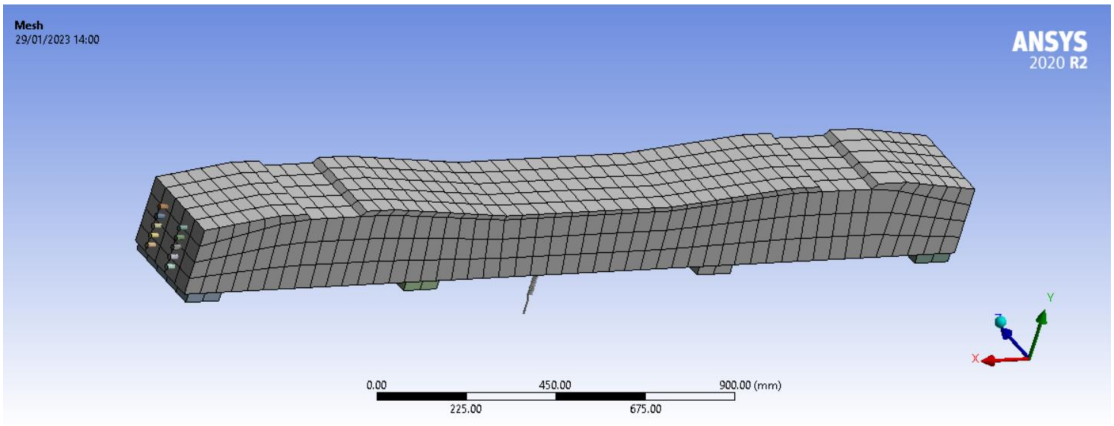

Figure A.1: meshing of the pre-stressed concrete sleeper.

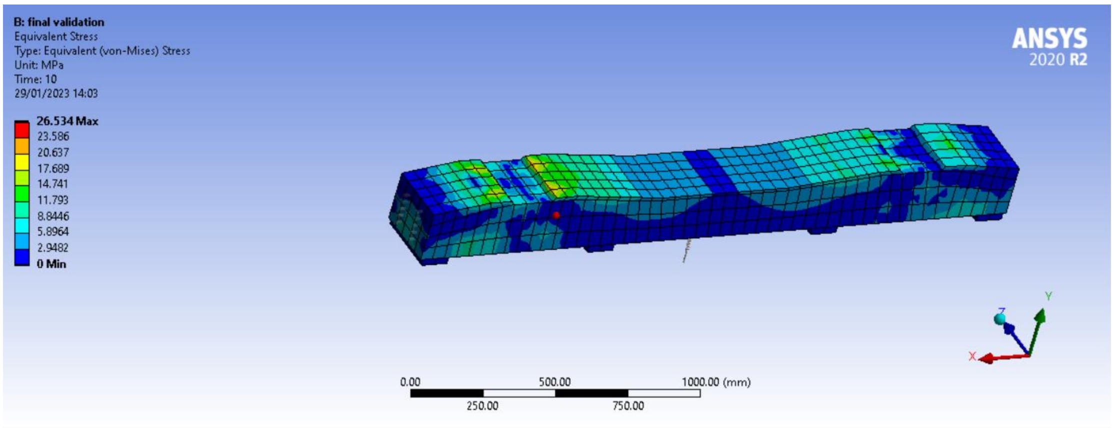

Figure A.2: Equivalent Von-misses stress of pre-stressed concrete sleeper.

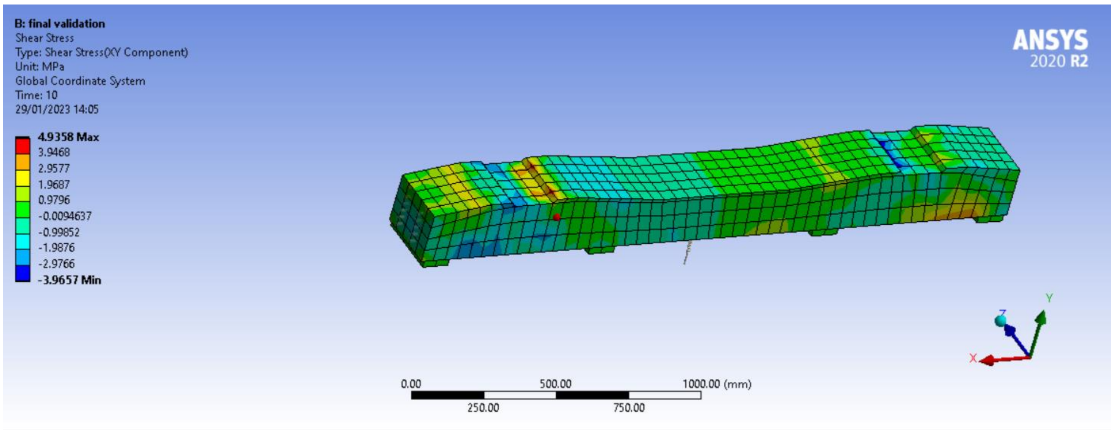

Figure A.3: Shear Stress of pre-stressed concrete sleeper.

APPENDIX B: MODEL AND REINFORCEMENT OF PRESTRESSED BOX GIRDER BRIDGE

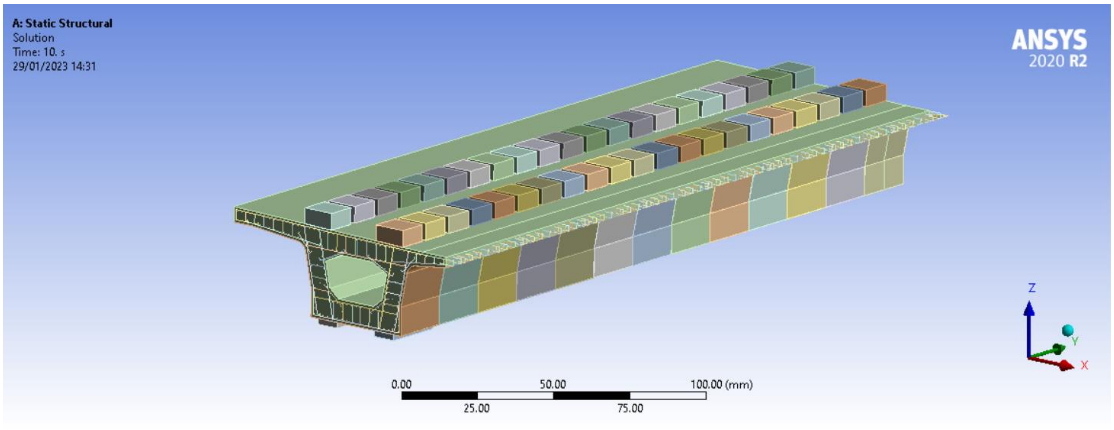

Figure B.1: Model of pre-stressed box girder of railway bridge

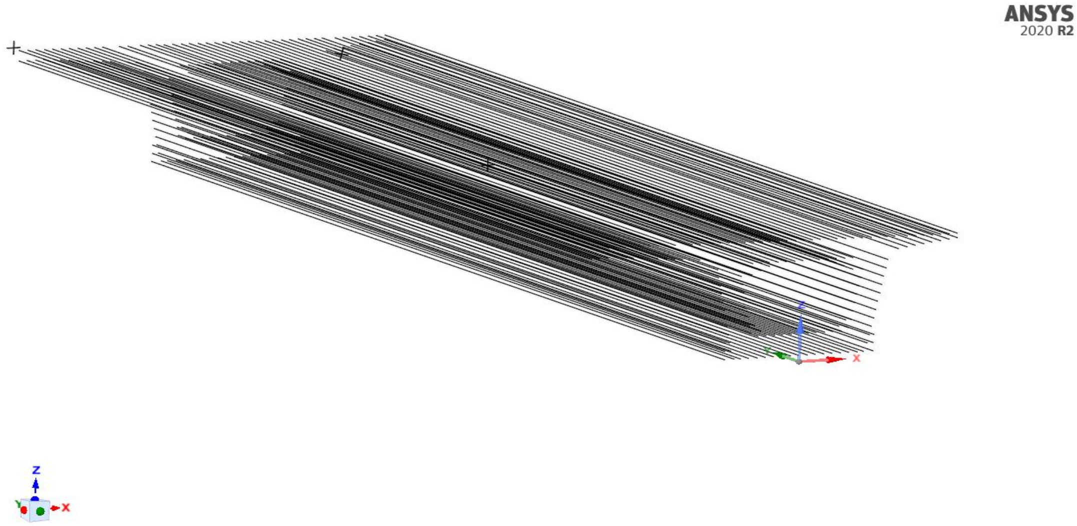

Figure B.2: Longitudinal Reinforcement of Diameter 12mm

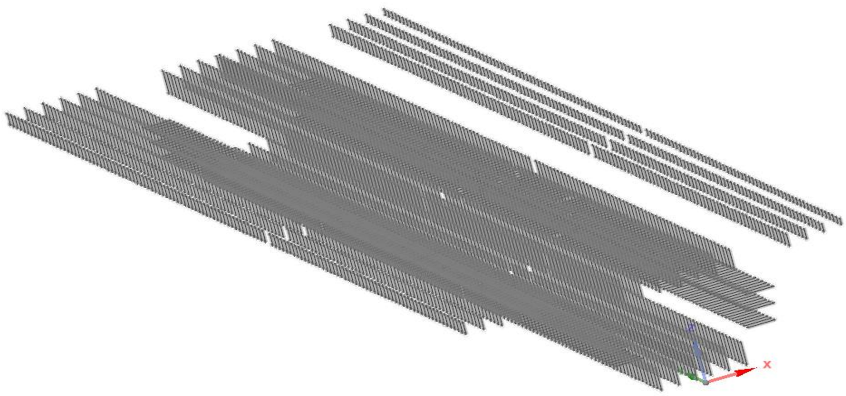

Figure B.3: Reinforcement of Diameter 10 mm

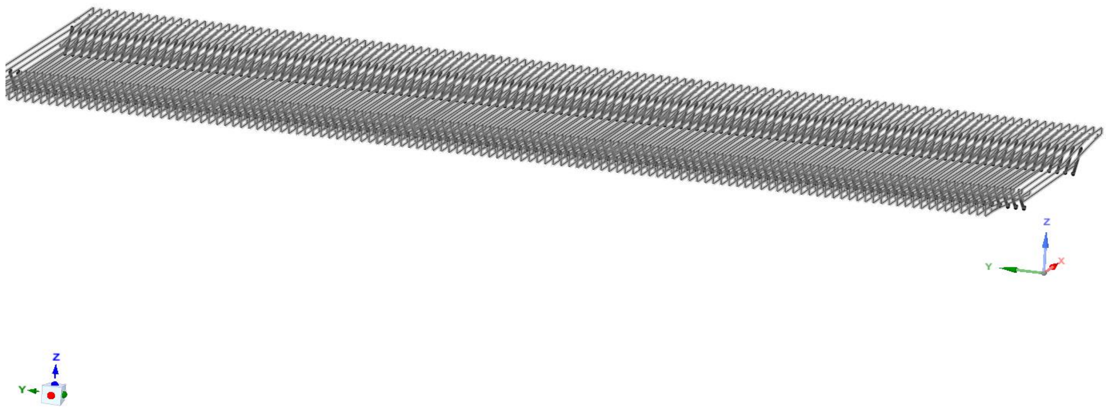

Figure B.4: Transversal Reinforcement of Diameter 16 mm and 12 mm

APPENDIX C: UNSTRENGTHENED PRE-STRESSED BOX GIRDER OF RAILWAY BRIDGE

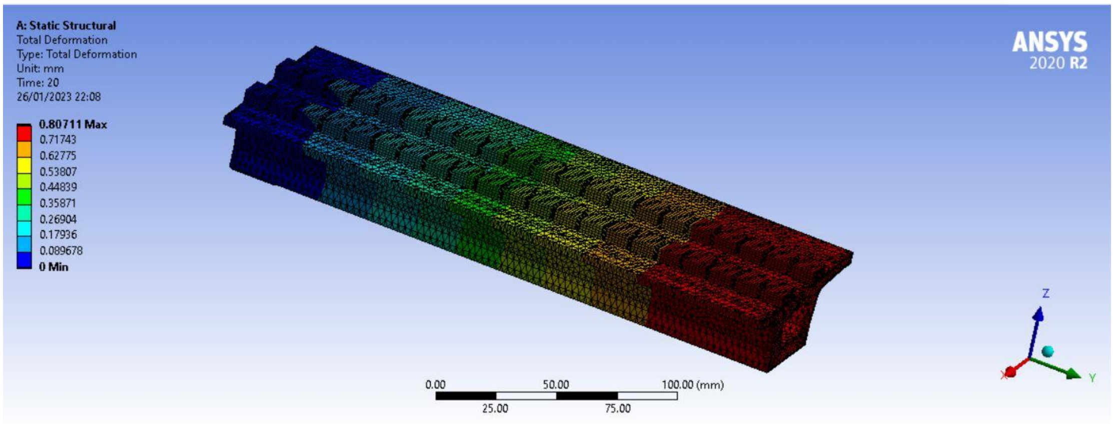

Figure C.1: directional Deformation of unstrengthened PSC-BGRB

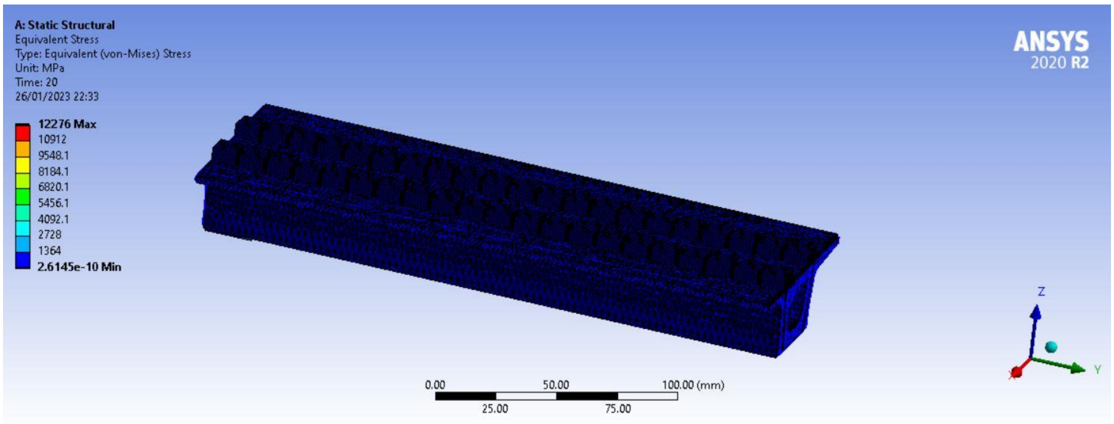

Figure C.2: Equivalent Stress of unstrengthened PSC-BGRB

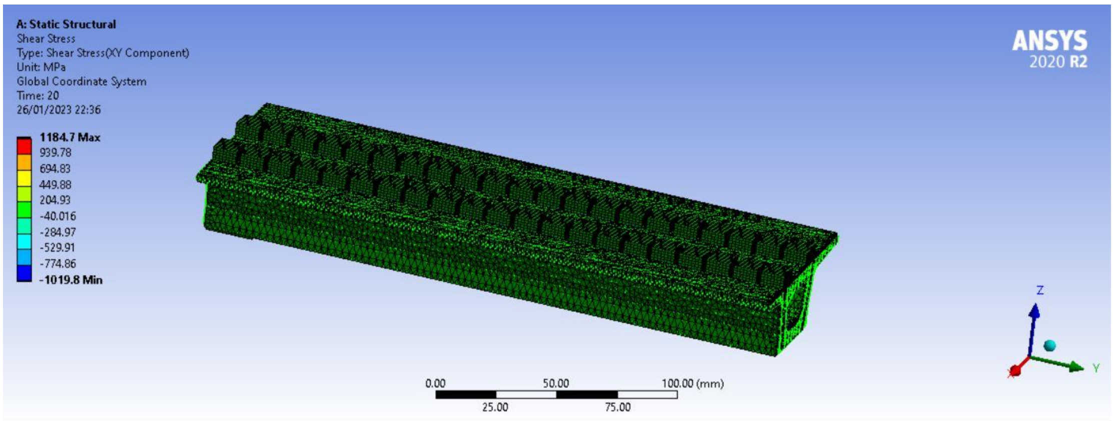

Figure C.3: Shear Stress of unstrengthened PSC-BGRB

APPENDIX D: RESULT OF STRENGTHENED PRE-STRESSED BOX GIRDER OF RAILWAY BRIDGE WITH SINGLE LAYER OF CFRP

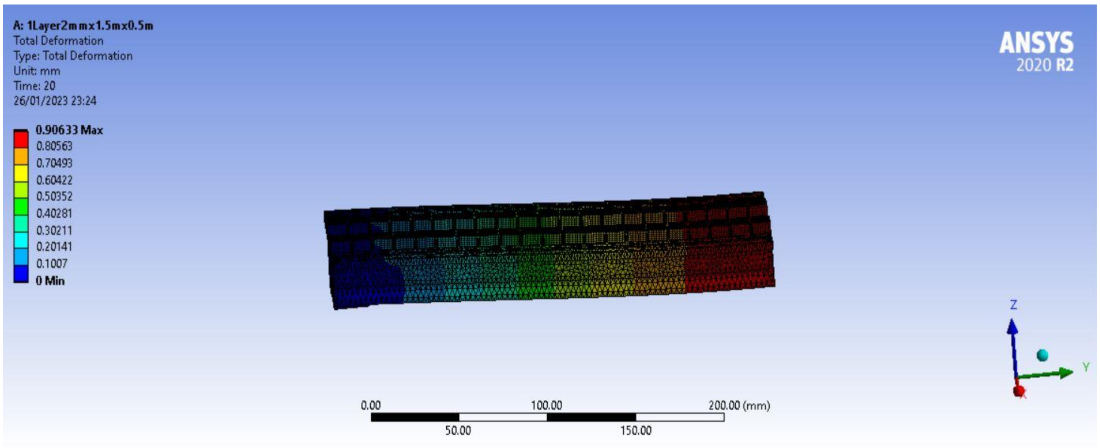

Figure D.1: directional Deformation of PSC-BGRB with 2 mm thickness, 1.5 m strip width and 0.5 m spacing

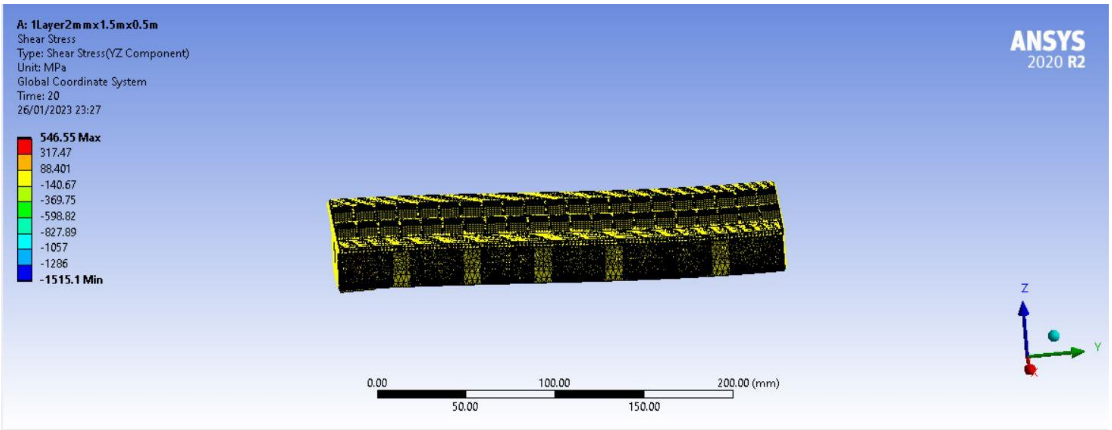

Figure D.2: Shear Stress of PSC-BGRB with 2 mm thickness, 1.5 m strip width and 0.5 m spacing

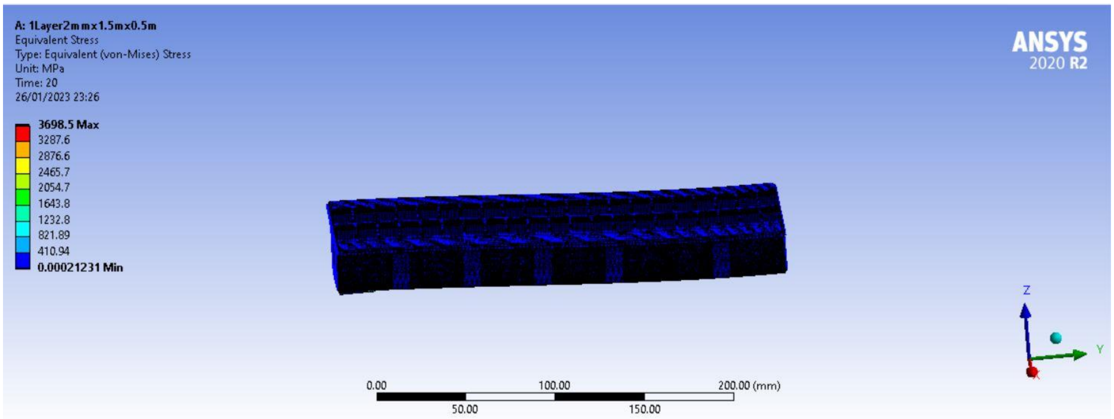

Figure D.3: Von – Mises stress of PSC-BGRB with 2 mm thickness, 1.5 m strip width and 0.5 m spacing

APPENDIX E: RESULT OF STRENGTHENED PRE-STRESSED BOX GIRDER OF RAILWAY BRIDGE WITH DOUBLE LAYERS OF CFRP

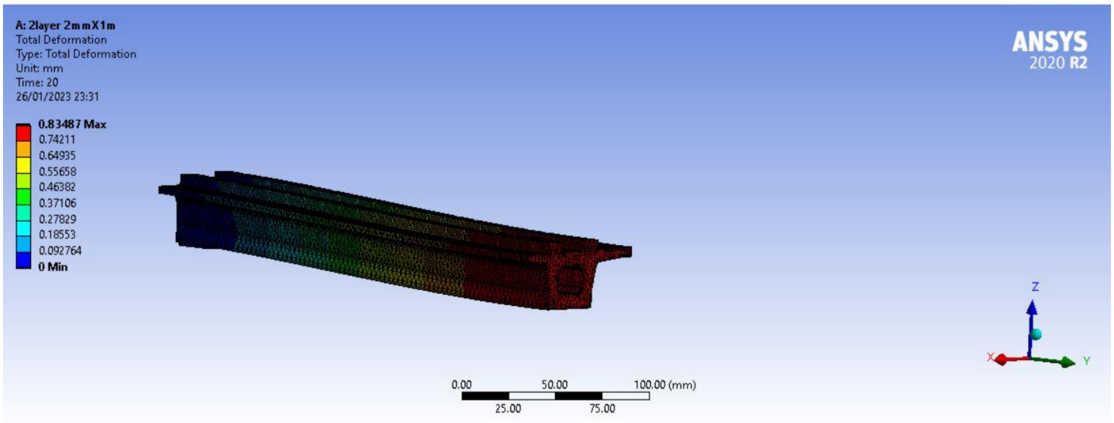

Figure E.1: directional Deformation of PSC-BGRB with 2 mm thickness, 1 m strip width with no spacing

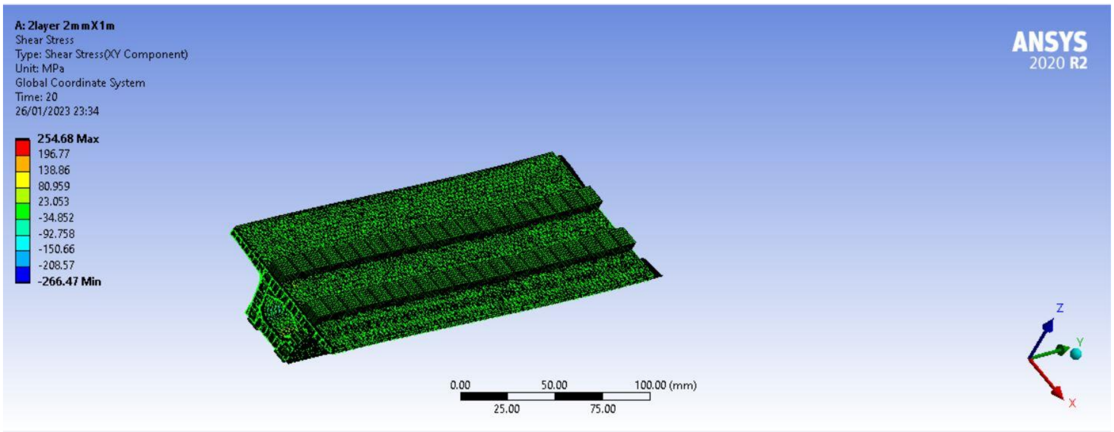

Figure E.2: shear stress of PSC-BGRB with 2 mm thickness, 1 m strip width with no spacing

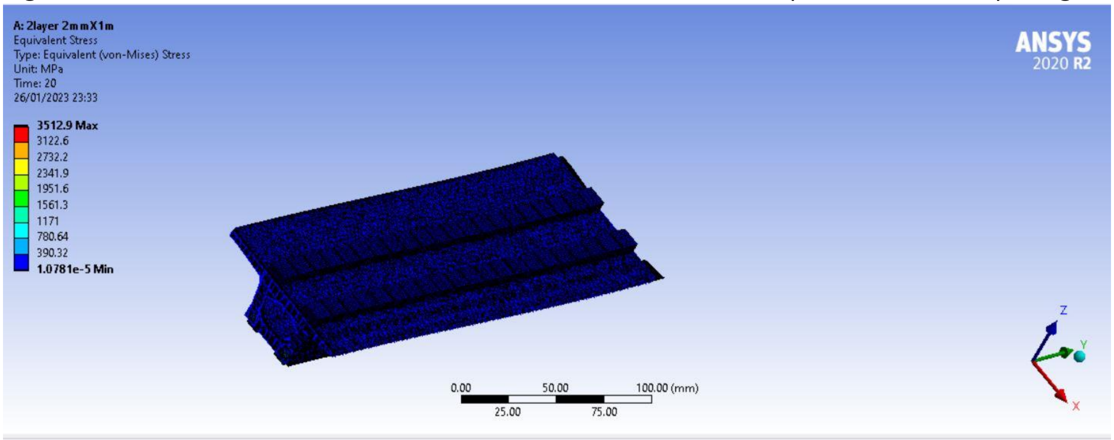

Figure E.3: von-misses stress of PSC-BGRB with 2 mm thickness, 1 m strip width with no spacing

APPENDIX F: RESULT OF STRENGTHENED PRE-STRESSED BOX GIRDER OF RAILWAY BRIDGE WITH TRIPLE LAYERS OF CFRP

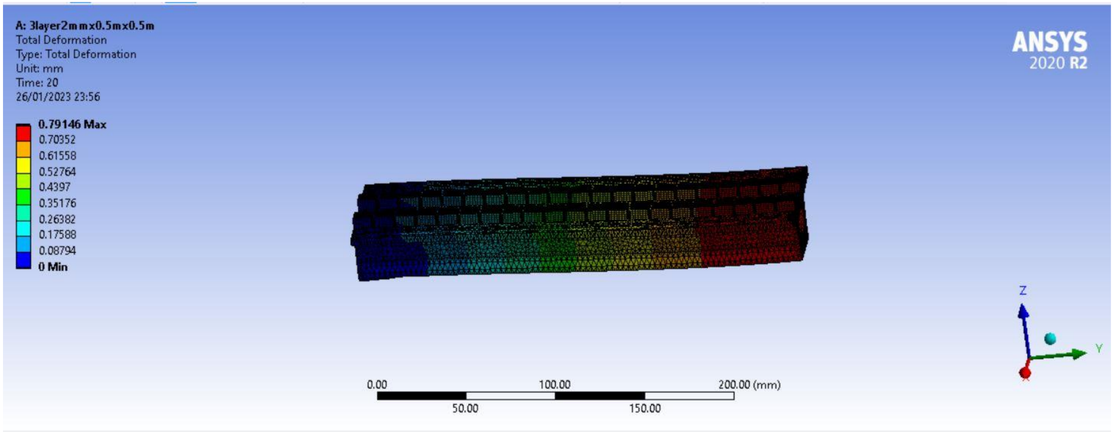

Figure F.1: directional Deformation of PSC-BGRB with 2 mm thickness, 0.5 m strip width and 0.5m spacing

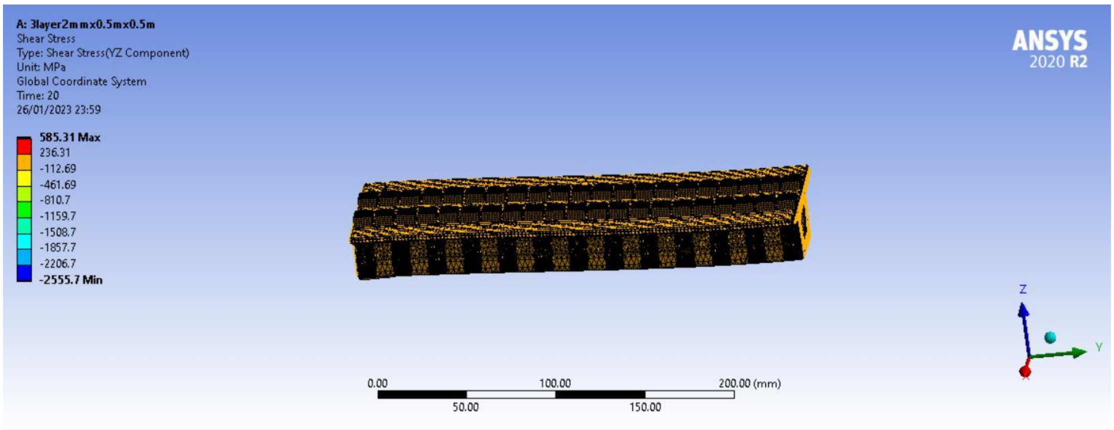

Figure F.2: shear stress of PSC-BGRB with 2 mm thickness, 0.5 m strip width and 0.5m spac-ing

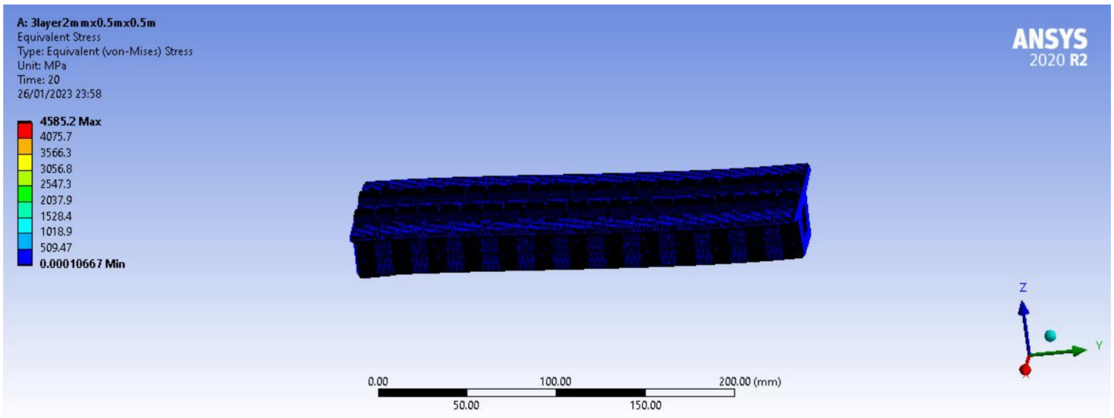

Figure F.3: Von – Mises Stress of PSC-BGRB with 2 mm thickness, 0.5 m strip width and 0.5m spacing