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**ANALYSIS AND DESIGN OF PRESTRESSED
CONCRETE SLEEPER**

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By

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A Thesis Submitted to the School of Graduate Studies of Addis Ababa University

In

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MASTER OF SCIENCE

In

CIVIL ENGINEERING

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Abstract

The track system consists of structural components like sleeper that has to be designed to accommodate the maximum tonnage. The main function of sleeper is to transfer the load from the rail to the ballast via the rail pad and to the under laying formation. The analysis and design of concrete sleepers requires the assessment of load on the sleepers, ballast pressure distribution, selection of the dimensions of the sleeper followed by bending moment calculations at rail seat and center section of sleeper and finally checking of the stresses in sleeper ensuring the factor of safety. The aim of this paper is to analyze and design a pre-stressed pre-tensioned concrete sleeper having an optimal shape, strength and tendon type and profile with reference to the current sleeper type which is used by ERC. The existing sleeper length, fastening system, spacing and area of reinforcement are maintained constant. The research is done by conducting literature review related to this paper work, design data and input parameters are collected from ERC, analysis of the existing sleeper have been made, proceeding the parametric optimization of new model with respect to geometry (shape), concrete grade, pre-stressing tendon type and profile. The optimization output shows that increasing the concrete grade results an increase in sleeper capacity but has no more effect on moment capacity which is largely dependent on the section dimension of the sleeper, tendon strength and eccentricity. Increasing the diameter of the tendons has direct relation on sleeper capacity and inversely related to pre-stresses losses which exceed the maximum limit beyond a certain magnitude (9mm diameter). The shape of the sleeper is investigated based on the ballast pressure which shows wider dimension at the end and tapering to the center; the reduction is gradual to avoid stress concentration. The final optimized design outputs and analysis result of the existing sleeper are compared with respect to raw material consumption for production and its capacity. The analysis and design of turnout sleepers, sleepers with additional rails, the effect of the length and spacing of sleeper on its capacity, and the fastening system with relation to lateral and longitudinal loading are recommended for further researches.

Keywords: Analysis and Design, current (existing) sleeper, modeling, optimization, prestressed concrete sleeper

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List of Symbols and Abbreviations

A	Attenuating dynamic strain
a	Length of pressure distribution (ballast support) beneath each rail seat, in meters
A_g	Gross cross-sectional area of concrete member
A_p	Cross-sectional area of pre-stressing tendon
A_t	Transformed area of nominal section being tested, in milliners squared
b	Average width of sleeper soffit supported by ballast, in meters
BOEF	Beam on Elastic Foundation
CGC	Center of gravity of concrete
DF	Distribution factor, in percent
E	Young's modulus for the rail steel, in megapascals
e	Eccentricity of the centroid of prestress at the section being tested, in millimeters
ε	Strain
E_c	Modulus of elasticity (Young's modulus) of concrete
ε_{ct}	Strain in concrete at transfer
ε_{cu}	Ultimate strain in concrete
E_p	Modulus of elasticity (Young's modulus) of prestressing steel
ε_{pt}	Strain in prestressing steel at transfer
ERC	Ethiopian Railway Corporation
ε_{sh}	Strain in concrete due to shrinkage
ϕ	Creep strain per unit of sustained stress
f_c	Stress in concrete
f'_c	The characteristics compressive strength of concrete required by the designer at 28 days (Mpa)
f'_{cp}	The minimum compressive strength of concrete required by the designer at transfer (Mpa)
FEA	Finite Element Analysis
f_p	The tensile strength of the prestressing steel, in megapascals
f_{pe}	Effective prestress
f_{pt}	Pretension force at transfer
f_{pu}	Ultimate prestress
f'_t	Flexural tensile strength of the concrete in the extreme fiber at testing, in megapascals
G	Track gauge, in millimeters
g	Distance between rail centers, in meters, at the head of the rail
g_1	Distance between rail centers for wider gauge of dual gauge, in meters
g_2	Distance between rail centers for narrower gauge of dual gauge, in meters
I	Second moment of area for the rail section, in meters
IF	Impact factor, in percent
I_g	Gross second moment of area of concrete member
j	Combined quasistatics and dynamic design load factor

k	Track modulus, in megapascals
L	Length of the sleeper at base
L_b	Bond length
LRT	Light Rail Transit
M_{c-}	Maximum negative design bending moment at the mid-span (center) of the sleeper (kN)
M_{c+}	Maximum positive design bending moment at the mid-span (center) of the sleeper (kN)
M^{cr}	Cracking moment at the section being tested, in kilonewton metres
M^{cr}_{c-}	Negative cracking moment at the mid-span (center) of the sleeper, in kilonewton meters
M^{cr}_{c+}	Positive cracking moment at the mid-span (center) of the sleeper, in kilonewton meters
M^{cr}_{R-}	Negative cracking moment at the rail seat of the sleeper, in kilonewton meters
M^{cr}_{R+}	Positive cracking moment at the rail seat of the sleeper, in kilonewton meters
M_{R-}	Maximum negative (design) moment at the rail seat, in kilonewton mertes
M_{R+}	Maximum positive (design) moment at the rail seat, in kilonewton mertes
ORE	Office of Research and Experiments of the International Union of Railways
P	Calculated prestress force at the section at the time of test, in newtons
P_1	Load required to produce proof rail seat negative moment (rail seat vertical load test) (kN)
P_2	Load required to produce proof rail seat positive moment (rail seat vertical load test) (kN)
P_3	Load required to produce proof negative center moment (center negative bending moment test)
P_4	Load required to produce proof positive center moment (center positive bending moment test)
P_{ab}	Maximum ballast pressure, in kilopascals
P_{jack}	Prestress force applied by jack (prior to before transfer losses)
PSC	Prestress concrete
p_t	Prestress force at transfer
Q	Static wheel load, in kilo Newton's
Q_x	The load carried by any sleeper, per rail, kilo Newton's, for a single wheel at distance x
R	Design rail seat load, in kilo Newton's
R.C.C	Reinforced cement Concrete
s	Sleeper spacing, in meters
ULS	Ultimate limit state
W	Maximum load per unit length of sleeper, in kilo Newton's per meter
W_1	Maximum load per unit length of sleeper for wider gauge of dual gauge (kN/m)
W_2	Maximum load per unit length of sleeper for narrower gauge of dual gauge (kN/m)
x	Distance from the sleeper to the wheel load, meters
Z	The transformed section modulus of the nominal un-cracked section
z_x	Rail deflection at distance x from a point load, in millimeters
λ	Stiffness ratio coefficient
τ_{bd}	Bond stress

1. INTRODUCTION

1.1 Background

Railway transportation is one of the safest transportation systems for both passenger and freight transport across the area of long distance and massive loads. Railways are required to guide and facilitate the safe, cost effective and convenient operation of goods and people. Among the mega projects that Ethiopia has been implementing, the construction of railway network via out the country is one of them. The rail infrastructure requires structural elements of ballast, sleeper, rail and others to carry and transfer the load effectively and to provide smooth and level riding surface. In the track system the load from the wheel will be transmitted to the rail and to the sleeper that can be transferred to the ballast material and then to foundation soil. Therefore the design and analysis of sleeper is very important for safe, economical and effective railway transport system.

The evolution of concrete sleepers has taken place due to the shortage of timber, economical consideration coupled with changing of traffic pattern. With the development of concrete technology in 19th century, cement concrete established its place as a versatile building material (Gupta, 2012).

Sleepers play important roles in railway track system. The primary function of the sleepers is to transfer the vertical, lateral and longitudinal rail seat loads to the ballast, sub-ballast and sub-grade layers. They also serve to maintain track gauge and alignment by providing a stable support for the rail fasteners. The vertical-loads cause bending moments in the sleeper which their amounts are dependent upon the degree and quality of ballast layer compaction underneath the sleeper. The performance of a sleeper to withstand lateral and longitudinal loading is relied on the sleeper's size, shape, surface geometry, weight, and spacing. Current practices regarding the analysis and design of sleepers comprise three steps. These are: 1) estimation of vertical rail seat load, 2) assuming a stress distribution pattern under the sleeper, and 3) applying vertical static equilibrium to a structural model of the sleeper (Sadeghi, 2012).

This thesis research focused on the analysis and design of pre-stressed concrete sleeper that will be used in the construction of ballasted track in Ethiopia. The design basis depends on Standard Australia 1085.14-2003 with reference to AREMA 2010 for some parameters. The suitable shape, cross section, concrete grade and the type and position of pre-stressing wires will be selected. The result obtained from the research has been compared with currently used type of concrete sleeper in terms of cost (indirectly with its raw material consumption) and strength and geometry of the concrete. The end product of the study was to produce an appropriate pre-stressed concrete sleeper compatible to our environment.

The functions of the sleepers are to transfer the vertical, lateral and longitudinal rail seat loads to the ballast and formation, and to maintain the track gauge and alignment by providing a reliable support for the rail fasteners. The vertical loads subject the sleeper to a bending moment which is dependent upon the condition of the ballast underneath the sleeper. The performance of a sleeper to withstand lateral and longitudinal loading is dependent upon the sleeper's size, shape, surface geometry, weight and spacing.

Before the sleeper can be analyzed in terms of its capacity to withstand the bending stresses caused by the vertical rail seat loads the sleeper support condition and its effect upon the contact pressure distribution must be quantified. The contact pressure distribution between the sleeper and the ballast is mainly dependent upon the degree of voiding in the ballast under the sleeper. This voiding is caused by traffic loading and is due to the gradual change in the structure of the ballast and the sub-grade (AREMA, 2010).

1.2 Statement of the Problem

There is a need and plan of construction of railway lines in Ethiopia to serve the country in the field of transportation to provide a mass and efficient way of transportation that is growing in fast all over the world, in Ethiopia majority of railway projects design, supervision and construction activities are conducted by experts came from abroad due to the limitation of the Technology in Ethiopia in all aspects of design, construction and supervision. The government of Ethiopia has planned to transfer the technology in design, construction, supervision and operation of the railway industry. As a result the capacity building of railway engineers in three different fields are ongoing that contains the civil engineers involved in the rail track which is important of analyzing and design of sleepers as one of the major structural element of track component.

This thesis research focused on the design and analysis of pre-stressed concrete sleeper to produce an optimal pre-stressed concrete sleeper in terms of concrete grade, shape of the sleeper, tendon (wire) profile and type based on the permissible limit state design approach of Standard Australian 1085.14-2003 with reference to AREMMA 2010 for some parameters.

1.3 Objectives

The main objective of this thesis research study was to design and analyze pre-stressed concrete sleeper in accordance with Standard Australia 1085.14-2003. The paper was focused on the design of pre-stressed concrete sleeper with high strength, durable and cost effective, the suitable size, shape and strength have been evaluated in the study. The appropriate grade of the concrete and the strength and types of pre-stressing wires has been selected. Finally the study came up

with proper size and quality pre-stressed concrete sleeper for the construction of ballasted track rail lines in Ethiopia.

Specific objectives:

The specific objectives are

- a) Identify the suitable type concrete grade in consideration of safety and economy.
- b) Determine the cross sectional size and shape of the pre-stressed concrete sleeper
- c) Determine the strength, type and Position of each pre-stressing tendon (wires)

The scope of the study was on the major railway projects that are being implemented and will come into implementation in the subsequent phases. Specifically it focuses on sleepers that are being used in the main track of Addis Ababa LRT and national rail line of Ethiopia (Addis Ababa to Djibouti).

1.4 Material and Methods

Design, modeling and analysis methods of pre-stressed concrete sleepers conducted by different researchers have been collected and reviewed as introductory and background knowledge. The basic design parameters have been identified and collected from ERC as input parameters for the design. Analyses of existing sleeper have been conducted as a bench mark for the optimization and analysis of the proposed sleeper. Theory of mechanics have been used for modeling and analysis. The optimization of the different parameters have been done by iteration of the variables using excel spread sheet except the soffit width of the sleeper which is done by using the software SAFE. Finally verification of the optimal sleeper capacity has been done with ANSYS based on the laboratory set up and procedure of AS 1085.14-2003.

1.5 Study Area

The study was carried out in Ethiopia, Addis Ababa located in east Africa 3° - 15° N latitude and 33° - 48° E longitude, taking in to consideration the National railway lines (Addis Ababa to Djibouti) and Addis Ababa LRT projects.

2. LITERATURE REVIEW

2.1 Introduction to Sleepers (Cross Ties)

Sleepers (cross ties) are member's which are laid transverse to the track alignment to support the rails and to transfer the load from the rails to the underlying ballast (Agarwal et al, 2012).

In supporting and guiding railway vehicles, the track structure must restrain repeated lateral, vertical, and longitudinal forces. As elements of the track structure, individual cross ties receive loads from the rails or fastenings and in turn, transmit loads to the ballast and sub-grade. Consequently, the design of a tie affects and is affected by characteristics of other components of the track structure. The design of cross tie track systems and components must consider (Gupta et al, 2012):

- ❖ The rail, fastenings, tie, ballast, sub-ballast, and sub-grade;
- ❖ The quality of each component, method of manufacture, installation, and maintenance;
- ❖ Durability and material specific degradation mode evaluation;
- ❖ The direction, magnitude, and frequency of traffic-imposed loads;
- ❖ The effect of climate and environmental factors such as temperature, sunlight and weather;
- ❖ The overall economics of installation and maintenance; and
- ❖ The need to support and guide railway vehicles while restraining repeated lateral, vertical, and longitudinal forces.

2.1.1 Functions of sleepers

In railway track, sleepers perform the following functions (Chandra et al, 2010):

- a) To hold the rails to proper gauge in all situations and support the rails firmly and evenly throughout.
- b) To distribute the load transmitted through rails over large area of ballast underneath or to the bridge girders as the case may be.
- c) To hold the rail to proper level in turnouts and crossovers, and at 1 in 20 in ward slope along straight tracks.
- d) To provide elastic medium between the rails and ballast, and also to absorb the vibrations caused due to moving axle loads.
- e) To maintain proper alignment of the track. On curves proper cant is provided by raising the outer rail and tamping the required quantity of ballast bellow the rails.
- f) To provide the general stability and of the permanent way throughout, insulation of track for the electrified tracks for signaling and easy replacement of the rail fastenings without any serious traffic disturbances.

2.1.2 Requirements of an ideal sleeper

An ideal sleeper should meet the following requirements (Chandra, 2010):

- a) The initial cost and the maintenance cost of the sleepers should be low.

- b) The fittings required for fixing on to the sleepers, should be simple which can be easily adjusted during the maintenance.
- c) The crushing strength of the sleeper should be more with moderate weight.
- d) They should be able to maintain a perfect alignment, gauge and level of the rails and should afford efficient adjustment and maintenance.
- e) They should provide sufficient bearing area to hold the rail seats and for the ballast to be supported on, to resist the crushing due to movement of heavy axle loads.
- f) The sleeper spacing's should be such as to remove and replace the ballast during regular maintenance operation.
- g) They should be capable to resist the shocks and vibrations caused due to fast moving vehicles at high speeds.
- h) They should provide insulation facilities for track circuiting on the electrified sections.
- i) The sleepers should be strong enough to withstand the pressure during packing process.
- j) The sleepers should be of such a design that they remain in their positions and do not get disturbed due to moving trains.
- k) The material used for the sleeper should be such that it does not attract the sabotage and the theft qualities.

2.2 Types of Sleepers

Based on the type of materials used for the construction of sleepers, they are classified as wooden (timber) sleepers, steel sleepers, cast iron sleepers, R.C.C sleepers and pre stressed concrete sleepers (Chandra et al, 2010). Since the intention of this thesis is on pre-stressed concrete sleepers, the discussion is entirely focused on it.

2.2.1 Pre-stressed concrete sleepers

Prestressed concrete, invented by Eugene Frevssinet in 1928, Pre-stressed sleepers are also two types (Raju, 2007)

- 1) Pre-tensioned sleepers
- 2) Post-tensioned sleepers

Sleepers Density

The number of sleepers per rail length is called sleeper density. The spacing of sleepers is generally indicated by a formula $(n+x)$ where n is the length of the rail in meters and x is the number of sleepers specified more than n (Chandra, 2010). The sleeper density varies according to the following factors:

- a. Speed and axle load
- b. Type of rail section
- c. Type sleepers
- d. Type and depth of ballast
- e. Bearing area of sleeper on ballast
- f. Nature of formation

Table 2.1: The numbers of sleepers per rail length provided on railways in different countries

Country	Track type	No. of sleepers
India	Main track	n+3 to n+6
Britain	Main track	n+4
America	Main track	n+9 to n+11

Where n is the rail length in meter

2.3 Concept of pre-Stressing

A pre-stressed concrete structure is different from a conventional reinforced concrete structure due to the application of an initial load on the structure prior to its use. The initial load or ‘pre-stress’ is applied to enable the structure to counteract the stresses arising during its service period. The pre-stressing of a structure is not the only instance of pre-stressing. The concept of Pre-stressing existed before the applications in concrete (Amlan, 2008).

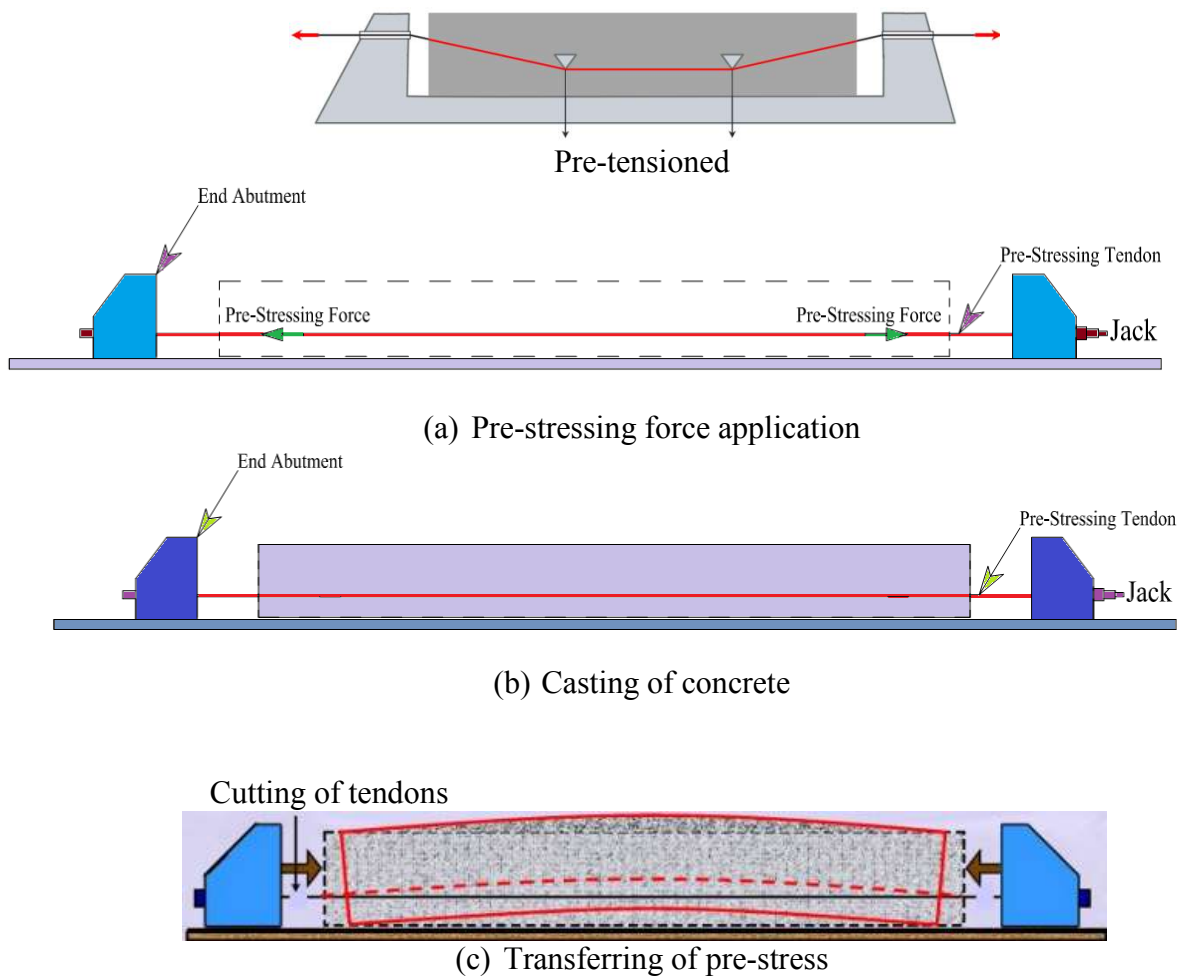


Figure 2.1: Pre-tensioning process

2.3.1 Materials and Manufacturing

A) Materials

Cement

For pre-tensioned sleepers, high early strength Portland cement is normally used sometimes specified with a low alkali content. Post tensioned and twin block sleepers can be made with ordinary Portland cement as early strength is less critical (British Rail Research, 1993).

Aggregates

The main requirement is for well-graded materials with a proven durability record especially in relation to abrasion resistance, frost resistance and freedom from alkali-aggregate reaction.

Admixtures

Water reducing admixtures are widely used to facilitate high early strength development.

Pre-stressing wire and strand

A short transmission length is an essential feature of pre-tensioned sleepers. 5mm wire and 9.3mm seven-wire strand are the most widely used tendons. Smaller diameter wires below 2.11mm and three-wire strand down to 6.3mm are also used in certain countries. For fully bonded systems the wire should be indented with the euro norm (European Standard pattern) of a similar pattern, and strand is also frequently indented. For end anchorage sleepers 7mm wire is mainly used (Amlan, 2008).



Figure 2.2: Types of pre-stressing wires

B) Manufacturing

The manufacturing of concrete sleepers is a highly specialized sector of the precast concrete industry. The special features are (British Rail Research, 1993):

- (a) Demanding tolerance, typically $\pm 3mm$ for overall dimensions and reinforcement location and $\pm 0.8mm$ for the position of cast-in fastening components.
- (b) For pre-tensioned sleepers, the development of high early strength (35-40Mpa) at early ages (14-15hrs) by means of heat curing.
- (c) Concrete of high durability to withstand arduous (difficult) in-track conditions, especially high frequency stress changes.

The manufacturing methods can be classified in to three types:

- a) **Long line** – for pre-tensioned, fully bonded, mono-block sleepers. It was first developed in UK in 1943-46. At this time, pre-stressing beds were designed to accommodate about 50 pairs of single cavity moulds placed end to end. These were filled at a central point and moved along the tensioned pre-stressing wire to their curing positions.
- b) **Short line** - for pre-tensioned, fully bonded and end-anchored mono-block sleepers
- c) **Instant demoulding** – for twin block reinforced concrete sleepers and post-tensioned mono-block sleepers

Current methods generally use gang moulds with four to eight cavities and 30-60 moulds end to end on each bed. The pre-stressing wire or strands are anchored with tapered wedges and tensioned in groups corresponding to a line or a complete bed using large double acting hydraulic jacks, which are also used for detensioning. The end of each mould is closed by means of plates or bars, which can be removed before the transfer of pre-stress. These also maintain the correct location of the wires or strands in the moulds. The moulds are positioned on the bed before concreting usually by a special purpose machine. Heat curing using free steam is giving way to steam or hot fluid enclosed in pipes under moulds, which is more efficient and capable of automatic control by monitoring concrete temperature. Electrical curing is also used with a low voltage alternating current being passed through the concrete during heat curing. Thermally insulated cover improves the efficiency.

Heat curing enables production to proceed on a 24 hour cycle with the main activity during the day and heating overnight. After the gentle transfer of the pre-stress, the wires or strands are cut with abrasive disc or with oxy-acetylene torches, and the sleepers are lifted from their mould and stacked for dispatch without further curing. In some factories the moulds are pushed off the sleepers before detensioning; this avoids the need to allow for elastic shortening in moulds. Before dispatch, rail pads are sometimes fixed to the sleepers with an adhesive which permits them to be peeled off for later renewal.

Short line method

The short line method is used for bonded wire and end-anchorage pre-tensioned sleepers, the pre-stressing wires being tensioned against the end of the moulds. Moulds with one to six cavities can be used, and for fully bonded sleepers there may be several moulds end to end in a structural frame. Fixed stations are used for each operation (tensioning, filling, curing, detensioning and demoulding), and the moulds are moved between them. Curing is an insulated enclosure, generally using free steam heating.

Wire is used for pre-stressing, and positive end anchorage such as button heating is preferred to avoid the loss in tension caused by wire which could be significant with wedge anchors over short lengths. In end anchorage sleepers, a steel plate used as a reaction for the button-headed wire is cast into the sleeper. A 24 hour production cycle is common, but the short line method can be operated on a continuous shift system with shorter or longer curing periods.

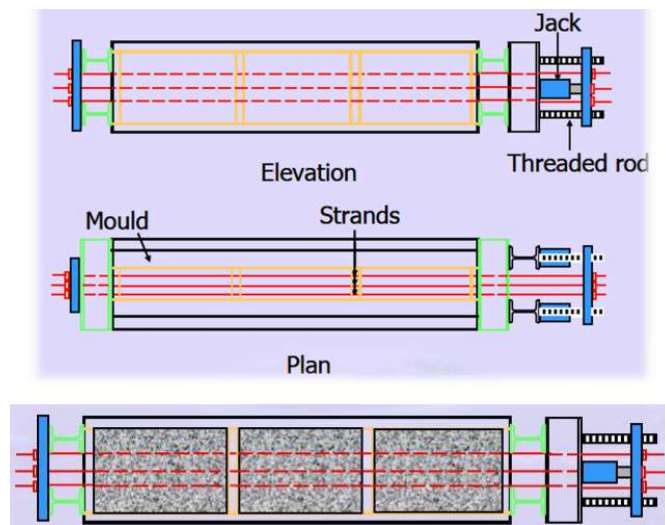


Figure 2.3: Short line method of sleeper production

2.4 Analysis and Design of Pre-stressed Concrete Sleepers

The major factors that affects the analysis and design of sleepers are the static and dynamic loads imposed on the rail seats depends upon the type of track (straight or curved), its construction and standard of maintenance, the axle load and axle spacing, the running characteristics, speed and the standard of maintenance of vehicle. The ballast reaction of sleeper is based on the shape of sleeper, its flexibility and spacing, the unit weight of the rail, the standard of maintenance of the track and ballast characteristics (UIC, 2004).

2.4.1 Limit States Concept

Limit state deems that the strength of a structure is satisfactory if its calculated *nominal capacity*, reduced by a capacity factor ϕ , exceeds the sum of the *nominal load effects* multiplied by load factors γ .

$\gamma \times \text{Nominal load effects} \leq \phi \times \text{Nominal capacity}$, where the nominal load effects (e.g. bending moments) are determined from the nominal applied loads by an appropriate method of structural analysis (static or dynamic) (Sakdirat, 2007).

Proposed limit states of pre-stressed concrete sleepers

Ultimate Limit State

A single once-off event such a severe wheel flat that generates an impulsive load capable of failing a single concrete sleeper. Failure under such a severe event would fit within failure definitions causing severe cracking at the rail seat or at the mid-span (Sakdirat, 2007).

Ultimate Moment Capacity:

The ULS moment capacity of a PSC section is calculated using the assumption that plane sections remain plane. This is similar to the approach for ordinary reinforced concrete. There is one difference; the strain in bonded pre-stress steel is equal to the strain caused by the initial pre-stress plus the change in strain in the concrete at the pre-stressing steel level. The following diagram shows the strain diagram at three stages of loading:

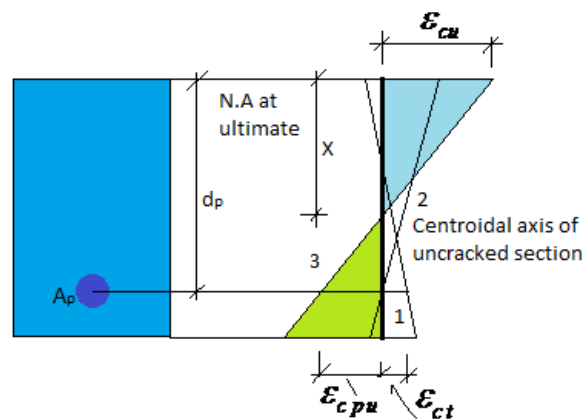


Figure 2.4: Strain diagram

Stage 1

This is the strain diagram at transfer. The strain in the concrete at steel is compressive, with magnitude of:

$$\varepsilon_{ct} = \frac{1}{E_c} \left(\frac{P_t}{A} + \frac{Pe^2}{I} \right) \quad (2.1)$$

The stress and strain in the pre-stressing steel are:

$$f_{pt} = \frac{P_t}{A_p} \quad (2.2)$$

$$\varepsilon_{pt} = \frac{f_{pt}}{E_p} \quad (2.3)$$

Stage 2

The applied moment is sufficient to determine the concrete at the steel level. Provided there is a bond between the steel and concrete, the change in strain in the pre-stressing steel is equal to that of the concrete at the steel level. Hence the strain in the pre-stressing steel is now $\varepsilon_{pt} + \varepsilon_{ct}$

Stage 3

This is the strain diagram at the ultimate load. The concrete strain at the steel level, ε_{cpu} , is related to the concrete strain at the top of the section by similar triangles.

$$\varepsilon_{cpu} = \varepsilon_{cu} \left(\frac{d_p - x}{x} \right) \quad (2.4)$$

The change in strain in the pre-stressing steel is, by compatibility, the same as ε_{cpu}

Final

The final strain in the pre-stressing steel at ultimate load is thus:

$$\varepsilon_{pu} = \varepsilon_{pt} + \varepsilon_{ct} + \varepsilon_{cpu} \quad (2.5)$$

In this equation, it is only ε_{cpu} that is not known. This can be obtained once a depth of neutral axis is found that balance horizontal forces.

Fatigue Limit State

A time-dependent limit state where a single concrete sleeper accumulates damage progressively over a period of years to a point where it is considered to have reached failure. Such failure

could come about from excessive accumulated abrasion or from cracking having grown progressively more severe under repeated loading impact forces over its lifetime (Sadeghi, 2010).

Serviceability Limit State

This limit state defines a condition where sleeper failure is beginning to impose some restrictions on the operational capacity of the track. The failure of a single sleeper is rarely a cause of a speed restriction or a line closure. However, when there is a failure of a cluster of sleepers, an operational restriction is usually applied until the problem is rectified (Sadeghi, 2010).

2.4.2 Permissible Stress Principle

This method is currently most commonly used to design sleepers. However, the permissible stress principle does not consider the ultimate strength of materials, probabilities of actual loads, and the risk associated with failure, all of which could lead to the conclusion of cost ineffectiveness and over design of current pre-stressed concrete sleepers.

Table 2.2: Maximum permissible stress in the concrete at transfer (AS 1085.14-2003)

Types of stress	Maximum permissible stress
Compression where the distribution of stress is triangular or approximately triangular	$0.6f'_{cp}$
Compression where the distribution of stress is uniform or approximately uniform	$0.5f'_{cp}$

Table 2.3: Maximum permissible stresses in the concrete, after allowing for all losses of pre-stress (AS 1085.14-2003)

Types of stress	Maximum permissible stress
Compression	$0.45f'_c$
Tension (flexure)	$0.4(f'_c)^{0.5}$

Proposed Ultimate Limit State Design Equations: (based on Murray and Bian , 2011)

$$0.8M_u \geq M^* = 1.1M_O + M_I \quad (2.6)$$

Where:

M_Q is the moment induced in the sleeper by the design value of the wagon weight force;

M_I is the moment induced in the sleeper by the ultimate impact force I for the specified return period;

M^* the bending moment at a cross-section calculated using the design load

2.4.3 Design Models and Method of Analysis

The Beam on an Elastic Foundation Model

The maximum rail seat load can be determined theoretically by using the beam on a continuous elastic foundation model, and this is the approach suggested by Talbot (1918-1934) and by Clarke (1957). Using this model the maximum rail seat load q_r (kN) can in general be determined by

$$q_r = SKy_m F_1 \quad (2.7)$$

Where

S = sleeper spacing (m),

k = track modulus (MPa) per rail,

y_m = the maximum rail deflection caused by the interaction of a number of axle loads about a given reference position (mm), and

F_1 = factor of safety to account for variations in the track support caused by variations in the standard of track maintenance (Clarke, 1957) adopts a value of F_1 equal to 1).

Sleeper strength based on China's standard approach

➤ Bearing stress on the top of wood sleeper

$$\sigma_s = \frac{R_d}{F} \leq [\sigma_s] \quad (2.8)$$

Bending moment in concrete sleeper

➤ Bending moment distribution is related to the support condition of the ballast

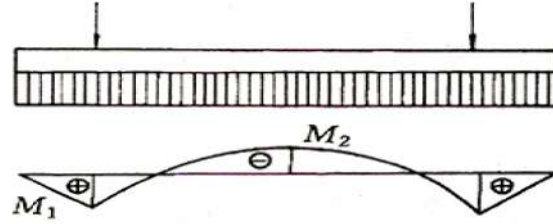


Figure 2.5: Full support condition of sleeper

- Maximum positive moment under the rail

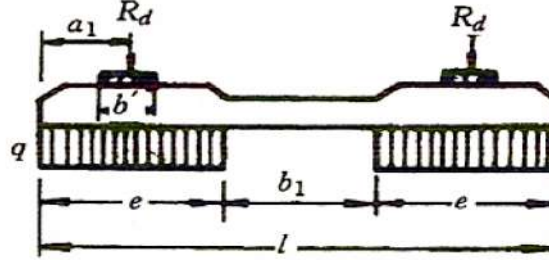


Figure 2.6: Zero center binding coefficient condition of sleeper

- Maximum negative moment at the middle

$$M_g = K_s \left(\frac{a_1^2}{2e} - \frac{b'}{8} \right) R_d \leq [M_g] \quad (2.9)$$

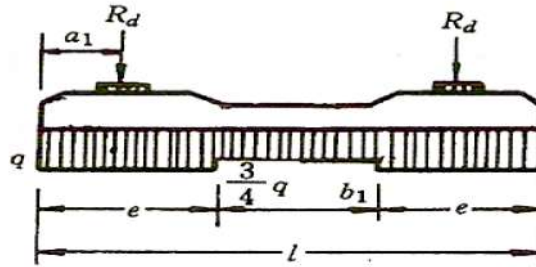


Figure 2.7: 75% center binding coefficient condition of sleeper

$$M_c = -K_s \frac{3l^2 + 4e^2 - 8a_1e - 12a_1l}{4(3l + 2e)} R_d \leq [M_c] \quad (2.10)$$

- Maximum negative moment of Type III (China)

$$M_c = -K_s \left(\frac{1}{2} + a_1 \right) R_d \leq [M_c] \quad (2.11)$$

2.5 Testing (AS 1085.14-2003)

Two types of testing of sleepers, their constituent concrete, and fastening components cast into the sleeper are recommended by AS 1085.14-2003. The first is type test and the second is proof tests.

a) Type tests

Concrete cylinder compressive strength testing, fastening system testing and sleeper testing are under the category of type test. Type tests are required when the following conditions are encountered.

1. A new design is submitted to the purchaser;
2. A new manufacturing plant or process is adopted by the manufacturer before or during production; or
3. The characteristic strength of the concrete or the pre-stressing is varied by the manufacturer.

b) Proof tests

Apart from type testing, proof testing shall be carried out on a routine basis on samples Selected from normal daily production. Where the appearance of the samples gives reason to believe that a line of production may not be typical of previous tests, additional testing may be carried out as agreed between the manufacturer and the purchaser.

c) Test loads

The test loads, (P_1, P_2, P_3, P_4) to be used in the tests shall be calculated from the cracking moment (M^{cr}) of the section being tested.

$$\text{Rail seat negative cracking moment, } P_1 = \frac{2M_{R-}^{cr}}{(0.33 - 0.075)} \quad (2.12)$$

$$\text{Rail seat positive cracking moment, } P_2 = \frac{2M_{R+}^{cr}}{(0.33 - 0.045)} \quad (2.13)$$

$$\text{Centre negative cracking moment, } P_3 = \frac{2M_{C-}^{cr}}{(0.5g - 0.075)} \quad (2.14)$$

$$\text{Centre positive cracking moment, } P_4 = \frac{2M_{C+}^{cr}}{(0.5g - 0.075)} \quad (2.15)$$

Where

g = distance between rail centers, in meters

$$M^{cr} = Z \left(f_t' + \frac{P}{A_t} \right) + Pe \quad (2.16)$$

$$f_t' = 0.85(f_c')^{0.5} \quad (2.17)$$

Since the scope of this thesis is on sleeper analysis and design, the setup of flexural capacity testing methods according to AS 1085.14-2003 are shown below.

(i) Centre negative bending moment tests

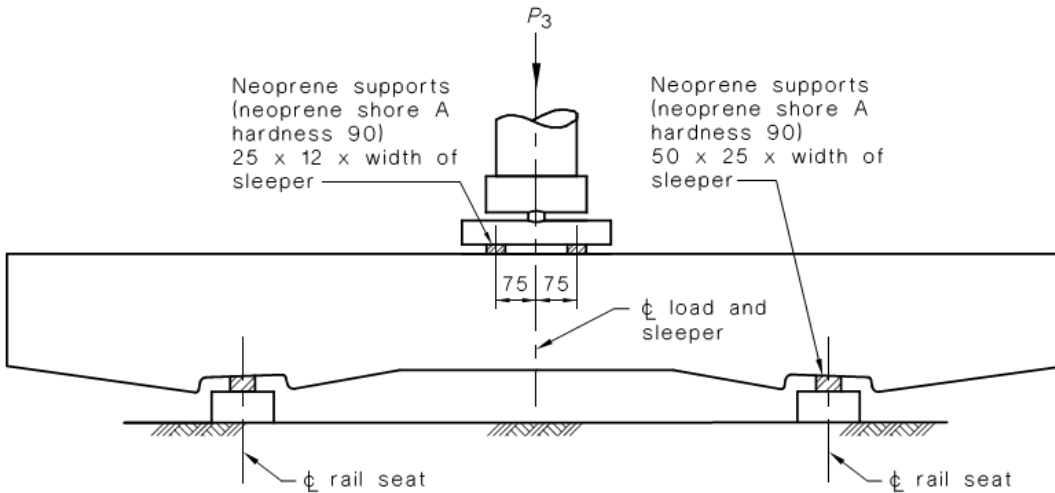


Figure 2.8: Centre negative moment test (dimensions are in millimeters)

(ii) Centre positive bending moment tests

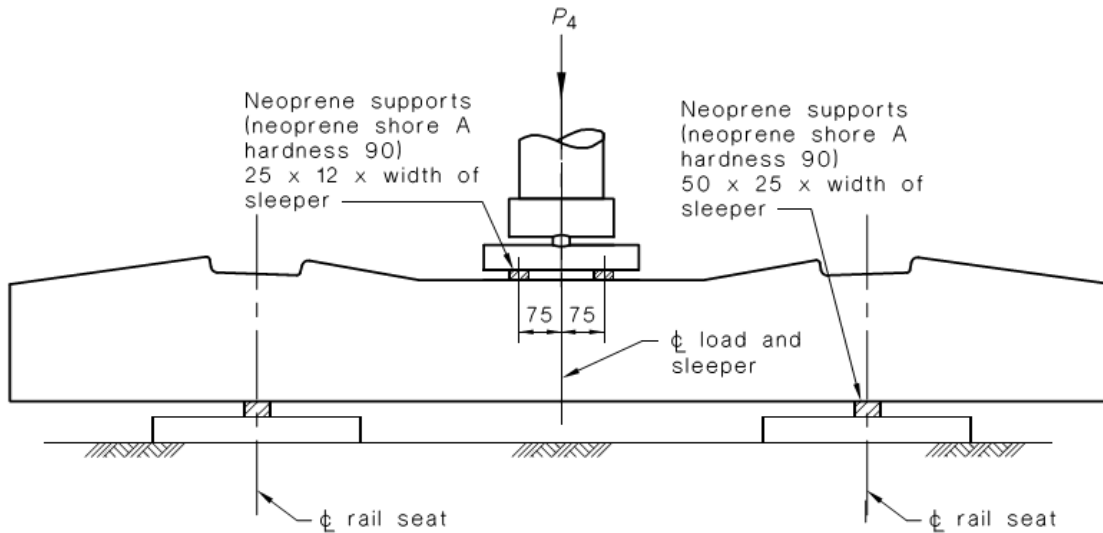


Figure 2.9: Centre positive moment test (dimensions are in millimeters)

(iii) Rail seat negative moment test

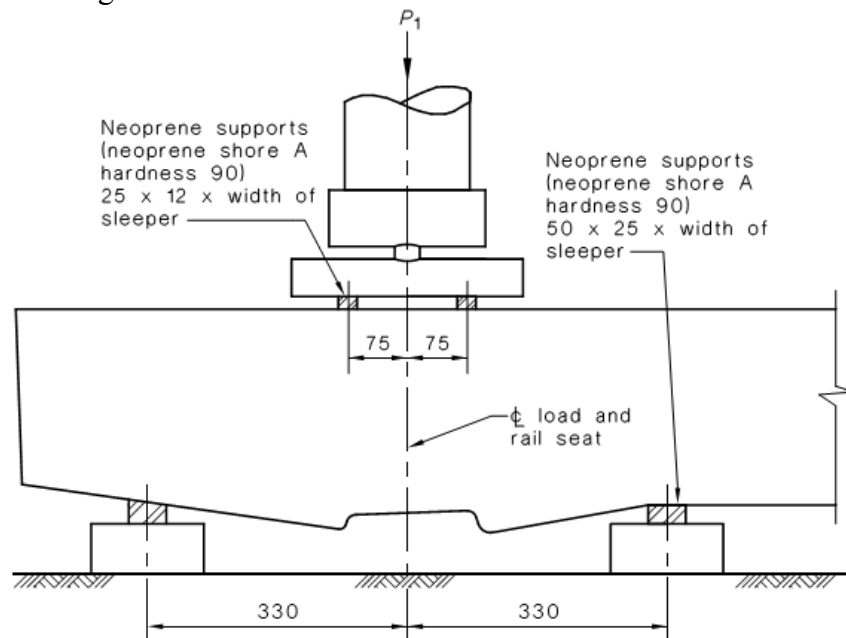


Figure 2.10: Rail seat negative moment test (dimensions are in millimeters)

(iv) Rail seat positive moment test

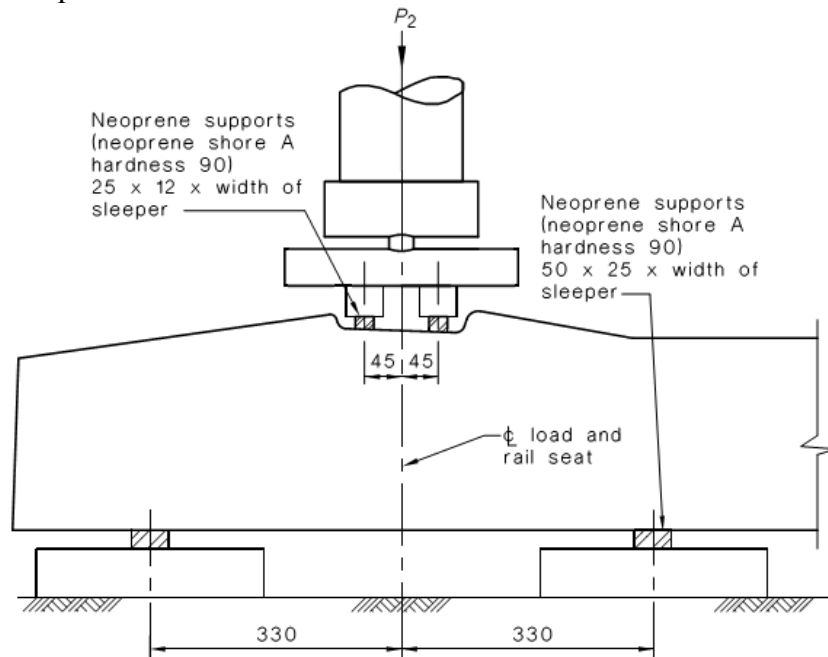


Figure 2.11: Rail seat positive moment test, repeated load test, bond development and ultimate load test (dimensions are in millimeters)

3. ANALYSIS OF THE PRE-STRESSED CONCRETE SLEEPER CURRENTLY USED BY ERC

3.1 Design Parameters

3.1.1 Design constants and material properties

For the analysis of the currently used type of sleeper, design requirements of the sleeper are acquired from the operating institution (ERC) based on the feasibility study of Addis Ababa Djibouti line, Part I general specification, 2012. This includes the service life, sleeper spacing, loading in MGT (Million gross tons annually), design speed and others. The basic design parameters are summarized in [table 3.1](#) below:

Table 3.1: Design parameters and specification

Description of parameters	Units	Values	Remarks (Data sources)
Axel load	Tone	25	ERC feasibility study
Track gauge	mm	1435	ERC feasibility study
Load distribution factor (DF)	%	50	AS 1085.14-2003
Dynamic augment factor (j)		2.5	AS 1085.14-2003
Maximum speed			
❖ Passenger train	Km/hr	120-160	ERC feasibility study
❖ Freight train	Km/hr	80-120	ERC feasibility study
Sleeper spacing	cm	60	ERC feasibility study
Rail type		50kg/m U71Mn	ERC feasibility study
Traction mass	Tone	3500	ERC feasibility study
Rail wheel inclination	Gradient	1:40	ERC feasibility study
Maximum Ballast pressure	kPa	600-750	AREMA 2010 & AS 1085.14
Minimum radius of curved section	m	800	ERC feasibility study
Sleeper stiffness	kN/mm	∞ (in compression)	(Esveld, 2001)
Ballast and sub-ballast thickness	cm	45	ERC feasibility study
Fastening system		Vossloh	ERC feasibility study
Track importance factor	Class	1	ERC feasibility study
Service life	Year	35-40	ERC feasibility study
Track modulus	MPa	20-40	AS 1085.14-2003
Factor of safety	Unit less	1.3	Assumed
Concrete grade	MPa	60	ERC Design department
Minimum compressive strength of concrete prior to transfer	MPa	30	AS 1085.14-2003
Modulus of elasticity of steel	MPa	200000	AS 3600
Modulus of elasticity of concrete	MPa	$5050\sqrt{f'_c}$	AS 3600

3.1.2 Section Properties

Geometry of the sleeper

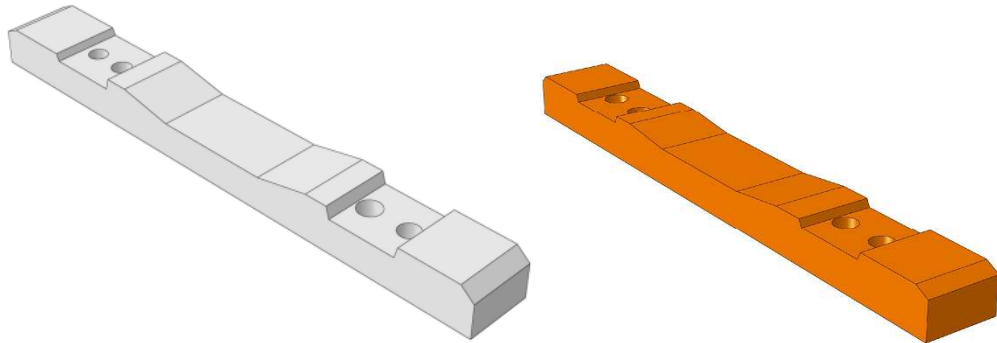


Figure 3.1: Geometry of the existing Prestressed concrete sleeper (not to scale)

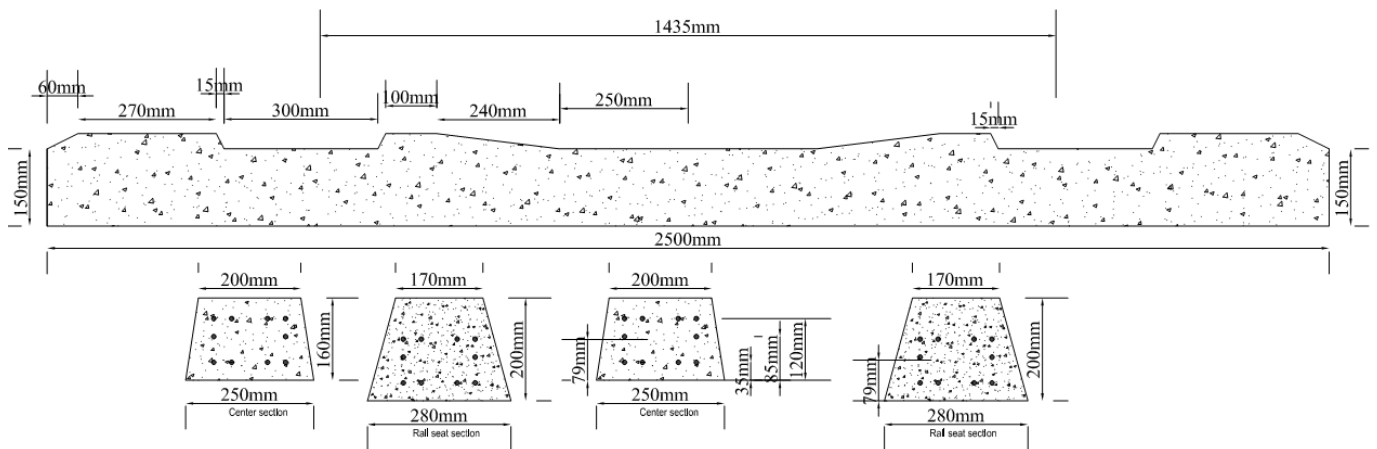


Figure 3.2: Cross-section of the existing sleeper

Contact area of the sleeper bottom at different sections

At rail seat

$$A_c = 300mm * 495mm = 148,500mm^2$$

At center

$$A_c = 300mm * 260mm = 78,000mm^2$$

Elevation cross section areas

At rail seat

$$A_g = \left(\frac{280 + 170}{2} \right) * 200 = 45,000mm^2$$

$$\text{Center of gravity from the bottom} = y_b = \left(\frac{2 * 170 + 280}{170 + 280} \right) * \frac{200}{3} = 91.85mm$$

$$\text{Center of gravity from the top} = y_t = \left(\frac{2 * 280 + 170}{170 + 280} \right) * \frac{200}{3} = 108.15 \text{mm}$$

$$I_g = \frac{(200)^3}{36} \left[\frac{170^2 + 280^2 + 4 * 170 * 280}{170 + 280} \right] = 147,012,345.68 \text{mm}^4$$

$$Z_b = \frac{I_g}{y_b} = \frac{147,012,345.68}{91.85} = 1,600,537.63 \text{mm}^3$$

$$Z_t = \frac{I_g}{y_t} = \frac{147,012,345.68}{108.15} = 1,359,360.73 \text{mm}^3$$

At center

$$A_g = \left(\frac{200 + 250}{2} \right) * 160 = 36,000 \text{mm}^2$$

$$\text{Center of gravity from the bottom} = y_b = \left(\frac{2 * 200 + 250}{200 + 250} \right) * \frac{160}{3} = 77.04 \text{mm}$$

$$\text{Center of gravity from the top} = y_t = \left(\frac{2 * 250 + 200}{200 + 250} \right) * \frac{160}{3} = 82.96 \text{mm}$$

$$I_g = \frac{(160)^3}{36} \left[\frac{200^2 + 250^2 + 4 * 200 * 250}{200 + 250} \right] = 76,483,950.62 \text{mm}^4$$

$$Z_b = \frac{I_g}{y_b} = \frac{76,483,950.62}{77.037} = 992,820.51 \text{mm}^3$$

$$Z_t = \frac{I_g}{y_t} = \frac{76,483,950.62}{82.963} = 921,904.76 \text{mm}^3$$

Pre-stressing wires

Nominal diameter of tendon (wire) is, $\phi_{\text{wire}} = 6.3 \text{mm}$

Area of a single wire, $A_{\text{wire}} = 31.17 \text{mm}^2$

Area of pre-stressing wires, $A_p = 10 * 31.17 \text{mm}^2 = 311.7 \text{mm}^2$

Table 3.2: Centroid of pre-stressing wires from the bottom of the sleeper

Layer	No bars	Area (mm ²)	y (mm)	Ay
1	4	28.26	35	98.91
2	2	14.13	85	120.105
3	4	28.26	120	339.12
Σ		70.65		558.135

$$\bar{y} = \frac{\sum Ay}{\sum A} = \frac{558.135 \text{ mm}^2}{70.65 \text{ mm}} = 79 \text{ mm}$$

Table 3.3: Eccentricity of pre-stressing wires

Location	Centroid (y _b) of the section (mm)	Eccentricity (mm)
Rail seat	91.85	12.85
Center	77.04	-1.96

The minus sign indicate the centroid of the pre-stressing wire is above the section centroid.

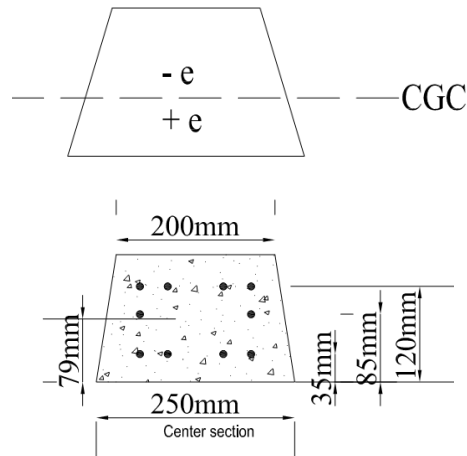


Figure 3.3: Arrangements of pre-stressed wires for current sleeper

The geometrical dimension of the sleepers, material property and the type and number of pre-stressing wire governs the flexural capacity of the sleepers. Shear capacity is determined by the concrete strength.

3.2 Loading Conditions

The load transfer mechanism from the rail to the sleeper and then to the underlying layer affects the design of sleepers. Loads considered for the analysis and design of sleepers in this research include; rail seat loads (static & dynamic), lateral loads and the ballast pressure. The flexural capacity of the sleeper is determined by the rail seat and ballast pressure loads. Based on AREMA 2010 the positive and negative moments are located at the rail seat and at the center of the sleeper. In curved sections of the track in addition to the vertical and rail seat & ballast pressure loads, it is encountered a lateral load which is important for the design of fasteners. Loads from the fastener will transfer in to the sleeper requires the analysis of its adequacy. (AREMA, 2010)

3.2.1 Rail Seat Load

The effective sleeper support area

The effective sleeper support area beneath the rail seat is defined as the product of the breadth of the sleeper and the assumed value of the effective length of sleeper support at the rail seat. AREMA defines the effective length of a sleeper as the distance from the end of the sleeper to the extent of tamping inside the rail foot. For common sleeper lengths this equation can be approximated by

$$L = \frac{l}{3} \quad (3.1)$$

Where

L = Effective length of sleeper support (mm)

l = Total sleeper length (mm)

There are no comparable equations derived for concrete or steel sleepers in which the effective length of sleeper support incorporates the effect of sleeper dimensions. Schramm defines the effective length of sleeper support under the rail seat for timber, steel and concrete sleepers as :

$$L = l - g \quad (3.2)$$

Where L & l are as previously defined, g is the distance between the center lines of the rail seats in mm. The quantity (l-g) can also be expressed as twice the overhang length of the sleeper Q as shown in [Figure 3.4](#) below (Doyle, 1980)

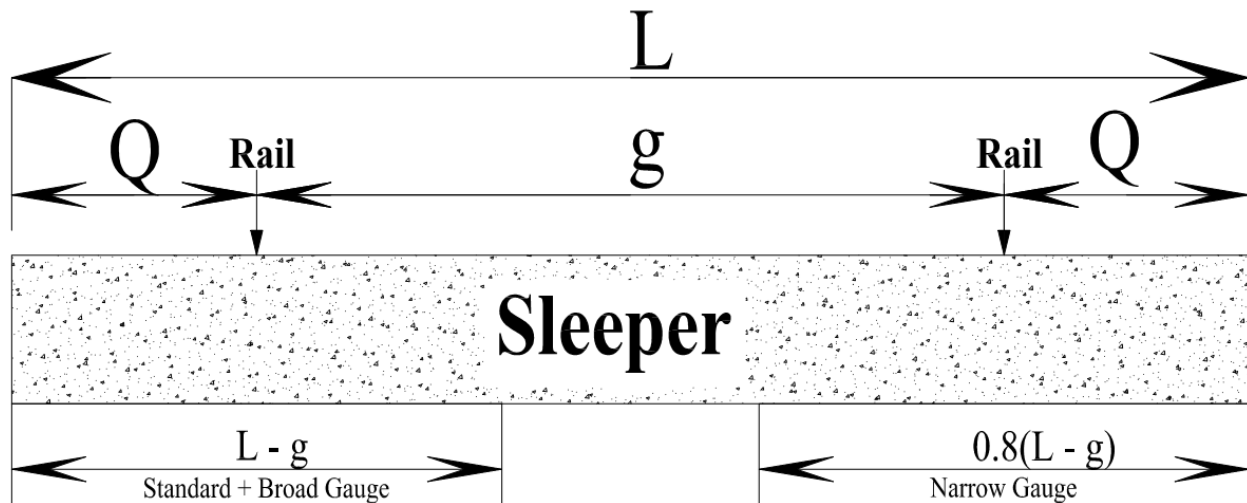


Figure 3.4: Principal Sleeper dimensions

If the sleepers are not of a uniform breadth such that centre breadth is less than the end-breadth, it is reasonable to assume an average sleeper breadth over the effective length of sleeper support when determining the effective support area.

The rail seat load on individual sleeper is dependent on tie spacing, fastening system, rail stiffness, and ballast and sub-grade conditions with tie spacing having the largest effect. Typical track design with concrete ties utilizes tie spacing of 60cm which correlates with 50% of the applied axle load being carried by an individual tie, refer to [figure 3.5 and 3.6](#) (AREMA, 2010 & AS 1085.14-2003).

i. Static wheel load

The design static wheel load is the maximum load of the wheel which is defined by the owner in consideration of the tonnage and passenger weight.

ii. Quasistatic load

It is the sum of static and the effect of speed on the static load that is governed by geometrical roughness and unbalanced super elevation. A minimum value is specified by AS 1085.14 as 140% to 160% of the static load.

iii. Dynamic load

It is the effect of the frequency of wheel rail interaction and the response of the track component which is to 150% of the static load as minimum value by AS 1085.14.

iv. Combined vertical design load factor (j)

This is the combination of the Quasistatic and dynamic load factor with minimum value of 250% of the static wheel load According to AS 1085.14.

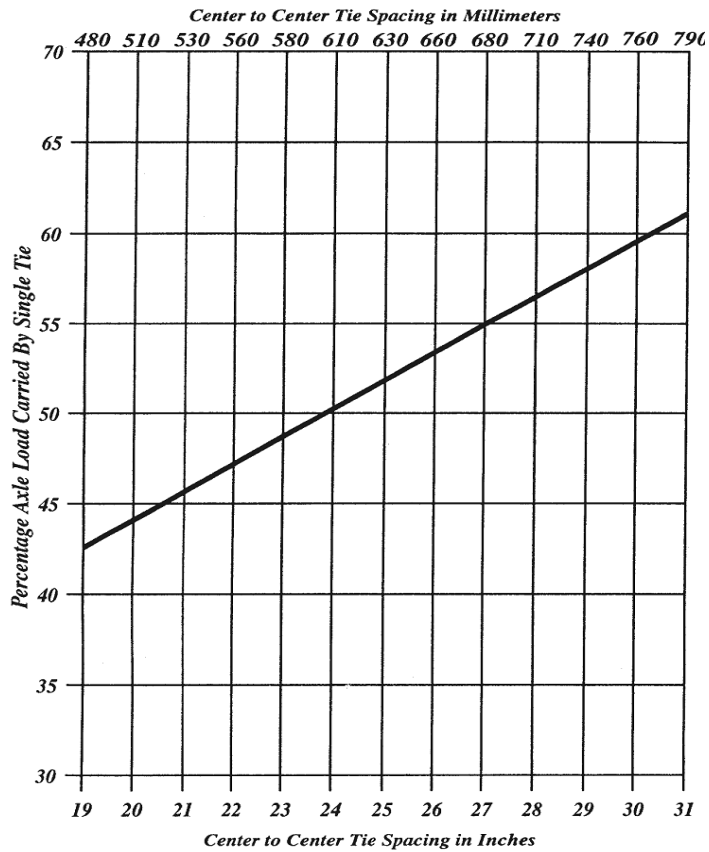


Figure 3.5: Estimated distribution of load (D.F), AREMA 2010

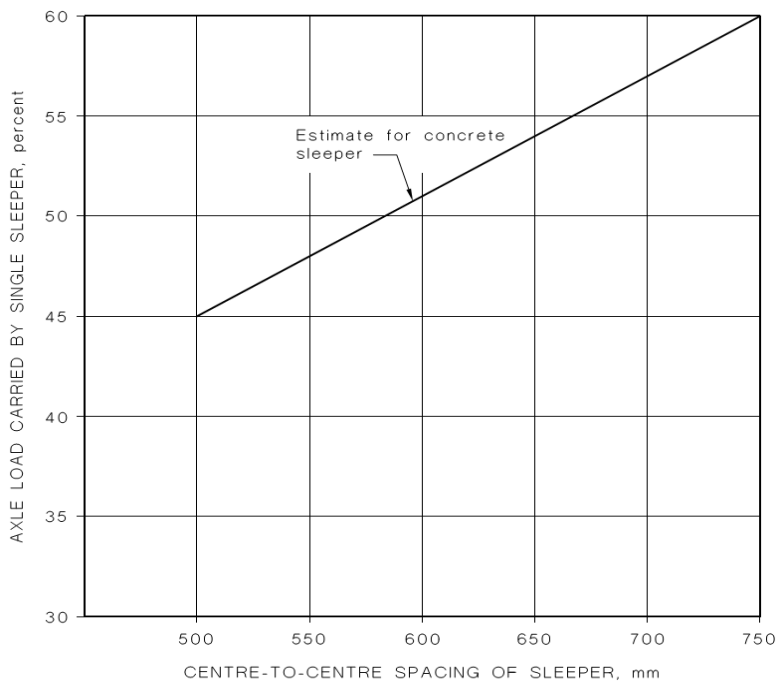


Figure 3.6: Estimated distribution of load (D.F), AS 1085.14-2003

The load carried by a single sleeper is the product of the D.F and static wheel load or it can be determined from the following equation:

$$Q_x = (kz_x)s = \frac{\lambda s Q}{2} e^{-\lambda x} (\cos \lambda x + \sin \lambda x) \quad (3.3)$$

Where

Q_x = the load carried by any sleeper, per rail, in kilo Newton's, for a single wheel at distance x

x = distance from the sleeper to the wheel load, in meters

z_x = rail deflection at distance x from a point load

s = sleeper spacing, in meters

Q = static wheel load, in kilo Newton's

$$\lambda = (k/4EI)^{0.25}$$

k = track modulus, in mega Pascal's

E = young's modulus for the rail steel, in megapascals

I = second moment of area for the rail section, in meters

According to AS 1085.14 the rail seat load (R) is given by:

$$R = \frac{Qj(D.F)}{100} \quad (3.4)$$

$$R = \frac{125kN * 250 * 0.5}{100} = 156.25kN$$

$$W = Qs (U/64EI)^{0.25} \quad (3.5)$$

$$W = 250kN * 0.6m \left(\frac{40MPa}{64 * 200,000MPa * 3.26 * 10^6 mm^4} \right) = 148.65kN$$

Where

W = Load at rail seat of the sleeper

Q = Static wheel load

S = spacing of sleepers

U = Track Modulus

E = Modulus of elasticity of rail section

I = Moment of inertia of rail section.

3.2.2 Load distribution on the ballast

The exact contact pressure distribution between the sleeper and the ballast and its variation with time will be of importance in the structural design of sleepers. It is practically impossible to predict the exact distribution for a sleeper in the in-track condition (ORE, 1969)

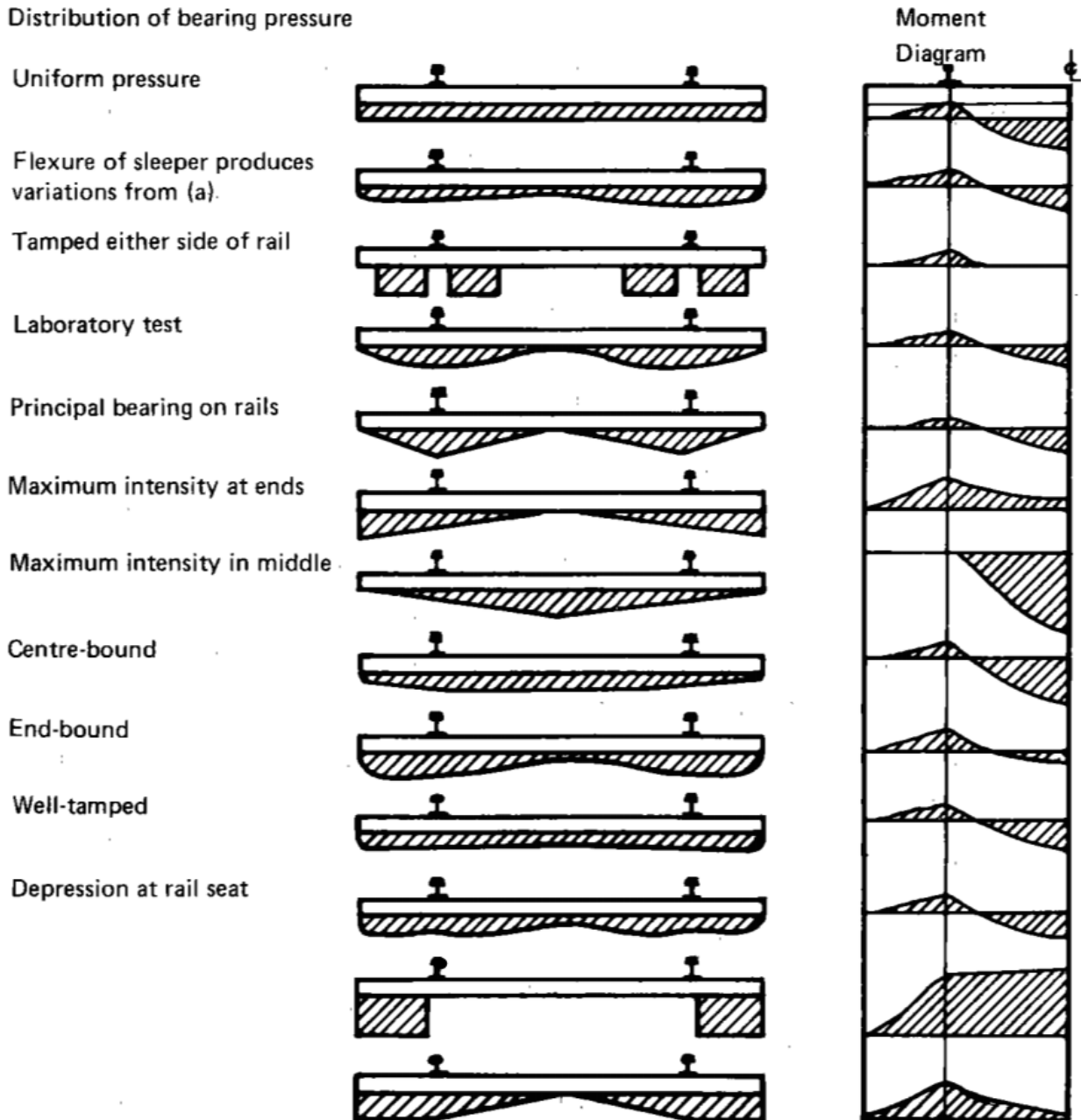


Figure 3.7: Hypothetical distributions of Sleeper Bearing Pressure and bending Moment diagrams (Talbot, 1920)

According to the AREMA design manual the bearing area of the sleeper is 2/3 of the total length of the sleeper (tamping zone)

$$A'_b = \frac{2}{3} A = \frac{2}{3} Lb \quad (3.6)$$

Unit load on ballast

$$P_a = \frac{2Q_o}{A'_b} = \frac{2Q_o}{\left(\frac{2}{3}Lb\right)} = \frac{3Q_o}{Lb} \quad (3.7)$$

Where;

P_a = unit sleeper pressure on ballast

A'_b = total tie bearing area (m²)

L = sleeper length (m)

b = sleeper width (m)

Q_o = static or dynamic rail seat load (kN)

Case 1

In accordance AS 1085.14 uniform ballast pressure is assumed and the maximum ballast pressure is estimated based on [table 3.4](#) with a maximum limiting value of 750kPa for high quality ballast material.

Table 3.4: Maximum ballast pressure (AS 1085.14-2003)

Distance between rail center (g), in meter	Length of ballast support beneath each rail seat (a), in meter	Equation for maximum ballast pressure(P_{ab}), in KPa
$g > 1.5m$ (standard & broad gauge)	$a = L - g$	$P_{ab} = \frac{R}{b(L - g)}$
$1.5m > g > 1.0m$ (narrow gauge)	$a = 0.8(L - g)$	$P_{ab} = \frac{R}{0.8b(L - g)}$

$$P_{ab} = \frac{R}{b(L - g)} \quad (3.8)$$

$$P_{ab} = \frac{R}{b(L-g)} = \frac{156.25kN}{0.2525m(2.5-1.51)m} = 625kN/m^2$$

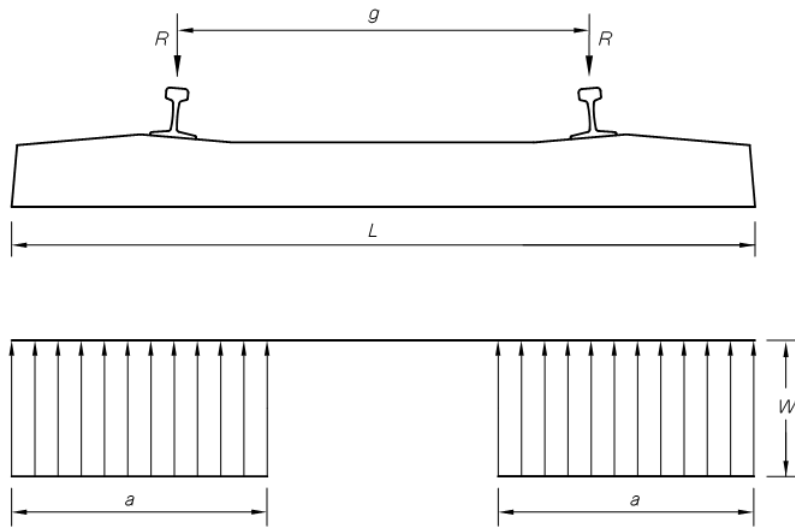


Figure 3.8: Pressure distributions for maximum positive rail seat and center moment (As 1085.14, 2003)

Case 2

According to AREMA 2010 the ballast pressure is

$$P_a = \frac{2Q_o}{A'_b} = \frac{2Q_o}{\left(\frac{2}{3}Lb\right)} = \frac{3Q_o}{Lb} = \frac{3*156.25kN}{2.5m*0.2525m} = 742.6kN$$

$$W = \frac{2R}{L} \tag{3.9}$$

$$W = \frac{2R}{L} = \frac{2*156.25}{2.5} = 125kN/m$$

Based on AREMA 2010 the average ballast pressure is given by:

$$P_{ab} = \frac{2P\left(1 + \frac{IF}{100}\right)\left(\frac{DF}{100}\right)}{A} \tag{3.10}$$

$$P_{ab} = \frac{2 * 125 \left(1 + \frac{150}{100} \right) \left(\frac{50}{100} \right)}{2500 * 252.5} = 544.55 \text{ kN} / \text{m}^2 \quad (3.11)$$

Where:

P = wheel load in KN

IF = Impact factor

DF = Distribution factor in percent (Figure 3.5 & 3.6)

A = Bearing area of cross ties in mm

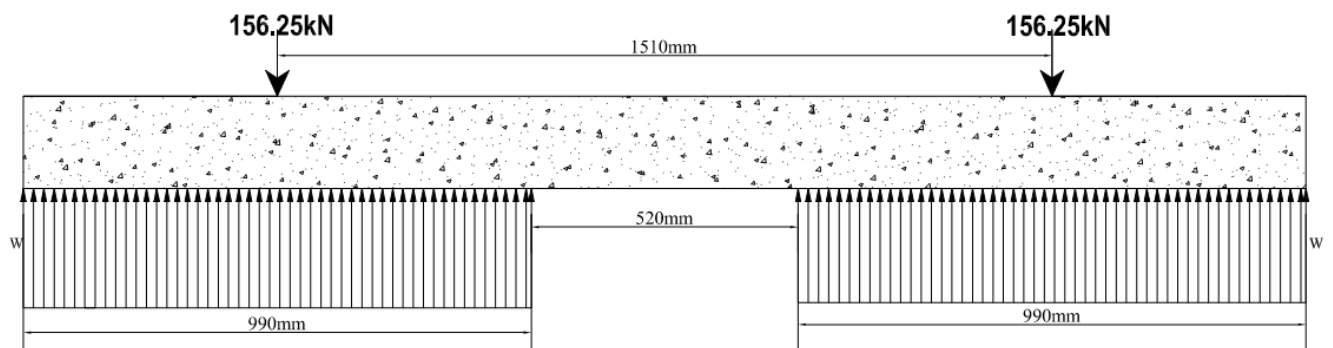


Figure 3.9: Ballast pressure distributions with zero center binding coefficients

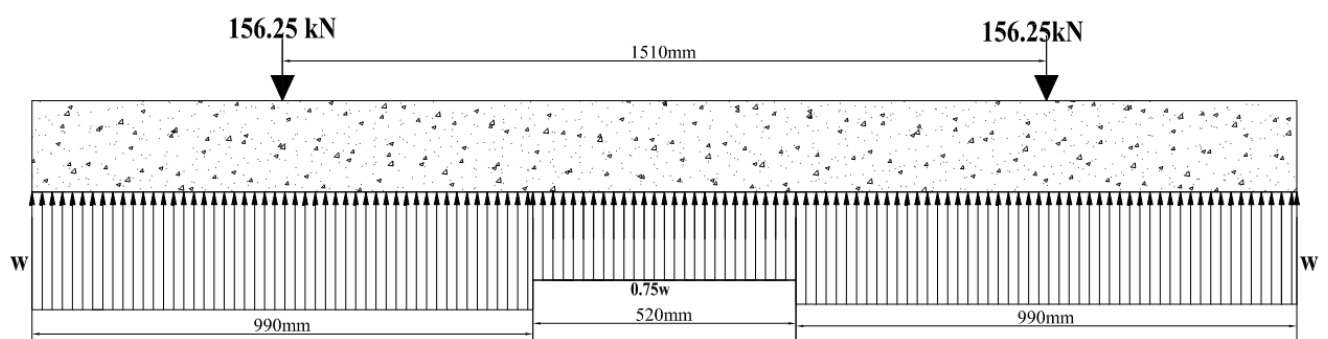


Figure 3.10: Ballast pressure distributions with 75% center binding coefficients

3.3 Design Moments

3.3.1 Moment at the rail seat

1. Rail Seat Positive Design Bending Moment

The maximum positive bending moment shall be taken to occur at the rail seat producing compressive stress at the top and tensile stress at the underside of the sleeper. The value of this moment, the rail seat positive design bending moment (M_{R+}), is based on a uniform ballast support beneath each rail seat. The length of the ballast support beneath each rail seat varies with track gauge and sleeper length. For track with gauge of 1435 mm or greater, the length of this support is taken to be equivalent to $(L - g)$ (AS 1085.14-2003).

Table 3.5: Maximum positive bending moment at the rail seat (AS 1085.14-2003)

Distance between rail center (g), in meter	Length of ballast support beneath each rail seat (a), in meter	Maximum positive bending moment at rail seat (M_{R+}), in KNm
$g > 1.5m$ (standard & broad gauge)	$a = L - g$	$M_{R+} = \frac{R(L - g)}{8}$
$1.5m > g > 1.0m$ (narrow gauge)	$a = 0.8(L - g)$	$M_{R+} = \frac{R(L - g)}{6.4}$

$$M_{R+} = \frac{R(L - g)}{8} \quad (3.12)$$

$$M_{R+} = \frac{R(L - g)}{8} = \frac{156.25kN(2.5m - 1.51m)}{8} = 19.34kNm$$

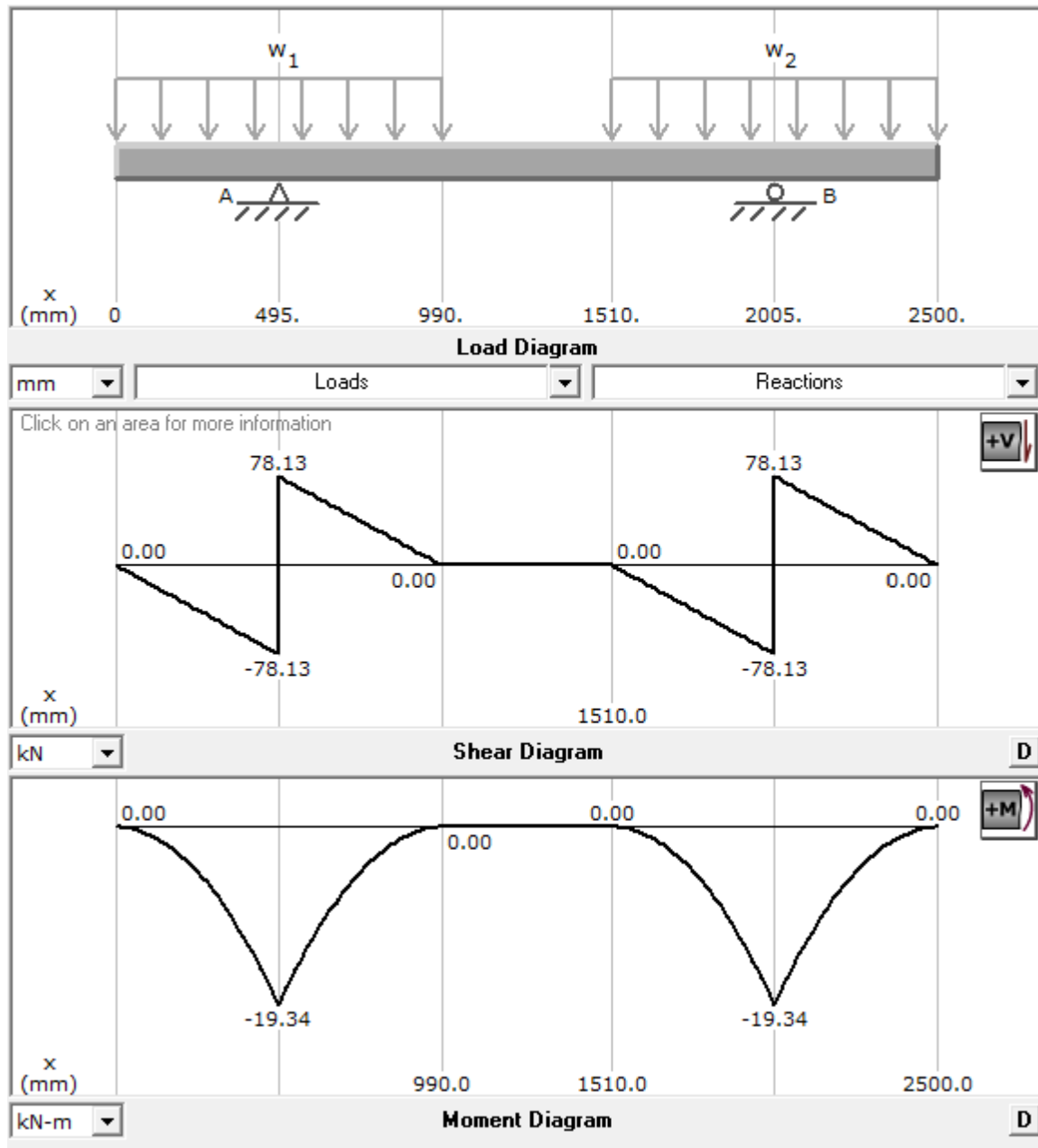


Figure 3.11: Shear force and bending moment diagrams for zero center binding coefficient ballast pressure (by using MDSolid 3.5)

2. Rail Seat Negative bending moment

The rail seat negative design bending moment (M_{R-}) shall be not less than 67 percent of the rail seat positive design bending moment or 14 kNm, whichever is greater.

$$M_{R-} = \max. \text{ of } (0.67 * 19.34 \text{ kNm}, 14 \text{ kNm}) = 14 \text{ kNm}$$

3.3.2 Moment at the center

1. Center Positive design bending moment

The maximum positive bending moment of the sleeper shall be based on a pressure distribution beneath each rail seat. The length of the ballast pressure distribution beneath each rail seat and the centre positive design bending moment (M_{C+}) shall be calculated from the appropriate equation given in [Table 3.6](#).

Table 3.6: maximum positive bending moment at the centre

Distance between rail center (g), in meter	Length of ballast support beneath each rail seat (a), in meter	Maximum positive bending moment at the centre (M_{C+}) (kNm)
$g > 1.5m$ (standard & broad gauge)	$a = 0.9(L - g)$	$M_{C+} = 0.05R(L - g)$
$1.5m > g > 1.0m$ (narrow gauge)	$a = 0.8(L - g)$	$M_{C+} = 0.05R(L - g)$

$$M_{C+} = 0.05R(L - g) \quad (3.13)$$

$$M_{C+} = 0.05R(L - g) = 0.05 * 156.25(2.5m - 1.51m) = 7.734kNm$$

2. Center Negative design bending moment

The maximum negative bending moment shall be taken to occur at the centre of the sleeper, under partially or totally centre bound conditions producing tensile stress at the top and compressive stress at the underside of the sleeper. The value of the maximum centre negative bending moment (M_{C-}) for track gauge of 1435 mm is based on a uniform distribution of ballast pressure on the sleeper soffit and is calculated as follows:

$$M_{C-} = R \left(\frac{2g - L}{4} \right) \quad (3.14)$$

$$M_{C-} = R \left(\frac{2g - L}{4} \right) = 156.25kN \left(\frac{2 * 1.51m - 2.5m}{4} \right) = 20.3kNm$$

But uniform pressure distribution is an ideal and part of the ballast pressure only considered. AS 1085.14 accounts 50% the uniform pressure and 75% in china's standard case. For this analysis the center binding coefficient is taken 0.75 and the design bending moment is **15.23kN.m**.

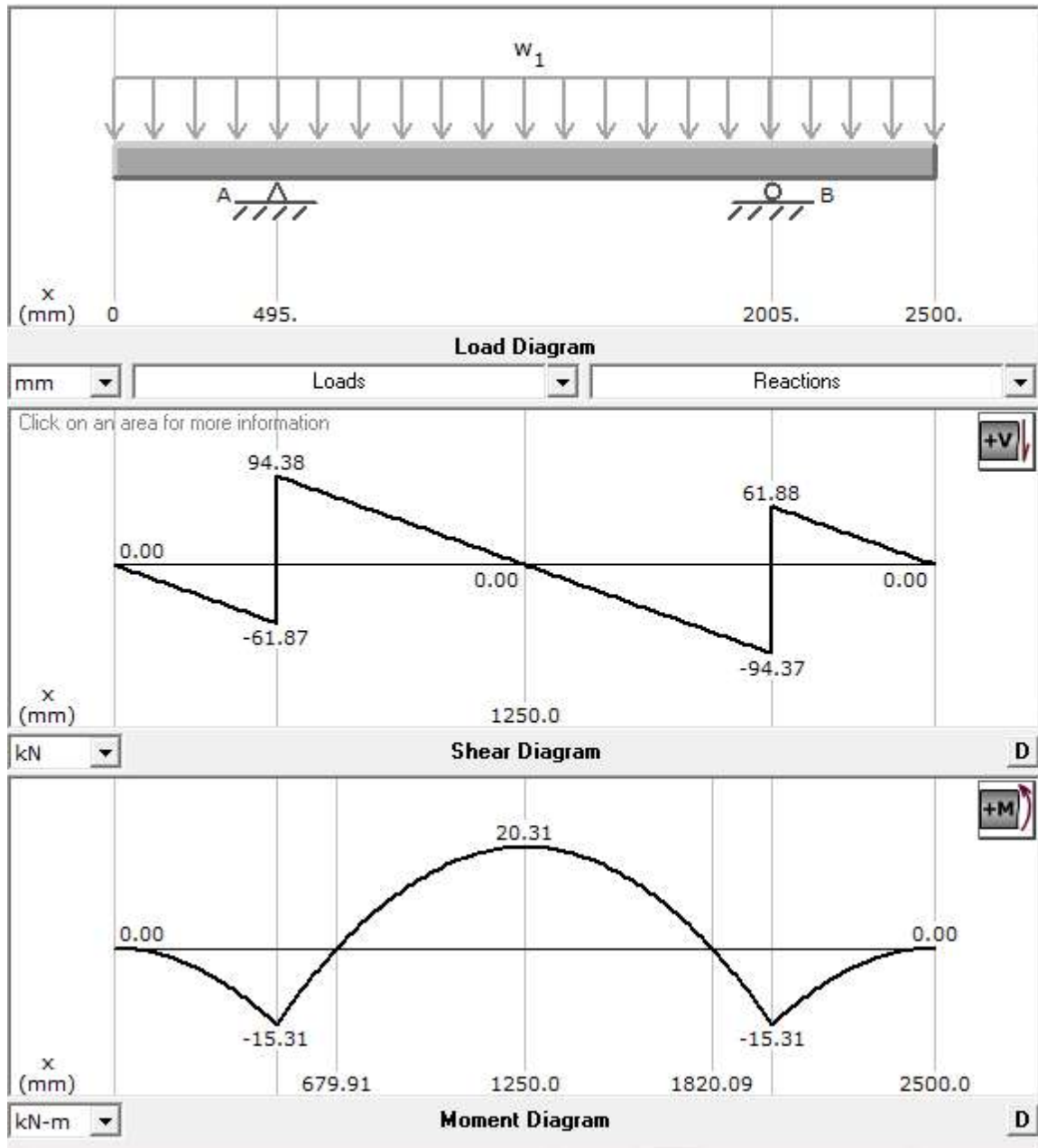


Figure 3.12: Shear force and bending moment diagrams for fully supported ballast pressure (by using MDSolid 3.5)

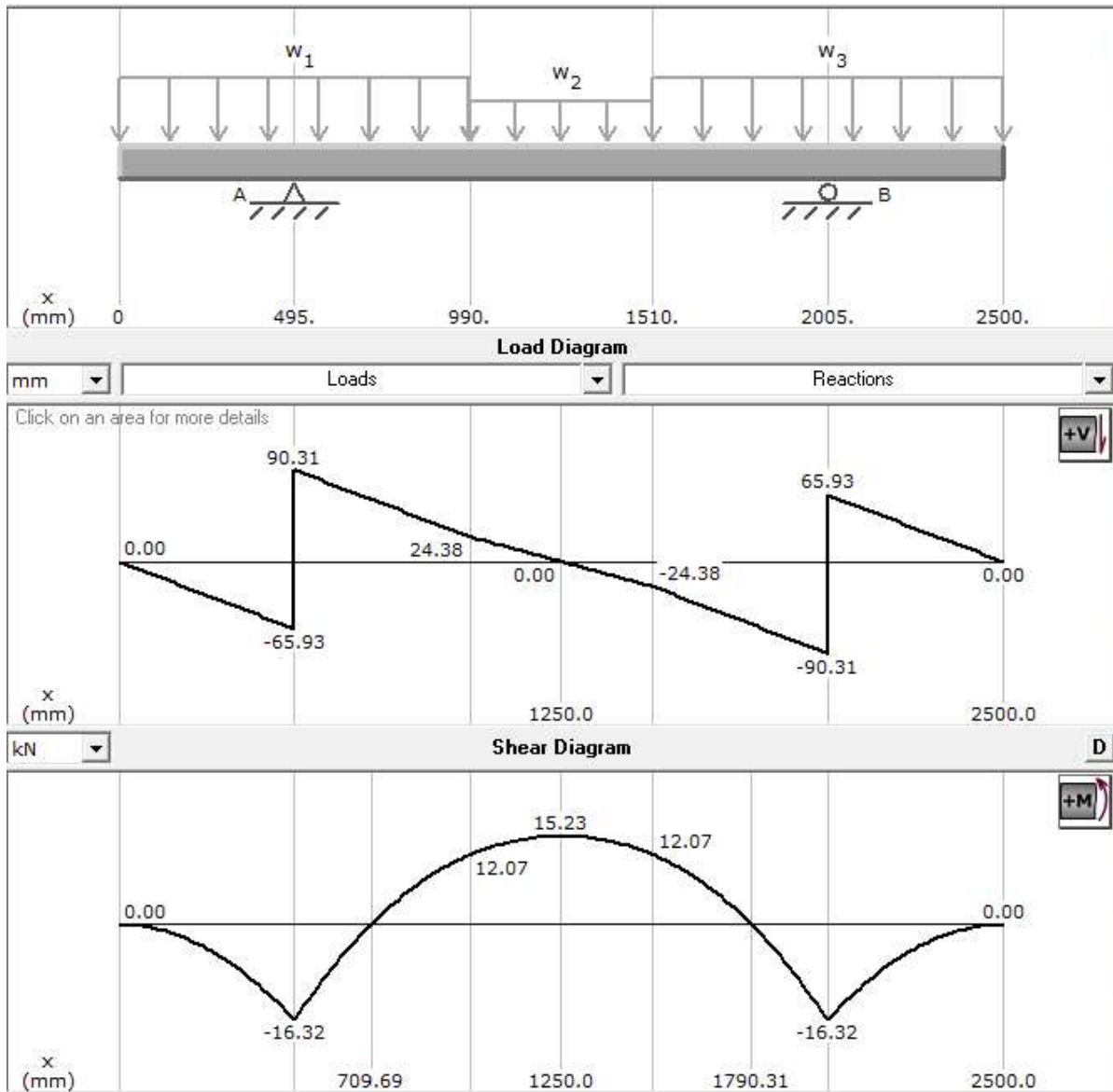


Figure 3.13: Shear force and bending moment diagrams for 75% center binding coefficient ballast pressure (by using MDSolid 3.5)

3.4 Stresses due to bending and pre-stresses at transfer

Source of stresses in the concrete at transfer is due to the self weight of the sleeper and the stresses due to the compression of pre-stressing wires after the releases of the applied tensile load on the wires. The self weight of the sleeper is modeled as simply supported beam with uniformly distributed load, even though its cross-section varies via its length. Two cases are treated to account the right side up and upside down position of the sleeper during casting and storage

conditions. The stresses at top and bottom fiber are calculated using the following general equations with some modifications of the subscripts and simplifications.

$$\sigma_t = \frac{-P}{A_g} \pm \frac{P.e.y_t}{I_g} \pm \frac{M.y_t}{I_g} \quad (3.15)$$

$$\sigma_b = \frac{-P}{A_g} \pm \frac{P.e.y_b}{I_g} \pm \frac{M.y_b}{I_g} \quad (3.16)$$

Where:

P = Prestressing force

e = the effective eccentricity

M = the bending moment at the rail or center section

A_g = the gross sectional area

I_g = the gross moment of inertia of the cross section

y_t = the distance between top fiber and neutral axis of the cross section

y_b = the distance between bottom fiber and neutral axis of the cross section

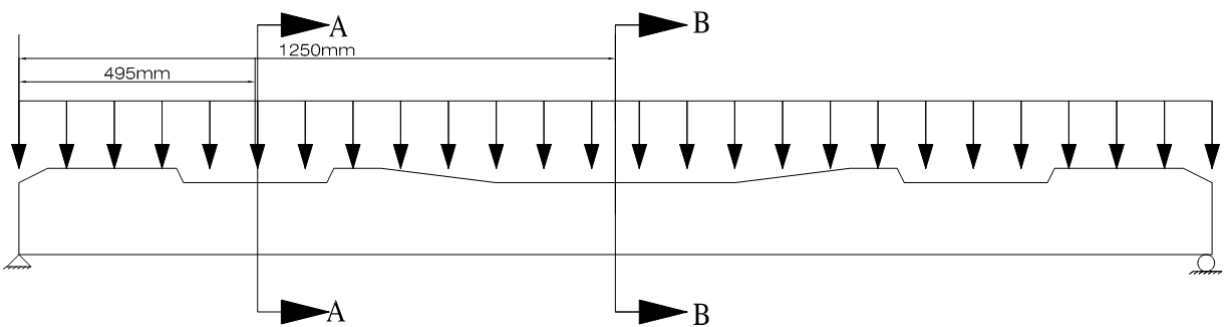


Figure 3.14: Right sides up positions

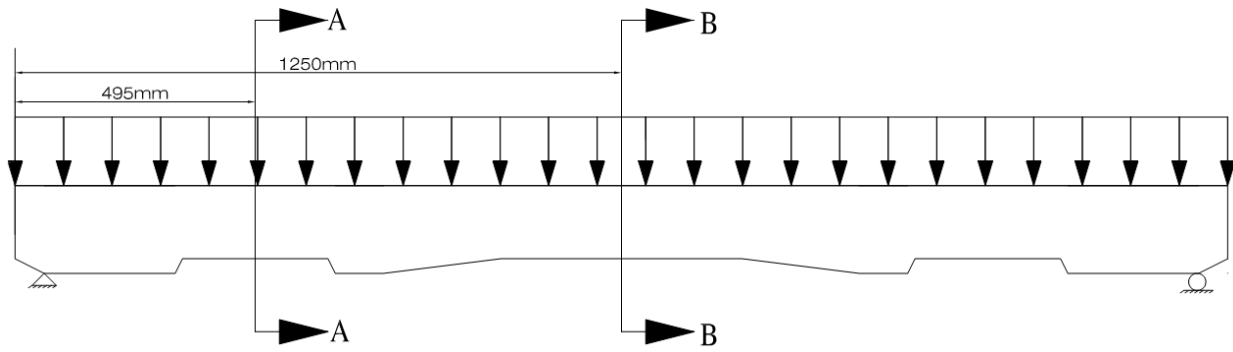


Figure 3.15: Upside down position

3.4.1 Bending stresses

First case (right side up)

At Rail seat (section A-A)

$$M_o = \frac{wx}{2}(L-x) = \frac{1.071 * 0.495}{2}(2.5 - 0.495) = 0.531 kN.m$$

Top fibers

$$\frac{M_o}{Z_t} = \frac{0.531 kN.m}{1,359,360.73 \text{ mm}^3} * 10^6 = 0.39 \text{ Mpa (compression)}$$

Bottom fibers

$$\frac{M_o}{Z_b} = \frac{0.531 kN.m}{1,600,537.63 \text{ mm}^3} * 10^6 = 0.33 \text{ Mpa (tension)}$$

At center (section B-B)

$$M_o = \frac{wx}{2}(L-x) = \frac{1.071 * 1.25}{2}(2.5 - 1.25) = 0.836 kN.m$$

Top fiber

$$\frac{M_o}{Z_t} = \frac{0.836 kN.m}{890,130.21 \text{ mm}^3} * 10^6 = 0.91 \text{ Mpa (compression)}$$

Bottom fiber

$$\frac{M_o}{Z_b} = \frac{0.836 kN.m}{958,601.76 \text{ mm}^3} * 10^6 = 0.84 \text{ Mpa (tension)}$$

Second case (Upright side down)

At Rail seat (section A-A)

$$M_o = \frac{wx}{2}(L-x) = \frac{1.071 * 0.495}{2}(2.5 - 0.495) = 0.531 kN.m$$

Top fiber

$$\frac{M_o}{Z_t} = \frac{0.531 kN.m}{1,359,360.73 \text{ mm}^3} * 10^6 = 0.39 \text{ Mpa (compression)}$$

Bottom fiber

$$\frac{M_o}{Z_b} = \frac{0.531 kN.m}{1,600,537.63 \text{ mm}^3} * 10^6 = 0.33 \text{ Mpa (tension)}$$

At center (section B-B)

$$M_o = \frac{wx}{2}(L-x) = \frac{1.071 * 1.25}{2}(2.5 - 1.25) = 0.836 kN.m$$

Top fiber

$$\frac{M_o}{Z_t} = \frac{0.836 kN.m}{921,904.74 \text{ mm}^3} * 10^6 = 0.91 \text{ Mpa (compression)}$$

Bottom fiber

$$\frac{M_o}{Z_b} = \frac{0.836 kN.m}{992,280.51 \text{ mm}^3} * 10^6 = 0.84 \text{ Mpa (tension)}$$

3.4.2 Stresses due to pre-stress

First case (right side up)

At rail seat (section A-A)

Top fibers

$$\left[\frac{P_i}{A_g} - \frac{P_i e}{z_t} \right] = \frac{267,635.13 \text{ N}}{45,000 \text{ mm}^2} - \frac{267,635.13 \text{ N} * 12.85 \text{ mm}}{1,359,360.73 \text{ mm}^3} = 3.42 \text{ MPa (compression)}$$

Bottom fibers

$$\left[\frac{P_i}{A_g} + \frac{P_i e}{z_b} \right] = \frac{267,635.13 \text{ N}}{45,000 \text{ mm}^2} + \frac{267,635.13 \text{ N} * 12.85 \text{ mm}}{1,600,537.63 \text{ mm}^3} = 8.10 \text{ MPa (compression)}$$

At center (section B-B)

Top fibers

$$\left[\frac{P_i}{A_g} - \frac{P_i e}{z_t} \right] = \frac{267,635.13 \text{ N}}{36,000 \text{ mm}^2} - \frac{267,635.13 \text{ N} * (-1.96 \text{ mm})}{921,904.76 \text{ mm}^3} = 7.97 \text{ MPa (compression)}$$

Bottom fibers

$$\left[\frac{P_i}{A_g} + \frac{P_i e}{z_b} \right] = \frac{267,635.13N}{36,000mm^2} + \frac{267,635.13N * (-1.96mm)}{992,820.51mm^3} = 6.87MPa \text{ (compression)}$$

Second case (Upright side down)

At rail seat (section A-A)

Top fibers

$$\left[\frac{P_i}{A_g} + \frac{P_i e}{z_t} \right] = \frac{267,635.13N}{45,000mm^2} + \frac{267,635.13N * 12.85mm}{1,359,360.73mm^3} = 8.48MPa \text{ (compression)}$$

Bottom fibers

$$\left[\frac{P_i}{A_g} - \frac{P_i e}{z_b} \right] = \frac{267,635.13N}{45,000mm^2} - \frac{267,635.13N * 12.85mm}{1,600,537.63mm^3} = 3.8MPa \text{ (compression)}$$

At center (section B-B)

Top fibers

$$\left[\frac{P_i}{A_g} + \frac{P_i e}{z_t} \right] = \frac{267,635.13N}{36,000mm^2} - \frac{267,635.13N * (-1.96mm)}{921,904.76mm^3} = 6.83MPa \text{ (compression)}$$

Bottom fibers

$$\left[\frac{P_i}{A_g} - \frac{P_i e}{z_b} \right] = \frac{267,635.13N}{36,000mm^2} + \frac{267,635.13N * (-1.96mm)}{992,820.51mm^3} = 7.93MPa \text{ (compression)}$$

Total stress at transfer for the first case

At rail seat (section A-A)

Top fibers

$$\frac{P_i}{A_g} - \frac{P_i e}{z_t} + \frac{M_o}{z_t} = 3.42MPa + 0.39MPa = 3.81MPa \text{ (compression)} < 15MPa \rightarrow OK$$

Bottom fibers

$$\frac{P_i}{A_g} + \frac{P_i e}{z_b} - \frac{M_o}{z_b} = 8.10MPa - 0.33MPa = 7.77MPa \text{ (compression)} < 15MPa \rightarrow OK$$

At center (section B-B)

Top fibers

$$\frac{P_i}{A_g} - \frac{P_i e}{z_t} + \frac{M_o}{z_t} = 7.97MPa + 0.91MPa = 8.7MPa \text{ (compression)} < 15MPa \rightarrow OK$$

Bottom fibers

$$\frac{P_i}{A_g} + \frac{P_i e}{z_b} - \frac{M_o}{z_b} = 6.87MPa - 0.84MPa = 6.03MPa \text{ (compression)} < 15MPa \rightarrow OK$$

Total stress at transfer for the second case

At rail seat (section A-A)

Top fibers

$$\frac{P_i}{A_g} - \frac{P_i e}{z_t} + \frac{M_o}{z_t} = 8.48MPa + 0.39MPa = 8.87MPa \text{ (compression)} < 15MPa \rightarrow OK$$

Bottom fibers

$$\frac{P_i}{A_g} + \frac{P_i e}{z_b} - \frac{M_o}{z_b} = 3.8MPa - 0.33MPa = 3.47MPa \text{ (compression)} < 15MPa \rightarrow OK$$

At center (section B-B)

Top fibers

$$\frac{P_i}{A_g} - \frac{P_i e}{z_t} + \frac{M_o}{z_t} = 6.83MPa + 0.91MPa = 7.74MPa \text{ (compression)} < 15MPa \rightarrow OK$$

Bottom fibers

$$\frac{P_i}{A_g} + \frac{P_i e}{z_b} - \frac{M_o}{z_b} = 7.93MPa - 0.84MPa = 7.09MPa \text{ (compression)} < 15MPa \rightarrow OK$$

3.5 Stresses calculations at working condition (service)

Rail seat section

Due to positive bending moment

Top fiber stress

$$\left[\frac{P_e}{A_g} - \frac{P_e e}{z_t} \right] + \frac{M_o}{z_t} + \frac{M}{z_t} = \frac{231,380N}{45,000mm^2} - \frac{231,380N * 12.85mm}{1,359,360.73mm^3} + \frac{531000N.mm + 1934 * 10^4 N.mm}{1,359,360.73mm^3} = 18.84MPa < 27MPa \rightarrow OK$$

Bottom fiber stress

$$\left[\frac{P_e}{A_g} + \frac{P_e e}{z_b} \right] - \frac{M_o}{z_b} - \frac{M}{z_b}$$

$$\frac{231,380N}{45,000mm^2} + \frac{231,380N * 12.85mm}{1,600,537.63mm^3} - \frac{531000N.mm + 1934 * 10^4 N.mm}{1,600,537.63mm^3} = -1.61MPa > -3.1MPa \rightarrow OK$$

Due to negative bending moment

Top fiber stress

$$\left[\frac{P_e}{A_g} - \frac{P_e e}{z_t} \right] + \frac{M_o}{z_t} + \frac{M}{z_t}$$

$$\frac{231,380N}{45,000mm^2} - \frac{231,380N * 12.85mm}{1,359,360.73mm^3} + \frac{531000N.mm + 1411 * 10^4 N.mm}{1,359,360.73mm^3} = 13.72MPa < 27MPa \rightarrow OK$$

Bottom fiber stress

$$\left[\frac{P_e}{A_g} + \frac{P_e e}{z_b} \right] - \frac{M_o}{z_b} - \frac{M}{z_b}$$

$$\frac{231,380N}{45,000mm^2} + \frac{231,380N * 12.85mm}{1,600,537.63mm^3} - \frac{531000N.mm + 1411 * 10^4 N.mm}{1,600,537.63mm^3} = -2.15MPa > -3.1MPa \rightarrow OK$$

Center section

Due to positive bending moment

Top fiber stress

$$\left[\frac{P_e}{A_g} - \frac{P_e e}{z_t} \right] + \frac{M_o}{z_t} + \frac{M}{z_t}$$

$$\frac{228,450N}{36,000mm^2} - \frac{228,450N * (-1.96mm)}{921,904.76mm^3} + \frac{836000N.mm + 8510000N.mm}{921,904.76mm^3} = 16.97MPa < 27MPa \rightarrow OK$$

Bottom fiber stress

$$\left[\frac{P_e}{A_g} + \frac{P_e e}{z_b} \right] - \frac{M_o}{z_b} - \frac{M}{z_b}$$

$$\frac{228,450N}{36,000mm^2} + \frac{228,450N * (-1.96mm)}{992,820.51mm^3} - \frac{836000N.mm + 7730000N.mm}{992,820.51mm^3} = -1.93MPa > -3.1MPa \rightarrow OK$$

Due to negative bending moment

Top fiber stress

$$\left[\frac{P_e}{A_g} - \frac{P_e e}{z_t} \right] + \frac{M_o}{z_t} + \frac{M}{z_t}$$

$$\frac{228,450N}{36,000mm^2} - \frac{228,450N * (-1.96mm)}{921,904.76mm^3} + \frac{836000N.mm + 8510000N.mm}{921,904.76mm^3} = 16.97MPa < 27MPa \rightarrow OK$$

Bottom fiber stress

$$\left[\frac{P_e}{A_g} + \frac{P_e e}{z_b} \right] - \frac{M_o}{z_b} - \frac{M}{z_b}$$

$$\frac{228,450N}{36,000mm^2} + \frac{228,450N * (-1.96mm)}{992,820.51mm^3} - \frac{836000N.mm + 7730000N.mm}{992,820.51mm^3} = -2.73MPa > -3.1MPa \rightarrow OK$$

3.6 Design Shear Forces

The shear design procedure for PSC is quite different from ordinary RC. It varies significantly from code to code. However, there is one issue with PSC that can have a significant influence on shear design. This is the vertical component of the pre-stress force which can have a significant beneficial effect (Caprani, 2006).

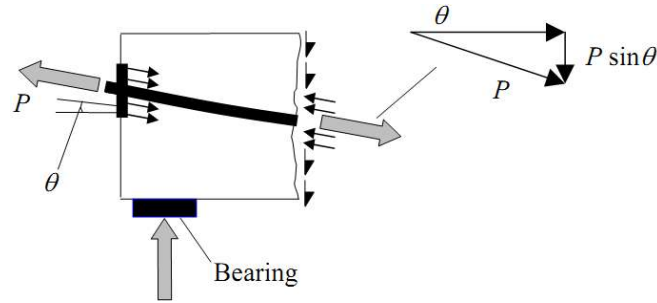


Figure 3.16: Shear force development in pre-stressed member

Also, the shear capacity depends on whether or not the section has cracked under the ultimate flexural moments at the section.

Note that nominal links are required in PSC members, similar to ordinary reinforced members.

Shear force at critical sections

At rail seat

The maximum Shear force at the rail seat is 94.38kN

$$\begin{array}{lll}
 A_p = 70.686\text{mm}^2 & A_g = 45,000\text{mm}^2 & e = 12.85\text{mm} \\
 f_p = 1860\text{Mpa} & I_g = 147,012,345.68\text{mm}^4 & \text{concrete} = C - 60 = 60\text{Mpa}
 \end{array}$$

$$f_{ps} = 1,362.22\text{Mpa} \qquad P_s = A_p (f_{pi} - \text{initial loss}) = 267.47\text{kN}$$

Shear Capacity for Cracked Sections

A section is cracked in flexure if the moment is greater than a design cracking moment, M_o , defined below. The cracked shear capacity, V_{cr} , is empirically given by (Caprani, 2006):

$$V_{cr} = \left(1 - 0.55 \frac{f_{ps}}{f_{pu}} \right) v_c b_v d + \frac{M_o}{M} V \geq 0.1 b_v d \sqrt{f_{cu}} \quad (3.17)$$

In which:

M = the moment acting at the section

V = the shear acting at the section

M_o = the moment required to remove 0.8 of the compressive stress at the level of the prestress

Where:

$$M_o = 0.8 f_{c,e} \frac{I}{e} = 0.8 * \frac{147,012,345.68}{12.85} * 6.24 = 57.14\text{ kNm}$$

$$f_{c,e} = \frac{P_s}{A_g} + \frac{P_s e^2}{I_g}, \text{ Assume initial loss } 2.35\%$$

$$= \frac{267,470.78}{45,000} + \frac{267,470.78 * 12.85^2}{147,012,345.68} = 6.24 \text{ Mpa}$$

f_{ps} = the stress in the tendon at SLS

f_{pu} = the ultimate tensile strength of the tendon

b_v = the shear width of the section

d = the effective depth

v_c = the design shear strength of the concrete

$$v_c = \frac{0.79}{1.25} \left(\frac{100 A_s}{b_v d} \right)^{0.33} \left(\frac{400}{d} \right)^{0.25} \left(\frac{f_{cu}}{25} \right)^{0.33} = 346.61 \text{ kN}$$

Shear capacity for un-cracked sections:

A section is un-cracked if the applied moment is less M_o , in such section, the principal tensile stress in the web is limited to

$$f_t = 0.24 \sqrt{f_{cu}} = 0.24 \sqrt{60} = 1.859 \text{ Mpa}$$

Based on a Mohr's circle analysis, the following equation is derived:

$$V_{co} = 0.67 b h \sqrt{(f_t^2 + 0.8 f_t f_{cp})} + V_p \quad (3.18)$$

$$V_{co} = 0.67 * 200 * 225 \sqrt{(1.859^2 + 0.8 * 1.859 * 5.94)} + 267,470.78 = 373.19 \text{ kN}$$

In which f_{cp} is the compressive stress due to pre-stress at the centroidal axis:

$$f_{cp} = \frac{P_s}{A} = \frac{267,470.78}{45,000} = 5.94 \text{ Mpa}$$

V_p is the vertical component of pre-stress at the section, resisting the applied shear; and the remaining variables have their previous meaning.

The design shear resistance at a section is:

Un-cracked: $V_c = V_{co}$

Cracked: $V_c = \min (V_{co}, V_{cr})$

The shear design is:

$$V \leq 0.5 V_c : \text{ No links are required}$$

$$V \leq V_c + 0.4 b_v d : \text{ Shear links are required}$$

$$\frac{A_{sv}}{S_v} = \frac{0.4b_v}{0.87f_{yv}} \quad (3.19)$$

Where:

A_{sv} = the link area

S_v = the link spacing

f_{yv} = the characteristics strength of the links

d_t = the depth to the furthest steel, ordinary or prestressed, from the compression face

Note:

Consideration need not be given to checking sleeper sections for stress other than flexural stress, subjected to the design complying with all other clauses of the AS 1085.14-2003.

3.7 Losses of Pre-Stress

In pre-stressed concrete applications, the most important variable is the pre-stressing force. Even during pre-stressing of the tendons and the transfer of pre-stress to the concrete member, there is a drop of the pre-stressing force from the recorded value in the jack gauge. The various reductions of the pre-stressing force are termed as the losses in pre-stress.

The losses are broadly classified into two groups, immediate and time-dependent. The immediate losses occur during pre-stressing of the tendons and the transfer of pre-stress to the concrete member. The time-dependent losses occur during the service life of the Pre-stressed member. The losses due to elastic shortening of the member, friction at the tendon-concrete interface and slip of the anchorage are the immediate losses. The losses due to the shrinkage and creep of the concrete and relaxation of the steel are the time-dependent losses.

The loss of pre-stress shall be determined by the methods specified in AS 3600. For Preliminary design, a value of 25 percent may be assumed.

3.7.1 Losses in Pre-Tensioned Pre-stressed Concrete

A. Short term (immediate) loss

1) Elastic Shortening (deformation) Loss

In pre-tensioning, the strands are stressed before the concrete is cast. Therefore, after jacking (P_{jack}) has been applied, at a level y , the concrete is subjected to the stress:

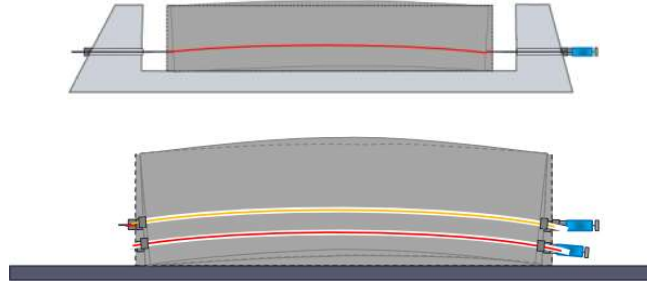


Figure 3.17: Pre-tensioning process

$$f_{c,y} = \frac{P_{jack}}{A_g} + \frac{(P_{jack}e)y}{I_g} + \frac{M_o y}{I_g} \quad (3.20)$$

At the level of the strands, $y = e$. Hence, the stress in the concrete at that level is:

$$f_{c,e} = \frac{P_{jack}}{A_g} + \frac{P_{jack}e^2}{I_g} + \frac{M_o e}{I_g} \quad (3.21)$$

And the concrete at the level of the strands has a strain of:

$$\varepsilon_{c,e} = \frac{f_{c,e}}{E_c} \quad (3.22)$$

Since the strands are bonded to the concrete, they undergo a loss of strain of the same amount, $\varepsilon_{c,e}$, with associated stress and force losses of $E_p \varepsilon_{c,e}$ and $A_p E_p \varepsilon_{c,e}$. Hence:

$$\Delta P_\varepsilon = \frac{A_p E_p}{E_c} \left(\frac{P_{jack}}{A_g} + \frac{P_{jack}e^2}{I_g} + \frac{M_o e}{I_g} \right) \quad (3.23)$$

At center

$$\Delta P_\varepsilon = \frac{70.69 * 200,000}{32,000} \left(\frac{98,606.74}{36,000} + \frac{98,606.74 * (1.963)^2}{76,483,950.62} + \frac{825,683.59 * 1.963}{76,483,950.62} \right) = 1.22164 kN$$

At rail seat

$$\Delta P_\varepsilon = \frac{196.35 * 200,000}{39,117.13} \left(\frac{267,470.78}{45,000.00} + \frac{267,470.78 * (12.85)^2}{147,012,345.68} + \frac{825,683.59 * 12.85}{147,012,345.68} \right) = 6.27 kN$$

Strain compatibility Equation:

Strain in pre-stressing wires = Strain in concrete

$$\Delta \varepsilon_p = \varepsilon_c \quad (3.24)$$

$$\frac{\Delta f_p}{E_p} = \frac{f_c}{E_c} \quad \Delta f_p = \frac{f_c}{E_c} E_p \quad \Delta f_p = m f_c$$

The concrete never feels the full jacking force since the strands shorten as the concrete strains. Hence, elastic shortening loss in pre-tensioning is ‘before-transfer’.

B. Long term (time dependent) losses

1) Shrinkage Loss

Concrete shrinks as it sets and for a period afterwards. The amount of shrinkage depends on the humidity and the surface area to volume ratio. Once again, as the strands are bonded to the concrete they undergo the same strain. Hence the loss of pre-stress is:

$$\Delta P_{sh} = A_p E_p \varepsilon_{sh} \quad (3.25)$$

In the absence of any test data a reasonable value of shrinkage strain (ε_{sh}) for design shall be assumed as 0.0003 for pre-tensioned members.

At rail seat and center

$$\Delta P_{sh} = 196.35 \text{ mm}^2 * 200 \text{ kN/mm}^2 * 0.0003 = 11.78 \text{ kN}$$

Shrinkage loss is long-term. Hence it is ‘after-transfer’.

2) Relaxation Loss

When maintained at a constant strain, pre-stressing strand gradually loses its stress with time (like a guitar going out of tune). It is due to a realignment of the steel fibers and is the same phenomenon as creep. Depending on the quality of the steel, relaxation losses can vary in the range of 3% to 8%. Relaxation is ‘after-transfer’.

Consider an average value 5.5%, then the relaxation loss both at rail seat at the center is $0.055 * 98,606.74 \text{ N} = 5.42337 \text{ kN}$

3) Creep loss

Creep is the ongoing increase in strain with time, when stress is kept constant. Creep causes a strain in the concrete adjacent to the strands and over a long time is:

$$\varepsilon_{\infty} = \phi_{c,e}^f \quad (3.26)$$

The creep factor ϕ depends on a number of things such as concrete quality and its age when loaded. Thus the strands slacken as before, and the loss of force is:

$$\begin{aligned} \Delta P_{creep} &= A_p E_p \varepsilon_{\infty} = A_p E_p \phi_{c,e}^f \\ &= A_p E_p \phi \left(\frac{\alpha P_t}{A_g} + \frac{\alpha P_t e^2}{I_g} + \frac{M_{perm} e}{I_g} \right) \end{aligned} \quad (3.27)$$

At the center

$$\begin{aligned} \Delta P_{creep} &= A_p E_p \varepsilon_{\infty} = A_p E_p \phi_{c,e}^f \\ &= 196.35 \text{mm}^2 * 200,000 \text{N/mm}^2 * 0.0003 * 78890 \text{N/mm}^2 = 9.31087 \text{kN} \end{aligned}$$

At rail seat

$$\begin{aligned} \Delta P_{creep} &= A_p E_p \varepsilon_{\infty} = A_p E_p \phi_{c,e}^f \\ &= 70.69 \text{mm}^2 * 200,000 \text{N/mm}^2 * 0.0003 * 1840 \text{N/mm}^2 = 7.81112 \text{kN} \end{aligned}$$

M_{perm} is the moment due to the permanent loads such as the pre-stress, dead load and superimposed dead loads such as parapets and road pavement. As creep loss contributes to α , an exact calculation is iterative. Creep is long-term; hence it is an ‘after-transfer’ loss.

$$\text{Total loss at Rail Seat} = \Delta P_{\varepsilon} + \Delta P_{sh} + \text{Relaxation} + \Delta P_{creep} = 20.1197 \text{kN}$$

$$\text{Total loss at the center} = \Delta P_{\varepsilon} + \Delta P_{sh} + \text{Relaxation} + \Delta P_{creep} = 18.46076 \text{kN}$$

3.8 Permissible Stresses

3.8.1 Permissible Stresses in Concrete

a) At transfer

The maximum permissible stress in the concrete immediately after transfer, and before deferred losses, shall be the applicable value given in [Table 3.7](#).

Table 3.7: Maximum permissible stress in the concrete at transfer

Type of stress	Maximum permissible stress
Compression where the distribution of stress is triangular or approximately triangular	$0.6 f'_{cp}$
Compression where the distribution of stress is uniform or approximately uniform	$0.5 f'_{cp}$

$$0.5f'_{cp} \tag{3.28}$$

$$f_{ct} = 0.5f'_{cp} = 0.5 * 40 = 20MPa$$

b) After all losses

The maximum permissible stress in the concrete under the working conditions assumed by the designer, and after allowing for all losses of pre-stress, shall be the applicable value given in **Table 3.8**.

The minimum compressive stress at any cross-section through the rail seat area shall be 1.0 MPa after all losses without any applied load.

Table 3.8: Maximum permissible stresses in the concrete after all losses

Type of stress	Maximum permissible stress
Compression	$0.45f'_c$
Tension (flexure)	$0.4(f'_c)^{0.5}$

$$0.45f'_c \tag{3.29}$$

$$0.4(f'_c)^{0.5} \tag{3.30}$$

$$f_{cw} = 0.45f'_c = 0.45 * 60Mpa = 27Mpa$$

$$f_{tw} = 0.4(f'_c)^{0.5} = 0.4 * (60)^{0.5} = 3.1Mpa$$

3.8.2 Permissible Stresses in Tendons (pre-stressing wires)

Under the working conditions assumed by the designer, the maximum permissible stress in the pre-stressing tendons shall not exceed $0.8f_p$ for the jacking stress in the pre-stressing tendons after losses due to jack friction only; and not exceed $0.7f_p$ for the initial stress in a pre-stressing tendon immediately after transfer.

For design purposes, the tensile strength (f_p) for wire tendons shall be the minimum strength in the selected tensile strength range given in AS 1310 for that tendon. For strand tendons, the minimum breaking force given in AS 1311 for the grade specified shall be used for design. Hence,

$$f_{pu} = 0.8f_p \quad (3.31)$$

$$f_{pe} = 0.7f_p \quad (3.32)$$

Permissible stress at transfer

$$f_{pu} = 0.8 * 1860 \text{Mpa} = 1488 \text{Mpa}$$

Permissible stress at working condition

$$f_{pe} = 0.7 * 1860 \text{Mpa} = 1302 \text{Mpa}$$

3.9 Development Length and end zone

3.9.1 Transfer of pre-stress in pre-tensioned member

Transfer mechanism of pre-stress

1. Adhesion between concrete and steel
2. Mechanical bond at the concrete and steel interface
3. Friction in presence transverse compression

Transmission (transfer) length

Transmission length is the length over which the pre-stressing force is transmitted from the ends of the member. The pre-stressing force transmitted beyond the transmission length remains constant in most cases. The pre-stressing force is zero at end and reaches effective pre-stressing force zero at the transmission length.

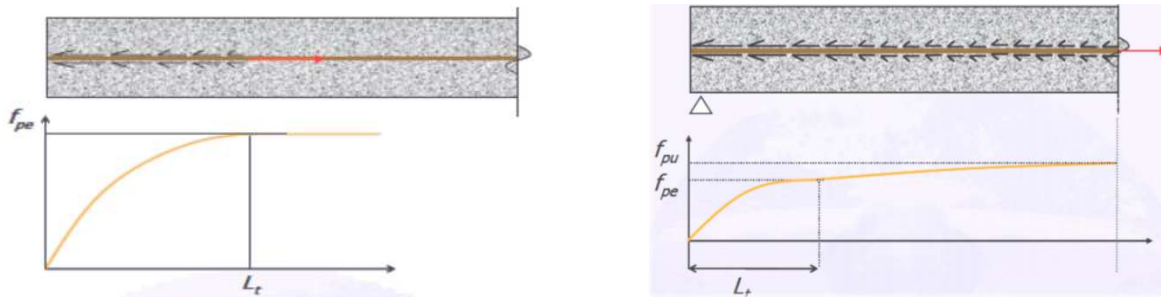


Figure 3.18: Transfer of pre-stress in pre-tensioned members

a) Transfer length

$$L_t = \sqrt{\frac{\sqrt{f_{cu}} * 10^3}{\beta}}$$

b) variation of prestress

(3.33)

$$L_t = \sqrt{\frac{\sqrt{f_{cu}} * 10^3}{\beta}} = \sqrt{\frac{\sqrt{60} * 10^3}{0.0235}} = 574 \text{mm}$$

Bond length

Bond length is the minimum length over which, the stress in the tendon can increase from the effective pre-stress (f_{pe}) to the ultimate pre-stress (f_{pu}) at the critical location.

$$L_b = \frac{f_{pu} - f_{pe}}{4\tau_{bd}} \phi \quad (3.34)$$

$$\tau_{bd} = 1.9 \text{ Mpa} \quad L_b = \frac{1860 - 1178.46}{4 * 1.9} * 5 = 564.93 \text{ mm}$$

Development Length

Minimum length over which the stress in tendon can increase from zero to the ultimate pre-stress (f_{pu}). The development length (L_d) is the sum of the transmission length (L_t) and bond length (L_b).

$$L_d = L_t + L_b \quad (3.35)$$
$$L_d = 574.12 + 564.93 = 1139 \text{ mm}$$

3.9.2 End zone reinforcement

Transverse tensile stress develops due to pre-stressing forces and hoyer effect which is critical during the transfer of pre-stress. End zone reinforcement is provided to prevent splitting of concrete. This reinforcement is provided along the transmission length to carry the tensile stress. The minimum amount of end zone reinforcement is calculated using the following expression.

$$A_{sv} = \frac{2.5M}{f_s h} \quad (3.36)$$

Where:

h = total depth of the section

M = moment at the horizontal plane at the level of CGC due to the compressive stress block above CGC

f_s = permissible stress in the reinforcement

3.10 Moment capacity of critical sections

Design moment capacity based on allowable concrete stress

Rail seat section

Positive moment capacity

$$Top \quad M_{R+} = \left(f_{cw} - \left(\frac{P_e}{A_g} \right) + \left(\frac{P_e e}{Z_t} \right) - \left(\frac{M_o}{Z_t} \right) \right) Z_t$$

$$M_{R+} = \left(27MPa - \left(\frac{353.24kN}{45,000mm^2} \right) + \left(\frac{353.24kN * 12.85mm}{1,359,360.73mm^3} \right) - \left(\frac{0.531kN.m}{1,359,360.73mm^3} \right) \right) * 1,359,360.73mm^3$$

$$M_{R+} = (27MPa - 7.85MPa + 3.34MPa - 0.39MPa) * 1,359,360.73mm^3 = 30kN.m$$

$$Bottom \quad M_{R+} = \left(f_{tw} - \left(\frac{P_e}{A_g} \right) - \left(\frac{P_e e}{Z_b} \right) + \left(\frac{M_o}{Z_b} \right) \right) Z_b$$

$$M_{R+} = \left(-3.1MPa - \left(\frac{353.24kN}{45,000mm^2} \right) - \left(\frac{353.24kN * 12.85mm}{1,600,537.63mm^3} \right) + \left(\frac{0.531kN.m}{1,600,537.63mm^3} \right) \right) * 1,600,537.63mm^3$$

$$M_{R+} = (-3.1MPa - 7.85MPa - 2.84MPa + 0.33MPa) * 1,600,537.63mm^3 = -21.5kN.m$$

Governing value 21.5kN.m

Negative moment capacity

$$Top \quad M_{R-} = \left(f_{tw} - \left(\frac{P_e}{A_g} \right) + \left(\frac{P_e e}{Z_t} \right) - \left(\frac{M_o}{Z_t} \right) \right) Z_t$$

$$M_{R-} = \left(-3.1MPa - \left(\frac{353.24kN}{45,000mm^2} \right) + \left(\frac{353.24kN * 12.85mm}{1,359,360.73mm^3} \right) - \left(\frac{0.531kN.m}{1,359,360.73mm^3} \right) \right) * 1,359,360.73mm^3$$

$$M_{R-} = (-3.1MPa - 7.85MPa + 3.34 - 0.39MPa) * 1,359,360.73mm^3 = -10.9kN.m$$

$$Bottom \quad M_{R-} = \left(f_{cw} - \left(\frac{P_e}{A_g} \right) - \left(\frac{P_e e}{Z_b} \right) + \left(\frac{M_o}{Z_b} \right) \right) Z_b$$

$$M_{R-} = \left(27MPa - \left(\frac{353.24kN}{45,000mm^2} \right) - \left(\frac{353.24kN * 12.85mm}{1,600,537.63mm^3} \right) + \left(\frac{0.531kN.m}{1,600,537.63mm^3} \right) \right) * 1,600,537.63mm^3$$

$$M_{R-} = (27MPa - 7.85MPa - 2.84MPa + 0.33MPa) * 1,600,537.63mm^3 = 26.6kN.m$$

Governing value 10.9kN.m

Center section

Positive moment capacity

$$\text{Top} \quad M_{C+} = \left(f_{cw} - \left(\frac{P_e}{A_g} \right) + \left(\frac{P_e e}{Z_t} \right) - \left(\frac{M_o}{Z_t} \right) \right) Z_t$$

$$M_{C+} = \left(27 \text{MPa} - \left(\frac{346.09 \text{kN}}{36,000 \text{mm}^2} \right) + \left(\frac{346.09 \text{kN} * (-1.96 \text{mm})}{921,904.76 \text{mm}^3} \right) - \left(\frac{0.836 \text{kN.m}}{921,904.76 \text{mm}^3} \right) \right) 921,904.76 \text{mm}^3$$

$$M_{C+} = (27 \text{MPa} - 9.61 \text{MPa} - 0.736 \text{MPa} - 0.91 \text{MPa}) * 921,904.76 \text{mm}^3 = 14.5 \text{kN.m}$$

$$\text{Bottom} \quad M_{C+} = \left(f_{tw} - \left(\frac{P_e}{A_g} \right) - \left(\frac{P_e e}{Z_b} \right) + \left(\frac{M_o}{Z_b} \right) \right) Z_b$$

$$M_{C+} = \left(-3.1 \text{MPa} - \left(\frac{346.09 \text{kN}}{36,000 \text{mm}^2} \right) - \left(\frac{346.09 \text{kN} * (-1.96 \text{mm})}{992,820.51 \text{mm}^3} \right) + \left(\frac{0.836 \text{kN.m}}{992,820.51 \text{mm}^3} \right) \right) 992,820.51 \text{mm}^3$$

$$M_{C+} = (-3.1 \text{MPa} - 9.61 \text{MPa} + 0.68 \text{MPa} + 0.84 \text{MPa}) 992,820.51 \text{mm}^3 = -11.1 \text{kN.m}$$

Governing value 11.1kN.m

Negative moment capacity

$$\text{Top} \quad M_{C-} = \left(f_{tw} - \left(\frac{P_e}{A_g} \right) + \left(\frac{P_e e}{Z_t} \right) - \left(\frac{M_o}{Z_t} \right) \right) Z_t$$

$$M_{C-} = \left(-3.1 \text{MPa} - \left(\frac{346.09 \text{kN}}{36,000 \text{mm}^2} \right) + \left(\frac{346.09 \text{kN} * (-1.96 \text{mm})}{921,904.76 \text{mm}^3} \right) - \left(\frac{0.836 \text{kN.m}}{921,904.76 \text{mm}^3} \right) \right) 921,904.76 \text{mm}^3$$

$$M_{C-} = (-3.1 \text{MPa} - 9.61 \text{MPa} - 0.736 \text{MPa} - 0.91 \text{MPa}) * 921,904.76 \text{mm}^3 = -13.2 \text{kN.m}$$

$$\text{Bottom} \quad M_{C-} = \left(f_{cw} - \left(\frac{P_e}{A_g} \right) - \left(\frac{P_e e}{Z_b} \right) + \left(\frac{M_o}{Z_b} \right) \right) Z_b$$

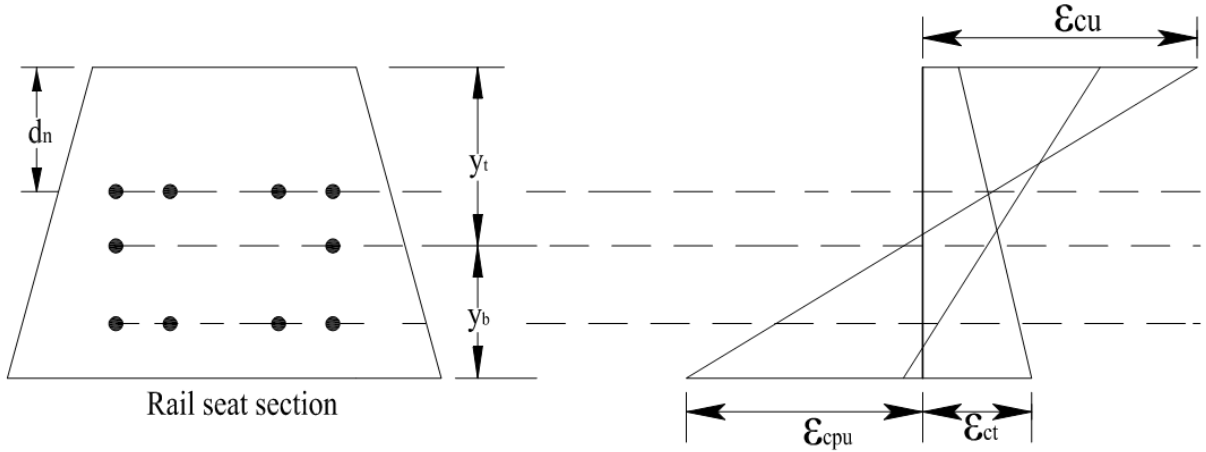
$$M_{C-} = \left(27 \text{MPa} - \left(\frac{346.09 \text{kN}}{36,000 \text{mm}^2} \right) - \left(\frac{346.09 \text{kN} * (-1.96 \text{mm})}{992,820.51 \text{mm}^3} \right) + \left(\frac{0.836 \text{kN.m}}{992,820.51 \text{mm}^3} \right) \right) 992,820.51 \text{mm}^3$$

$$M_{C-} = (27 \text{MPa} - 9.61 \text{MPa} + 0.68 \text{MPa} + 0.84 \text{MPa}) 992,820.51 \text{mm}^3 = 18.77 \text{kN.m}$$

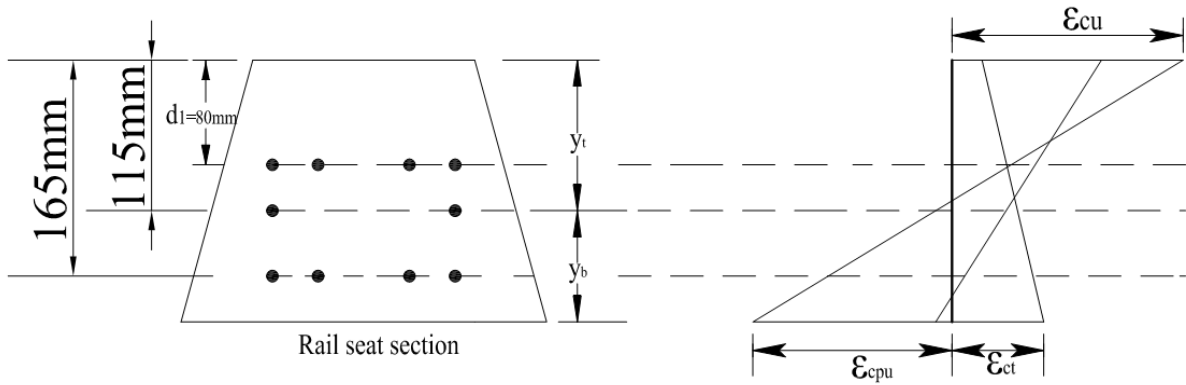
Governing value 13.2kN.m

Ultimate moment capacity based on strain compatibility method

Concrete and steel yields at same time, the total strain is the sum of strain components specified in section 2.3.1. The positive ultimate moment at the rail seat is demonstrated and the rest are completed by using excel spread sheet.



(a)



(b)

Figure 3.19: Strain compatibility diagram

First layer (1)

$$\epsilon_{pt} = \frac{f_{pt}}{E_p} = \frac{1,110.25MPa}{200,000MPa} = 0.0055$$

$$\text{Assume } x_u = 74.07mm$$

$$d_1 = 80mm$$

$$A_{p1} = 124.69mm^2$$

$$d_{max} = 165mm$$

Where: d_1 is the distance to the first layer

A_{p1} is the area of the pre-stressing wires at the first layer

d_{max} lowest level of steel in the decompression zone

$$\epsilon_{ct} = \frac{1}{E_c} \left(\frac{P_t}{A} + \frac{P_t e^2}{I} \right) = \frac{1}{39,117MPa} \left(\frac{353.24kN}{45,000mm^2} + \frac{353.24kN * (165mm - 108.15)^2}{147,012,345.68mm^3} \right) = 0.0004$$

Apply similarity of triangle to find the strain in the first layer of pre-stressing steel corresponding to decompression.

$$\varepsilon_{ct-1} = \frac{\varepsilon_{ct}(y_t - d_1)}{d_{\max} - y_t} = \frac{0.0004(108.15\text{mm} - 80\text{mm})}{165\text{mm} - 108.15\text{mm}} = 0.0002$$

$$\varepsilon_{ct-2} = \frac{\varepsilon_{ct}(y_t - d_2)}{d_{\max} - y_t} = \frac{0.0004(108.15\text{mm} - 115\text{mm})}{165\text{mm} - 108.15\text{mm}} = -0.000048$$

$$\varepsilon_{ct-3} = \frac{\varepsilon_{ct}(y_t - d_3)}{d_{\max} - y_t} = \frac{0.0004(108.15\text{mm} - 165\text{mm})}{165\text{mm} - 108.15\text{mm}} = -0.0004$$

The ultimate concrete strain is considered as

$$\varepsilon_{cu} = 0.0035$$

$$\varepsilon_{cpu-1} = \varepsilon_{cu} \left(\frac{d_1 - x_u}{x_u} \right) = 0.0035 \left(\frac{80\text{mm} - 74.07\text{mm}}{74.07\text{mm}} \right) = 0.00028$$

$$\varepsilon_{cpu-2} = \varepsilon_{cu} \left(\frac{d_2 - x_u}{x_u} \right) = 0.0035 \left(\frac{115\text{mm} - 74.07\text{mm}}{74.07\text{mm}} \right) = 0.001934$$

$$\varepsilon_{cpu-3} = \varepsilon_{cu} \left(\frac{d_3 - x_u}{x_u} \right) = 0.0035 \left(\frac{165\text{mm} - 74.07\text{mm}}{74.07\text{mm}} \right) = 0.0043$$

Summation of strain components

$$\varepsilon_{pu} = \varepsilon_{pt} + \varepsilon_{ct} + \varepsilon_{cpu}$$

$$\varepsilon_{pu-1} = \varepsilon_{pt} + \varepsilon_{ct-1} + \varepsilon_{cpu-1} = 0.0055 + 0.0002 + 0.00028 = 0.006$$

$$\varepsilon_{pu-2} = \varepsilon_{pt} + \varepsilon_{ct-2} + \varepsilon_{cpu-2} = 0.0055 - 0.000048 + 0.001934 = 0.00755$$

$$\varepsilon_{pu-3} = \varepsilon_{pt} + \varepsilon_{ct-3} + \varepsilon_{cpu-3} = 0.0055 - 0.0004 + 0.0043 = 0.00956$$

The stress at failure corresponding to the total strain is

$$f_p = E_p * \varepsilon_{pu} \quad \text{if } \varepsilon_{pu} \leq 0.0076$$

$$f_p = 1860MPa - \frac{0.3MPa}{\varepsilon_{pu} - 0.0064} \quad \text{if } \varepsilon_{pu} > 0.0076$$

$$f_{p_{-1}} = E_p * \varepsilon_{pu_{-1}} = 200,000MPa * 0.006144 = 1229MPa$$

$$f_{p_{-2}} = 200,000MPa * 0.00755 = 1510MPa$$

$$f_{p_{-3}} = 1860MPa - \frac{0.3Pa}{0.0043 - 0.0064} = 1765MPa$$

The corresponding tensile forces are calculated as

$$T = A_p * f_p$$

$$T_{-1} = A_{p_{-1}} * f_{p_{-1}} = 124.69mm^2 * 1229MPa = 153.2kN$$

$$T_{-2} = A_{p_{-2}} * f_{p_{-2}} = 62.34mm^2 * 1510MPa = 94kN$$

$$T_{-3} = A_{p_{-3}} * f_{p_{-3}} = 124.69mm^2 * 1765MPa = 220kN$$

The moment produced by each layer of pre-stressing

$$M_u = -T(y_t - d_n)$$

$$M_{u_{-1}} = -T_{-1}(y_t - d_1) = -153.2kN(108.15mm - 80mm) = -4.3kN.m$$

$$M_{u_{-2}} = -T_{-2}(y_t - d_2) = -94kN(108.15mm - 115mm) = 0.65kN.m$$

$$M_{u_{-3}} = -T_{-3}(y_t - d_3) = -220kN(108.15mm - 165mm) = 12.5kN.m$$

For fully bonded tendon the depth of the compression zone is estimated by

$$\beta_1 = \begin{cases} 0.65 \\ 0.85 - 0.05 \left(\frac{f'_c - 28}{7} \right) \end{cases} \quad \text{if } f'_c \leq 55MPa$$

$$\beta_1 = 0.65 \quad a = \beta_1 * x_u = 0.65 * 74.07mm = 48.15mm$$

$$A_c = (170mm + 20.37mm) * 48.15mm = 9,165.4mm^2$$

The compressive force is

$$C = 0.85A_c f'_c = 0.85 * 9,165.4mm^2 * 60MPa = 467.44kN$$

The total tension force T should be balanced to the compression force C

$$T = C \qquad T = T_1 + T_2 + T_3 = 467.48kN$$

$$M_U = M_{U_{-1}} + M_{U_{-2}} + M_{U_{-3}} + C \left(y_t - \frac{a}{2} \right) = 48.15kN.m$$

Following the same fashion the nominal moment capacity at rail seat and center section are summarized in [table 3.9](#) below.

Table 3.9: Nominal Moment Capacity of the sections

Section	Nominal moment capacity (kN.m)	
	Positive	Negative
Rail seat	48	32
Center	28	27

Cracking moment capacity

Applying the equation discussed in the literature review (section 2.5) results in

$$M_{R-}^{cr} = 24.16kN.m \qquad M_{R+}^{cr} = 27.64kN.m$$

$$M_{C-}^{cr} = 15.61kN.m \qquad M_{C+}^{cr} = 16.76kN.m$$

Table 3.10: Summary of the design moments and stresses

Location	Design bending moment (kNm)	Stress at the top of sleeper at design moment (MPa)	Stress at the bottom of sleeper at design moment (MPa)	Maximum allowable compression stress (MPa)	Maximum allowable tensile stress (MPa)
Rail seat	14	15.2	1.61	27	3.1
Center	12.55	2.51	14.13	27	3.1

4. DESIGN AND PARAMETRIC OPTIMIZATION OF PRESTRESSED CONCRETE SLEEPER

4.1 Modeling of the sleeper

The variables that are being optimized for this design are concrete grade, geometry of the sleeper and position and type of pre-stressing. The analysis part of the following model is replaced by the soft ware SAFE to show the interaction of the sleeper and the ballast in static loading case.

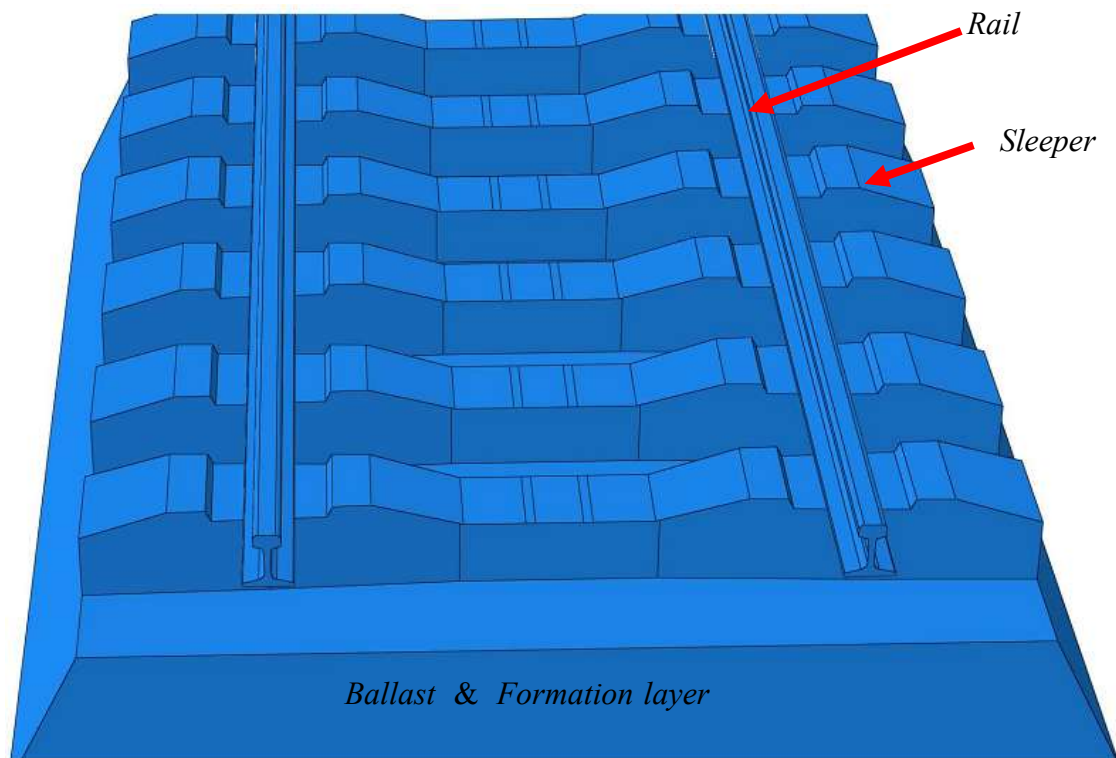


Figure 4.1: Proposed models

4.2 Parametric Optimization

4.2.1 Geometry of the sleeper

The geometry of the sleeper has an influence on the ballast pressure distribution and flexural capacity of the sleeper. The cross-sectional geometry at critical sections (Rail seat and center) has been evaluated with reference to safety and economy satisfying the minimum requirement based on AS 1085.14. Six distinct types of geometries are identified and modeled to evaluate their capacity, whichever is modified to the best one.

The geometry of the sleeper is directly related to the cross-sectional dimension of the sleeper especially at the critical sections of rail seat and center part. In this study six types of geometrical dimensions are proposed and analyzed the response of each case under loading. The better in

load carrying capacity and minimum in raw material consumption for production have been selected as **best** of the others. The proposed types of sleepers are shown in **figure 4.2** via **figure 4.7** below. The length of the sleeper under each case is kept constant 2.5m as the existing one.

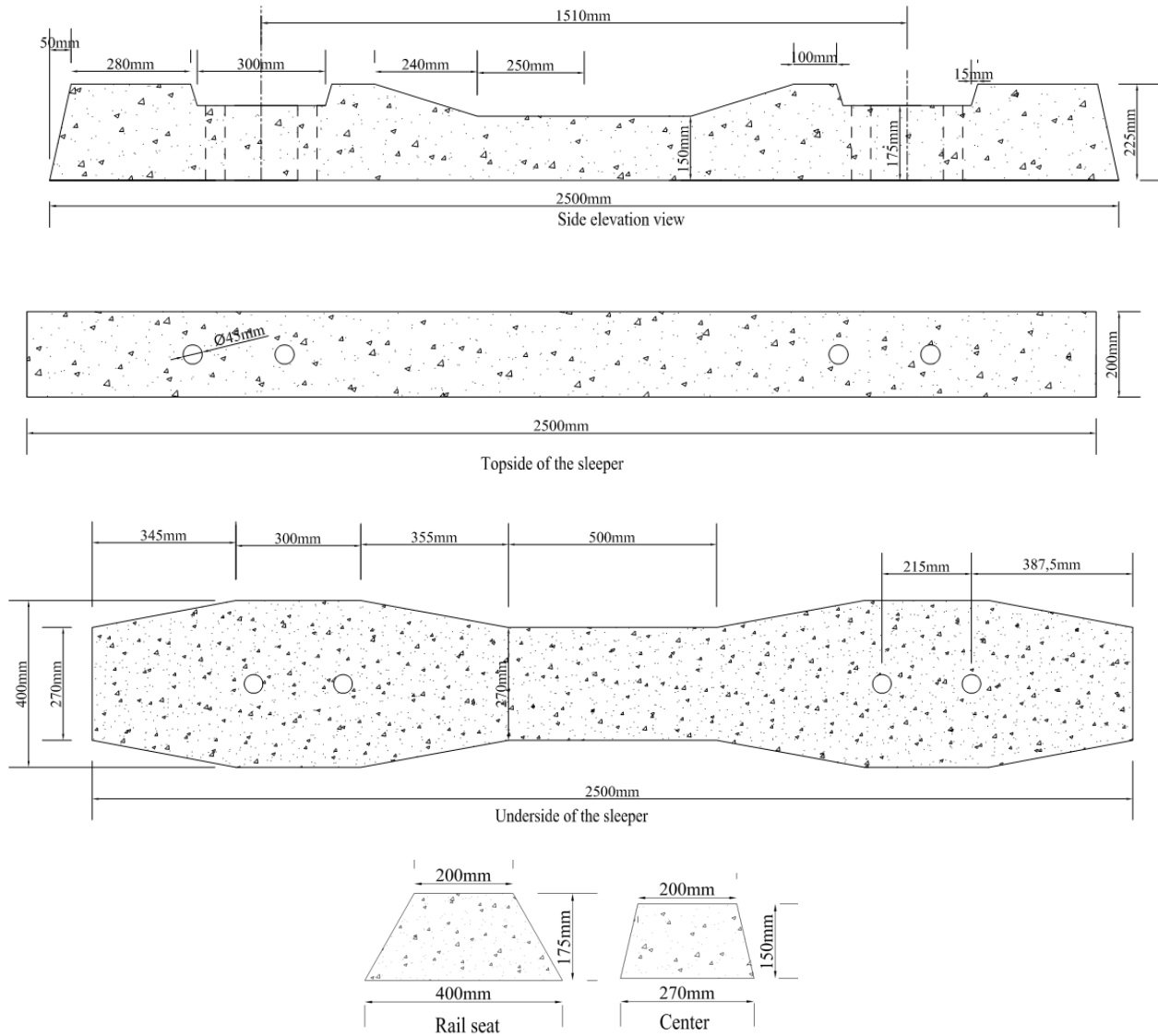


Figure 4.2: Geometrical dimension of Type-I Sleeper

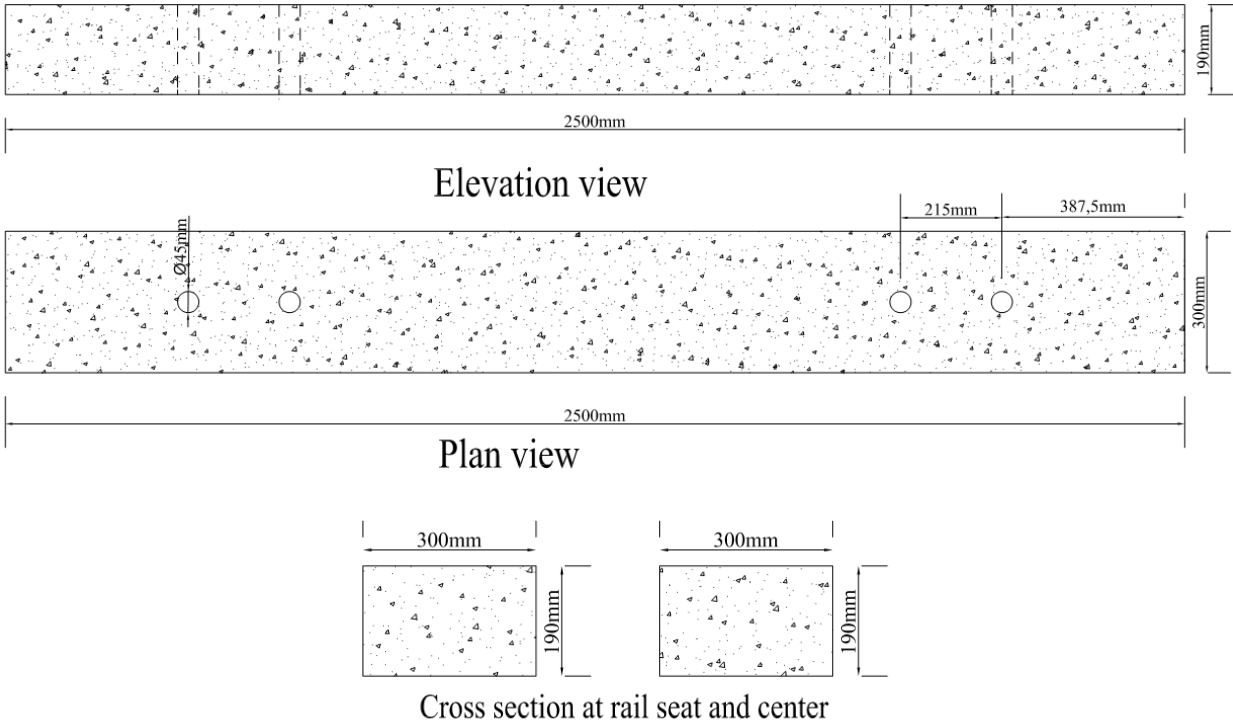
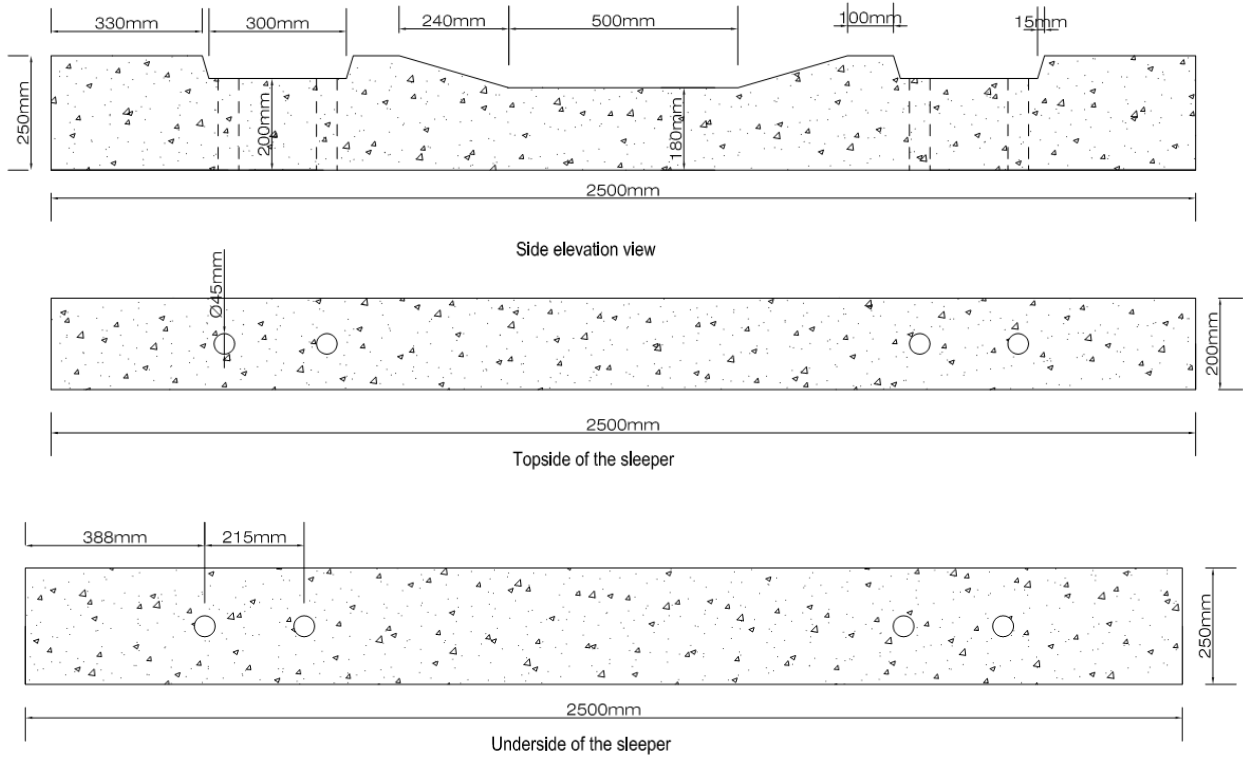
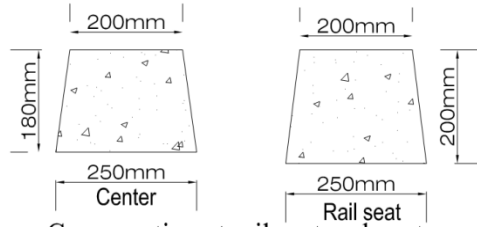


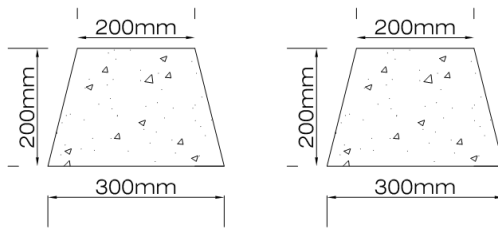
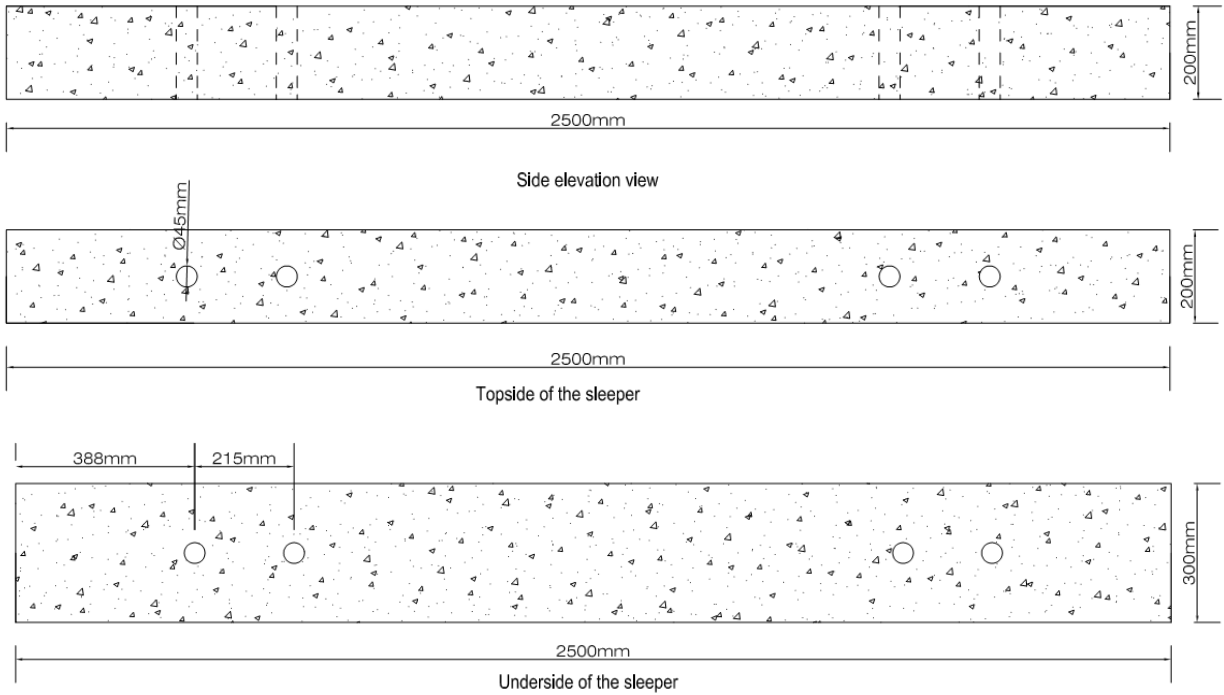
Figure 4.3: Geometrical dimension of Type-II Sleeper





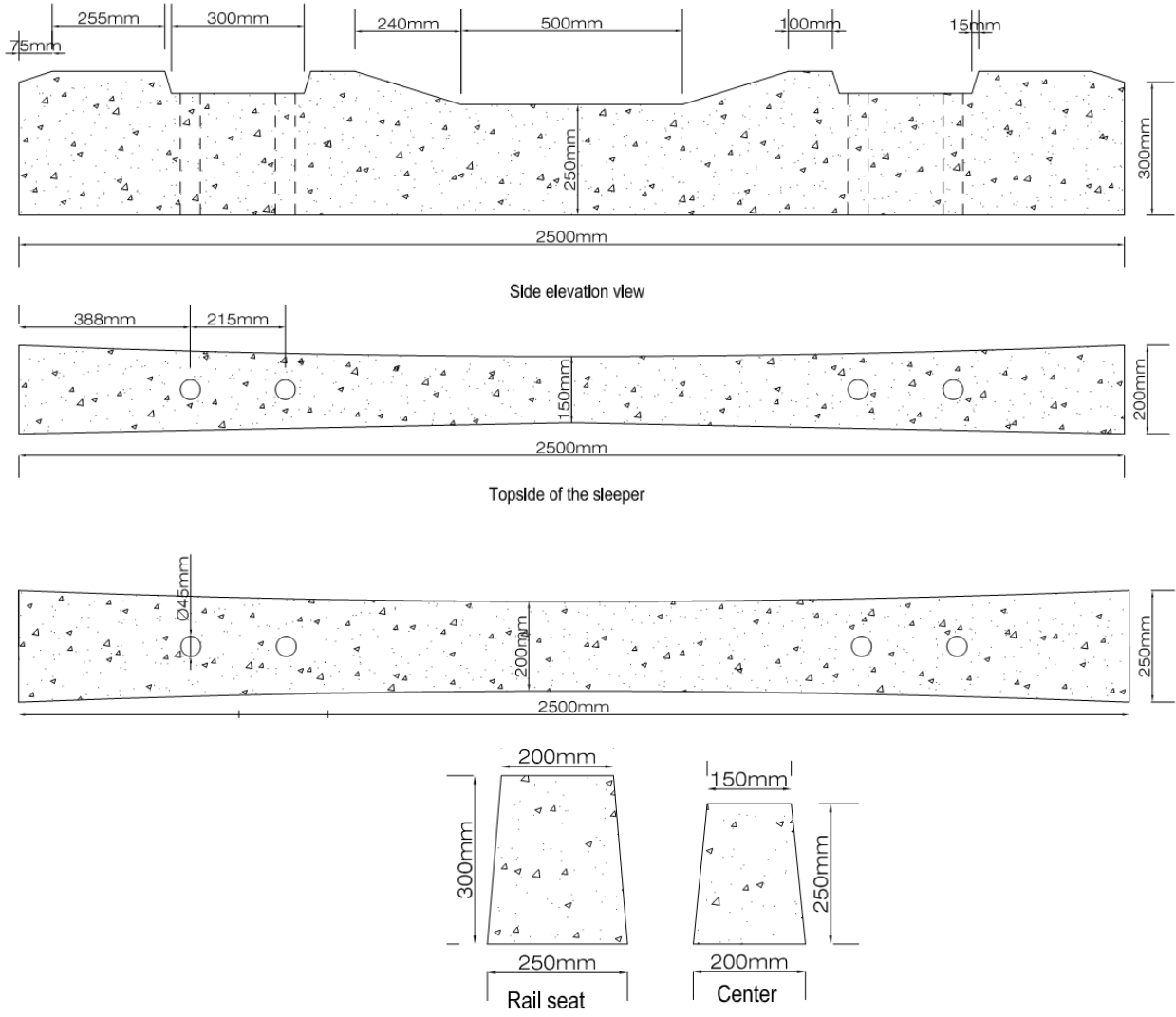
Cross section at rail seat and center

Figure 4.4: Geometrical dimension of Type-III Sleeper



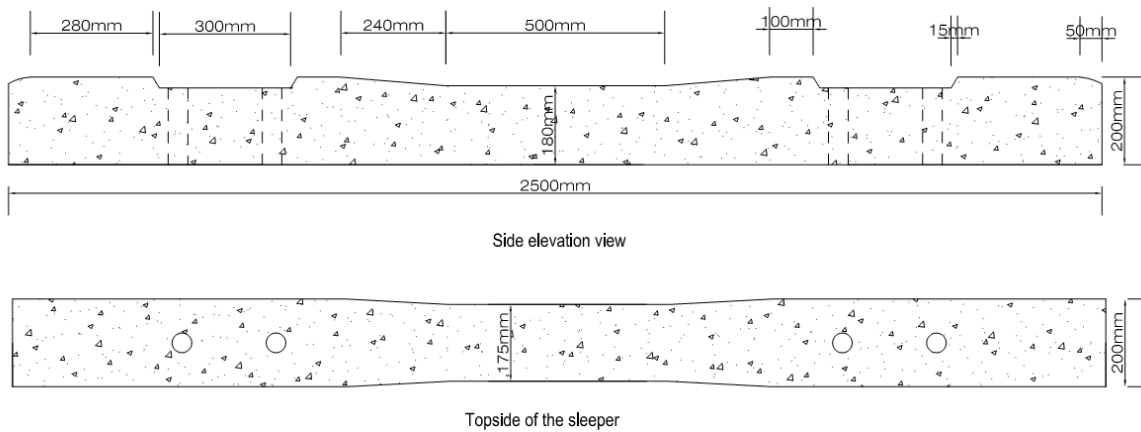
Cross section at rail seat and center

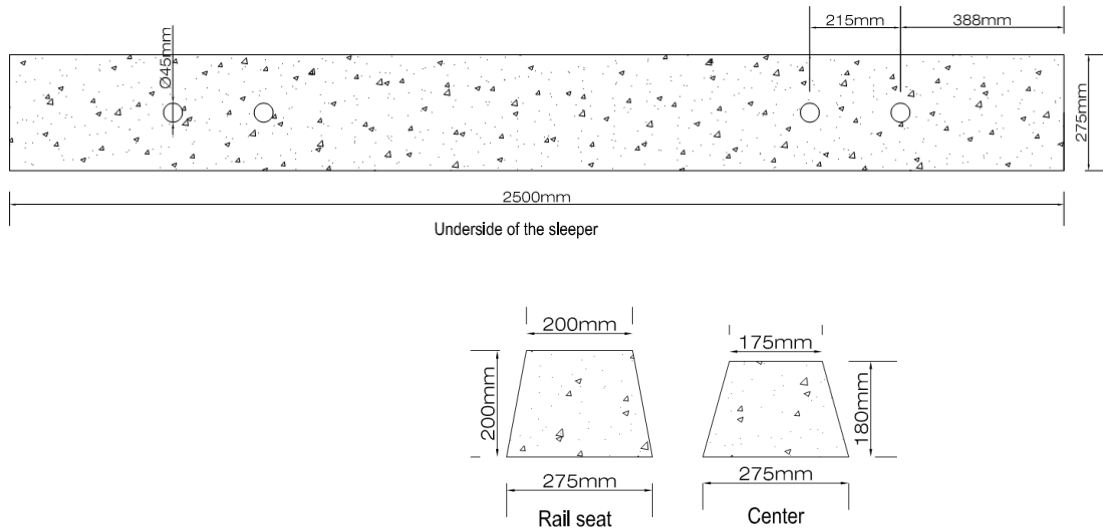
Figure 4.5: Geometrical dimension of Type-IV Sleeper



Cross section at rail seat and center

Figure 4.6: Geometrical dimension of Type-V Sleeper





Cross section at rail seat and center

Figure 4.7: Geometrical dimension of Type-VI Sleeper

The geometrical optimization is largely dependent on the allowable ballast pressure under the sleeper and positive and negative bending moments developed at the rail seat and center section of the sleeper. The ranging values of the ballast pressure are from 300kPa to 750 kPa, usually 600kPa is adopted as an appropriate average value for design (Talbot et al, 1920).

Table 4.1: Ballast pressure of proposed sleepers with limiting values

Sleeper Types	Sleepers Code	P_{ab} (kPa)	Max. P_{ab} (kPa)	Min. P_{ab} (kPa)	Av. P_{ab} (kPa)
Type-I	1	518.24	750	300	600
Type-II	10	578.7	750	300	600
Type-III	20	694.44	750	300	600
Type-IV	30	578.7	750	300	600
Type-V	40	771.6	750	300	600
Type-VI	50	631.31	750	300	600
Current	60	578.7	750	300	600

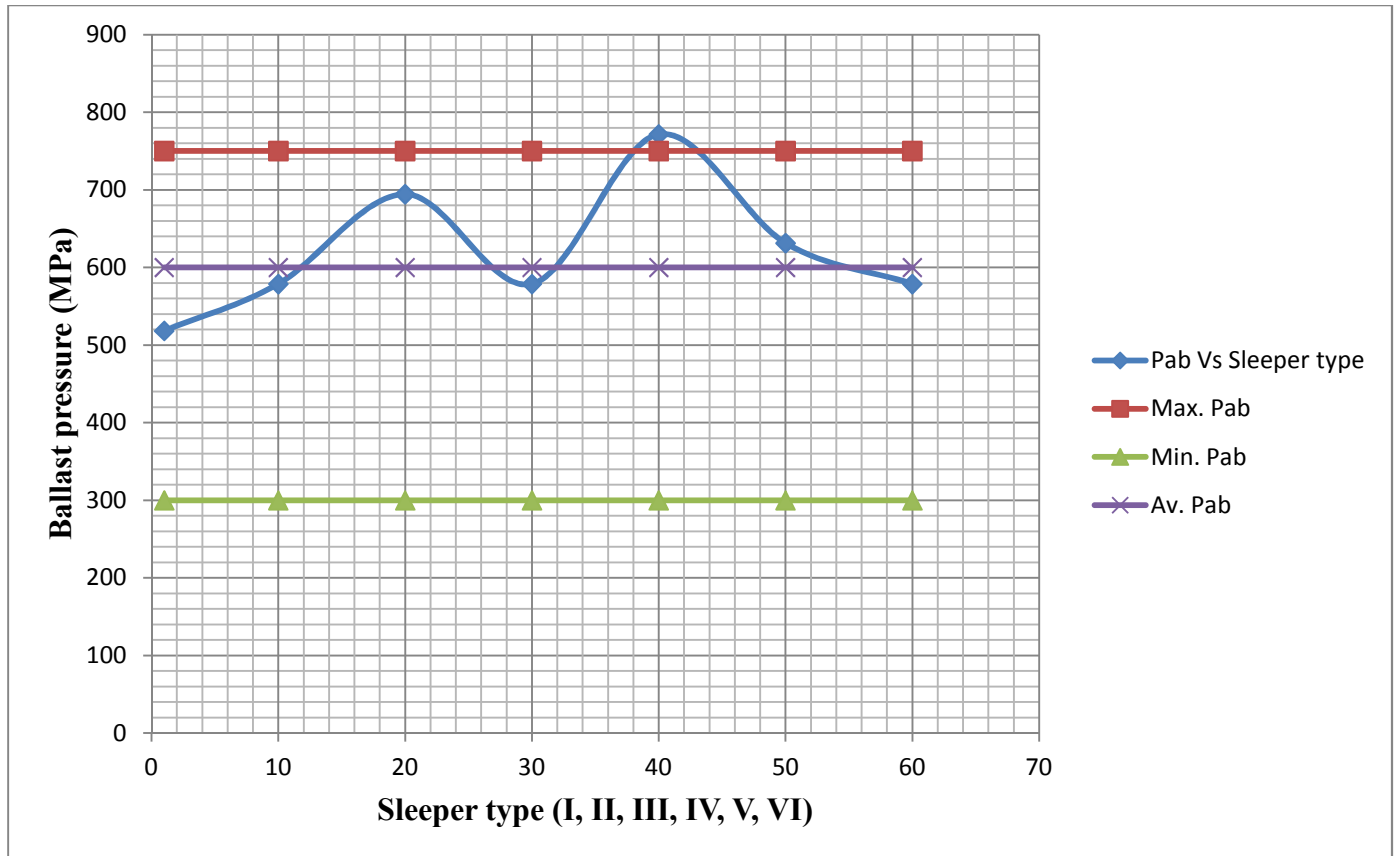


Figure 4.8: Ballast pressure Vs Sleeper types

From the above result the ballast pressure for both sleepers except Type-V seems visible because of the values are within the ranges. For more accurate and tangible result the ballast pressure distribution have been analyzed by using the software SAFE. The result shows that the ballast pressure concentrates more on the right and left **end** edges of the sleeper and decreases to the center. Based on these results the shape of Type-I sleeper has been **redefined** by making more wider at the **edges** and tapering to the center due to the assumptions for the design is uniform ballast pressure along the effective length **of the sleeper**. The analysis results from SAFE software are depicted in **appendix E**.

Table 4.2: Moment Capacity based on allowable stress

Parts	Moment Capacity at bottom fibers (kN.m)		Moment Capacity at top fibers (kN.m)	
	Positive	Negative	Positive	Negative
Rail seat	15.55	33.85	25.75	14.19
Center	8.34	18.53	10.88	14.2

Note: the reinforcement type and profile are kept constant of the current sleeper while the cross-section is type-I.

In order to determine the optimal cross sectional dimensions, the cross sectional area required carrying the maximum shear at the rail seat and the bending moment at the rail seat and center section has to be determined.

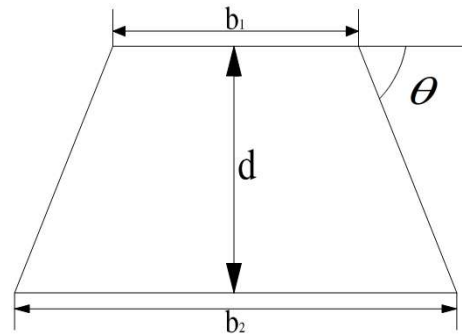


Figure 4.9: Cross section to be optimized

The bottom width b_2 is determined from the ballast pressure requirement, which is found to be 280mm at the rail seat and 235mm for the center section.

4.2.2 Concrete Grade

The concrete grade is one determinant factor for the optimization process. In most design codes including EBCS the minimum compressive strength of concrete is kept 40Mpa for pre-tensioned members. The iteration is done in between 40Mpa and 70Mpa, including 60Mpa of the existing grade of concrete (refer appendix F for the iterations).

The design strength of the concrete should be as high as the required level. As the concrete strength increases the capacity will increase directly but it will be uneconomical beyond the load imposed. The capacity of the concrete starting from the minimum design strength has been iterated to get the optimum capacity. The iteration has been employed for the optimized geometry done in appendix D based on SAFE software. The limiting factors are the stress levels allowed during the transfer and service load which are compared with the stresses due to imposed loads.

4.2.3 Position and type of pre-stressing wires

The pre-stressing wires position and its type **has been** varied for each geometry case and the best profile has been identified. The type of wire includes 7-wire strands, 3-wire strands and single indented wires of different diameters.

Pre-stressing wires used for pre-tensioned members are high strength wires. In practical case 1770MPa and 1860 MPa ultimate strength are used for pre-stressing. The type of wires used for this optimal design includes the EN10138-BS5896 7-wire strands having 9.3mm & 8mm diameter and 1860 MPa ultimate strength, 7mm diameter and 2060MPa ultimate strength, 3-wire strands 5.2mm and 6.5mm diameter and 1960MPa and 1860MPa ultimate strength respectively, single wires of 4mm, 5mm, 6mm, 7mm and 8mm diameter with 1860MPa, 1860MPa, 1770MPa, 1770MPa and 1670MPa ultimate strength respectively (ArcelorMittal, 2012) online version and (AS 3600 table 6.3.1).

The profile of each pre-stressing wire has been tested by alternating the position along the vertical cross sectional elevation of the sleeper. Tabular values of the different trials are shown in Appendix F₁ via F₁₀.

4.2.4 Selection of the optimized Sleeper

The selection of an optimal result is based on the ballast pressure and flexural capacity requirements. The average ballast pressure is kept 600kPa. The soffit dimension of the sleeper is tested by taking random geometry of the sleeper, in which the result shows the stress concentrates towards the end edges of the sleeper and none of them meets the requirements. Further reshaping of type-I geometry by widening at the edge and tapering to the center. Finite element software SAFE is used to evaluate the distribution of the ballast pressure, increasing the width at the end beyond 310mm **did** not results reduction in ballast pressure over the effective length. The center section bottom width is still possible to reduce further, but to avoid stress concentration it is fixed to 235mm.

The top width of the sleeper determined based on the fastening requirements and reinforcement accommodation with adequate **concrete** cover. The minimum clear concrete cover at the soffit of the sleeper shall be 35mm. elsewhere, the minimum clear concrete cover to tendons generally shall be 25mm with exception that the tendon may be exposed at end faces. The minimum clear tendon cover to an insert hole of fitting shall be 12mm. It should be noted that the top width be enough to the rail load without crashing, assessing all the above conditions the top width is fixed to 175mm kept constant via the length of the sleeper offsetting 230mm from both ends for lateral stability purpose.

The concrete grade, pre-stressing wire profiles and types, and depth of the critical cross sections are determined simultaneously. The iterations are shown in Appendix F₁ via F₁₀. Different types of pre-stressing wires are **tested** with different nominal diameter, as the diameters of the pre-stressing wires are increased the losses at the critical sections are increased, obviously higher at the center section. More loss is encountered at the center in both cases; losses are limited to 22% to 25%. Pre-tensioned members are limited to 22% of pre-stress loss. Even though the length of

the sleeper is kept constant 2.5m, the development length of tendons will govern the minimum required length.

4.3 Analysis of Optimized Sleeper

The design parameters depicted in section 3.1.1 are kept constant and all the analysis procedures are identical to the current sleeper except the optimized parameters. The geometry of the optimized sleeper is shown in [figure 4.11](#) and its cross-sectional properties are calculated below.

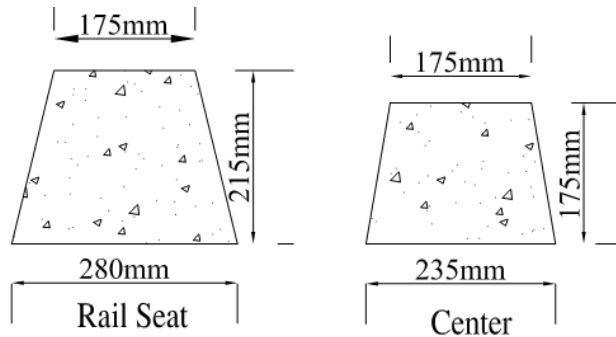


Figure 4.10: Cross section of optimized sleeper

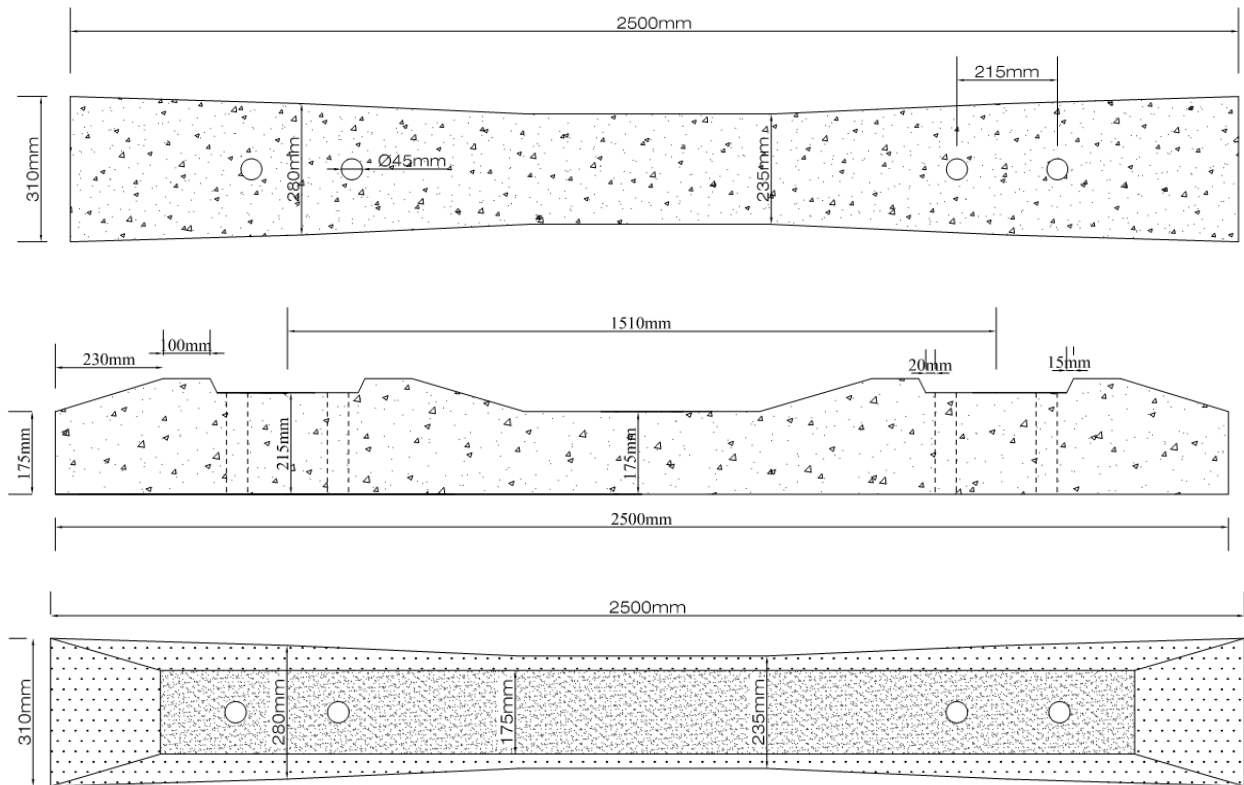


Figure 4.11: Geometry of the optimized sleeper

Cross sectional areas

At rail seat

$$A_g = \left(\frac{280+175}{2} \right) * 215 = 48,912.5 \text{ mm}^2$$

$$\text{Center of gravity from the bottom} = y_b = \left(\frac{2*175+280}{280+175} \right) * \frac{215}{3} = 99.23 \text{ mm}$$

$$\text{Center of gravity from the top} = y_t = \left(\frac{2*280+175}{280+175} \right) * \frac{215}{3} = 115.77 \text{ mm}$$

$$I_g = \frac{(215)^3}{36} \left[\frac{175^2 + 280^2 + 4*280*175}{175+280} \right] = 185,070,380.61 \text{ mm}^4$$

$$Z_b = \frac{I_g}{y_b} = \frac{185,070,380.61}{99.23} = 1,865,050.35 \text{ mm}^3$$

$$Z_t = \frac{I_g}{y_t} = \frac{185,070,380.61}{115.77} = 1,598,614.58 \text{ mm}^3$$

At center

$$A_g = \left(\frac{235+175}{2} \right) * 175 = 35,875 \text{ mm}^2$$

$$\text{Center of gravity from the bottom} = y_b = \left(\frac{2*175+235}{175+235} \right) * \frac{175}{3} = 83.23 \text{ mm}$$

$$\text{Center of gravity from the top} = y_t = \left(\frac{2*235+175}{235+175} \right) * \frac{175}{3} = 91.77 \text{ mm}$$

$$I_g = \frac{(175)^3}{36} \left[\frac{175^2 + 235^2 + 4*235*175}{235+175} \right] = 90,902,407.27 \text{ mm}^4$$

$$Z_b = \frac{I_g}{y_b} = \frac{90,902,407.27}{83.23} = 1,092,160.79 \text{ mm}^3$$

$$Z_t = \frac{I_g}{y_t} = \frac{90,902,407.27}{91.77} = 990,564.44 \text{ mm}^3$$

Pre-stressing wires

Nominal diameter of tendon (wire) is, $\phi_{wire} = 7mm$

Area of a single wire, $A_{wire} = 38.48mm^2$

Area of pre-stressing wires, $A_p = 8 * 38.48mm^2 = 307.87mm^2$

Table 4.3: Centroid of pre-stressing wires from the bottom of the sleeper

Layer	No bars	Area (mm ²)	Y (mm)	Ay (mm ³)
1	4	153.938	39	6003.58
2	4	153.938	147	22,628.89
	Σ	307.88		28,632.472

$$\bar{y} = \frac{\sum Ay}{\sum A} = \frac{28,632.472mm^3}{307.88mm} = 93mm$$

Table 4.4: Eccentricity of pre-stressing wires

Location	Centroid (y _b) of the section (mm)	Eccentricity (mm)
Rail seat	99.23	6.23
Center	83.23	-9.77

4.3.1 Design Forces

The maximum rail seat load (R) and ballast pressure is determined based on axel load (25 tones) and spacing of the sleeper (60cm). To account the dynamic and quasistatic load effects an augment factor is taken as 2.5 which is adopted by most known railway institutions. The distribution factor (D.F) is 0.5 based on [figure 3.5 & 3.6](#) of section 3.2.1.

$$R = Qj(D.F) = 125 * 2.5 * 0.5 = 156.25kN$$

The maximum ballast pressure (P_{ab}) is calculated by taking the effective length a=0.99m. For standard and broad gauge, the maximum ballast pressure is given by AS 1085.14 as

$$P_{ab} = \frac{R}{b(L-g)} = \frac{156.25kN}{0.2725(2.5-1.51)} = 579.2kPa, \text{ Where } b \text{ is the average bottom width over the effective length}$$

4.3.2 Design Moments

Based on table 3.5 of section 3 the maximum rail seat positive bending moment is given by $M_{R+} = \frac{R(L-g)}{8}$ and the maximum rail seat negative bending moment is 67% of the positive rail seat bending moment or 14kN.m whichever is greater. (AS 1085.14)

Therefore:

$$M_{R+} = \frac{R(L-g)}{8} = \frac{156.25kN(2.5m-1.51m)}{8} = 19.34kN.m$$

$$M_{R-} = 0.67 * 19.34kN.m = 12.96kN.m$$

But the design rail seat negative bending moment should not be less than 14kN.m (AS 1085.14)

The maximum center positive and negative bending moments are determined in similar fashion of section 3.3.2.

$$M_{C+} = 0.05R(L-g) = 0.05 * 156.25kN(2.5m-1.51m) = 7.73kN.m$$

$$M_{C-} = \frac{R(2g-L)}{4} * 0.75 = \frac{156.25kN(2 * 1.51m - 2.5m)}{4} = 15.23kN.m$$

4.3.3 Design Shears

Including the Australian standards, most of the railway institutions dictate that, if the section is adequate for flexure, it does not require to compute the shear force due to the continuously supported condition of the sleeper by the ballast. The maximum shear force occurs at the rail seat with uniform loads.

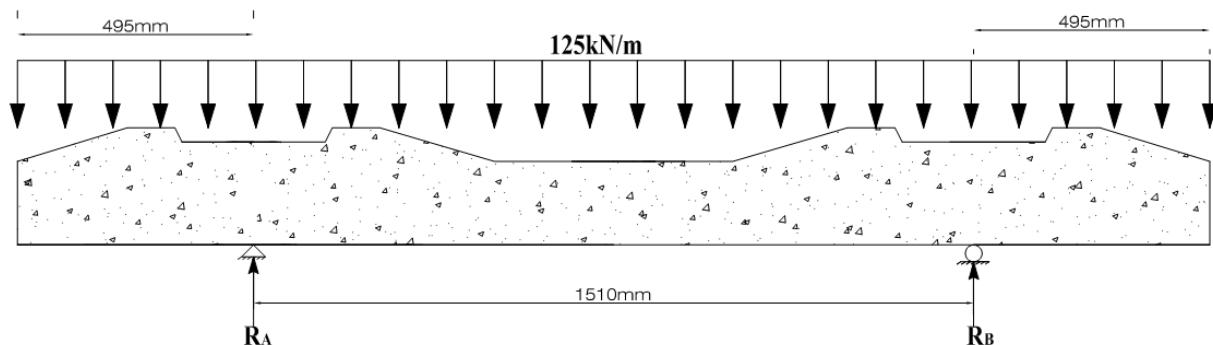
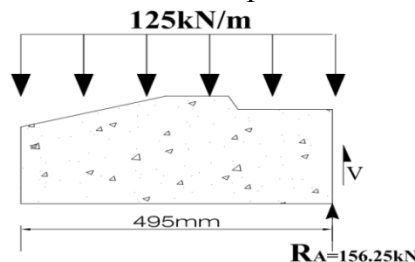


Figure 4.12: Uniform ballast pressure distribution diagrams

Reaction forces:



$$R_A = R_B = 156.25kN$$

$$\sum F_y = 0$$

$$156.25kN + V - 125kN/m * 0.495m = 0$$

$$V = 94.38kN$$

4.3.4 Capacity of the critical sections

Table 4.5: Losses of pre-stresses

Loss types		Rail Seat	Center
Immediate loss	Elastic shortening loss	3.29%	4.55%
	Shrinkage loss	4.52%	4.52%
Time dependent loss	Relaxation loss	4.93%	6.82%
	Creep loss	5.5%	5.5%
Total loss		18.23%	21.39%

Stress calculations

Table 4.6: Right side up position (Positive moment case)

Components			Stresses (MPa)		Remark
			Applied	Allowable	
Rail seat	At transfer	Top	6.87	16.37	OK
		Bottom	9.11	16.37	OK
	At service	Top	17.83	24.75	OK
		Bottom	-2.61	-2.97	OK
Center	At transfer	Top	15.59	16.37	OK
		Bottom	6.63	16.37	OK
	At service	Top	20.80	24.75	OK
		Bottom	-1.75	-2.97	OK

Table 4.7: Upright side down position (Negative Moment case)

Components			Stresses (MPa)		Remark
			Applied	Allowable	
Rail seat	At transfer	Top	9.96	16.37	OK
		Bottom	6.48	16.37	OK
	At service	Top	-2.16	-2.97	OK
		Bottom	14.54	24.75	OK
Center	At transfer	Top	7.88	16.37	OK
		Bottom	13.62	16.37	OK
	At service	Top	-2.41	-2.97	OK
		Bottom	19.27	24.75	OK

Table 4.8: Moment Capacity

Rail seat		Center		Design moment				Remark
Positive	Negative	Positive	Negative	Positive		Negative		
19.82	14.11	9.47	16.18	Rail seat	19.34	Rail seat	14	OK
				Center	7.73	Center	15.23	

Shear capacity

The critical section considered for shear check is the rail seat and all the parameters are related to this section. The design shear strength of a section shall be taken as ϕV_u according to AS 3600, where $V_u = V_{uc} + V_{us}$

Shear strength of a section excluding shear reinforcement

$$\text{For flexural shear cracking: } V_{uc} = \beta_1 \beta_2 \beta_3 b_v d_o \left[\frac{(A_{st} + A_{pt}) f_c'}{b_v d_o} \right]^{1/3} + V_o + P_v$$

$$\beta_1 = 1.1 \left(1.6 - \frac{d_o}{1000} \right) \geq 1.1 \Rightarrow \beta_1 = 1.1 \left(1.6 - \frac{180}{1000} \right) = 1.56$$

$$\beta_2 = \beta_3 = 1$$

$$A_{st} = 4 * 3.5^2 * \pi = 154 \text{ mm}^2$$

A_{st} = cross-sectional area of longitudinal reinforcement provided in the tension zone and fully anchored at the cross-section under consideration.

V_o = the shear force which would occur at the section when the bending moment at that section was equal to the decompression moment, M_o , given by $M_o = Z\sigma_{cp.f} = 14.8kN.m$

Where $\sigma_{cp.f}$ = the compressive stress due to pre-stress, at the extreme fiber where cracking occurs.

$$\text{For simply supported conditions: } V_o = \frac{M_o}{\left(\frac{M^*}{V^*}\right)} = \frac{14.8kN.m}{\frac{19.34kN.m}{94.38kN}} = 72kN$$

Where, M^* and V^* are the bending moment and shear force respectively, at the section under consideration, due to the same design loading.

$$b_v = b_w - 0.5 \sum d_d = 227.5mm$$

Σd_b = the sum of the diameter of the grouted ducts, if any, in a horizontal plane across the web.

$$P_v = \sin 30 * 334.18kN = 167kN$$

P_v = the vertical component of the pre-stressing force at the section under consideration.

$$V_{uc} = 285.5kN$$

Requirements for shear reinforcement:

The following requirements for shear reinforcement shall apply

$$V^* = 94.38kN < 0.5 * 0.7 * 285.5kN = 99.93kN, \text{ no shear reinforcement is required}$$

Minimum shear reinforcement:

The minimum area of shear reinforcement $A_{sv,min}$ is given by: $A_{sv,min} = \frac{0.35b_v s}{f_{sy.f}}$

Use 7mm diameter wire with 500MPa ultimate tensile strength

$$A_{sv,min} = 2 * 7^2 * \pi / 4 = 77mm^2, \text{ then the spacing stirrups will be}$$

$$s = \frac{A_{sv,min} f_{sy.f}}{0.35b_v} = \frac{77 * 500}{0.35 * 227.5} = 483.5mm$$

Use $\phi 7$ c/c spacing 480mm

Shear strength of a section with minimum reinforcement:

The ultimate shear strength of a section with a minimum shear reinforcement, $A_{sv, \min}$ shall be taken as $V_{u, \min} = V_{uc} + 0.6b_v d_o$

Contribution to shear strength by the shear reinforcement:

The contribution to the ultimate shear strength by shear reinforcement V_{us} shall be determined from the following equations:

$$V_{us} = \left(\frac{A_{sv} f_{sv} f d_o}{s} \right) (\sin \alpha_v \cot \theta_v + \cos \alpha_v)$$

Where:

s = the center to center spacing of shear reinforcement, measured parallel to the longitudinal axis of the member

θ_v = the angle between the axis of the concrete compression strut and the longitudinal axis of the member, taken conservatively as 45 degree or, more accurately, to vary linearly from 30 degree when $V^* = \phi V_{u, \min}$ to 45 degree when $V^* = \phi V_{u, \max}$

α_v = angle between the inclined shear reinforcement and the longitudinal tensile reinforcement.

Development length and end zone reinforcement

Development length of pre-tensioned tendons:

In the absence of substantiated test data, the development length, L_p , of pre-tensioned tendons for gradual release shall be taken as the transmission length given in **Table 4.9**, as appropriate to type of tendon and the strength of the concrete at transfer f_{cp} . Where strand or wire is untensioned, the development length shall be taken as not less than 1.5 times the value given in **Table 4.9**, as appropriate. It shall be assumed that no change in the position of the inner end of the transmission length occurs with time but that a completely unstressed zone of length $0.1L_p$ develops at the end of the tendon.

Table 4.9: Minimum transmission length for pre-tensioned members (AS 3600)

Type of tendon	L_p for gradual release	
	$f_{cp} \geq 32MPa$	$f_{cp} < 32MPa$
Indented wire	100d _b	175d _b
Crimped wire	70d _b	100d _b
Regular, super and compact strand	60d _b	60d _b

Where d_b is diameter of tendon (wire)

Transmission (transfer) length

Transmission length is the length over which the pre-stressing force is transmitted from the ends of the member. The pre-stressing force transmitted beyond the transmission length remains constant in most cases. The pre-stressing force is zero at end and reaches effective pre-stressing force zero at the transmission length.

$$L_t = \sqrt{\frac{\sqrt{f_{cu}} * 10^3}{\beta}} = \sqrt{\frac{\sqrt{55} * 10^3}{0.0235}} = 561.77mm$$

Bond length

Bond length is the minimum length over which, the stress in the tendon can increase from the effective pre-stress (f_{pe}) to the ultimate pre-stress (f_{pu}) at the critical location.

$$L_b = \frac{f_{pu} - f_{pe}}{4\tau_{bd}} \phi, \quad \tau_{bd} = 1.9Mpa$$

$$L_b = \frac{1770 - 1085.45}{4 * 1.9} * 7 = 631.23mm$$

Development Length

Minimum length over which the stress in tendon can increase from zero to the ultimate pre-stress (f_{pu}). The development length (L_d) is the sum of the transmission length (L_t) and bond length (L_b).

$$\begin{aligned} L_d &= L_t + L_b \\ &= 561.77 + 631.23 = 1193mm > 1.5 * 100 * 7mm = 1050mm \quad OK \end{aligned}$$

Transverse tensile stress develops due to pre-stressing forces and hoyer effect which is critical during the transfer of pre-stress. End zone reinforcement is provided to prevent splitting of concrete. This reinforcement is provided along the transmission length to carry the tensile stress. The minimum amount of end zone reinforcement is calculated using the following expression.

$$A_{sv} = \frac{2.5M}{f_s h} = \frac{2.5 * 19.34kN.m}{434.78MPa * 215mm} = 517mm^2$$

Provide 2 ϕ 7 at each end having 500MPa ultimate tensile strength

Where

h = total depth of the section

M = moment at the horizontal plane at the level of CGC due to the compressive stress block above CGC

f_s = permissible stress in the reinforcement

Lateral and Longitudinal Loads

Lateral loads

In order to prevent gauge-widening under traffic, fastenings shall restrain the rail from lateral movement when a lateral load is applied at the rail head in addition to vertical wheel load as specified in Clause 4.2.1.1. AS 1085.19 provides requirements for resilient fastenings. The loads and appropriate limits on lateral movement depend upon the type of traffic and track under consideration which is not more significant in this analysis as the tensile strength of the tendons and the shear capacity of the concrete is larger than the overburden loads in to consideration.

Longitudinal loads

The rail shall be restrained to avoid excessive longitudinal movement. A minimum longitudinal restraint force of 10 kN per rail seat shall be allowed. Maximum movement of the rail relative to the rail seat under such a load shall not exceed the values given in AS 1085.19.

The fastening system shall be in accordance with AS 1085.19. Where cast-in components are used, they shall be designed for the full life of the sleeper. The cast-in component shall be set in the concrete to a level below that of the top tendons.

The resilient fastening assembly shall have a tolerance from the rail seat centre-line to the gauge-restraining face within the requirements of the purchaser. Abrasion-resistant pads or abrasion-vibration and impact-reducing pads shall be used between the rail and concrete sleepers to minimize the possibility of abrasive action in the rail-bearing area of the sleepers.

The rail pads are integral components of the concrete sleeper system. The degree of softness or hardness of the rail pads should be considered individually for each installation. Factors such as wheel loads, speed of traffic, grade and degree of curvature should be considered. Based on these considerations dealing with those parameters are slight importances of PSC.

4.4 FEA of the optimized model as design verification

Finite element analysis (FEA) is a powerful tool which can be applied to the design of irregular shaped members, whose geometry causes standard analysis to be difficult or more importantly inaccurate. For flexural members that are exposed to regions of high stress concentration or

exhibit varying cross-sectional dimensions along their length, the application of FEA modeling techniques is a valued addition to the analysis process. It allows for the addition of sophisticated geometry which would have previously been simplified or neglected (Logan, 2007).

For the reasons discussed above, pre-stressed concrete railroad sleepers are an excellent candidate for analysis using FEA modeling methods. Using the FEA modeling techniques, an evaluation of an optimized sleeper designs can be completed. Reasons for modeling the sleeper designs include:

- Having a second numerical analysis technique to compare with theoretical results,
- There are currently few examples of FEA analysis on pre-stressed concrete railroad sleepers,
- FEA analysis offers the ability to evaluate member behavior through the entire loading range to ultimate capacity,
- FEA analysis allows for the evaluation of many iterations with relatively little computational expense on the part of the user compared to other numerical

The following sections outline the application of FEA modeling to pre-stressed concrete railroad sleeper design. To validate the application of FEA modeling to the analysis of pre-stressed concrete sleeper, a model of an optimized sleeper design can be completed and compared to numerical results in the calculations. Experimental results for the baseline sleeper design are available from the sleeper manufacturer and summarized on the design sheet. The validation model would consist of the overall member geometry and the associated concrete and pre-stressing materials. Factors to be considered in the FEA model are material properties, pre-stressing force itself, transfer lengths, bond slip, loading stages and boundary conditions.

In this study, the ANSYS finite element computer program was used to simulate the behavior of the pre-stressed concrete sleeper capacity done by numerically. The finite element model uses a discrete model approach. Three dimensional elements have been used to model pre-stressed concrete sleeper and reinforcement bar elements. This model can help to confirm the theoretical calculations as well as to provide a valuable supplement to the experimental investigations of behavior of pre-stressed concrete sleepers.

Element selection

A variety of element types exists for both steel and concrete materials because the purpose and desired output may vary from model to model. The following section summarizes suggested elements for use in modeling pre-stressed concrete members.

Solid Elements

Characteristics of solid elements which are necessary for modeling concrete included; the ability to model the cracking and crushing of the solid matrix, user defined inelastic response. It is recommended that the user start with the SOLID65 three-dimensional reinforced concrete solid

element which is defined by eight nodes with each having three degrees of freedom (Figure 4.13). This element must be used in association with the discrete model since edge nodes are not available. To obtain non planar surfaces associated with the tie geometry prism and tetrahedral options are available. The SOLID65 is capable of cracking tension and crushing in compression due to built in algorithms which are dependent on user input of material parameters.

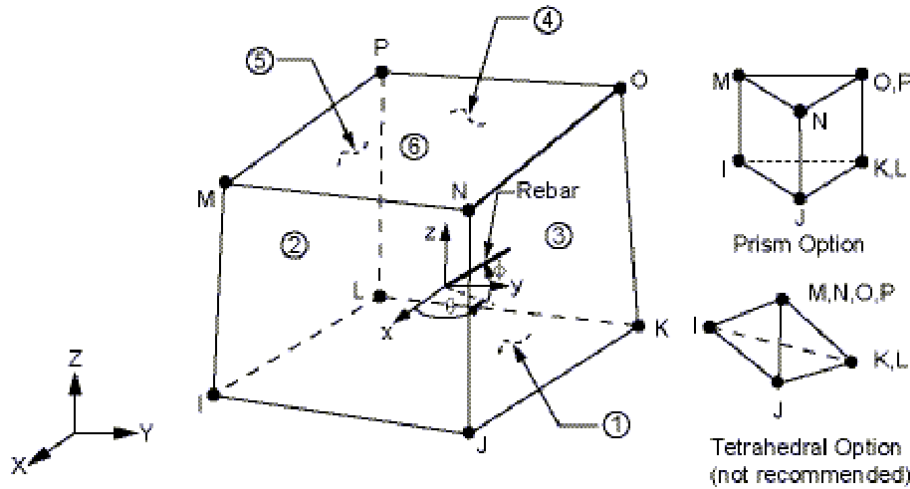


Figure 4.13: SOLID65 Element

Bar Elements

To model pre-stressing the two necessary element characteristics are the ability to perform inelastic behavior and define an initial strain. It is recommended starting with the LINK8 element (Figure 4.14). This is a truss element which is capable of compression and tension with three degrees of freedom at each node. Each end node is modeled as a pin connection so no bending of the element is considered. An advantage of the LINK8 element is the ability to specify an initial strain. This is useful for defining the initial pre-stressing force. In addition, pre-stressing transfer can be completed by simply varying the initial strain along the length of the steel mesh.

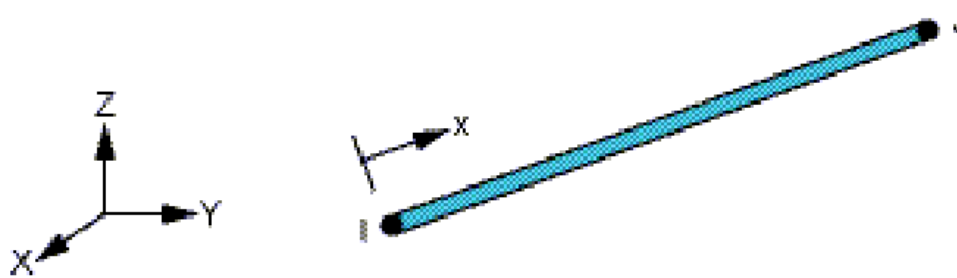


Figure 4.14: LINK8 Element

Material constants

Parameters needed to define the material models are summarized below in [table 4.10](#)

Table 4.10: Material constants for FEA

Parameters	Solid 65 element (concrete)	Link 8 element (steel)
Poisson ratio	0.2	0.3
Elastic modulus	37452 MPa	200000 MPa
Density	2400kg/m ³	7800kg/m ³
shear transfer coefficient	0.9	-----
Yield stress	55 MPa	1770Mpa
Tensile stress	2.97 MPa	1085MPa
Strain value	0.003	0.00542

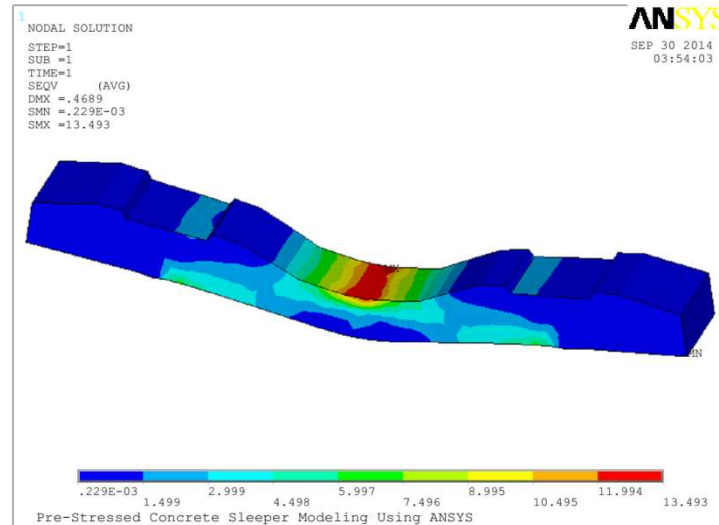
Load application and boundary conditions

The applied load and boundary conditions for the FEA model is based on the laboratory testing setup of AS 1085.14-2003 which is discussed in section 2.5. The four models are developed with respect to the laboratory setup and analyzed. The aim of the model and analysis is to verify the theoretical calculations done in the design and analysis process instead of laboratory testing.

By employing the same principles of section 2.5, the cracking moments and applied test loads are calculated as follows:

$$M_{R-}^{cr} = 23.1kN.m \quad M_{R+}^{cr} = 26.6kN.m \quad M_{C-}^{cr} = 18.25kN.m \quad M_{C+}^{cr} = 19.8kN.m$$

$$P_1 = 181.0kN \quad P_2 = 186.54kN \quad P_3 = 53.69kN \quad P_4 = 58.25kN$$



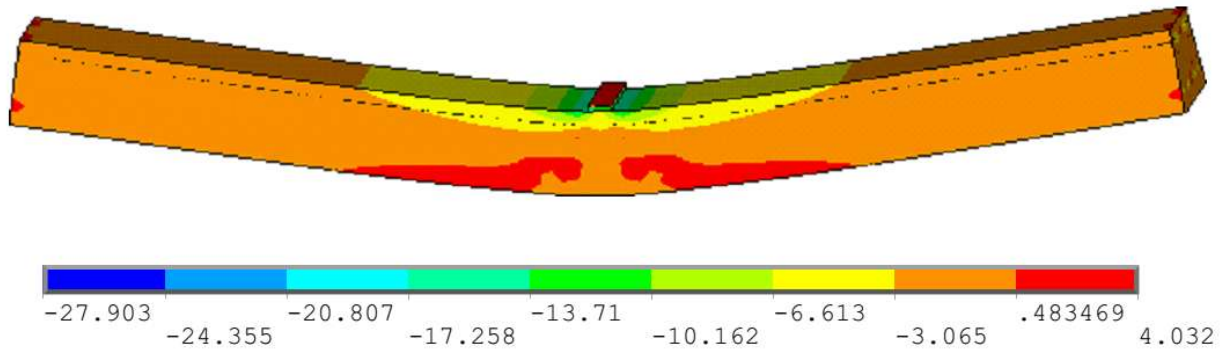


Figure 4.15: Center positive moment analysis result

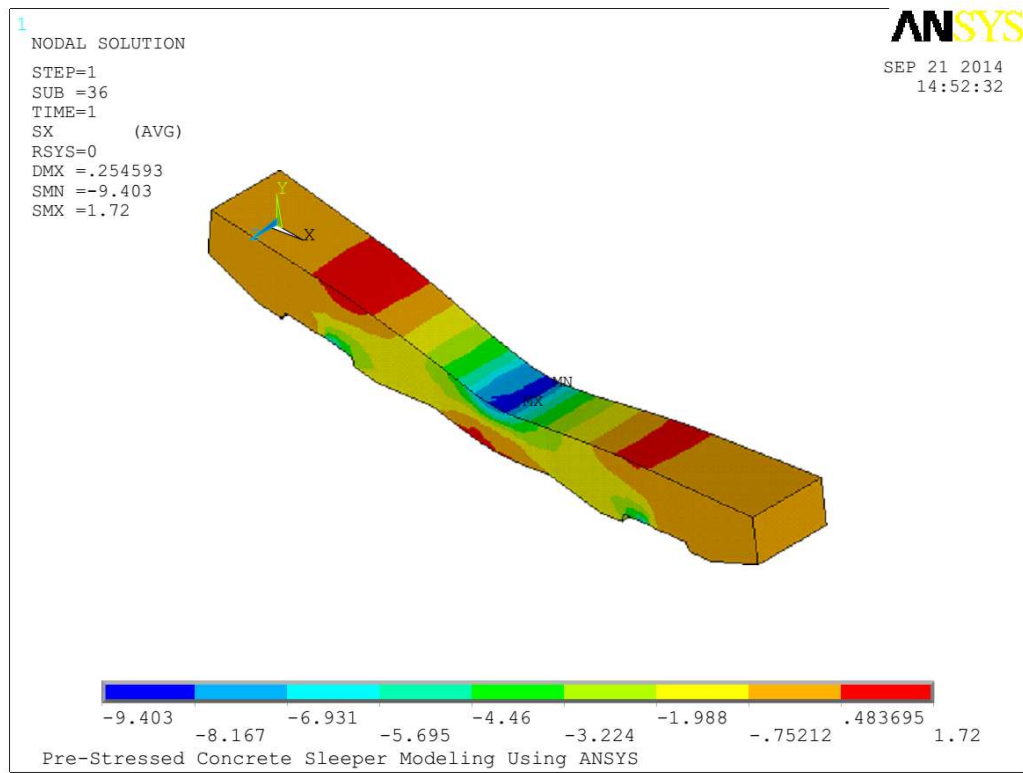


Figure 4.16: Center negative moment analysis results

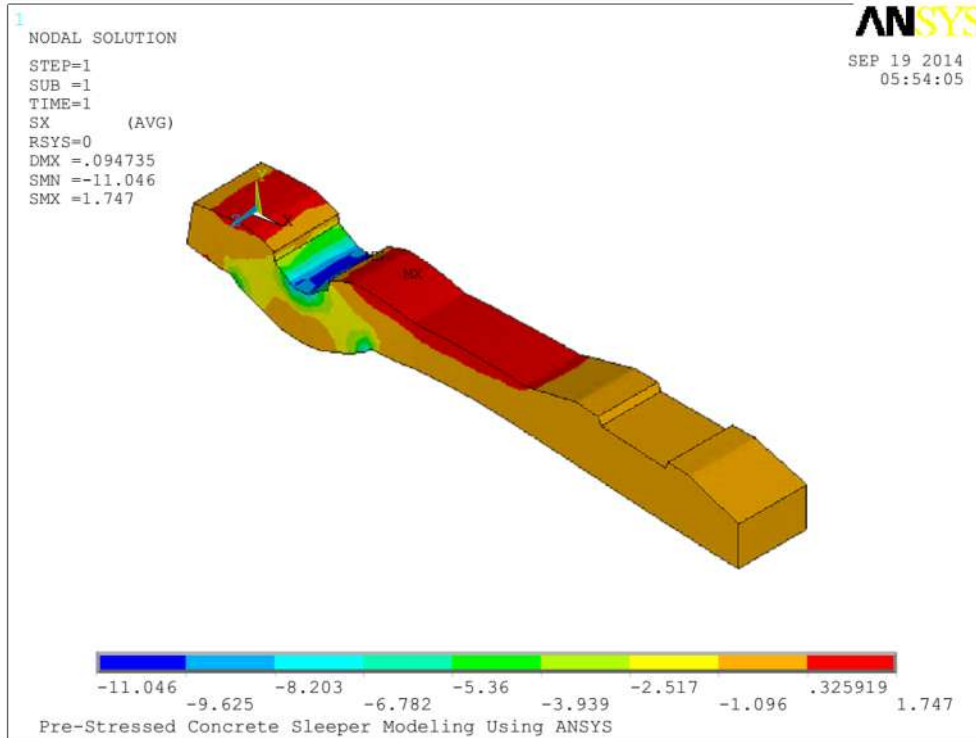
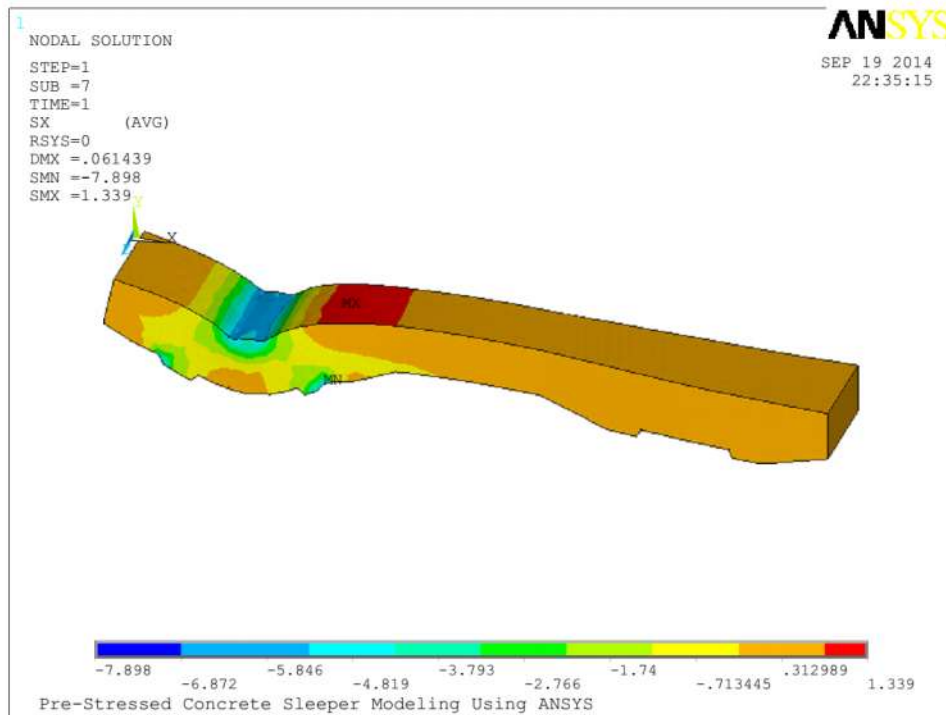


Figure 4.17: Rail seat positive moment analysis results



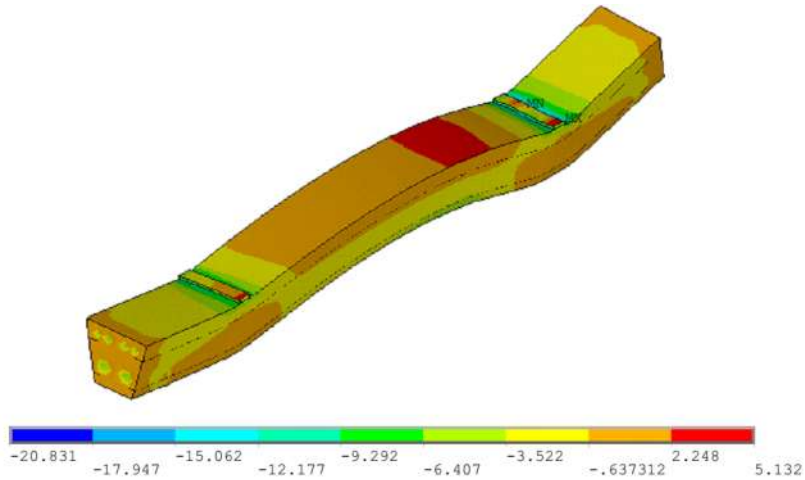


Figure 4.18: Rail seat negative moment analysis results

Table 4.11: ANSYS analysis summary of the optimized sleeper

Location	Design bending moment (kNm)	Stress at the top of sleeper at design moment (Mpa)	Stress at the bottom of sleeper at design moment (Mpa)	Maximum allowable compression stress (Mpa)	Maximum allowable tensile stress (Mpa)
Rail seat	17.97	10.45	1.65	27	3.1
Sleeper center	12.81	1.4	12.93	27	3.1

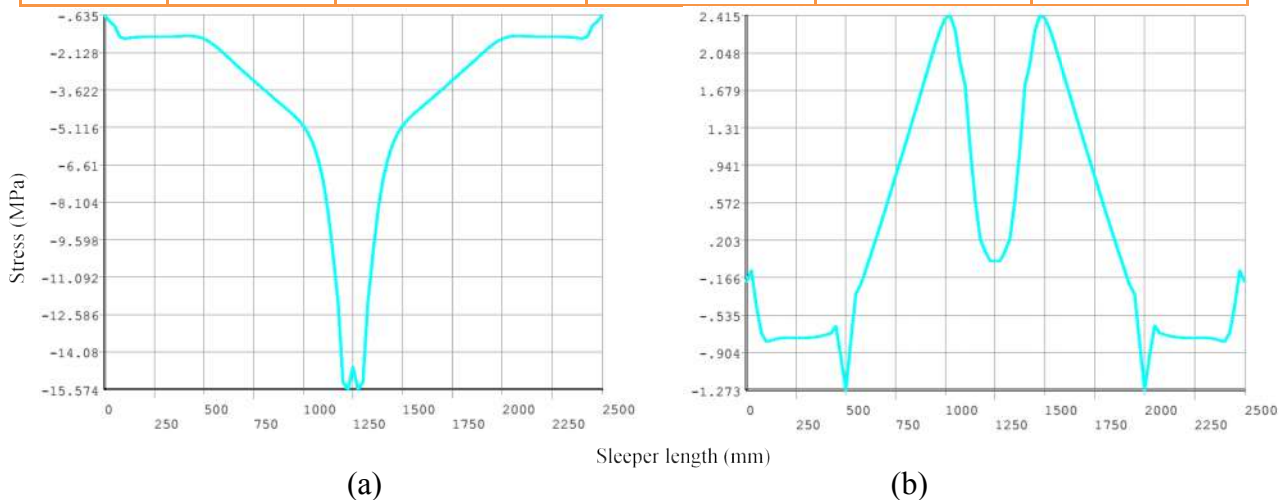
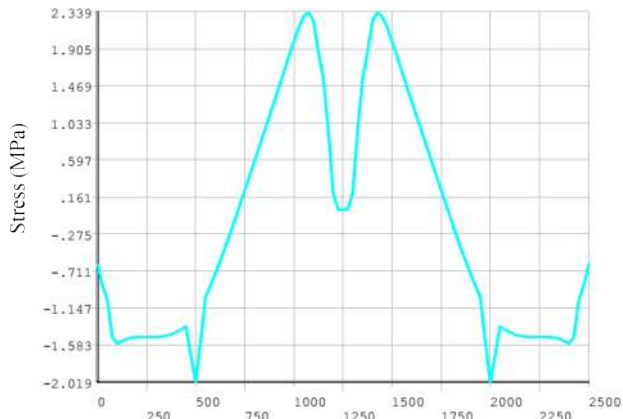
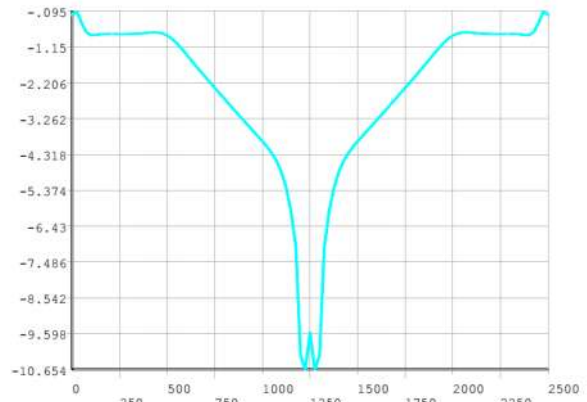


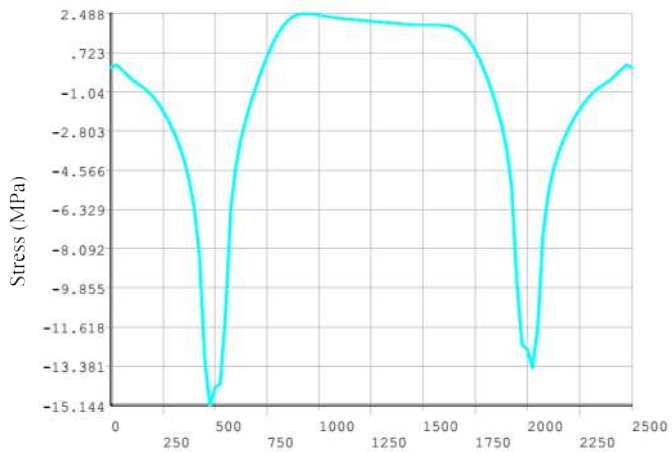
Figure 4.19 (a) Top and (b) Bottom fiber stress vs sleeper length (Center positive)



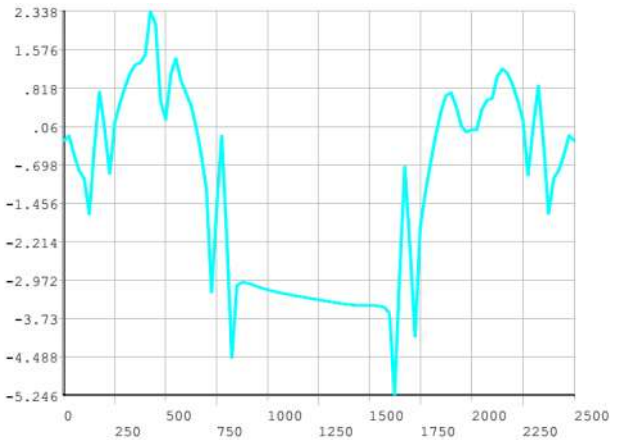
(a)



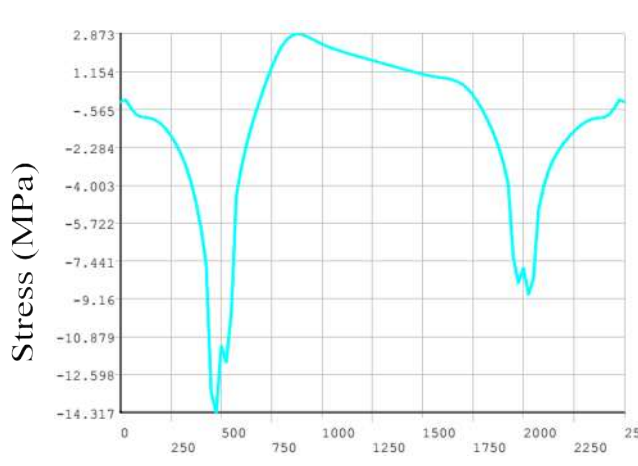
(b)

Figure 4.20 (a) Bottom and (b) Top fiber stress v_s sleeper length (Center negative)

(a)



(b)

Figure 4.21 (a) Top and (b) Bottom fiber stress v_s sleeper length (Rail seat positive)

(a)



(b)

Figure 4.22 (a) Bottom and (b) Top fiber stress v_s sleeper length (Rail seat negative)

The moments induced at the critical sections are calculated using the section modulus and maximum stresses developed from the analysis by using ANSYS.

Rail seat section

Positive moment (M_{R+})

$$M_{R+} = Z_t f_c = 1,598,614.58 \text{mm}^3 * 15.144 \text{N/mm}^2 = 24.21 \text{kNm}$$

Negative moment (M_{R-})

$$M_{R-} = Z_b f_c = 1,865,050.35 \text{mm}^3 * 14.32 \text{N/mm}^2 = 26.71 \text{kNm}$$

Center section

Positive moment (M_{C+})

$$M_{C+} = Z_t f_c = 990,564.44 \text{mm}^3 * 15.574 \text{N/mm}^2 = 15.43 \text{kNm}$$

Negative moment (M_{C-})

$$M_{C-} = Z_b f_c = 1,092,160.79 \text{mm}^3 * 10.654 \text{MPa} = 11.64 \text{kNm}$$

Stresses due to pre-stress forces

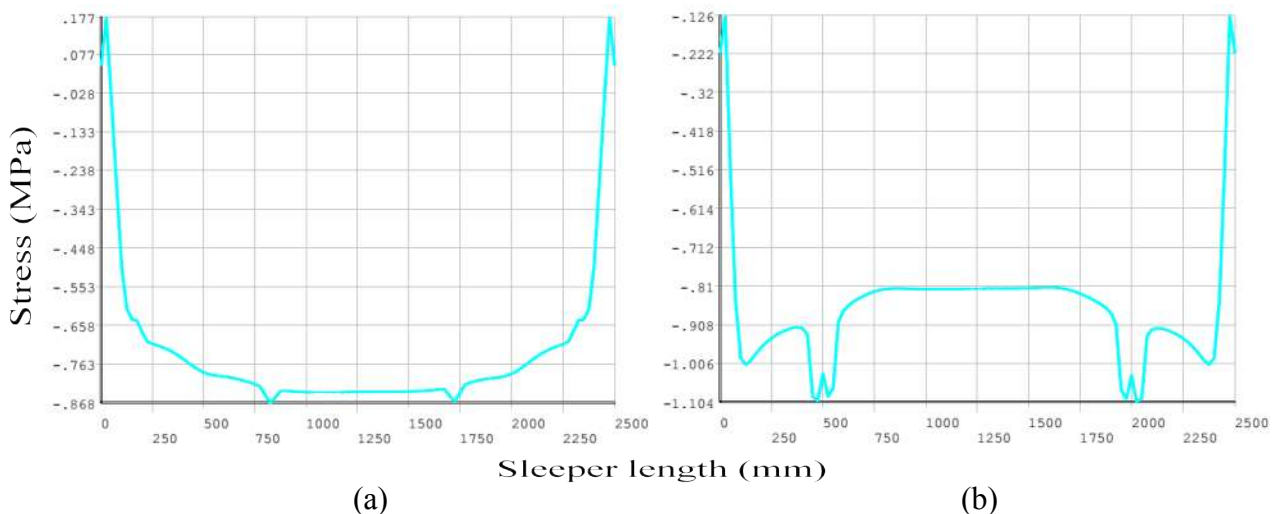


Figure 4.23 (a) Top and (b) Bottom fiber stresses v_s sleeper length due to pre-stress force

5. CONCLUSION AND RECOMMENDATIONS

5.1 Conclusion

From the analysis procedure for the existing and optimized sleepers, the following points are stipulated for conclusion.

- The analysis result of existing sleeper shows that, its flexural capacity is adequate for the planned 25 tone axel load based the design Code of AS 1085.14. But it is possible to attain the required load carrying capacity with lower concrete volume and slight shape refinement by arranging the profile of pre-stressing wires, which is done in this thesis research. Failure occurs due to fatigue crack at the top of the center section and deterioration of concrete at the PE holes.
- The optimization process in this research is not fully expressed mathematically with objective function rather an iterative procedure has been employed to make the design and analysis economical with reference to the existing sleeper. So it is open to further optimization researches on pre-stressed concrete sleepers.
- Iterative procedures have been adopted to observe the response of the proposed sleeper capacity by varying the shape of the sleeper, concrete grade, tendon (wire) type and profile. This results in a reduction of concrete volume used and relatively lower concrete grade (C-55) than the existing one (C-60) satisfying the flexural capacity of the sleeper.
- The profile of the pre-stressing wires above and below the CGC is symmetrical (requires same steel area) to attain the flexural capacity requirements at critical sections (rail seat and center section).
- The soffit of the sleeper dimension is determined by using the software SAFE which shows that wider dimension is required at the ends and narrowing to the center taking care to avoid stress concentration.
- Lower strength concrete grade below C-40 is not suitable for pre-stressed concrete sleepers due to insufficiency of transfer strength as a result of pre-stress forces.
- The eccentricity of tendons at the rail seat and center section highly governs the flexural capacity of the section. At the rail seat the eccentricity is below the centroid of the section, at the center above the CGC ensures the negative moment capacity of the section.
- From the optimized result the diameter of 7mm wire having 1770MPa ultimate tensile strength is selected considering the capacity and safety of the structure. The final optimized geometry of the sleeper is depicted in figure 4.11.
- FEA by using the software ANSYS has been applied to model and verify the numerical analysis done by code provision. From this analysis the stress induced at critical sections are proximate to the analysis result and the possible errors are the time dependent losses are not accounted in case of ANSYS analysis and the analysis setup (model) is based on lab setup which results in the maximum values for design purpose.
- Lateral and Longitudinal loads are significantly considered in the analysis of fastening systems which is not part of this research and taken as less important of taking in to consideration during the analysis.

5.2 Recommendations

Further researches required related to pre-stressed concrete sleepers which are not covered in this thesis are recommended as follows:

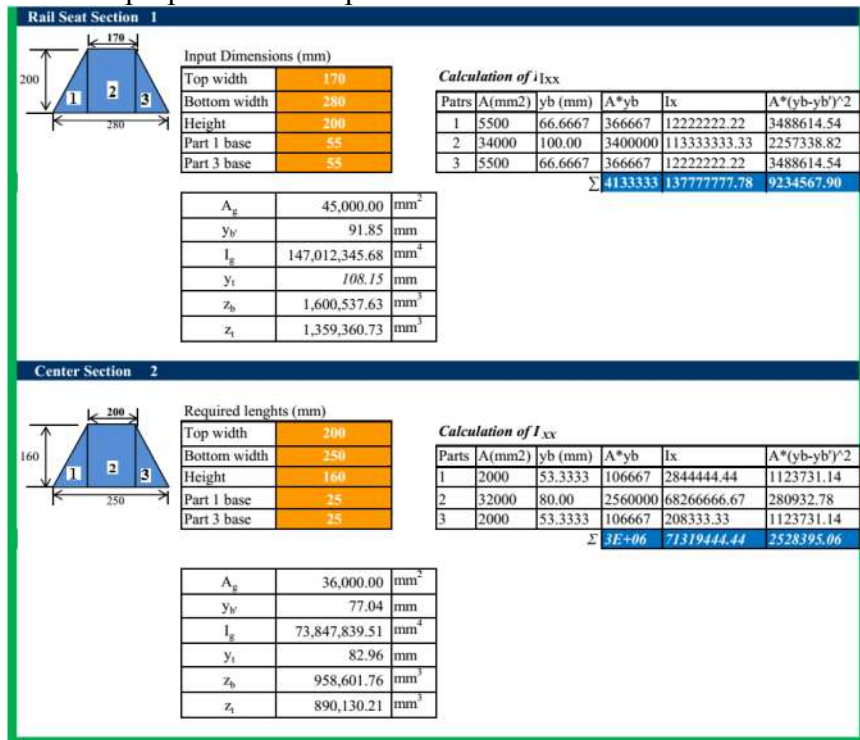
- ❖ Analysis of special sleepers used for turnouts, “dual gauge” sleepers and sleepers with additional rails
- ❖ The effect of sleeper spacing on the capacity of the sleeper
- ❖ Validation by testing of sleepers obtained via FEA and theoretical calculations based on code provisions.
- ❖ The fastening system in relation to lateral load adequacy and its stability
- ❖ The effect of sleeper length in development length of the tendon
- ❖ The design and Analysis of post-tensioned concrete sleepers
- ❖ Most common failure types found in the current sleepers include the failure of the polyethylene (PE) pipe around the bolt hole. This PE pipe is used for the screw type fastening system and can lead to concrete deterioration around the hole. Ties which are found to have PE pipe failures are commonly replaced with a new concrete tie by providing reinforcement around the hole. Another failure mechanism is fatigue cracking in the center top of the tie, usually observed on heavy freight lines. Thus, it is vital to conduct researches on these critical issues which are last but not least recommendation.

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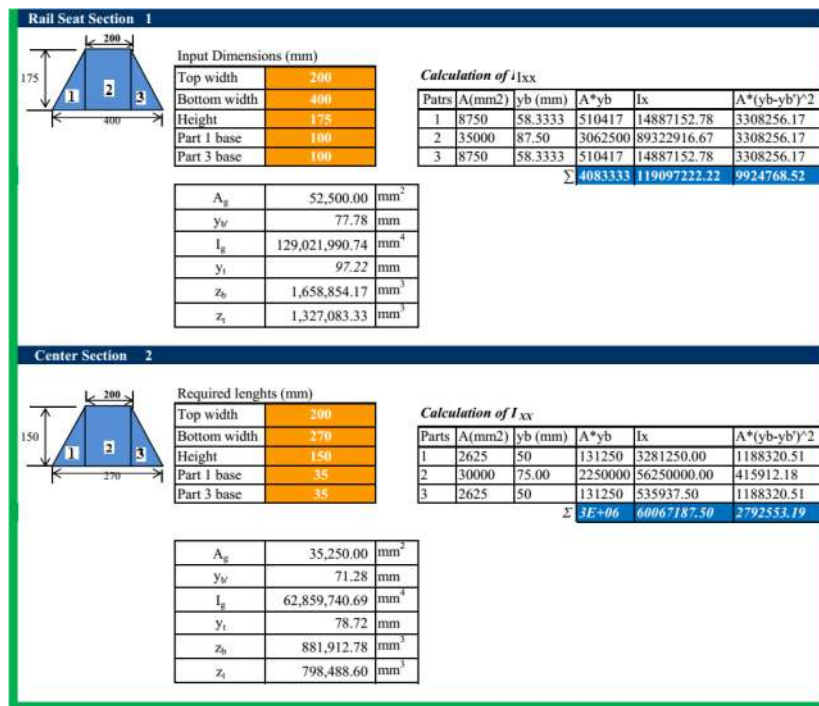
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APPENDICES

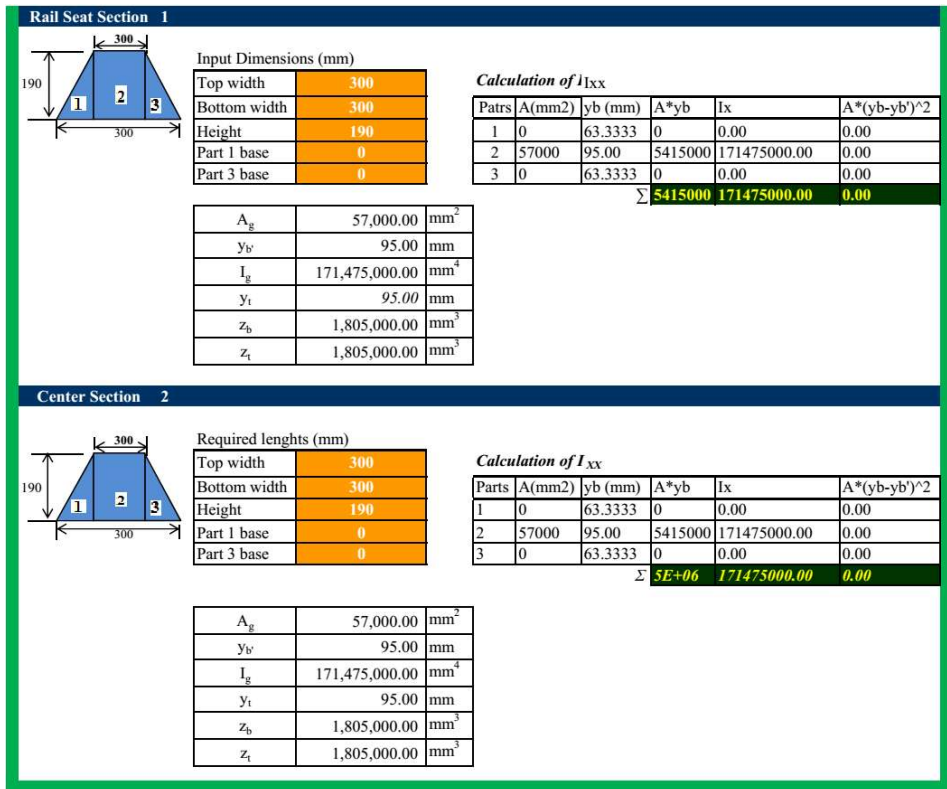
Appendix A: Section properties of sleepers at rail seat and center section



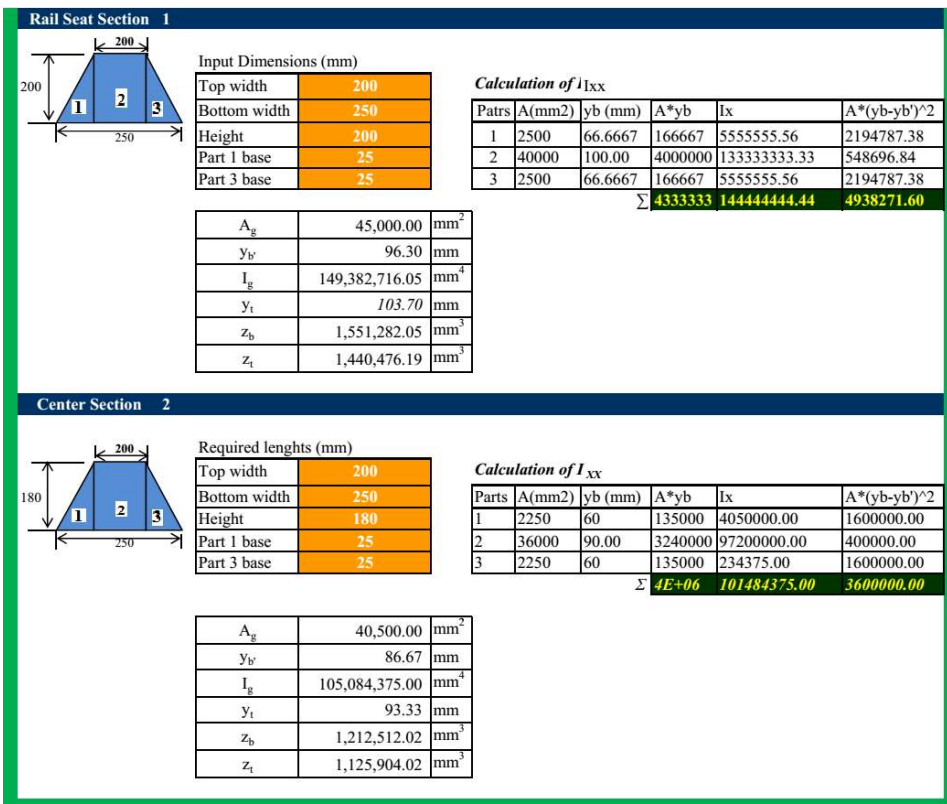
a) Currently used type sleeper



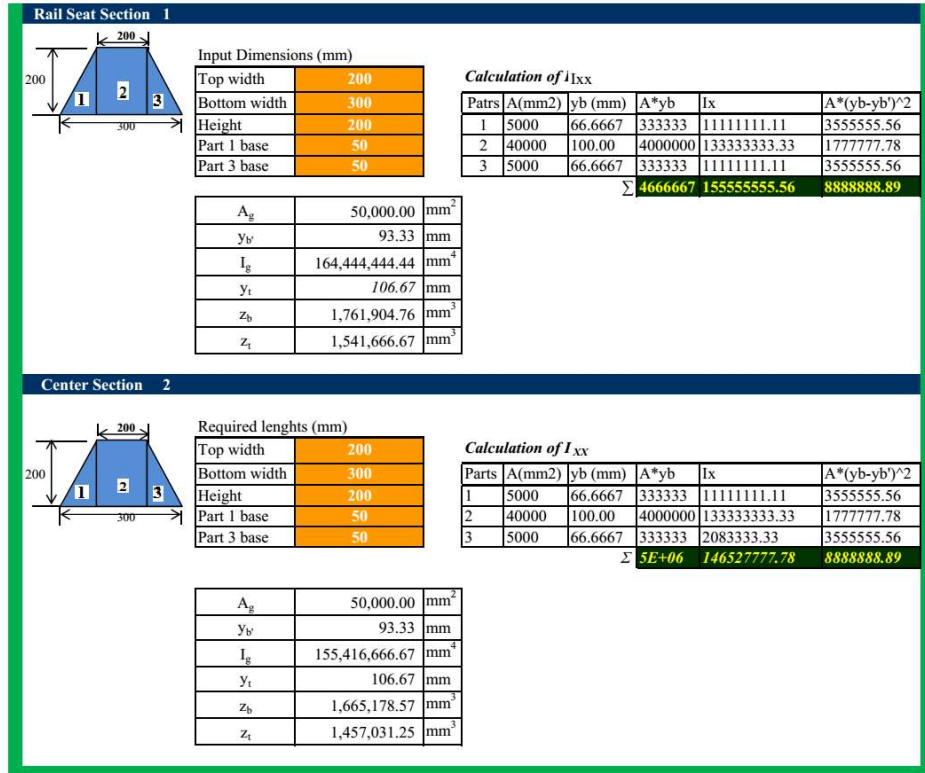
b) Type-I Sleeper



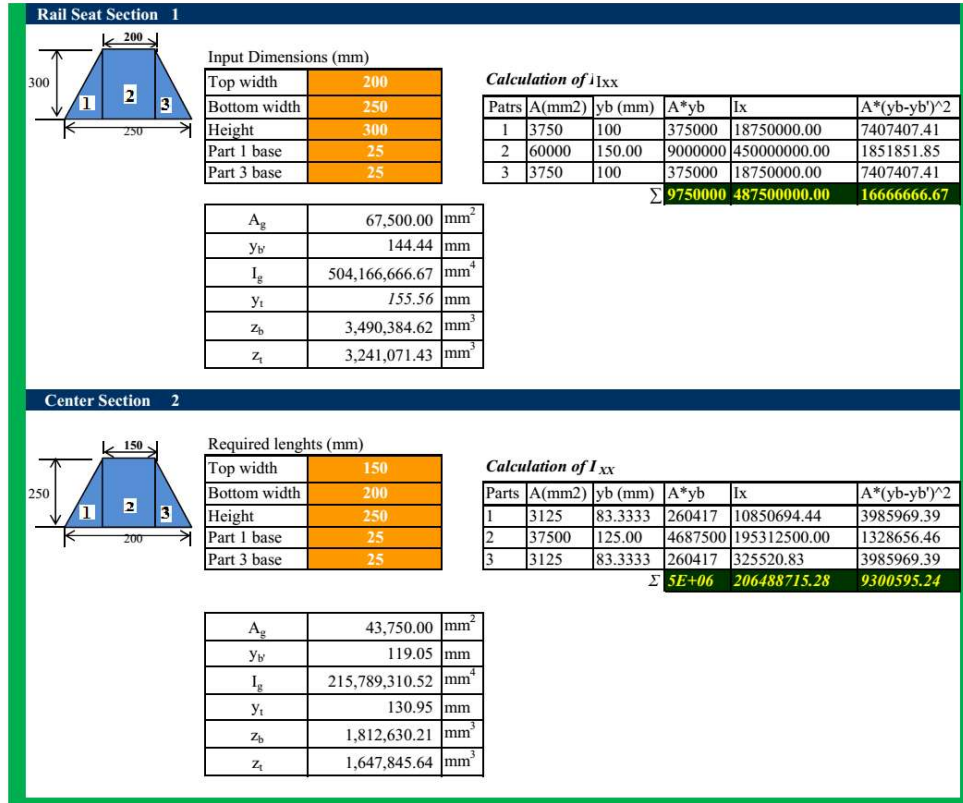
c) Type-II Sleeper



d) Type-III Sleeper

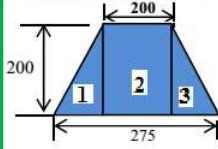


e) Type-IV Sleeper



f) Type-V Sleeper

Rail Seat Section 1



Input Dimensions (mm)

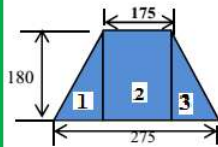
Top width	200
Bottom width	275
Height	200
Part 1 base	37.5
Part 3 base	37.5

Calculation of I_{xx}

Parts	A(mm ²)	yb (mm)	A*yb	I _x	A*(yb-yb') ²		
1	3750	66.6667	250000	8333333.33	2954755.31		
2	40000	100.00	4000000	133333333.33	1108033.24		
3	3750	66.6667	250000	8333333.33	2954755.31		
Σ					4500000	150000000.00	7017543.86

A_g	47,500.00	mm ²
$y_{b'}$	94.74	mm
I_g	157,017,543.86	mm ⁴
y_t	105.26	mm
z_b	1,657,407.41	mm ³
z_t	1,491,666.67	mm ³

Center Section 2



Required lengths (mm)

Top width	175
Bottom width	275
Height	180
Part 1 base	50
Part 3 base	50

Calculation of I_{xx}

Parts	A(mm ²)	yb (mm)	A*yb	I _x	A*(yb-yb') ²		
1	4500	60	270000	8100000.00	2450000.00		
2	31500	90.00	2835000	85050000.00	1400000.00		
3	4500	60	270000	18750000.00	2450000.00		
Σ					3E+06	95025000.00	6300000.00

A_g	40,500.00	mm ²
$y_{b'}$	83.33	mm
I_g	101,325,000.00	mm ⁴
y_t	96.67	mm
z_b	1,215,900.00	mm ³
z_t	1,048,189.66	mm ³

g) Type-VI Sleeper

Appendix B: Design parameters obtained from ERC



Ethiopian Railways Corporation (ERC)
National Railway Network of Ethiopia (NRNE)
Salient Features and Technical Specifications

Table A.1B: Salient Features and Technical specifications of ERC

TECHNICAL ITEM	REQUIREMENT
TRACK	
Track Length	Project Specific
Gauge	1,435 mm
Passing Loops	3*km long at 30*km intervals approximately or at stations (Subject to capacity assessment, performance modelling and route optimisation studies).
Rail Section	UIC 54 or 60 kg rails CWR on concrete sleepers at 60 cm spacing.
Turnouts and Passing Loops	Suitable for 100 kph in the loop line
Alignment	Where possible, construct as open route (i.e. in cutting/embankment, on bridges/viaducts as much as possible). Where tunnels are required, these to be as short as possible.
Formation Width	*Double Track or Single Track (Suitable for future Double Track).
Horizontal Curvature	>2,000 meters minimum (in urban areas and approaching developed cities, lower radii can be permitted).
Ruling Gradient	<1.0% (In exceptional conditions 2% maximum gradient will be permitted to minimize extent of cut/fill + tunneling works).
Maximum Passenger Train Speeds	160 kph (with future provision for 225 kph operation)
Maximum Freight Train Speeds	120 kph
Permanent Speed Restrictions	<10% of the route mileage
Axle Loading	25 tonnes maximum
Structure Gauge	UIC Compatible
Track Drainage	Pipe with Filter Material or Open Channel (Other Railway Operators Where Risk of “Flash Flooding”).
ELECTRIFICATION	
Traction Supply	25 kv 50 Hz via Overhead Line Equipment
Sub-stations Supply	From two separate sources
ROLLING STOCK	
Passenger Rolling Stock	EMU and Locomotive hauled passenger trains
Mainline Locomotives	6,000 HP Electric Traction
Freight Rolling Stock	100 Tonnes gross weight with flats. Examine option for double stacking containers. Freight train length 775m
Maintainance Locomotives	2,500 HP Diesel Electric Traction (Can be used for project construction train operations, initial revenue earning services and perturbations recovery).
Shunting Locomotives	1,000 HP Diesel Hydraulic Traction or similar

SIGNALS AND COMMUNICATION	
Signalling	Fixed block + Lineside Signals + In Cab Technology. (Moving Block Signalling option to be assessed).
Communication	GSM-R or similar fibre optic based. Fixed + mobile telephones.
Train Control	CTC, ATC, ATS, remotely controlled points machines
OPERATION	
Trailing Load (Passenger Train)	*600 Tonnes (10 x Passenger Coaches [@23m] + DVT/Baggage
Predicted Journey Time from Addis to Bedele	Passenger Train 5 Hours (Fastest Train)
Predicted Journey Time from Addis to Bedele	Freight Train 9 Hours (Fastest Train)
INFRASTRUCTURE	
Overbridge (Road over Rail)	*Work in progress
Underbridge (Rail over Road)	*Work in progress
Accommodation Overbridge/ Underpass Arrangements on the "Open" route	*Work in progress
Intersection Bridge (Rail over Rail)	*Work in progress
Culvert	*Work in progress
Viaduct	*Work in progress
Tunnel	*Work in progress
Earthworks	*Work in progress
MISCELLANEOUS	
Level Crossings	To be avoided-use grade separation wherever possible. Where necessary in urban/developed areas, remote controlled and monitored by CCTV
Lineside Fencing	Animal proof fence to be provided in the open country with accommodation crossings or elevated sections to suit environment and wildlife
Marshalling Yards	Simple layout (to suit current capacity requirements with provision for future capacity aspirations).
Strategic Maintenance Depots	Addis Ababa (Sebeta) or Jimma (to be decided on completion of Transport Planning Studies and associated Capacity Assessment + Rail Infrastructure Requirements) and Bedele
General Maintenance Depots	At intervals of about 90 km, or convenient nearest town or city. Provision to be made for stabling of "on track" maintenance plant (tamping/rail grinding machines etc., provision also to be made to stable diesel rescue locomotives for recovery of broken down trains
Towns Served	See Route Corridor map
Station Structures	Platforms (length circa 300m, number to be determined by capacity assessments/performance modelling), ticket offices, train maintenance/cleaning sheds, shopping complex at main stations
Environment	Compliant with national regulation. Pay particular attention to wild life conservation, forests waterways and water towers

Appendix D: Variation of Ballast Pressure distribution analyzed by the software SAFE. Contour values are in kN/mm^2 , e.g $-379 \times 10^{-6} \text{ kN/mm}^2 = 379 \text{ kPa}$ compressive pressure. The total length of sleeper is kept constant 2.5m for all iterations.

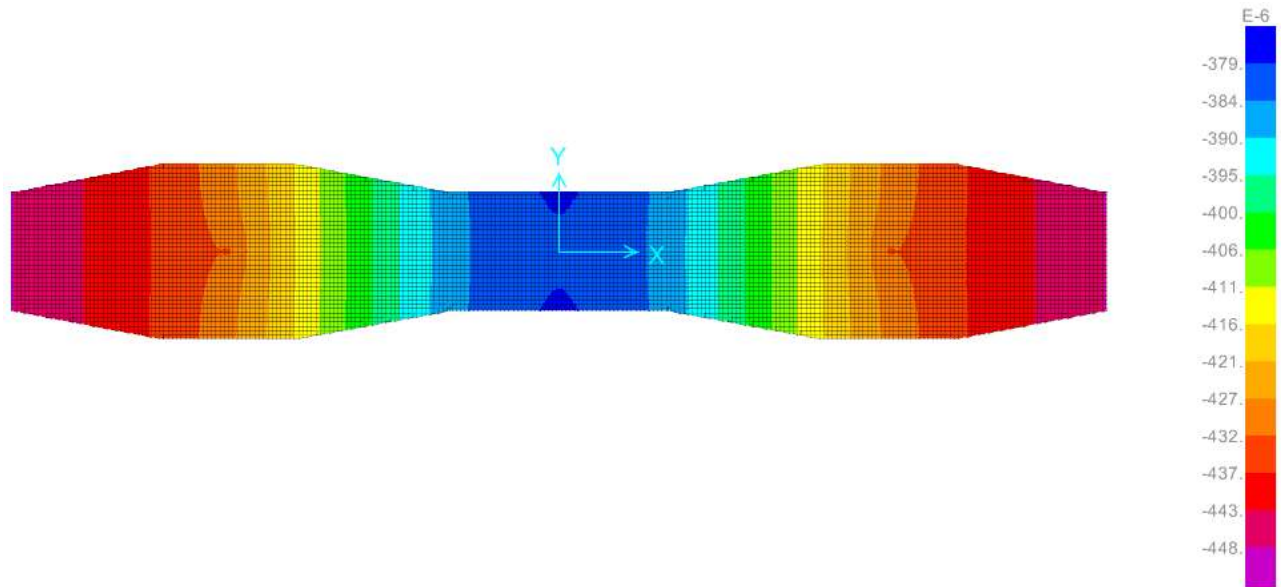


Figure A.2D: Ballast Pressure Response of Type-I Sleeper

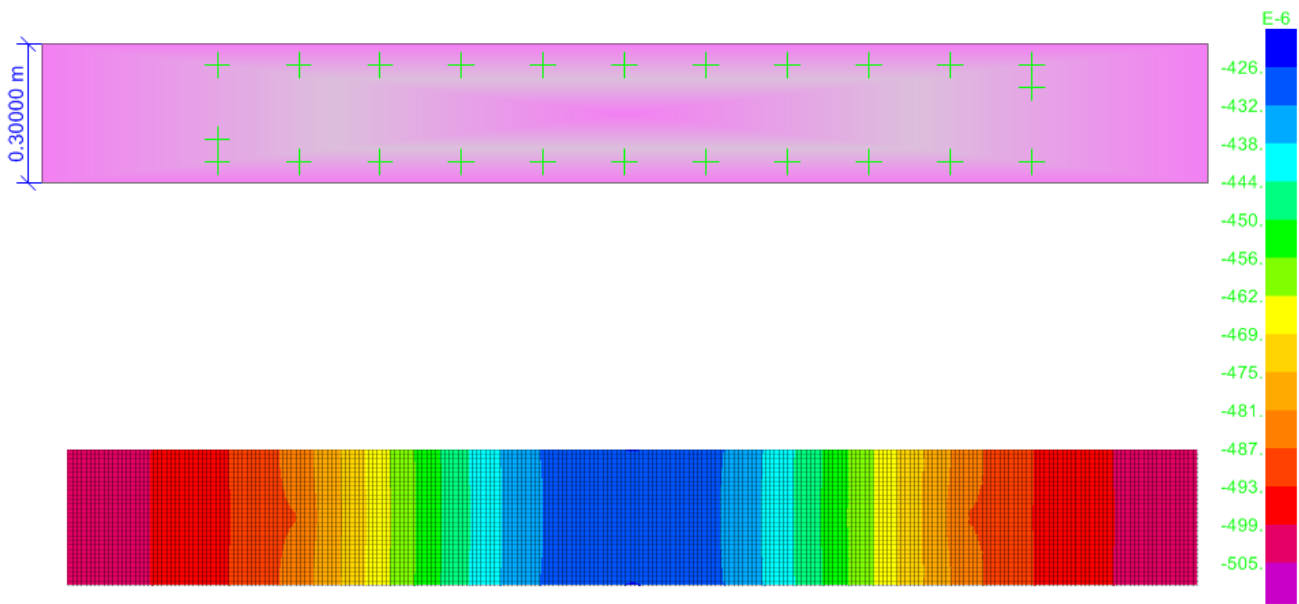


Figure A.3D: Ballast Pressure Response of Type-II Sleeper

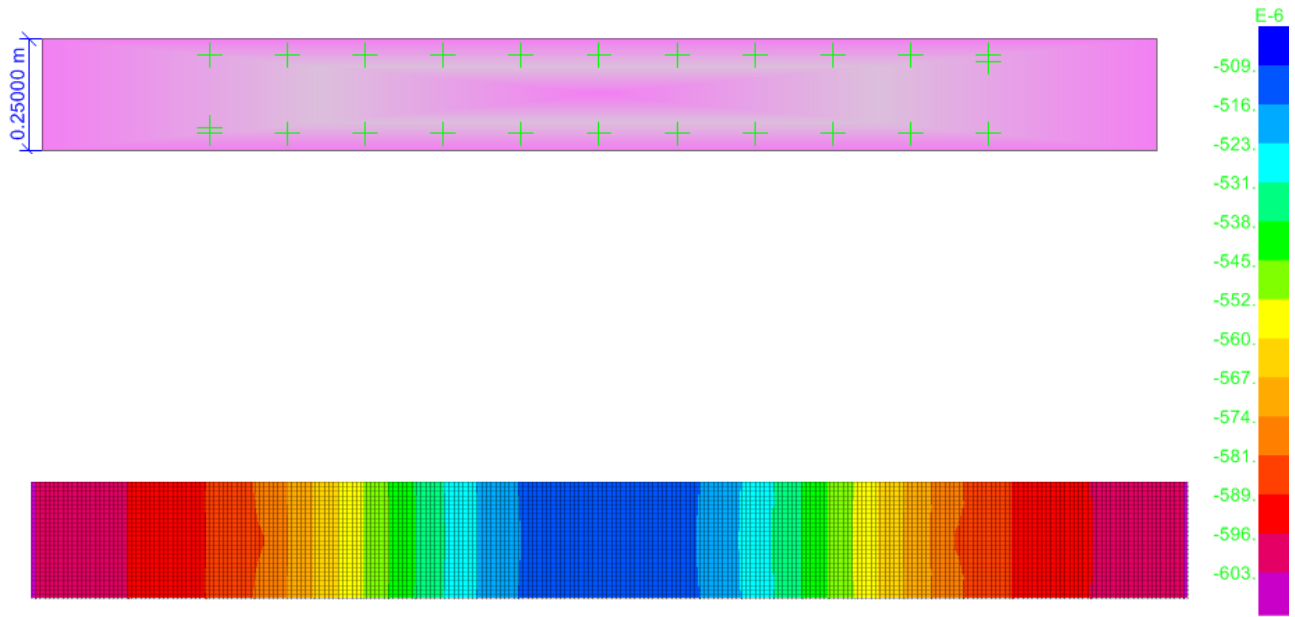


Figure A.4D: Ballast Pressure Response of Type-III Sleeper

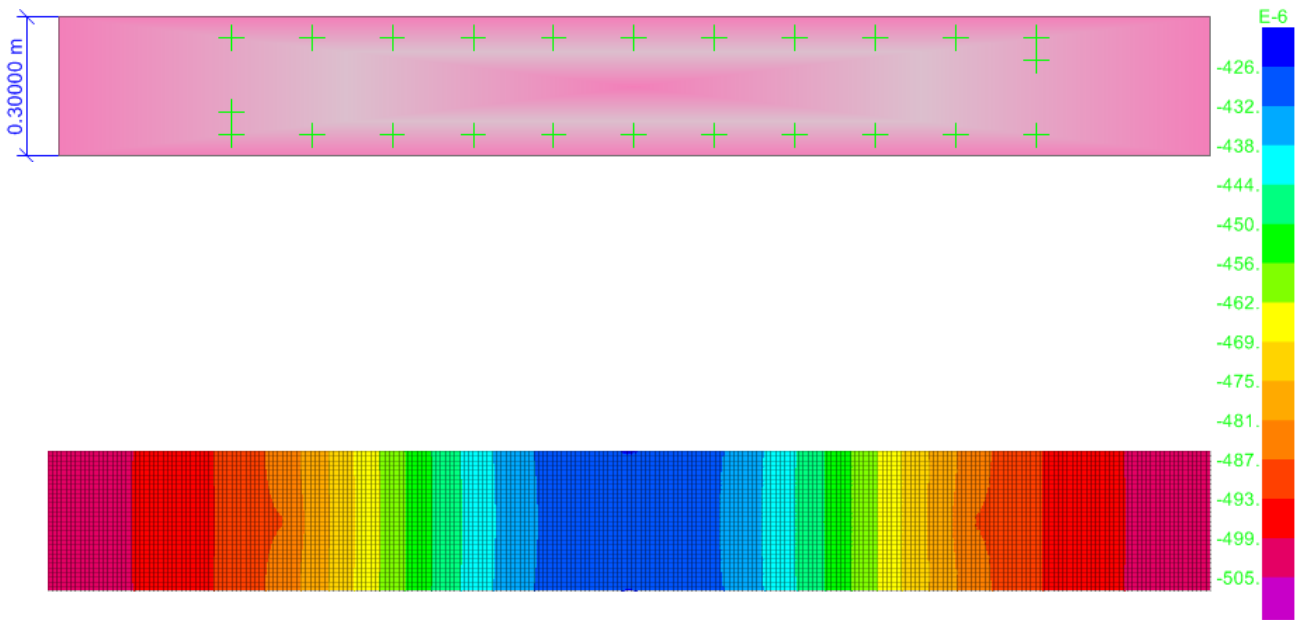


Figure A.5D: Ballast Pressure Response of Type-IV Sleeper

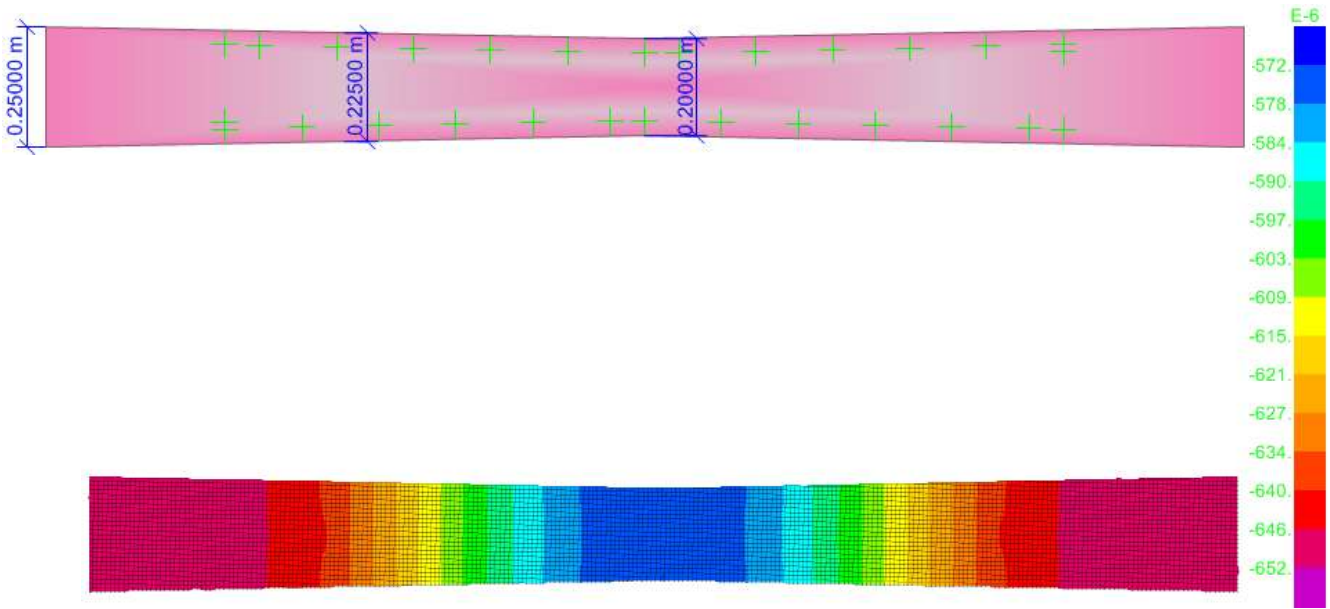


Figure A.6D: Ballast Pressure Response of Type-V Sleeper

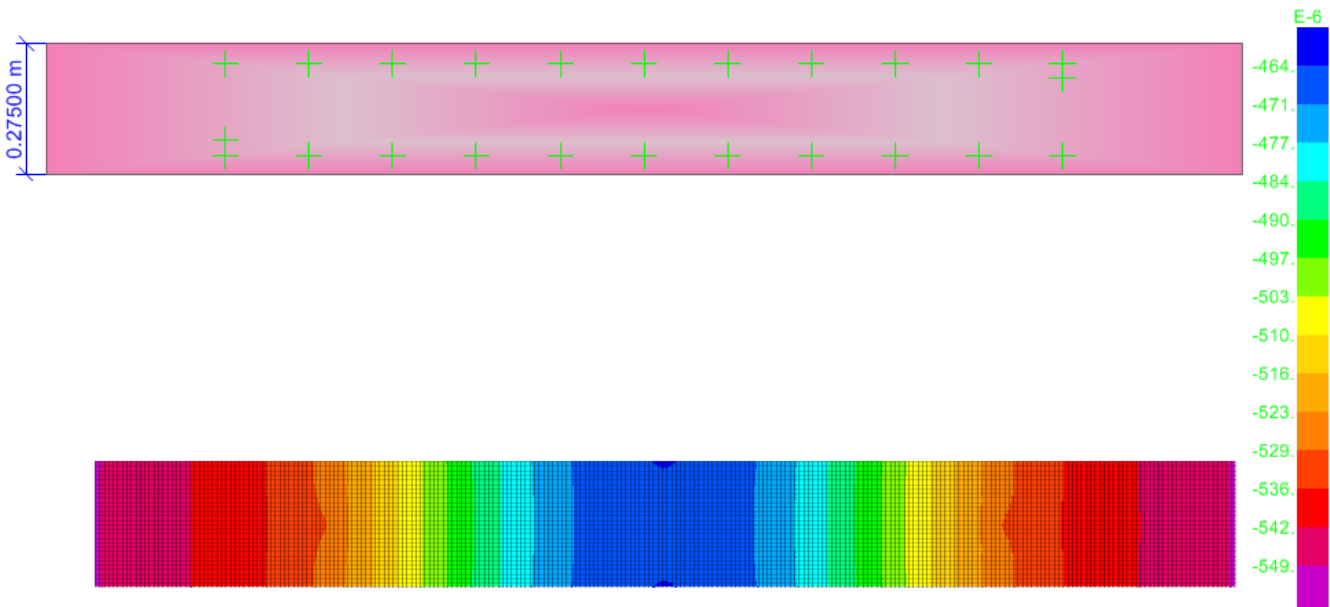


Figure A.7D: Ballast Pressure Response of Type-VI Sleeper

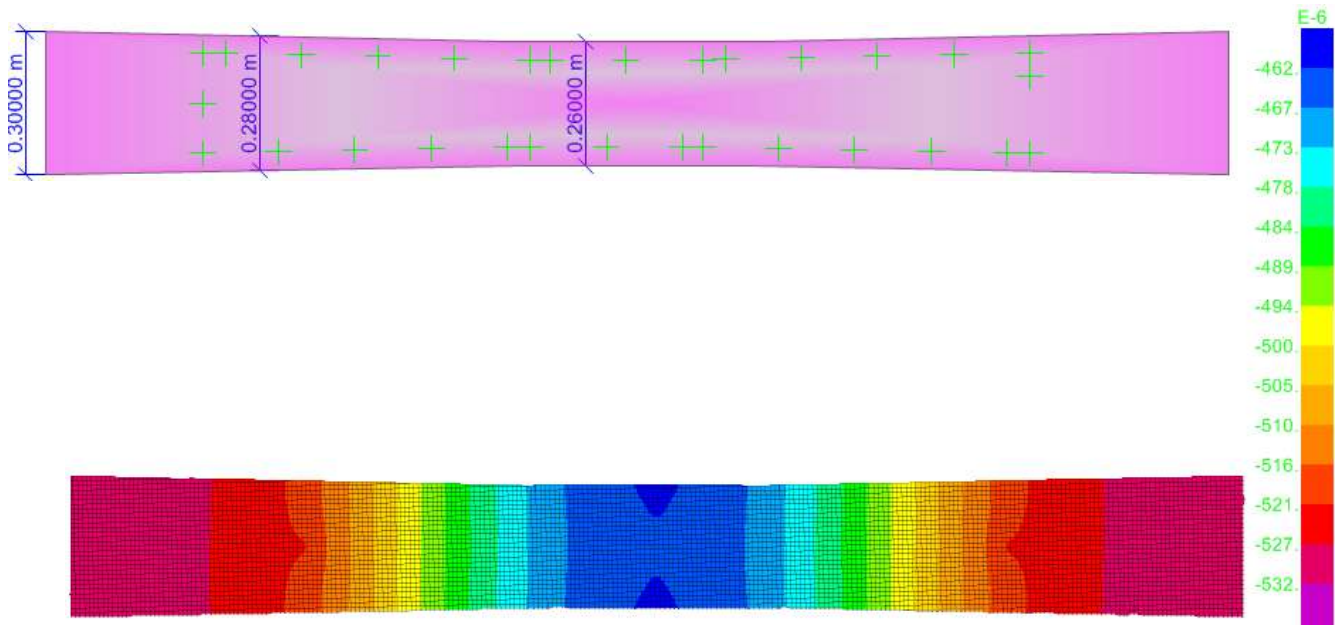


Figure A.8D: Ballast Pressure Response of Modified Type-V Sleeper (Iteration-1)

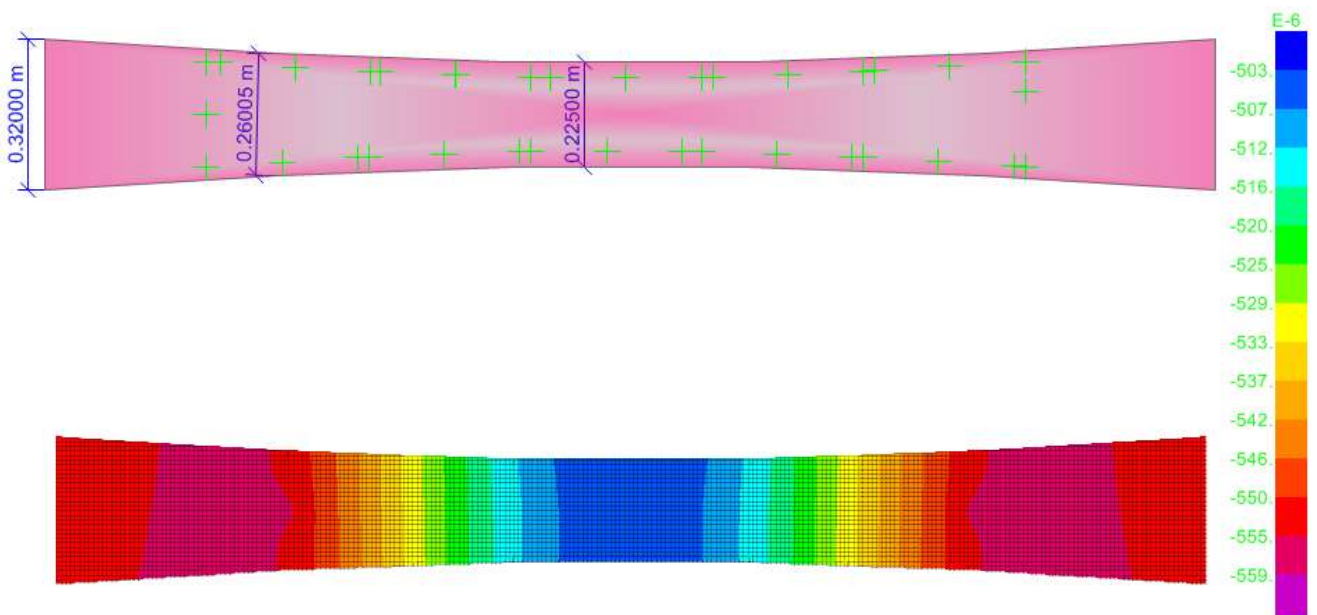


Figure A.9D: Ballast Pressure Response of Modified Type-V Sleeper (Iteration-2)

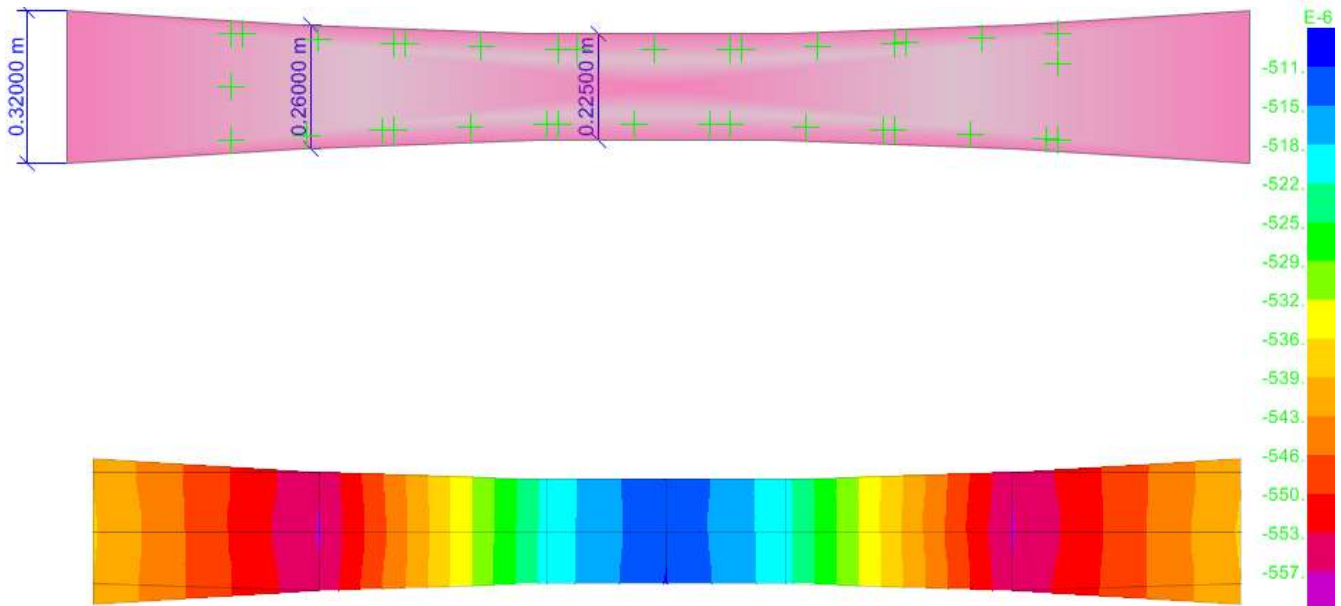


Figure A.10D: Ballast Pressure Response of Modified Type-V Sleeper (Iteration-3)

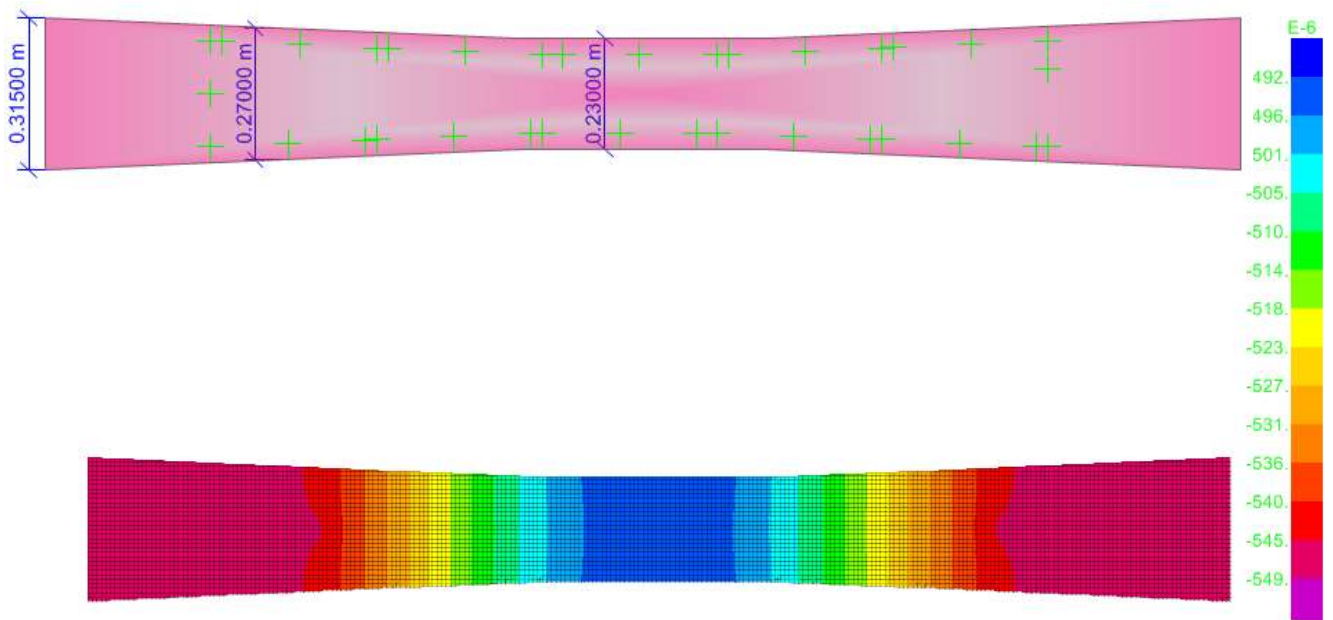


Figure A.11D: Ballast Pressure Response of Modified Type-V Sleeper (Iteration-4)

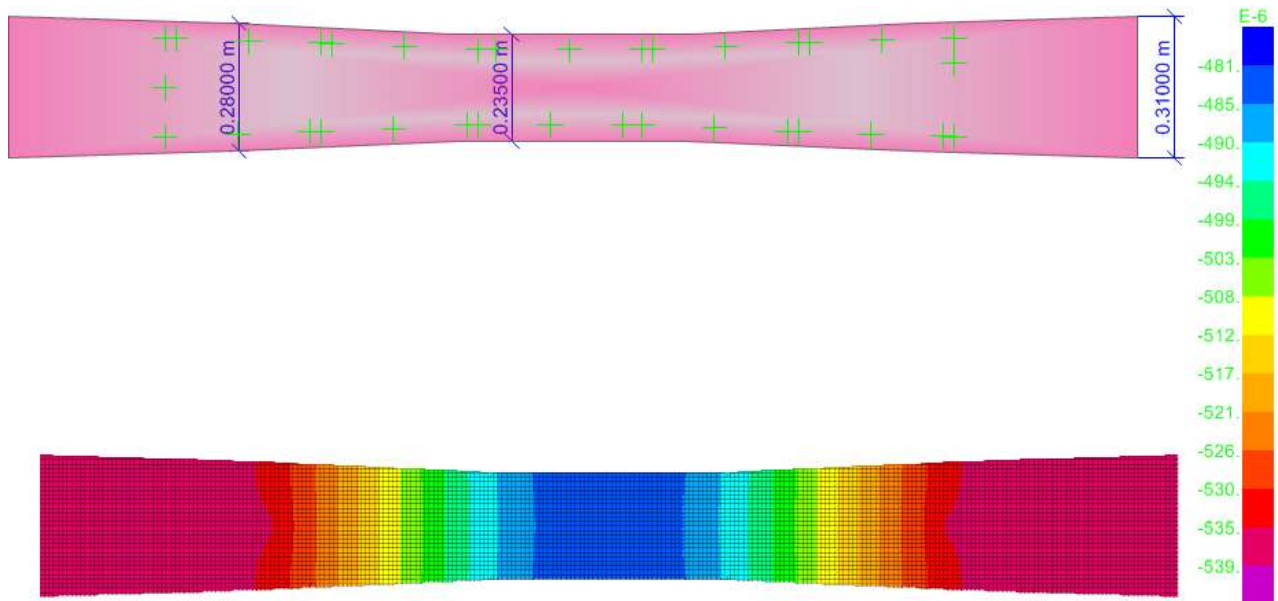


Figure A.12D: Ballast Pressure Response of Final optimal sleeper (Iteration-5)

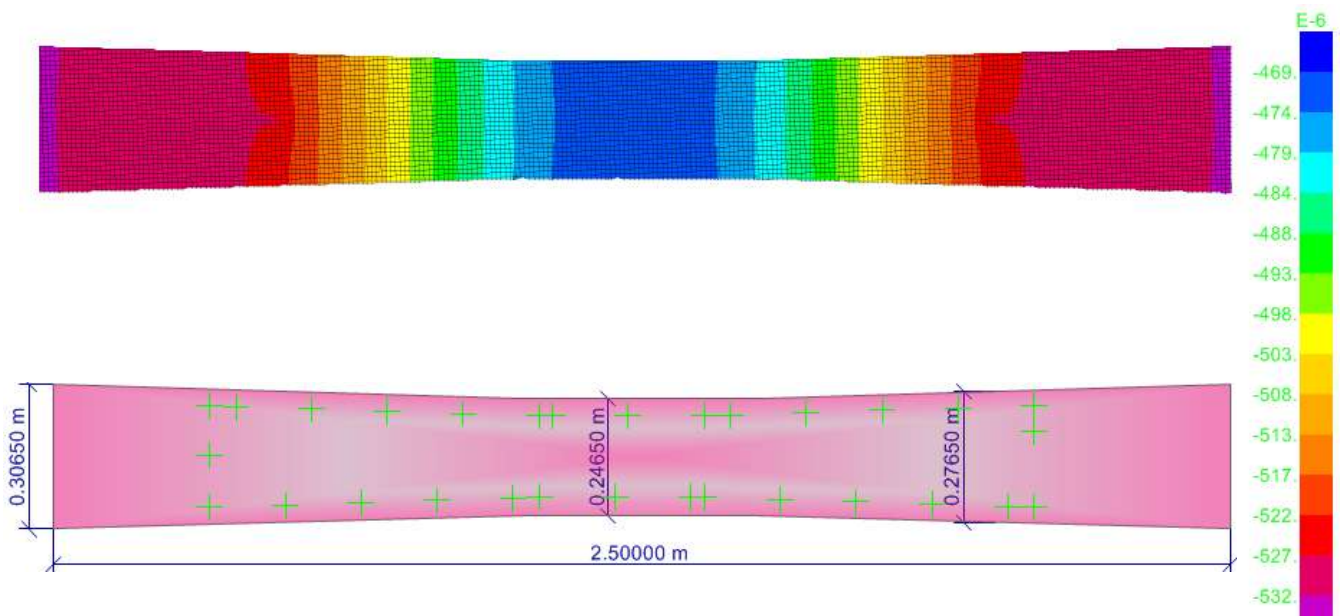
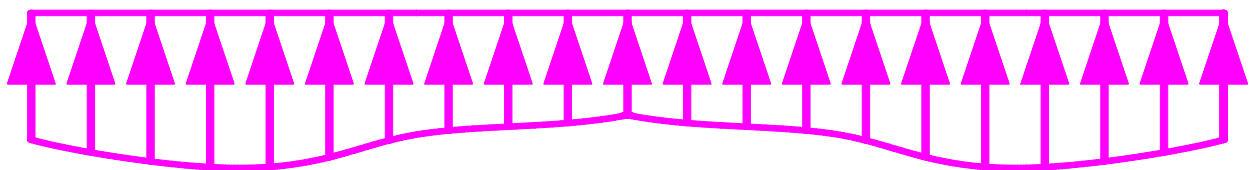


Figure A.13D: Ballast Pressure Response of existing Sleeper



Typical Ballast Pressure Distribution Analysed by SAFE

Appendix E: Analysis Summary Sheet of the existing sleeper

Table A.2E: Analysis Summary Sheet of the existing sleeper

Pre-Stressing Wires						
Concrete Grade	Type	Nominal Diameter (mm)	Quantity	Area (mm ²)	Eccentricity (mm)	
					Rail seat	Center
C-60	7-wire strand	6.30	10.00	311.72	12.85	-1.96

Pre-Stressing forces							
Concrete Grade	Jacking Force (kN)	Initial Pre-Stress (MPa)		Final Pre-Stress (MPa)		Pre-Stress force after loss (kN)	
		Rail seat	Center	Rail seat	Center	Rail seat	Center
C-60	434.86	1,344.78	1,335.02	1,133.00	1,109.47	353.18	345.85

Applied Stresses in Concrete (Mpa)												
Concrete Grade	At transfer				At service (M+)				At service (M-)			
	Rail seat		Center		Rail seat		Center		Rail seat		Center	
	Top	Bottom	Top	Bottom	Top	Bottom	Top	Bottom	Top	Bottom	Top	Bottom
C-60	5.74	12.35	13.35	9.89	18.98	-1.61	19.64	0.29	-4.53	18.37	-5.27	23.43

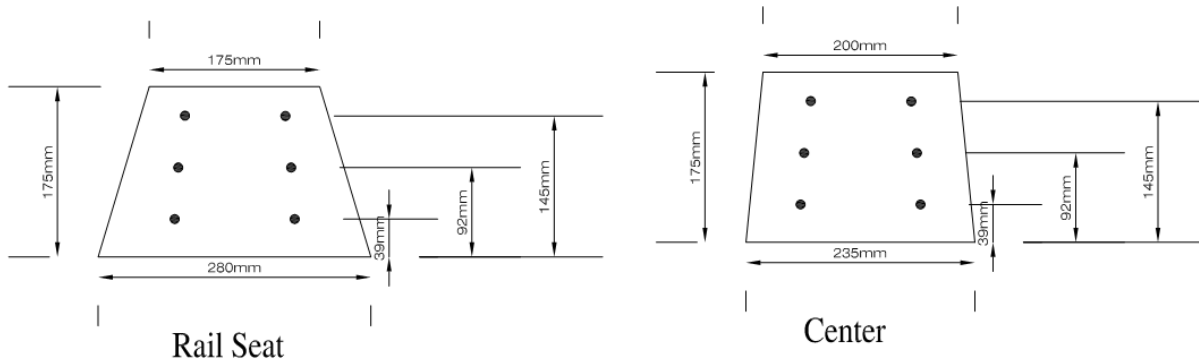
Moment Capacity of the section (kN.m)										
Concrete Grade	Allowable				Ultimate					
	Rail seat		Center		Rail seat			Center		
	Positive	Negative	Positive	Negative	Positive	Negative	Positive	Negative	Positive	Negative
C-60	21.53	10.87	11.10	13.23	48.10	32.45	28.09	27.39		

Allowable Stresses (MPa)							
Concrete Grade	Concrete				Pre-stressing tendon		
	At transfer		At Service		At transfer		At service
	Compression		Tension		Tension		Tension
C-60	17.86	0.00	27.00	-3.10	1,488.00	1,302.00	

Concrete grade	Losses of Pre-stress (%)		Transfer Length (mm)		Bond Length (mm)		Development Length (mm)	
	Rail seat	Center	Rail seat	Center	Rail seat	Center	Rail seat	Center
C-60	18.78	20.47	574.12	574.12	602.65	622.15	1,176.77	1,196.27

Appendix F: Iteration of optimization parameters

F.1 9.3mm diameter (7-wire strand)



Pre-Stressing Wires						
Concrete Grade	Type	Nominal Diameter (mm)	Quantity	Area (mm ²)	Eccentricity (mm)	
					Rail seat	Center
C-40 to C-70	7-wire strand	9.3	6	407.57	2.33	-2.51

Pre-Stressing forces							
Concrete Grade	Jacking Force (kN)	Initial Pre-Stress (MPa)		Final Pre-Stress (MPa)		Pre-Stress force after loss (kN)	
		Rail seat	Center	Rail seat	Center	Rail seat	Center
C-40	568.57	1332.23	1321.07	1068.34	1038.62	435.43	423.31
C-45	568.57	1332.23	1321.07	1078.63	1050.47	439.62	428.15
C-50	568.57	1332.23	1321.07	1087.49	1060.34	443.23	432.17
C-55	568.57	1332.23	1321.07	1094.93	1069.15	446.26	435.76
C-60	568.57	1332.23	1321.07	1101.55	1076.82	448.96	438.88
C-65	568.57	1332.23	1321.07	1107.39	1083.57	451.34	441.64
C-70	568.57	1332.23	1321.07	1112.72	1089.57	453.52	444.08

Applied Stresses in Concrete (Mpa)								
Concrete Grade	At transfer				At service			
	Rail seat		Center		Rail seat		Center	
	Top	Bottom	Top	Bottom	Top	Bottom	Top	Bottom
C-40	11.68	12.72	16.18	12.22	9.04	-2.35	-5.95	27.30

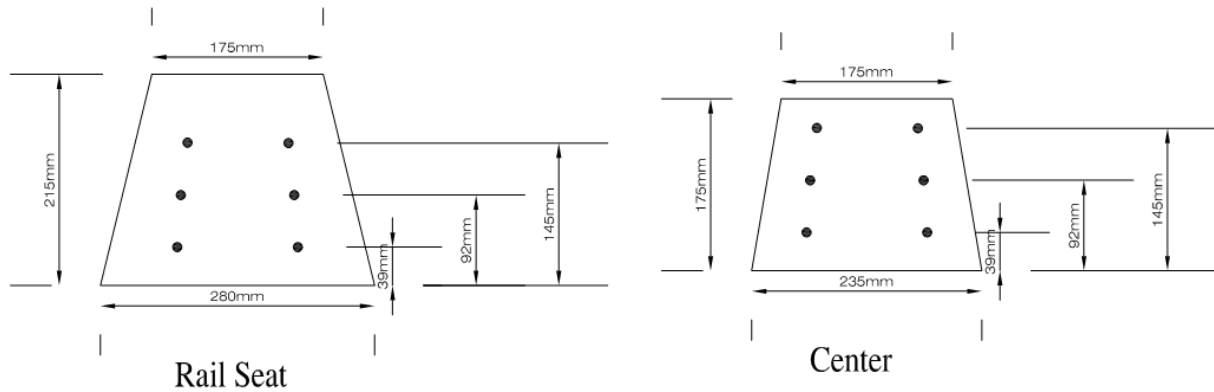
<i>C-45</i>	11.68	12.72	16.18	12.22	9.13	-2.25	-5.81	27.41
<i>C-50</i>	11.68	12.72	16.18	12.22	9.20	-2.16	-5.69	27.51
<i>C-55</i>	11.68	12.72	16.18	12.22	9.27	-2.09	-5.59	27.57
<i>C-60</i>	11.68	12.72	16.18	12.22	9.32	-2.02	-5.50	27.67
<i>C-65</i>	11.68	12.72	16.18	12.22	9.37	-1.96	-5.42	27.74
<i>C-70</i>	11.68	12.72	16.18	12.22	9.42	-1.91	-5.35	27.80

Moment Capacity of the section (kN.m)									
Concrete Grade	Allowable				Ultimate				
	Rail seat		Center		Rail seat		Center		
	Positive	Negative	Positive	Negative	Positive	Negative	Positive	Negative	Negative
<i>C-40</i>	20.76	16.89	13.68	17.54	40.99	33.17	30.17	30.77	30.77
<i>C-45</i>	20.88	16.97	13.82	17.71	42.46	34.43	31.26	31.80	31.80
<i>C-50</i>	21.02	17.08	13.93	17.85	43.86	35.63	32.29	32.78	32.78
<i>C-55</i>	21.13	17.16	14.03	17.96	45.18	36.76	33.27	33.71	33.71
<i>C-60</i>	21.23	17.23	14.11	18.06	46.44	37.85	34.21	34.60	34.60
<i>C-65</i>	21.32	17.30	14.19	18.16	47.66	38.89	35.11	35.45	35.45
<i>C-70</i>	21.40	17.36	14.26	18.25	48.83	39.89	35.98	36.27	36.27

Allowable Stresses (MPa)						
Concrete Grade	Concrete				Pre-stressing tendon	
	At transfer		At Service		At transfer	At service
	Compression	Tension	Compression	Tension	Tension	Tension
<i>C-40</i>	11.90	0	18.00	2.53	1488	1302
<i>C-45</i>	13.39	0	22.50	-2.68	1488	1302
<i>C-50</i>	14.88	0	22.50	-2.83	1488	1302
<i>C-55</i>	16.37	0	24.75	-2.97	1488	1302
<i>C-60</i>	17.86	0	27.00	-3.10	1488	1302
<i>C-65</i>	19.35	0	29.25	-3.22	1488	1302
<i>C-70</i>	20.83	0	31.50	-3.35	1488	1302

Concrete grade	Losses of Pre-stress (%)	
	Rail seat	Center
<i>C-40</i>	23.56	25.72
<i>C-45</i>	22.77	24.81
<i>C-50</i>	22.11	24.04
<i>C-55</i>	21.54	23.37
<i>C-60</i>	21.04	22.79
<i>C-65</i>	20.59	22.29
<i>C-70</i>	20.2	21.83

Transfer Length (mm)		Bond Length (mm)		Development Length (mm)	
Rail seat	Center	Rail seat	Center	Rail seat	Center
518.78	518.78	968.86	1005.11	1487.64	1523.89
534.28	534.28	956.14	990.61	1490.43	1524.89
548.54	548.54	945.55	978.53	1494.09	1527.07
561.77	561.77	936.25	967.75	1498.02	1529.52
574.12	574.12	928.10	958.37	1502.22	1523.49
585.73	585.73	920.96	950.11	1506.69	1535.83
596.68	596.68	914.43	942.76	1511.11	1539.44



Pre-Stressing Wires						
Concrete Grade	Type	Nominal Diameter (mm)	Quantity	Area (mm ²)	Eccentricity (mm)	
					Rail seat	Center
C-40 to C-70	7-wire strand	9.30	6.00	407.57	11.56	-4.43

Pre-Stressing forces							
Concrete Grade	Jacking Force (kN)	Initial Pre-Stress (MPa)		Final Pre-Stress (MPa)		Pre-Stress force after loss (kN)	
		Rail seat	Center	Rail seat	Center	Rail seat	Center
C-40	568.57	1,325.25	1,301.54	1,081.13	1,024.84	440.64	417.70
C-45	568.57	1,326.78	1,307.12	1,088.69	1,037.86	443.72	423.01
C-50	568.57	1,330.83	1,311.30	1,097.65	1,048.44	447.37	427.32
C-55	568.57	1,333.62	1,314.79	1,104.73	1,057.48	450.26	431.00
C-60	568.57	1,335.71	1,317.58	1,110.61	1,065.16	452.66	434.13
C-65	568.57	1,338.50	1,321.07	1,116.69	1,072.89	455.13	437.28
C-70	568.57	1,340.73	1,323.86	1,121.88	1,079.51	457.25	439.98

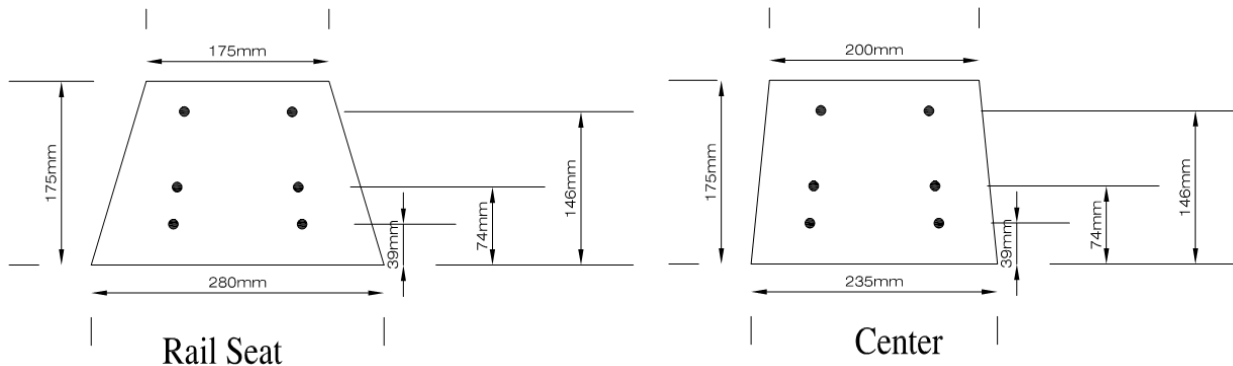
Applied Stresses in Concrete (Mpa)												
Concrete Grade	At transfer				At service (M+)				At service (M-)			
	Rail seat		Center		Rail seat		Center		Rail seat		Center	
	Top	Bottom	Top	Bottom	Top	Bottom	Top	Bottom	Top	Bottom	Top	Bottom
C-40	7.47	14.11	18.01	11.87	18.13	1.19	22.17	2.10	-1.87	18.33	-1.02	23.13
C-45	7.48	14.12	18.08	11.92	18.17	1.27	22.34	2.23	-1.83	18.42	-0.85	23.26
C-50	7.50	14.17	18.13	11.96	18.22	1.37	22.48	2.33	-1.78	18.51	-0.71	23.36
C-55	7.51	14.20	18.18	12.00	18.25	1.45	22.60	2.42	-1.74	18.59	-0.59	23.45
C-60	7.52	14.22	18.22	12.02	18.29	1.51	22.70	2.49	-1.71	18.65	-0.49	23.52
C-65	7.54	14.25	18.26	12.06	18.32	1.58	22.80	2.57	-1.68	18.72	-0.39	23.60
C-70	7.55	14.28	18.30	12.08	18.35	1.63	22.89	2.63	-1.65	18.78	-0.30	23.66

Moment Capacity of the section (kN.m)										
Concrete Grade	Allowable				Ultimate					
	Rail seat		Center		Rail seat			Center		
	Positive	Negative	Positive	Negative	Positive	Negative	Positive	Negative	Positive	Negative
C-40	27.61	15.19	13.68	17.54	52.20	34.93	28.71	29.75	28.71	29.75
C-45	27.76	15.25	13.82	17.71	53.99	36.46	29.75	30.70	29.75	30.70
C-50	27.94	15.33	13.93	17.85	55.68	37.91	30.74	31.60	30.74	31.60
C-55	28.09	15.39	14.03	17.96	57.29	39.29	31.69	32.46	31.69	32.46
C-60	28.21	15.44	14.11	18.06	58.83	40.61	32.59	33.27	32.59	33.27
C-65	28.33	15.49	14.19	18.16	60.30	41.87	33.45	34.06	33.45	34.06
C-70	28.43	15.54	14.26	18.25	61.72	43.09	34.28	34.81	34.28	34.81

Allowable Stresses (MPa)							
Concrete Grade	Concrete				Pre-stressing tendon		
	At transfer		At Service		At transfer	At service	
	Compression	Tension	Compression	Tension	Tension	Tension	
C-40		11.90	0.00	18.00	-2.53	1,488.00	1,302.00
C-45		13.39	0.00	20.25	-2.68	1,488.00	1,302.00
C-50		14.88	0.00	22.50	-2.83	1,488.00	1,302.00
C-55		16.37	0.00	24.75	-2.97	1,488.00	1,302.00
C-60		17.86	0.00	27.00	-3.10	1,488.00	1,302.00
C-65		19.35	0.00	29.25	-3.22	1,488.00	1,302.00
C-70		20.83	0.00	31.50	-3.35	1,488.00	1,302.00

Concrete grade	Losses of Pre-stress (%)		Transfer Length (mm)		Bond Length (mm)		Development Length (mm)	
	Rail seat	Center	Rail seat	Center	Rail seat	Center	Rail seat	Center
C-40	22.50	26.53	518.78	518.78	953.09	1,021.97	1,471.87	1,540.75
C-45	21.96	25.60	534.28	534.28	943.84	1,006.04	1,478.12	1,540.32
C-50	21.32	24.84	548.54	548.54	932.88	993.09	1,481.42	1,541.63
C-55	20.81	24.19	561.77	561.77	924.21	982.03	1,485.98	1,543.80
C-60	20.39	23.64	574.12	574.12	917.02	972.63	1,491.14	1,546.75
C-65	19.95	23.09	585.73	585.73	909.58	963.17	1,495.31	1,548.90
C-70	19.58	22.62	596.68	596.68	903.22	955.07	1,499.90	1,551.75

F.2 8mm diameter (7-wire strand)



Pre-Stressing Wires						
Concrete Grade	Type	Nominal Diameter (mm)	Quantity	Area (mm ²)	Eccentricity (mm)	
					Rail seat	Center
C-40 to C-70	7-wire strand	8.00	6.00	301.59	3.67	-1.18

Pre-Stressing forces							
Concrete Grade	Jacking Force (kN)	Initial Pre-Stress (MPa)		Final Pre-Stress (MPa)		Pre-Stress force after loss (kN)	
		Rail seat	Center	Rail seat	Center	Rail seat	Center
C-40	420.72	1,337.81	1,329.44	1,115.28	1,093.28	336.36	329.72
C-45	420.72	1,340.60	1,332.23	1,123.18	1,102.39	338.74	332.47
C-50	420.72	1,343.39	1,336.41	1,129.84	1,102.39	340.75	334.74
C-55	420.72	1,346.18	1,339.20	1,135.57	1,116.53	342.48	336.74
C-60	420.72	1,347.57	1,340.73	1,140.67	1,122.41	344.02	338.51
C-65	420.72	1,349.66	1,342.69	1,145.11	1,127.55	345.36	340.06
C-70	420.72	1,351.76	1,344.92	1,149.05	1,132.10	346.55	341.43

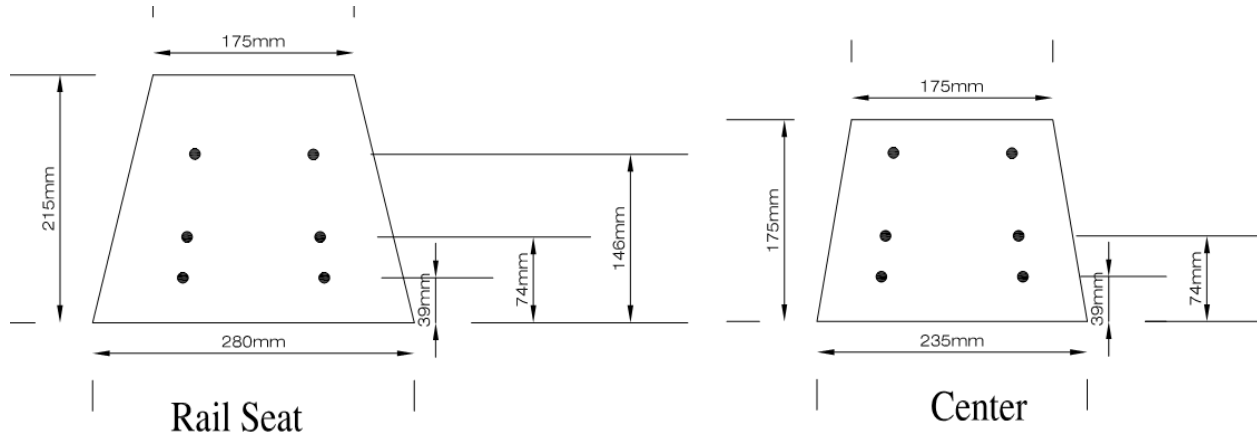
Applied Stresses in Concrete (Mpa)									
Concrete Grade	At transfer				At service				
	Rail seat		Center		Rail seat		Center		
	Top	Bottom	Top	Bottom	Top	Bottom	Top	Bottom	Bottom
C-40	8.37	9.71	11.75	9.38	6.64	-4.44	-9.03	25.43	
C-45	8.39	9.73	11.77	9.40	6.69	-4.38	-8.95	25.50	
C-50	8.39	9.75	11.81	9.44	6.73	-4.33	-8.89	25.56	
C-55	8.42	9.78	11.83	9.46	6.77	-4.28	-8.81	25.61	
C-60	8.43	9.79	11.84	9.47	6.80	-4.25	-8.79	25.65	
C-65	8.44	9.80	11.86	9.48	6.92	-4.21	-8.75	25.69	
C-70	8.46	9.82	11.88	9.50	6.85	-4.18	-8.71	25.73	

Moment Capacity of the section (kN.m)									
Concrete Grade	Allowable				Ultimate				
	Rail seat		Center		Rail seat		Center		
	Positive	Negative	Positive	Negative	Positive	Negative	Positive	Negative	Negative
C-40	17.47	13.67	11.78	14.22	37.51	29.79	27.81	27.14	
C-45	17.57	13.74	11.86	14.30	38.98	31.06	28.90	28.17	
C-50	17.63	13.78	11.92	14.38	40.38	32.25	29.93	29.15	
C-55	17.70	13.83	11.98	14.45	41.70	33.38	30.91	30.08	
C-60	17.76	13.87	12.03	14.50	42.97	34.47	31.85	30.97	
C-65	17.81	13.90	12.07	14.55	44.18	35.51	32.75	31.82	
C-70	17.86	13.94	12.12	14.60	45.35	36.51	33.62	32.65	

Allowable Stresses (MPa)						
Concrete Grade	Concrete				Pre-stressing tendon	
	At transfer		At Service		At transfer	At service
	Compression	Tension	Compression	Tension	Tension	Tension
C-40	11.90	0.00	18.00	-2.53	1,448.00	1,302.00
C-45	13.39	0.00	20.25	-2.68	1,448.00	1,302.00
C-50	14.88	0.00	22.50	-2.83	1,448.00	1,302.00
C-55	16.37	0.00	24.75	-2.97	1,448.00	1,302.00
C-60	17.86	0.00	27.00	-3.10	1,448.00	1,302.00
C-65	19.35	0.00	29.25	-3.22	1,448.00	1,302.00
C-70	20.83	0.00	31.50	-3.35	1,448.00	1,302.00

Concrete grade	Losses of Pre-stress (%)	
	Rail seat	Center
C-40	20.05	21.63
C-45	19.49	20.98
C-50	19.01	20.44
C-55	18.60	19.96
C-60	18.23	19.54
C-65	17.91	19.17
C-70	17.63	18.85

Transfer Length (mm)		Bond Length (mm)		Development Length (mm)	
Rail seat	Center	Rail seat	Center	Rail seat	Center
518.78	518.78	783.91	807.08	1,302.69	1,325.85
534.28	534.28	775.60	797.49	1,309.88	1,331.77
548.54	548.54	768.59	789.56	1,317.13	1,338.10
561.77	561.77	762.56	782.60	1,324.33	1,344.37
574.12	574.12	757.19	776.41	1,331.31	1,350.53
585.73	585.73	752.52	771.00	1,338.24	1,356.73
596.68	596.68	748.36	766.21	1,345.04	1,362.89



Pre-Stressing Wires						
Concrete Grade	Type	Nominal Diameter (mm)	Quantity	Area (mm ²)	Eccentricity (mm)	
					Rail seat	Center
C-40 to C-70	7-wire strand	8.00	6.00	301.59	12.90	-3.1

Pre-Stressing forces							
Concrete Grade	Jacking Force (kN)	Initial Pre-Stress (MPa)		Final Pre-Stress (MPa)		Pre-Stress force after loss (kN)	
		Rail seat	Center	Rail seat	Center	Rail seat	Center
C-40	420.72	1,337.81	1,328.74	1,120.19	1,086.69	337.84	327.74
C-45	420.72	1,341.99	1,332.23	1,128.77	1,095.94	340.43	330.53
C-50	420.72	1,343.39	1,335.71	1,134.01	1,104.29	342.01	333.05
C-55	420.72	1,345.48	1,338.50	1,139.38	1,111.30	343.63	335.16
C-60	420.72	1,347.57	1,340.73	1,144.32	1,117.24	345.12	336.95
C-65	420.72	1,349.66	1,342.69	1,148.92	1,122.47	346.51	338.53
C-70	420.72	1,351.76	1,344.92	1,153.25	1,127.61	347.81	340.08

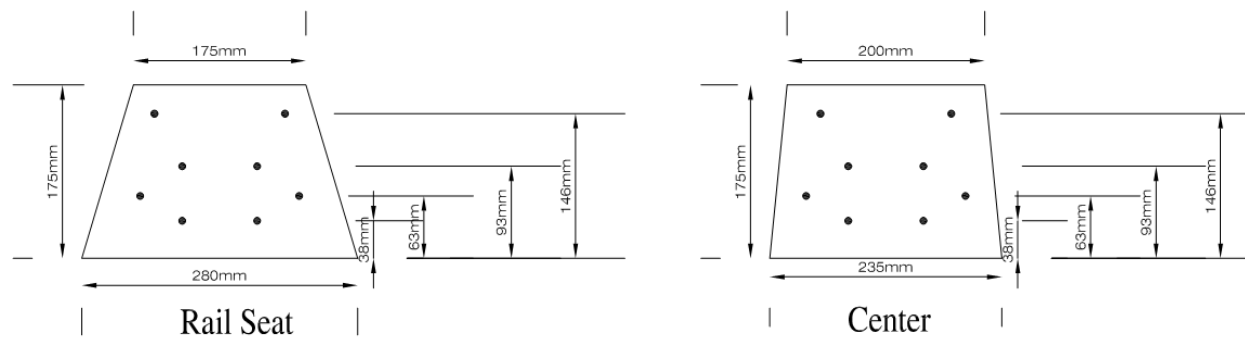
Applied Stresses in Concrete (Mpa)														
Concrete Grade	At transfer						At service (M ⁺)				At service (M ⁻)			
	Rail seat		Center		Rail seat		Center		Rail seat		Center			
	Top	Bottom	Top	Bottom	Top	Bottom	Top	Bottom	Top	Bottom	Top	Bottom		
C-40	5.33	10.75	13.27	9.27	16.49	-1.31	18.81	0.36	-3.51	15.84	-4.37	21.39		
C-45	5.34	10.79	13.30	9.29	16.52	-1.23	18.90	0.43	-3.48	15.91	-4.29	21.46		
C-50	5.35	10.80	13.33	9.32	16.54	-1.19	18.98	0.49	-3.46	15.95	-4.21	21.52		
C-55	5.35	10.82	13.36	9.34	16.56	-1.15	19.04	0.54	-3.44	15.99	-4.14	21.57		
C-60	5.36	10.83	13.38	9.36	16.58	-1.11	19.10	0.59	-3.42	16.03	-4.09	21.62		
C-65	5.37	10.85	13.40	9.37	16.60	-1.07	19.15	0.63	-3.40	16.07	-4.04	21.66		
C-70	5.38	10.87	13.42	9.39	16.61	-1.03	19.20	0.67	-3.39	16.11	-3.99	21.70		

Moment Capacity of the section (kN.m)								
Concrete Grade	Allowable				Ultimate			
	Rail seat		Center		Rail seat		Center	
	Positive	Negative	Positive	Negative	Positive	Negative	Positive	Negative
C-40	22.95	12.57	11.78	14.22	47.27	32.17	26.54	26.07
C-45	23.08	12.62	11.86	14.30	49.06	33.70	27.58	27.02
C-50	23.16	12.65	11.92	14.38	50.75	35.15	28.58	27.92
C-55	23.24	12.68	11.98	14.45	52.36	36.53	29.52	28.78
C-60	23.32	12.71	12.03	14.50	53.90	37.85	30.42	29.59
C-65	23.39	12.74	12.07	14.55	55.37	39.12	31.28	30.38
C-70	23.46	12.76	12.12	14.60	56.79	40.33	32.11	31.13

Allowable Stresses (MPa)							
Concrete Grade	Concrete				Pre-stressing tendon		
	At transfer		At Service		At transfer	At service	
	Compression	Tension	Compression	Tension	Tension	Tension	
C-40		11.90	0.00	18.00	-2.53	1,488.00	1,302.00
C-45		13.39	0.00	20.25	-2.68	1,488.00	1,302.00
C-50		14.88	0.00	22.50	-2.83	1,488.00	1,302.00
C-55		16.37	0.00	24.75	-2.97	1,488.00	1,302.00
C-60		17.86	0.00	27.00	-3.10	1,488.00	1,302.00
C-65		19.35	0.00	29.25	-3.22	1,488.00	1,302.00
C-70		20.83	0.00	31.50	-3.35	1,488.00	1,302.00

Concrete grade	Losses of Pre-stress (%)		Transfer Length (mm)		Bond Length (mm)		Development Length (mm)	
	Rail seat	Center	Rail seat	Center	Rail seat	Center	Rail seat	Center
C-40	19.70	22.10	518.78	518.78	778.74	814.01	1,297.52	1,332.79
C-45	19.08	21.44	534.28	534.28	769.72	804.27	1,304.00	1,338.55
C-50	18.71	20.84	548.54	548.54	764.20	795.48	1,312.74	1,344.02
C-55	18.32	20.34	561.77	561.77	758.55	788.11	1,320.32	1,349.88
C-60	17.97	19.91	574.12	574.12	753.35	781.85	1,327.47	1,355.97
C-65	17.64	19.54	585.73	585.73	748.50	776.34	1,334.23	1,362.07
C-70	17.33	19.17	596.68	596.68	743.95	770.94	1,340.63	1,367.62

F.3 7mm diameter (7-wire strand)



Pre-Stressing Wires						
Concrete Grade	Type	Nominal Diameter (mm)	Quantity	Area (mm ²)	Eccentricity (mm)	
					Rail seat	Center
C-40 to C-70	7-wire strand	7.00	8.00	307.88	5.00	0.15

Pre-Stressing forces							
Concrete Grade	Jacking Force (kN)	Initial Pre-Stress (MPa)		Final Pre-Stress (MPa)		Pre-Stress force after loss (kN)	
		Rail seat	Center	Rail seat	Center	Rail seat	Center
		C-40	475.67	1,480.11	1,470.84	1,237.93	1,213.77
C-45	475.67	1,483.20	1,474.24	1,246.88	1,224.02	383.88	376.85
C-50	475.67	1,486.29	1,476.25	1,254.44	1,232.83	386.21	379.56
C-55	475.67	1,489.38	1,480.88	1,260.92	1,240.11	388.21	381.80
C-60	475.67	1,491.70	1,483.20	1,266.64	1,246.67	389.97	383.82
C-65	475.67	1,493.24	1,485.52	1,271.74	1,252.46	391.54	385.60
C-70	475.67	1,495.56	1,488.61	1,276.21	1,257.53	392.92	387.16

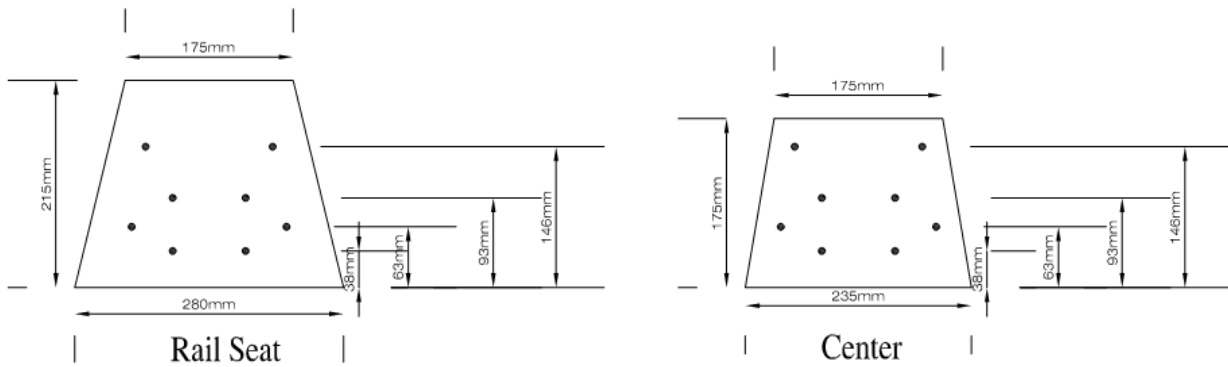
Applied Stresses in Concrete (Mpa)									
Concrete Grade	At transfer					At service			
	Rail seat		Center			Rail seat		Center	
	Top	Bottom	Top	Bottom	Top	Bottom	Top	Bottom	
	C-40	8.94	11.41	12.61	11.22	7.14	-2.99	-8.29	26.98
C-45	8.96	11.44	12.64	11.25	7.19	(2.92)	(8.21)	27.06	
C-50	8.98	11.46	12.65	11.27	7.24	(2.86)	(8.14)	27.13	
C-55	9.00	11.48	12.69	11.31	7.27	(2.81)	(8.08)	27.19	
C-60	9.01	11.50	12.71	11.32	7.31	(2.76)	(8.02)	27.25	
C-65	9.02	11.52	12.73	11.34	7.34	(2.72)	(7.89)	27.29	
C-70	9.03	11.53	12.75	11.37	7.36	(2.69)	(7.94)	27.33	

Moment Capacity of the section (kN.m)									
Concrete Grade	Allowable				Ultimate				
	Rail seat		Center		Rail seat		Center		
	Positive	Negative	Positive	Negative	Positive	Negative	Positive	Negative	
C-40	19.72	14.35	13.44	15.03	39.81	30.47	29.64	27.97	
C-45	19.83	14.41	13.53	15.13	41.28	31.73	30.73	29.01	
C-50	19.92	14.47	13.61	15.21	42.67	32.93	31.76	29.99	
C-55	20.01	14.52	13.68	15.28	44.00	34.06	32.74	30.92	
C-60	20.07	14.56	13.74	15.34	45.26	35.15	33.68	31.81	
C-65	20.12	14.59	13.80	15.41	46.47	36.19	34.58	32.66	
C-70	20.18	14.63	13.85	15.46	47.64	37.19	35.45	33.48	

Allowable Stresses (MPa)							
Concrete Grade	Concrete				Pre-stressing tendon		
	At transfer		At Service		At transfer		At service
	Compression	Tension	Compression	Tension	Tension	Tension	
C-40	11.90	0.00	18.00	-2.53	1,647.00	1,442.00	
C-45	13.39	0.00	20.25	-2.68	1,648.00	1,442.00	
C-50	14.88	0.00	22.50	-2.83	1,649.00	1,442.00	
C-55	16.37	0.00	24.75	-2.97	1,650.00	1,442.00	
C-60	17.86	0.00	27.00	-3.10	1,651.00	1,442.00	
C-65	19.35	0.00	29.25	-3.22	1,652.00	1,442.00	
C-70	20.83	0.00	31.50	-3.35	1,653.00	1,442.00	

Concrete grade	Losses of Pre-stress (%)	
	Rail seat	Center
C-40	19.88	21.44
C-45	19.30	20.78
C-50	18.81	20.21
C-55	18.39	19.73
C-60	18.02	19.31
C-65	17.69	18.93
C-70	17.40	18.61

Transfer Length (mm)		Bond Length (mm)		Development Length (mm)	
Rail seat	Center	Rail seat	Center	Rail seat	Center
518.78	518.78	757.17	779.42	1,275.95	1,298.20
534.28	534.28	748.93	769.98	1,283.21	1,304.26
548.54	548.54	741.97	761.87	1,290.51	1,310.41
561.77	561.77	735.99	755.17	1,297.76	1,316.93
574.12	574.12	730.73	749.12	1,304.85	1,323.24
585.73	585.73	726.03	743.49	1,311.76	1,329.51
596.68	596.68	721.91	739.11	1,318.59	1,335.79



Pre-Stressing Wires						
Concrete Grade	Type	Nominal Diameter (mm)	Quantity	Area (mm ²)	Eccentricity (mm)	
					Rail seat	Center
C-40 to C-70	7-wire strand	7.00	8.00	307.88	14.23	-1.77

Pre-Stressing forces								
Concrete Grade	Jacking Force (kN)	Initial Pre-Stress (MPa)		Final Pre-Stress (MPa)		Pre-Stress force after loss (kN)		
		Rail seat	Center	Rail seat	Center	Rail seat	Center	
		C-40	475.67	1,483.20	1,466.21	1,245.84	1,202.89	383.56
C-45	475.67	1,486.29	1,470.07	1,254.03	1,213.23	386.09	373.52	
C-50	475.67	1,489.38	1,474.24	1,261.43	1,222.84	388.36	376.48	
C-55	475.67	1,492.47	1,477.02	1,268.22	1,230.38	390.45	378.81	
C-60	475.67	1,494.02	1,479.34	1,273.06	1,236.88	391.94	380.80	
C-65	475.67	1,495.56	1,483.20	1,277.51	1,244.32	393.31	383.10	
C-70	475.67	1,497.88	1,485.52	1,282.38	1,249.91	394.81	384.82	

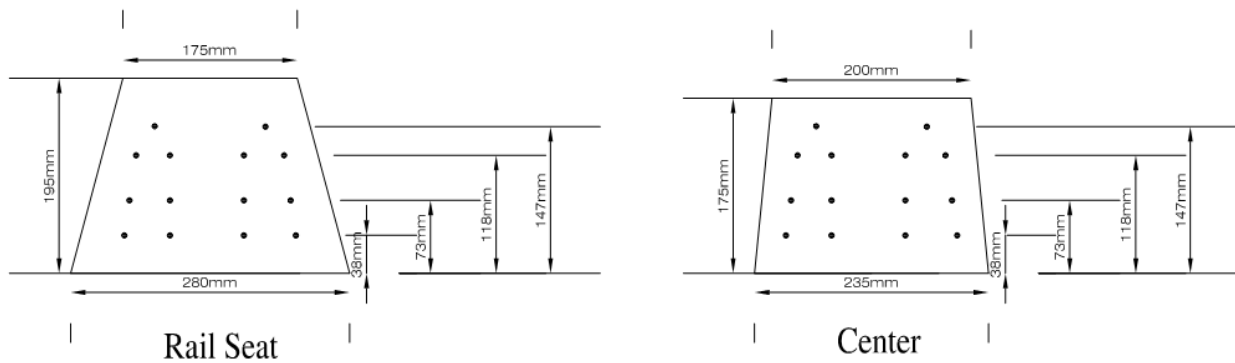
Applied Stresses in Concrete (Mpa)												
Concrete Grade	At transfer				At service (M ⁺)				At service (M ⁻)			
	Rail seat		Center		Rail seat		Center		Rail seat		Center	
	Top	Bottom	Top	Bottom	Top	Bottom	Top	Bottom	Top	Bottom	Top	Bottom
C-40	5.60	12.54	14.23	11.09	16.73	0.22	19.64	1.88	-3.26	17.36	-3.55	22.91
C-45	5.61	12.56	14.27	11.12	16.76	0.29	19.73	1.96	-3.23	17.43	-3.46	22.99
C-50	5.63	12.59	14.31	11.15	16.79	0.35	19.82	2.04	-3.21	17.50	-3.37	23.07
C-55	5.64	12.62	14.33	11.17	16.81	0.41	19.89	2.10	-3.18	17.55	-3.30	23.13
C-60	5.64	12.63	14.35	11.19	16.83	0.46	19.95	2.15	-3.17	17.60	-3.24	23.18
C-65	5.65	12.64	14.39	11.22	16.85	0.49	20.01	2.21	-3.15	17.63	-3.17	23.24
C-70	5.66	12.66	14.41	11.24	16.86	0.54	20.07	2.26	-3.13	17.68	-3.12	23.29

Moment Capacity of the section (kN.m)										
Concrete Grade	Allowable				Ultimate					
	Rail seat		Center		Rail seat			Center		
	Positive	Negative	Positive	Negative	Positive	Negative	Positive	Negative	Positive	Negative
C-40	25.79	12.96	13.44	15.03	50.16	32.56	28.29	26.96		
C-45	25.93	13.01	13.53	15.13	51.95	34.10	29.34	27.91		
C-50	26.05	13.05	13.61	15.21	53.64	35.55	30.33	28.81		
C-55	26.16	13.09	13.68	15.28	55.25	36.92	31.27	29.66		
C-60	26.23	13.11	13.74	15.34	56.79	38.24	32.18	30.48		
C-65	26.31	13.14	13.80	15.41	58.27	39.51	33.04	31.26		
C-70	26.38	13.17	13.85	15.46	59.68	40.72	33.87	32.02		

Allowable Stresses (MPa)							
Concrete Grade	Concrete				Pre-stressing tendon		
	At transfer		At Service		At transfer	At service	
	Compression	Tension	Compression	Tension	Tension	Tension	
C-40	11.90	0.00	18.00	-2.53	1,648.00	1,442.00	
C-45	13.39	0.00	20.25	-2.68	1,648.00	1,442.00	
C-50	14.88	0.00	22.50	-2.83	1,648.00	1,442.00	
C-55	16.37	0.00	24.75	-2.97	1,648.00	1,442.00	
C-60	17.86	0.00	27.00	-3.10	1,648.00	1,442.00	
C-65	19.35	0.00	29.25	-3.22	1,648.00	1,442.00	
C-70	20.83	0.00	31.50	-3.35	1,648.00	1,442.00	

Concrete grade	Losses of Pre-stress (%)		Transfer Length (mm)		Bond Length (mm)		Development Length (mm)	
	Rail seat	Center	Rail seat	Center	Rail seat	Center	Rail seat	Center
C-40	19.36	22.14	518.78	518.78	749.88	789.44	1,268.66	1,308.22
C-45	18.83	21.47	534.28	534.28	742.34	779.92	1,276.62	1,314.20
C-50	18.35	20.85	548.54	548.54	735.53	771.07	1,284.07	1,319.61
C-55	17.91	20.36	561.77	561.77	729.27	764.12	1,291.04	1,325.89
C-60	17.60	19.94	574.12	574.12	724.81	758.14	1,298.93	1,332.26
C-65	17.31	19.46	585.73	585.73	720.72	751.28	1,306.45	1,337.01
C-70	17.00	19.10	596.68	596.68	716.23	746.13	1,312.91	1,342.81

F.4 5.2mm diameter (3-wire strand)



Pre-Stressing Wires						
Concrete Grade	Type	Nominal Diameter (mm)	Quantity	Area (mm ²)	Eccentricity (mm)	
					Rail seat	Center
C-40 to C-70	3-wire strand	5.20	14.00	297.32	3.57	-1.28

Pre-Stressing forces							
Concrete Grade	Jacking Force (kN)	Initial Pre-Stress (MPa)		Final Pre-Stress (MPa)		Pre-Stress force after loss	
		Rail seat	Center	Rail seat	Center	Rail seat	Center
C-40	437.06	1,411.20	1,402.38	1,180.48	1,157.55	350.98	344.16
C-45	437.06	1,414.14	1,405.32	1,188.69	1,167.02	353.42	346.98
C-50	437.06	1,417.08	1,408.26	1,195.62	1,175.02	355.48	349.36
C-55	437.06	1,420.02	1,411.20	1,201.57	1,181.89	357.25	351.40
C-60	437.06	1,421.49	1,414.14	1,206.88	1,187.86	358.83	353.18
C-65	437.06	1,422.96	1,415.61	1,211.55	1,193.27	360.22	354.78
C-70	437.06	1,425.90	1,415.61	1,215.00	1,198.21	361.42	356.25

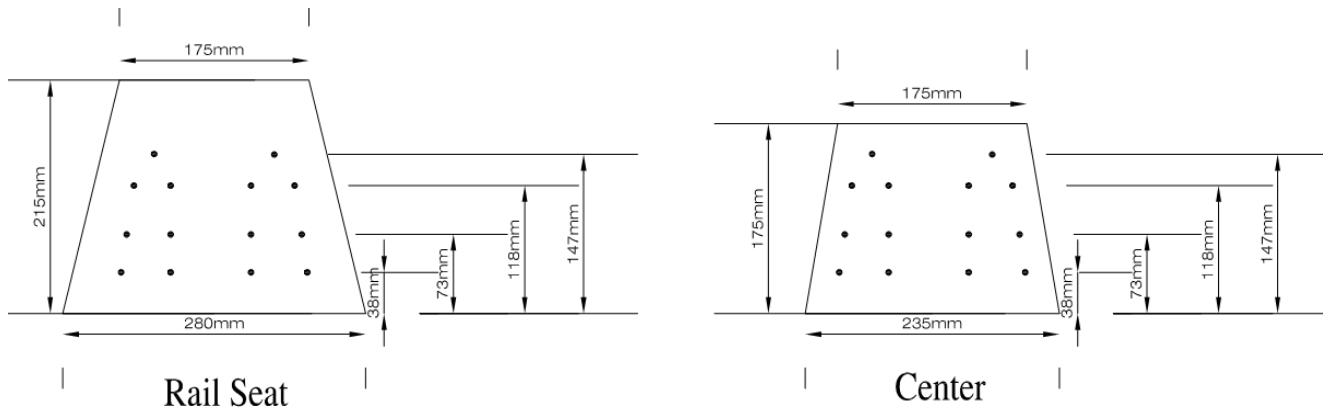
Applied Stresses in Concrete (Mpa)									
Concrete Grade	At transfer				At service				
	Rail seat		Center		Rail seat		Center		
	Top	Bottom	Top	Bottom	Top	Bottom	Top	Bottom	
C-40	8.72	10.09	12.22	9.75	6.96	-4.09	-8.60	25.77	
C-45	8.74	10.00	12.25	9.77	7.01	-4.03	(8.53)	25.84	
C-50	8.76	10.13	12.27	9.80	7.05	-3.98	(8.46)	25.90	
C-55	8.77	10.15	12.29	9.82	7.08	-3.94	(8.41)	25.95	
C-60	8.78	10.16	12.32	9.84	7.11	-3.9	(8.36)	25.99	
C-65	8.79	10.18	12.33	9.85	7.14	-3.87	(8.31)	26.03	
C-70	8.81	10.20	12.33	9.85	7.17	-3.84	(8.27)	26.07	

Moment Capacity of the section (kNm)										
Concrete Grade	Allowable					Ultimate				
	Rail seat		Center			Rail seat		Center		
	Positive	Negative	Positive	Negative	Positive	Negative	Positive	Negative	Positive	Negative
C-40	18.03	14.10	12.11	14.63	38.05	30.21	28.20	27.61		
C-45	18.12	14.16	12.19	14.75	39.52	31.48	29.29	28.64		
C-50	18.20	14.22	12.26	14.83	40.91	32.67	30.32	29.62		
C-55	18.26	14.27	12.32	14.89	42.23	33.80	31.30	30.55		
C-60	18.32	14.31	12.38	14.96	43.50	34.89	32.24	31.44		
C-65	18.38	14.35	12.42	15.01	44.71	35.93	33.14	32.30		
C-70	18.43	14.38	12.46	15.06	45.88	36.93	34.01	33.12		

Allowable Stresses (MPa)						
Concrete Grade	Concrete				Pre-stressing tendon	
	At transfer		At Service		At transfer	At service
	Compression	Tension	Compression	Tension	Tension	Tension
C-40	11.90	0.00	18.00	-2.53	1,567.00	1,372.00
C-45	13.39	0.00	20.25	-2.68	1,568.00	1,372.00
C-50	14.88	0.00	22.50	-2.83	1,568.00	1,372.00
C-55	16.37	0.00	24.75	-2.97	1,568.00	1,372.00
C-60	17.86	0.00	27.00	-3.10	1,568.00	1,372.00
C-65	19.35	0.00	29.25	-3.22	1,568.00	1,372.00
C-70	20.83	0.00	31.50	-3.35	1,568.00	1,372.00

Concrete grade	Losses of Pre-stress (%)	
	Rail seat	Center
C-40	19.70	21.26
C-45	19.14	20.61
C-50	18.67	20.07
C-55	18.26	19.60
C-60	17.90	19.19
C-65	17.58	18.83
C-70	17.31	18.49

Transfer Length (mm)		Bond Length (mm)		Development Length (mm)	
Rail seat	Center	Rail seat	Center	Rail seat	Center
518.78	518.78	533.36	549.05	1,052.13	1,067.82
534.28	534.28	527.74	542.56	1,062.02	1,076.84
548.54	548.54	523.00	537.09	1,071.54	1,085.63
561.77	561.77	518.92	532.39	1,080.69	1,094.16
574.12	574.12	515.29	528.30	1,089.42	1,102.43
585.73	585.73	512.10	524.61	1,097.82	1,110.33
596.68	596.68	509.33	521.23	1,106.01	1,117.90



Pre-Stressing Wires						
Concrete Grade	Type	Nominal Diameter (mm)	Quantity	Area (mm ²)	Eccentricity (mm)	
					Rail seat	Center
C-40 to C-70	3-wire strand	5.20	14.00	297.32	12.80	-3.2

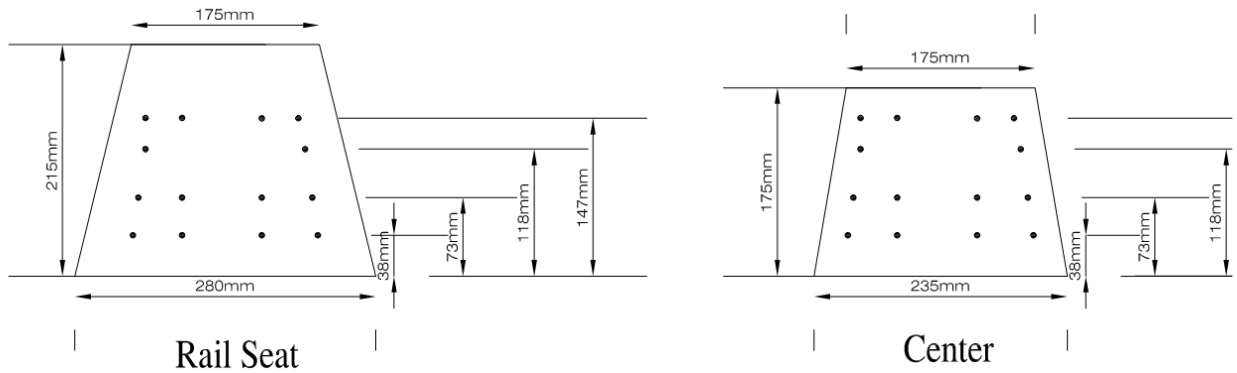
Pre-Stressing forces							
Concrete Grade	Jacking Force (kN)	Initial Pre-Stress (MPa)		Final Pre-Stress (MPa)		Pre-Stress force after loss (kN)	
		Rail seat	Center	Rail seat	Center	Rail seat	Center
C-40	437.06	1,413.41	1,396.50	1,188.36	1,146.50	353.32	340.88
C-45	437.06	1,416.35	1,400.91	1,195.95	1,156.83	355.58	343.95
C-50	437.06	1,419.29	1,404.59	1,202.82	1,165.54	357.62	346.54
C-55	437.06	1,421.49	1,407.53	1,208.43	1,172.86	359.29	348.71
C-60	437.06	1,423.70	1,411.20	1,213.60	1,180.29	360.83	350.92
C-65	437.06	1,425.90	1,412.96	1,218.42	1,185.48	362.26	352.47
C-70	437.06	1,427.52	1,414.88	1,222.39	1,190.43	363.44	353.94

Applied Stresses in Concrete (Mpa)													
Concrete Grade	At transfer				At service (M+)				At service (M-)				
	Rail seat		Center		Rail seat		Center		Rail seat		Center		
	Top	Bottom	Top	Bottom	Top	Bottom	Top	Bottom	Top	Bottom	Top	Bottom	Bottom
C-40	5.56	11.19	13.76	9.59	16.70	-0.90	19.25	0.66	-3.30	16.24	-3.93	21.69	
C-45	5.57	11.22	13.80	9.63	16.73	-0.84	19.35	0.73	-3.27	16.30	-3.84	21.76	
C-50	5.58	11.24	13.83	9.65	16.75	-0.78	19.43	0.80	-3.24	16.36	-3.76	21.83	
C-55	5.59	11.26	13.86	9.67	16.78	-0.74	19.50	0.85	-3.22	16.40	-3.69	21.88	
C-60	5.60	11.27	13.89	9.70	16.79	-0.69	19.57	0.91	-3.20	16.45	-3.62	21.94	
C-65	5.60	11.29	13.91	9.71	16.81	-0.66	19.61	0.95	-3.19	16.48	-3.57	21.98	
C-70	5.61	11.31	13.93	9.73	16.83	-0.62	19.66	0.98	-3.17	16.52	-3.53	22.01	

Moment Capacity of the section (kN.m)								
Concrete Grade	Allowable				Ultimate			
	Rail seat		Center		Rail seat		Center	
	Positive	Negative	Positive	Negative	Positive	Negative	Positive	Negative
C-40	23.71	12.91	12.11	14.63	47.99	32.50	26.91	26.56
C-45	23.82	12.95	12.19	14.75	49.78	34.03	27.95	27.51
C-50	23.92	12.99	12.26	14.83	51.48	35.48	28.95	28.41
C-55	24.01	13.02	12.32	14.89	53.08	36.86	29.89	29.26
C-60	24.09	13.05	12.38	14.96	54.62	38.18	30.79	30.08
C-65	24.16	13.08	12.42	15.01	56.10	39.44	31.65	30.86
C-70	24.22	13.11	12.46	15.06	57.52	40.66	32.48	31.62

Allowable Stresses (MPa)							
Concrete Grade	Concrete				Pre-stressing tendon		
	At transfer		At Service		At transfer		At service
	Compression		Tension		Tension		Tension
C-40		11.90	0.00	18.00	-2.53	1,568.00	1,372.00
C-45		13.39	0.00	20.25	-2.68	1,568.00	1,372.00
C-50		14.88	0.00	22.50	-2.83	1,568.00	1,372.00
C-55		16.37	0.00	24.75	-2.97	1,568.00	1,372.00
C-60		17.86	0.00	27.00	-3.10	1,568.00	1,372.00
C-65		19.35	0.00	29.25	-3.22	1,568.00	1,372.00
C-70		20.83	0.00	31.50	-3.35	1,568.00	1,372.00

Concrete grade	Losses of Pre-stress (%)		Transfer Length (mm)		Bond Length (mm)		Development Length (mm)	
	Rail seat	Center	Rail seat	Center	Rail seat	Center	Rail seat	Center
C-40	19.16	22.01	518.78	518.78	527.96	556.60	1,046.74	1,075.38
C-45	18.64	21.30	534.28	534.28	522.77	549.54	1,057.05	1,083.82
C-50	18.18	20.71	548.54	548.54	518.07	543.58	1,066.61	1,092.12
C-55	17.79	20.21	561.77	561.77	514.23	538.57	1,076.00	1,100.34
C-60	17.44	19.71	574.12	574.12	510.70	533.48	1,084.82	1,107.60
C-65	17.11	19.36	585.73	585.73	507.40	529.93	1,093.13	1,115.66
C-70	16.84	19.02	596.68	596.68	504.68	526.55	1,101.36	1,123.23



Pre-Stressing Wires						
Concrete Grade	Type	Nominal Diameter (mm)	Quantity	Area (mm ²)	Eccentricity (mm)	
					Rail seat	Center
C-40 to C-70	3-wire strand	5.20	14.00	297.32	8.66	-7.34

Pre-Stressing forces							
Concrete Grade	Jacking Force (kN)	Initial Pre-Stress (MPa)		Final Pre-Stress (MPa)		Pre-Stress force after loss (kN)	
		Rail seat	Center	Rail seat	Center	Rail seat	Center
C-40	437.06	1,413.41	1,396.50	1,190.26	1,144.63	353.89	340.32
C-45	437.06	1,416.35	1,400.91	1,197.74	1,155.06	356.11	343.42
C-50	437.06	1,419.29	1,404.59	1,204.52	1,163.86	358.13	346.04
C-55	437.06	1,421.49	1,407.53	1,210.05	1,171.25	359.77	348.24
C-60	437.06	1,423.70	1,411.20	1,215.16	1,178.75	361.29	350.47
C-65	437.06	1,425.90	1,412.96	1,219.92	1,183.99	362.71	352.03
C-70	437.06	1,427.52	1,414.88	1,223.83	1,189.00	363.87	353.51

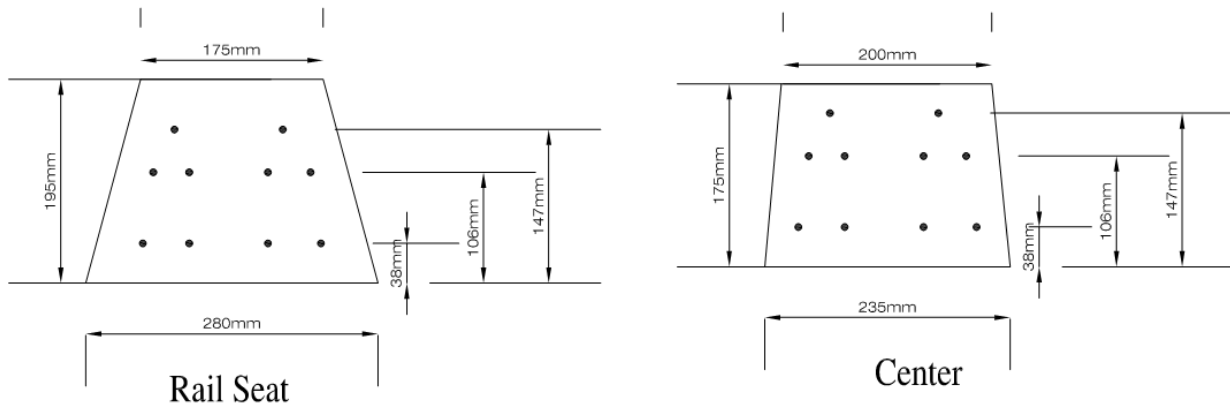
Applied Stresses in Concrete (Mpa)														
Concrete Grade	At transfer						At service (M+)				At service (M-)			
	Rail seat		Center				Rail seat		Center		Rail seat		Center	
	Top	Bottom	Top	Bottom	Top	Bottom	Top	Bottom	Top	Bottom	Top	Bottom	Top	Bottom
C-40	6.63	10.26	15.49	8.02	17.62	-1.67	20.66	-0.65	-2.37	15.47	-2.53	20.38		
C-45	6.66	10.28	15.54	8.05	17.66	-1.61	20.77	-0.58	-2.34	15.53	-2.42	20.45		
C-50	6.67	10.30	15.58	8.07	17.69	-1.56	20.86	-0.53	-2.31	15.58	-2.33	20.50		
C-55	6.68	10.32	15.61	8.09	17.71	-1.52	20.94	-0.48	-2.28	15.62	-2.25	20.55		
C-60	6.69	10.33	15.65	8.11	17.74	-1.48	21.02	-0.43	-2.26	15.66	-2.17	20.60		
C-65	6.70	10.35	15.67	8.12	17.76	-1.45	21.07	-0.40	-2.24	15.69	-2.11	20.63		
C-70	6.71	10.36	15.69	8.13	17.77	-1.42	21.13	-0.37	-2.22	15.72	-2.06	20.66		

Moment Capacity of the section (kNm)												
Concrete Grade	Allowable						Ultimate					
	Rail seat		Center				Rail seat		Center			
	Positive	Negative	Positive	Negative	Positive	Negative	Positive	Negative	Positive	Negative	Positive	Negative
C-40	22.27	14.38	10.68	16.05	46.52	34.02	25.43	28.00				
C-45	22.37	14.44	10.75	16.15	48.31	35.56	26.47	28.95				
C-50	22.47	14.48	10.81	16.25	50.00	37.01	27.46	29.85				
C-55	22.54	14.52	10.86	16.32	51.61	38.38	28.41	30.71				
C-60	22.62	14.56	10.92	16.40	53.15	39.70	29.31	31.52				
C-65	22.68	14.59	10.95	16.46	54.62	40.97	30.17	32.30				
C-70	22.74	14.62	10.99	16.51	56.04	42.18	31.00	33.06				

Allowable Stresses (MPa)							
Concrete Grade	Concrete				Pre-stressing tendon		
	At transfer		At Service		At transfer		At service
	Compression	Tension	Compression	Tension	Tension	Tension	
C-40		11.90	0.00	18.00	-2.53	1,568.00	1,372.00
C-45		13.39	0.00	20.25	-2.68	1,568.00	1,372.00
C-50		14.88	0.00	22.50	-2.83	1,568.00	1,372.00
C-55		16.37	0.00	24.75	-2.97	1,568.00	1,372.00
C-60		17.86	0.00	27.00	-3.10	1,568.00	1,372.00
C-65		19.35	0.00	29.25	-3.22	1,568.00	1,372.00
C-70		20.83	0.00	31.50	-3.35	1,568.00	1,372.00

Concrete grade	Losses of Pre-stress (%)		Transfer Length (mm)		Bond Length (mm)		Development Length (mm)	
	Rail seat	Center	Rail seat	Center	Rail seat	Center	Rail seat	Center
C-40	19.03	22.13	518.78	518.78	526.67	557.89	1,045.45	1,076.67
C-45	18.52	21.42	534.28	534.28	521.55	550.75	1,055.83	1,085.03
C-50	18.06	20.83	548.54	548.54	516.91	544.73	1,065.45	1,093.27
C-55	17.68	20.32	561.77	561.77	513.12	539.67	1,074.89	1,101.44
C-60	17.34	19.81	574.12	574.12	509.63	534.54	1,083.75	1,108.66
C-65	17.01	19.46	585.73	585.73	506.37	530.95	1,092.10	1,116.68
C-70	16.75	19.12	596.68	596.68	503.69	527.53	1,100.37	1,124.21

F.5 6.5mm diameter (3-wire strand)



Pre-Stressing Wires							
Concrete Grade	Type	Nominal Diameter (mm)	Quantity	Area (mm ²)	Eccentricity (mm)		
					Rail seat	Center	
C-40 to C-70	3-wire strand	6.50	10.00	331.83	3.00	-1.28	

Pre-Stressing forces							
Concrete Grade	Jacking Force (kN)	Initial Pre-Stress (MPa)		Final Pre-Stress (MPa)		Pre-Stress force after loss (kN)	
		Rail seat	Center	Rail seat	Center	Rail seat	Center
C-40	462.90	1,332.23	1,322.46	1,101.82	1,077.54	365.62	357.56
C-45	462.90	1,335.02	1,325.25	1,110.46	1,087.52	368.49	360.87
C-50	462.90	1,339.20	1,330.83	1,117.61	1,095.60	370.86	363.55
C-55	462.90	1,341.99	1,332.23	1,123.87	1,103.10	372.94	366.01
C-60	462.90	1,343.39	1,335.02	1,129.46	1,109.31	374.79	368.10
C-65	462.90	1,346.18	1,337.81	1,134.26	1,114.85	376.38	369.94
C-70	462.90	1,346.87	1,339.20	1,138.71	1,119.93	377.86	371.63

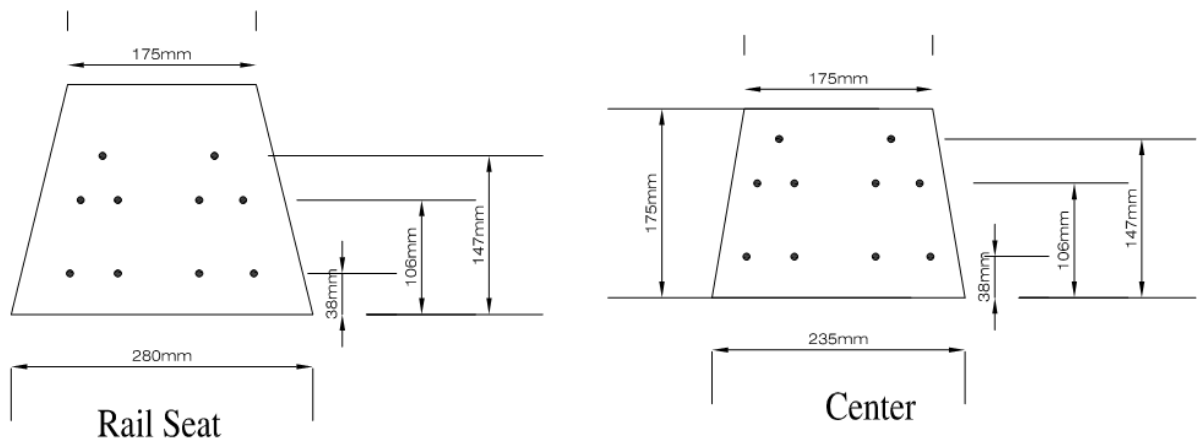
Applied Stresses in Concrete (Mpa)									
Concrete Grade	At transfer				At service				
	Rail seat		Center		Rail seat		Center		
	Top	Bottom	Top	Bottom	Top	Bottom	Top	Bottom	Bottom
C-40	9.36	10.48	13.06	10.08	7.41	-3.87	-8.05	25.92	
C-45	9.38	10.51	13.08	10.11	7.47	-3.8	-7.95	26.01	
C-50	9.41	10.51	13.13	10.15	7.51	-3.74	-7.88	26.07	
C-55	9.43	10.56	13.15	10.16	7.56	-3.69	-7.81	26.13	
C-60	9.44	10.57	13.17	10.19	7.59	-3.64	-7.75	26.18	
C-65	9.45	10.60	13.20	10.21	7.63	-3.6	-7.7	26.23	
C-70	9.46	10.60	13.21	10.22	7.66	-3.57	-7.65	26.27	

Moment Capacity of the section (kNm)									
Concrete Grade	Allowable				Ultimate				
	Rail seat		Center		Rail seat		Center		
	Positive	Negative	Positive	Negative	Positive	Negative	Positive	Negative	Negative
C-40	13.37	13.63	12.26	15.26	37.99	30.53	28.04	27.86	
C-45	13.29	13.70	12.35	15.36	39.46	31.79	29.13	28.89	
C-50	13.23	13.77	12.43	15.46	40.86	32.98	30.16	29.87	
C-55	13.17	13.82	12.49	15.53	42.18	34.12	31.14	30.80	
C-60	13.13	13.87	12.56	15.61	43.44	35.20	32.08	31.69	
C-65	13.08	13.92	12.62	15.68	44.66	36.24	32.98	32.55	
C-70	13.05	13.92	12.66	15.72	45.83	37.24	33.85	33.37	

Allowable Stresses (MPa)						
Concrete Grade	Concrete				Pre-stressing tendon	
	At transfer		At Service		At transfer	At service
	Compression	Tension	Compression	Tension	Tension	Tension
C-40	11.90	0.00	18.00	-2.53	1,487.00	1,302.00
C-45	13.39	0.00	20.25	-2.68	1,488.00	1,302.00
C-50	14.88	0.00	22.50	-2.83	1,488.00	1,302.00
C-55	16.37	0.00	24.75	-2.97	1,488.00	1,302.00
C-60	17.86	0.00	27.00	-3.10	1,488.00	1,302.00
C-65	19.35	0.00	29.25	-3.22	1,489.00	1,302.00
C-70	20.83	0.00	31.50	-3.35	1,490.00	1,302.00

Concrete grade	Losses of Pre-stress (%)	
	Rail seat	Center
C-40	21.02	22.76
C-45	20.40	22.04
C-50	19.88	21.46
C-55	19.44	20.93
C-60	19.03	20.48
C-65	18.69	20.08
C-70	18.37	19.72

Transfer Length (mm)		Bond Length (mm)		Development Length (mm)	
Rail seat	Center	Rail seat	Center	Rail seat	Center
518.78	518.78	648.44	669.21	1,167.22	1,187.98
534.28	534.28	641.05	660.67	1,175.33	1,194.95
548.54	548.54	634.94	653.76	1,175.33	1,202.30
561.77	561.77	629.58	647.43	1,191.35	1,209.19
574.12	574.12	624.80	642.04	1,198.92	1,216.16
585.73	585.73	620.70	637.30	1,206.43	1,223.02
596.68	596.68	616.89	632.96	1,213.57	1,229.64



Pre-Stressing Wires						
Concrete Grade	Type	Nominal Diameter (mm)	Quantity	Area (mm ²)	Eccentricity (mm)	
					Rail seat	Center
C-40 to C-70	3-wire strand	6.50	10.00	331.83	12.23	-3.77

Pre-Stressing forces							
Concrete Grade	Jacking Force (kN)	Initial Pre-Stress (MPa)		Final Pre-Stress (MPa)		Pre-Stress force after loss (kN)	
		Rail seat	Center	Rail seat	Center	Rail seat	Center
C-40	462.90	1,336.41	1,318.28	1,111.16	1,066.38	368.72	353.86
C-45	462.90	1,339.20	1,322.46	1,118.84	1,076.80	371.26	357.32
C-50	462.90	1,341.99	1,326.78	1,125.75	1,086.38	373.56	360.49
C-55	462.90	1,344.78	1,328.74	1,132.09	1,093.01	375.66	362.69
C-60	462.90	1,346.18	1,332.23	1,136.64	1,100.47	377.17	365.17
C-65	462.90	1,348.97	1,335.02	1,142.14	1,106.79	379.00	367.27
C-70	462.90	1,349.66	1,336.41	1,145.35	1,111.42	380.06	368.80

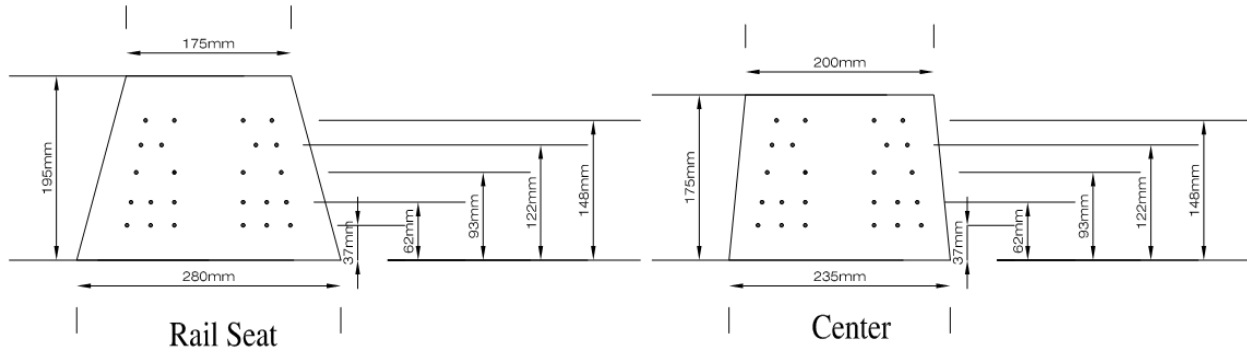
Applied Stresses in Concrete (Mpa)													
Concrete Grade	At transfer					At service (M+)				At service (M-)			
	Rail seat		Center			Rail seat		Center		Rail seat		Center	
	Top	Bottom	Top	Bottom		Top	Bottom	Top	Bottom	Top	Bottom	Top	Bottom
C-40	6.01	11.69	14.70	9.92		17.02	-0.59	19.86	0.80	-2.97	16.55	-3.33	21.83
C-45	6.02	11.71	14.73	9.95		17.06	-0.52	19.97	0.88	-2.94	16.62	-3.22	21.91
C-50	6.03	11.74	14.79	9.99		17.09	-0.46	20.07	0.96	-2.91	16.68	-3.12	21.99
C-55	6.04	11.76	14.81	10.00		17.11	-0.40	20.14	1.01	-2.88	16.74	-3.05	22.04
C-60	6.05	11.78	14.85	10.03		17.13	-0.36	20.22	1.07	-2.87	16.78	-2.97	22.10
C-65	6.06	11.80	14.88	10.05		17.16	-0.31	20.29	1.12	-2.84	16.83	-2.90	22.15
C-70	6.06	11.81	14.89	10.07		17.17	-0.29	20.34	1.16	-2.83	16.85	-2.85	22.19

Moment Capacity of the section (kN.m)									
Concrete Grade	Allowable				Ultimate				
	Rail seat		Center		Rail seat		Center		
	Positive	Negative	Positive	Negative	Positive	Negative	Positive	Negative	Positive
C-40	20.70	12.12	12.26	15.26	48.03	32.81	26.71	26.77	
C-45	20.65	12.17	12.35	15.36	49.84	34.35	27.75	27.72	
C-50	20.60	12.22	12.43	15.46	51.53	35.80	28.75	28.61	
C-55	20.56	12.26	12.49	15.53	53.14	37.18	29.69	29.47	
C-60	20.53	12.29	12.56	15.61	54.68	38.50	30.39	30.29	
C-65	20.49	12.33	12.62	15.68	56.15	39.76	31.45	31.07	
C-70	20.47	12.35	12.66	15.72	57.57	40.98	32.28	31.82	

Allowable Stresses (MPa)							
Concrete Grade	Concrete				Pre-stressing tendon		
	At transfer		At Service		At transfer		At service
	Compression		Tension	Compression	Tension	Tension	
C-40	11.90		0.00	18.00	-2.53	1,488.00	1,302.00
C-45	13.39		0.00	20.25	-2.68	1,488.00	1,302.00
C-50	14.88		0.00	22.50	-2.83	1,488.00	1,302.00
C-55	16.37		0.00	24.75	-2.97	1,488.00	1,302.00
C-60	17.86		0.00	27.00	-3.10	1,488.00	1,302.00
C-65	19.35		0.00	29.25	-3.22	1,488.00	1,302.00
C-70	20.83		0.00	31.50	-3.35	1,488.00	1,302.00

Concrete grade	Losses of Pre-stress (%)		Transfer Length (mm)		Bond Length (mm)		Development Length (mm)	
	Rail seat	Center	Rail seat	Center	Rail seat	Center	Rail seat	Center
C-40	20.35	23.56	518.78	518.78	640.46	678.76	1,159.24	1,197.54
C-45	19.80	22.81	534.28	534.28	633.89	669.84	1,168.17	1,204.12
C-50	19.30	22.12	548.54	548.54	627.97	661.65	1,176.51	1,210.19
C-55	18.85	21.65	561.77	561.77	622.56	655.98	1,184.33	1,217.75
C-60	18.52	21.11	574.12	574.12	618.66	649.60	1,192.78	1,223.72
C-65	18.13	20.66	585.73	585.73	613.96	644.19	1,199.69	1,229.92
C-70	17.90	20.33	596.68	596.68	611.21	640.23	1,207.89	1,236.91

F.6 4mm diameter (wire)



Pre-Stressing Wires						
Concrete Grade	Type	Nominal Diameter (mm)	Quantity	Area (mm ²)	Eccentricity (mm)	
					Rail seat	Center
C-40 to C-70	single wire	4.00	24.00	301.59	4.75	-0.1

Pre-Stressing forces							
Concrete Grade	Jacking Force (kN)	Initial Pre-Stress (MPa)		Final Pre-Stress (MPa)		Pre-Stress force after loss (kN)	
		Rail seat	Center	Rail seat	Center	Rail seat	Center
C-40	420.72	1,337.81	1,329.44	1,114.86	1,093.37	336.23	329.75
C-45	420.72	1,340.60	1,332.23	1,122.78	1,102.50	338.62	332.50
C-50	420.72	1,343.39	1,335.71	1,129.47	1,110.08	340.64	334.79
C-55	420.72	1,345.48	1,338.50	1,135.27	1,168.68	342.39	336.78
C-60	420.72	1,347.57	1,340.60	1,140.33	1,122.50	343.91	338.54
C-65	420.72	1,349.66	1,342.69	1,144.78	1,127.62	345.26	340.08
C-70	420.72	1,351.76	1,344.78	1,148.74	1,132.18	346.45	341.46

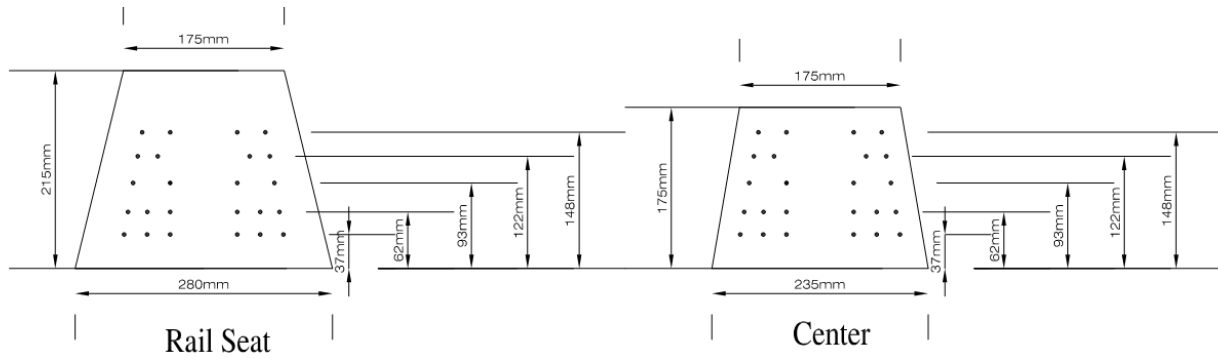
Applied Stresses in Concrete (Mpa)									
Concrete Grade	At transfer				At service				
	Rail seat		Center		Rail seat		Center		
	Top	Bottom	Top	Bottom	Top	Bottom	Top	Bottom	Bottom
C-40	8.04	10.00	11.35	9.77	6.36	-4.20	-9.36	25.75	
C-45	8.06	10.02	11.37	9.79	6.41	(4.14)	-9.29	25.82	
C-50	8.07	10.04	11.40	9.81	6.45	(4.09)	-9.23	25.88	
C-55	8.09	10.06	11.42	9.84	6.48	(4.05)	-9.17	25.93	
C-60	8.10	10.07	11.43	9.85	6.51	(4.01)	-9.13	25.98	
C-65	8.11	10.09	11.45	9.87	6.54	(3.97)	-9.09	26.02	
C-70	8.12	10.11	11.47	9.89	6.56	(3.94)	-9.05	26.05	

Moment Capacity of the section (kN.m)									
Concrete Grade	Allowable				Ultimate				
	Rail seat		Center		Rail seat		Center		
	Positive	Negative	Positive	Negative	Positive	Negative	Positive	Negative	Positive
C-40	17.86	13.32	12.11	13.84	37.88	29.42	28.18	26.77	27.81
C-45	17.95	13.38	12.19	13.92	39.36	30.68	29.27	27.81	27.81
C-50	18.03	13.43	12.26	13.99	40.75	31.87	30.30	28.79	28.79
C-55	18.11	13.48	12.33	14.06	42.07	33.00	31.29	29.72	29.72
C-60	18.16	13.51	12.37	14.11	43.34	34.09	32.22	30.61	30.61
C-65	18.21	13.54	12.43	14.17	44.55	35.13	33.12	31.46	31.46
C-70	18.25	13.57	12.46	14.20	45.72	36.13	33.99	32.28	32.28

Allowable Stresses (MPa)						
Concrete Grade	Concrete				Pre-stressing tendon	
	At transfer		At Service		At transfer	At service
	Compression	Tension	Compression	Tension	Tension	Tension
C-40	11.90	0.00	18.00	-2.53	1,488.00	1,302.00
C-45	13.39	0.00	20.25	-2.68	1,488.00	1,302.00
C-50	14.88	0.00	22.50	-2.83	1,488.00	1,302.00
C-55	16.37	0.00	24.75	-2.97	1,488.00	1,302.00
C-60	17.86	0.00	27.00	-3.10	1,488.00	1,302.00
C-65	19.35	0.00	29.25	-3.22	1,488.00	1,302.00
C-70	20.83	0.00	31.50	-3.35	1,488.00	1,302.00

Concrete grade	Losses of Pre-stress (%)	
	Rail seat	Center
C-40	20.08	21.62
C-45	19.51	20.97
C-50	19.03	20.42
C-55	18.62	19.95
C-60	18.26	19.53
C-65	17.94	19.17
C-70	17.65	18.84

Transfer Length (mm)		Bond Length (mm)		Development Length (mm)	
Rail seat	Center	Rail seat	Center	Rail seat	Center
518.78	518.78	392.18	403.49	910.95	922.27
534.28	534.28	388.01	398.70	922.29	932.98
548.54	548.54	384.49	394.69	933.03	943.23
561.77	561.77	381.44	391.22	943.20	952.99
574.12	574.12	378.78	388.16	952.90	962.28
585.73	585.73	376.43	385.46	962.16	971.19
596.68	596.68	374.35	383.06	971.03	979.74



Pre-Stressing Wires						
Concrete Grade	Type	Nominal Diameter (mm)	Quantity	Area (mm ²)	Eccentricity (mm)	
					Rail seat	Center
C-40 to C-70	Single wire	4.00	24.00	301.59	13.98	-2.02

Pre-Stressing forces							
Concrete Grade	Jacking Force (kN)	Initial Pre-Stress (MPa)		Final Pre-Stress (MPa)		Pre-Stress force after loss (kN)	
		Rail seat	Center	Rail seat	Center	Rail seat	Center
C-40	420.72	1,340.60	1,325.25	1,122.22	1,083.71	338.45	326.84
C-45	420.72	1,343.39	1,328.74	1,129.52	1,092.93	340.65	329.62
C-50	420.72	1,346.18	1,332.23	1,136.11	1,101.26	342.64	332.13
C-55	420.72	1,348.97	1,335.71	1,142.17	1,108.90	344.47	334.43
C-60	420.72	1,350.08	1,337.81	1,146.21	1,114.69	345.69	336.18
C-65	420.72	1,351.76	1,340.60	1,150.44	1,120.69	346.97	337.99
C-70	420.72	1,353.15	1,341.29	1,154.12	1,124.38	348.08	339.10

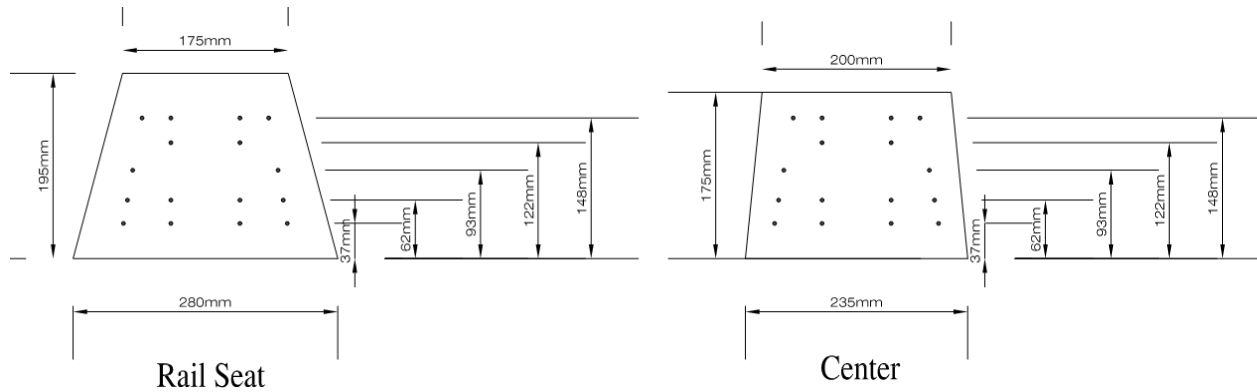
Applied Stresses in Concrete (Mpa)												
Concrete Grade	At transfer					At service (M+)				At service (M-)		
	Rail seat		Center			Rail seat		Center		Rail seat		Center
	Top	Bottom	Top	Bottom	Top	Bottom	Top	Bottom	Top	Bottom	Top	Bottom
C-40	5.06	11.01	12.80	9.64	16.27	-1.09	18.43	0.66	-3.73	16.05	-4.76	21.69
C-45	5.07	11.04	12.83	9.66	16.29	-1.03	18.51	0.73	-3.71	16.11	-4.68	21.76
C-50	5.08	11.06	12.86	9.69	16.32	-0.97	18.59	0.80	-3.68	16.17	-4.60	21.83
C-55	5.09	11.08	12.89	9.72	16.34	-0.92	18.66	0.86	-3.66	16.22	-4.53	21.89
C-60	5.10	11.09	12.91	9.74	16.35	-0.89	18.71	0.90	-3.65	16.25	-4.48	21.93
C-65	5.10	11.11	12.94	9.76	16.37	-0.85	18.76	0.95	-3.63	16.29	-4.43	21.98
C-70	5.11	11.12	12.94	9.76	16.38	-0.82	18.80	0.98	-3.62	16.32	-4.39	22.01

Moment Capacity of the section (kN.m)									
Concrete Grade	Allowable				Ultimate				
	Rail seat		Center		Rail seat		Center		
	Positive	Negative	Positive	Negative	Positive	Negative	Positive	Negative	Negative
C-40	23.35	12.21	12.11	13.84	47.63	31.79	26.91	25.71	
C-45	23.46	12.25	12.19	13.92	49.42	33.32	27.96	26.66	
C-50	23.57	12.29	12.26	13.99	51.11	34.77	28.95	27.56	
C-55	23.66	12.32	12.33	14.06	52.72	36.15	29.89	28.42	
C-60	23.72	12.35	12.37	14.11	54.26	37.47	30.79	29.23	
C-65	23.79	12.37	12.43	14.17	55.73	38.73	31.65	30.02	
C-70	23.85	12.39	12.46	14.20	57.15	39.93	32.49	30.77	

Allowable Stresses (MPa)						
Concrete Grade	Concrete				Pre-stressing tendon	
	At transfer		At Service		At transfer	At service
	Compression	Tension	Compression	Tension	Tension	Tension
C-40	11.90	0.00	18.00	-2.53	1,488.00	1,302.00
C-45	13.39	0.00	20.25	-2.68	1,488.00	1,302.00
C-50	14.88	0.00	22.50	-2.83	1,488.00	1,302.00
C-55	16.37	0.00	24.75	-2.97	1,488.00	1,302.00
C-60	17.86	0.00	27.00	-3.10	1,488.00	1,302.00
C-65	19.35	0.00	29.25	-3.22	1,488.00	1,302.00
C-70	20.83	0.00	31.50	-3.35	1,488.00	1,302.00

Concrete grade	Losses of Pre-stress (%)		Transfer Length (mm)		Bond Length (mm)		Development Length (mm)	
	Rail seat	Center	Rail seat	Center	Rail seat	Center	Rail seat	Center
C-40	19.55	22.31	518.78	518.78	388.31	408.57	907.09	927.35
C-45	19.03	21.65	534.28	534.28	384.47	403.72	918.75	938.00
C-50	18.56	21.06	548.54	548.54	380.99	399.34	929.53	947.88
C-55	18.12	20.51	561.77	561.77	377.80	395.32	939.57	957.09
C-60	17.83	20.09	574.12	574.12	375.68	392.27	949.80	966.39
C-65	17.53	19.66	585.73	585.73	373.45	389.11	959.18	974.84
C-70	17.27	19.40	596.68	596.68	371.51	387.17	968.19	983.85

F.7 5mm diameter (wire)



Pre-Stressing Wires						
Concrete Grade	Type	Nominal Diameter (mm)	Quantity	Area (mm ²)	Eccentricity (mm)	
					Rail seat	Center
C-40 to C-70	Single wire	5.00	16.00	314.16	1.38	-3.47

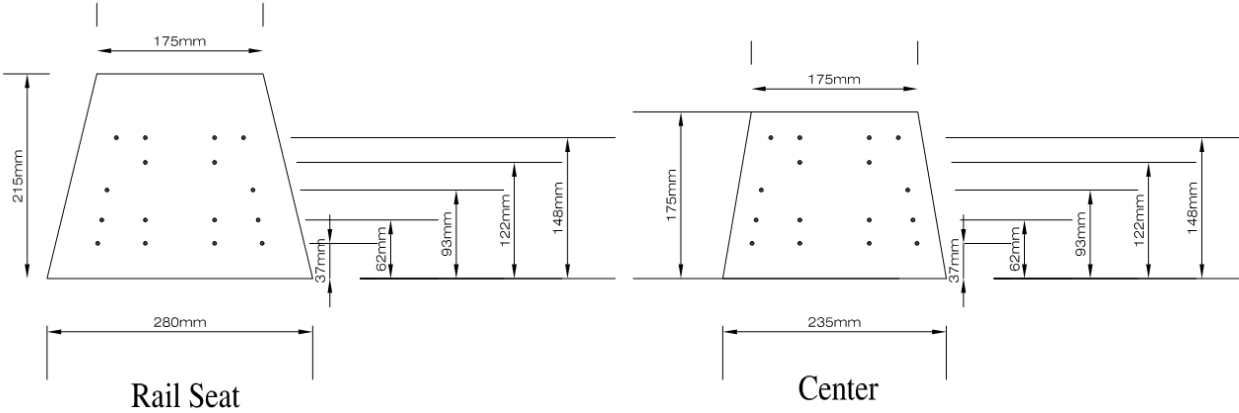
Pre-Stressing forces							
Concrete Grade	Jacking Force (kN)	Initial Pre-Stress (MPa)		Final Pre-Stress (MPa)		Pre-Stress force after loss (kN)	
		Rail seat	Center	Rail seat	Center	Rail seat	Center
C-40	438.25	1,336.41	1,326.65	1,110.03	1,086.05	348.73	341.19
C-45	438.25	1,339.20	1,330.13	1,118.21	1,095.47	351.30	344.15
C-50	438.25	1,341.29	1,334.32	1,125.19	1,103.34	353.49	346.62
C-55	438.25	1,343.39	1,336.41	1,131.19	1,110.32	355.37	348.82
C-60	438.25	1,346.18	1,339.20	1,136.35	1,116.32	356.99	350.70
C-65	438.25	1,348.97	1,340.73	1,140.89	1,121.73	358.42	352.40
C-70	438.25	1,351.06	1,342.69	1,144.98	1,126.51	359.71	353.90

Applied Stresses in Concrete (Mpa)								
Concrete Grade	At transfer				At service			
	Rail seat		Center		Rail seat		Center	
	Top	Bottom	Top	Bottom	Top	Bottom	Top	Bottom
C-40	9.43	9.49	13.07	8.94	7.50	-4.65	-7.99	25.03
C-45	9.45	9.51	13.10	8.97	7.55	-4.59	(7.90)	25.10
C-50	9.46	9.53	13.14	9.00	7.60	-4.54	(7.83)	25.16
C-55	9.48	9.55	13.16	9.02	7.64	-4.49	(7.77)	25.21
C-60	9.49	9.57	13.18	9.04	7.67	-4.46	(7.71)	25.25
C-65	9.51	9.59	13.20	9.05	7.70	-4.42	(7.66)	25.29
C-70	9.53	9.60	13.21	9.06	7.73	-4.39	(7.62)	25.33

Moment Capacity of the section (kN.m)									
Concrete Grade	Allowable				Ultimate				
	Rail seat		Center		Rail seat		Center		
	Positive	Negative	Positive	Negative	Positive	Negative	Positive	Negative	Negative
C-40	17.18	14.82	11.28	15.30	37.19	30.96	27.36	28.32	28.32
C-45	17.27	14.89	11.35	15.40	38.66	32.22	28.45	29.36	29.36
C-50	17.35	14.95	11.43	15.49	40.05	33.41	29.46	30.33	30.33
C-55	17.39	14.98	11.48	15.57	41.38	34.55	30.46	31.26	31.26
C-60	17.48	15.05	11.54	15.64	42.64	35.63	31.40	32.15	32.15
C-65	17.52	15.09	11.57	15.69	43.86	36.67	32.30	33.01	33.01
C-70	17.58	15.13	11.62	15.75	45.02	37.67	33.17	33.83	33.83

Allowable Stresses (MPa)						
Concrete Grade	Concrete				Pre-stressing tendon	
	At transfer		At Service		At transfer	At service
	Compression	Tension	Compression	Tension	Tension	Tension
C-40	11.90	0.00	18.00	-2.53	1,488.00	1,302.00
C-45	13.39	0.00	20.25	-2.68	1,488.00	1,302.00
C-50	14.88	0.00	22.50	-2.83	1,488.00	1,302.00
C-55	16.37	0.00	24.75	-2.97	1,488.00	1,302.00
C-60	17.86	0.00	27.00	-3.10	1,488.00	1,302.00
C-65	19.35	0.00	29.25	-3.22	1,488.00	1,302.00
C-70	20.83	0.00	31.50	-3.35	1,488.00	1,302.00

Concrete grade	Losses of Pre-stress (%)		Transfer Length (mm)		Bond Length (mm)		Development Length (mm)	
	Rail seat	Center	Rail seat	Center	Rail seat	Center	Rail seat	Center
C-40	20.43	22.15	518.78	518.78	493.40	509.18	1,012.18	1,027.96
C-45	19.84	21.47	534.28	534.28	488.02	502.98	1,022.30	1,037.26
C-50	19.34	20.91	548.54	548.54	483.42	497.80	1,031.97	1,046.34
C-55	18.91	20.41	561.77	561.77	479.48	493.21	1,041.25	1,054.98
C-60	18.54	19.98	574.12	574.12	476.09	489.26	1,050.21	1,063.38
C-65	18.22	19.59	585.73	585.73	473.10	485.70	1,058.83	1,071.43
C-70	17.92	19.25	596.68	596.68	470.41	482.56	1,067.08	1,079.24



Pre-Stressing Wires						
Concrete Grade	Type	Nominal Diameter (mm)	Quantity	Area (mm ²)	Eccentricity (mm)	
					Rail seat	Center
C-40 to C-70	Single wire	5.00	16.00	314.16	10.61	-5.39

Pre-Stressing forces							
Concrete Grade	Jacking Force (kN)	Initial Pre-Stress (MPa)		Final Pre-Stress (MPa)		Pre-Stress force after loss (kN)	
		Rail seat	Center	Rail seat	Center	Rail seat	Center
C-40	438.25	1,339.20	1,321.76	1,119.28	1,075.07	351.63	337.74
C-45	438.25	1,342.69	1,325.25	1,127.32	1,084.57	354.16	340.73
C-50	438.25	1,344.78	1,329.44	1,133.33	1,093.78	356.05	343.62
C-55	438.25	1,344.78	1,332.23	1,136.81	1,100.98	357.14	345.88
C-60	438.25	1,349.66	1,335.02	1,144.48	1,107.60	359.55	347.96
C-65	438.25	1,351.06	1,336.41	1,148.49	1,112.46	360.81	349.49
C-70	438.25	1,353.15	1,339.20	1,152.88	1,118.25	362.19	351.31

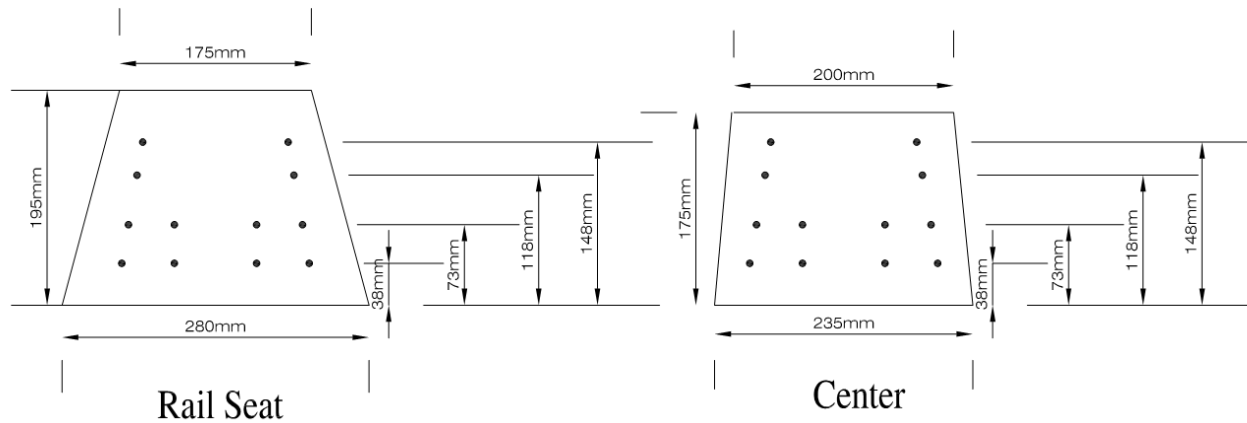
Applied Stresses in Concrete (Mpa)														
Concrete Grade	At transfer						At service (M+)				At service (M-)			
	Rail seat		Center		Center		Rail seat		Center		Rail seat		Center	
	Top	Bottom	Top	Bottom	Top	Bottom	Top	Bottom	Top	Bottom	Top	Bottom	Top	Bottom
C-40	6.14	10.71	14.68	8.76	17.16	-1.36	19.91	-0.10	-2.83	15.78	-3.28	20.93		
C-45	6.16	10.74	14.72	8.78	17.20	-1.29	20.01	-0.03	-2.80	15.85	-3.18	21.00		
C-50	6.17	10.75	14.76	8.81	17.22	-1.24	20.10	0.03	-2.77	15.90	-3.09	21.06		
C-55	6.17	10.75	14.79	8.83	17.24	-1.22	20.18	0.09	-2.76	15.92	-3.01	21.12		
C-60	6.19	10.80	14.82	8.85	17.27	-1.15	20.25	0.13	-2.73	15.99	-2.94	21.16		
C-65	6.19	10.81	14.83	8.86	17.29	-1.12	20.30	0.17	-2.71	16.02	-2.89	21.20		
C-70	6.20	10.82	14.86	8.88	17.31	-1.08	20.36	0.21	-2.69	16.06	-2.83	21.24		

Moment Capacity of the section (kN.m)								
Concrete Grade	Allowable				Ultimate			
	Rail seat		Center		Rail seat		Center	
	Positive	Negative	Positive	Negative	Positive	Negative	Positive	Negative
C-40	22.85	13.64	11.28	13.30	47.13	33.27	26.07	27.25
C-45	22.97	13.70	11.35	13.40	48.92	34.80	27.11	28.20
C-50	23.06	13.74	11.43	13.49	50.61	36.25	28.10	29.10
C-55	23.12	13.77	11.48	13.57	52.22	37.63	29.05	29.96
C-60	23.23	13.82	11.54	13.64	53.76	38.95	29.95	30.77
C-65	23.29	13.83	11.57	13.69	55.24	40.21	30.81	31.56
C-70	23.36	13.88	11.62	13.75	56.65	41.43	31.64	32.31

Allowable Stresses (MPa)							
Concrete Grade	Concrete				Pre-stressing tendon		
	At transfer		At Service		At transfer	At service	
	Compression	Tension	Compression	Tension	Tension	Tension	
C-40		11.90	0.00	18.00	-2.53	1,488.00	1,302.00
C-45		13.39	0.00	20.25	-2.68	1,488.00	1,302.00
C-50		14.88	0.00	22.50	-2.83	1,488.00	1,302.00
C-55		16.37	0.00	24.75	-2.97	1,488.00	1,302.00
C-60		17.86	0.00	27.00	-3.10	1,488.00	1,302.00
C-65		19.35	0.00	29.25	-3.22	1,488.00	1,302.00
C-70		20.83	0.00	31.50	-3.35	1,488.00	1,302.00

Concrete grade	Losses of Pre-stress (%)		Transfer Length (mm)		Bond Length (mm)		Development Length (mm)	
	Rail seat	Center	Rail seat	Center	Rail seat	Center	Rail seat	Center
C-40	19.76	22.93	518.78	518.78	487.32	516.40	1,006.10	1,035.18
C-45	19.19	22.25	534.28	534.28	482.03	510.15	1,016.31	1,044.43
C-50	18.76	21.59	548.54	548.54	478.07	504.09	1,026.61	1,052.63
C-55	18.51	21.08	561.77	561.77	475.78	499.36	1,037.55	1,061.13
C-60	17.96	20.60	574.12	574.12	470.74	495.00	1,044.86	1,069.12
C-65	17.67	20.25	585.73	585.73	468.10	491.80	1,053.83	1,077.53
C-70	17.36	19.84	596.68	596.68	465.21	487.99	1,061.89	1,084.67

F.8 6mm diameter (wire)



Pre-Stressing Wires						
Concrete Grade	Type	Nominal Diameter (mm)	Quantity	Area (mm ²)	Eccentricity (mm)	
					Rail seat	Center
C-40 to C-70	Single wire	6.00	12.00	339.29	8.67	3.82

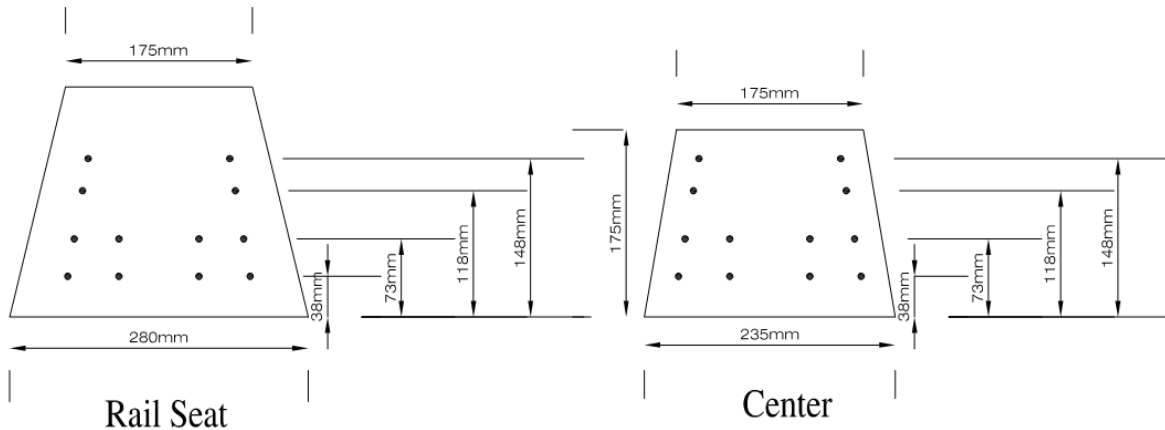
Pre-Stressing forces							
Concrete Grade	Jacking Force (kN)	Initial Pre-Stress (MPa)		Final Pre-Stress (MPa)		Pre-Stress force after loss (kN)	
		Rail seat	Center	Rail seat	Center	Rail seat	Center
C-40	450.41	1,265.11	1,257.14	1,039.36	1,018.05	352.65	345.42
C-45	450.41	1,267.76	1,259.80	1,047.92	1,027.79	355.55	348.72
C-50	450.41	1,271.75	1,262.45	1,055.01	1,036.01	357.96	351.51
C-55	450.41	1,273.00	1,265.11	1,061.36	1,043.07	360.11	353.90
C-60	450.41	1,274.40	1,267.76	1,066.90	1,049.21	361.99	355.99
C-65	450.41	1,275.73	1,271.75	1,071.77	1,054.47	363.64	357.77
C-70	450.41	1,278.38	1,274.40	1,075.99	1,059.28	365.08	359.41

Applied Stresses in Concrete (Mpa)									
Concrete Grade	At transfer					At service			
	Rail seat		Center		Rail seat		Center		
	Top	Bottom	Top	Bottom	Top	Bottom	Top	Bottom	
C-40	7.25	11.75	10.47	11.90	5.63	-2.88	-10.20	27.34	
C-45	7.27	11.78	10.49	11.93	5.67	-2.80	-10.13	27.44	
C-50	7.92	11.82	10.51	11.96	5.71	-2.73	-10.06	27.52	
C-55	7.29	11.83	10.53	11.98	5.74	-2.67	-10.01	27.60	
C-60	7.30	11.84	10.55	12.01	5.77	-2.62	-9.96	27.66	
C-65	7.31	11.86	10.58	12.05	5.80	-2.57	-9.92	27.71	
C-70	7.32	11.88	10.60	12.08	5.82	-2.53	-9.88	27.76	

Moment Capacity of the section (kN.m)										
Concrete Grade	Allowable				Ultimate					
	Rail seat		Center		Rail seat			Center		
	Positive	Negative	Positive	Negative	Positive	Negative	Positive	Negative	Positive	Negative
C-40	19.89	12.34	13.89	12.95	40.04	28.45	30.12	25.88		
C-45	20.01	12.40	14.00	13.04	41.51	29.71	31.22	26.91		
C-50	20.11	12.45	14.09	13.11	42.91	30.90	32.25	27.89		
C-55	20.21	12.50	14.17	13.17	44.23	32.04	33.23	28.82		
C-60	20.28	12.54	14.24	13.23	45.49	33.12	34.17	29.71		
C-65	20.36	12.57	14.31	13.28	46.71	34.16	35.07	30.56		
C-70	20.41	12.60	14.36	13.33	47.88	35.16	35.94	31.38		

Allowable Stresses (MPa)						
Concrete Grade	Concrete				Pre-stressing tendon	
	At transfer		At Service		At transfer	At service
	Compression	Tension	Compression	Tension	Tension	Tension
C-40	11.90	0.00	18.00	-2.53	1,488.00	1,302.00
C-45	13.39	0.00	20.25	-2.68	1,488.00	1,302.00
C-50	14.88	0.00	22.50	-2.83	1,488.00	1,302.00
C-55	16.37	0.00	24.75	-2.97	1,488.00	1,302.00
C-60	17.86	0.00	27.00	-3.10	1,488.00	1,302.00
C-65	19.35	0.00	29.25	-3.22	1,488.00	1,302.00
C-70	20.83	0.00	31.50	-3.35	1,488.00	1,302.00

Concrete grade	Losses of Pre-stress (%)		Transfer Length (mm)		Bond Length (mm)		Development Length (mm)	
	Rail seat	Center	Rail seat	Center	Rail seat	Center	Rail seat	Center
C-40	21.71	23.31	518.78	518.78	576.82	593.64	1,095.60	1,112.42
C-45	21.06	22.58	534.28	534.28	570.06	585.96	1,104.34	1,120.24
C-50	20.53	21.96	548.54	548.54	564.47	579.47	1,113.01	1,128.01
C-55	20.05	21.43	561.77	561.77	559.45	573.89	1,121.22	1,135.66
C-60	19.63	20.96	574.12	574.12	555.08	569.04	1,129.20	1,143.16
C-65	19.26	20.57	585.73	585.73	551.23	564.89	1,136.96	1,150.62
C-70	18.95	20.20	596.68	596.68	547.90	561.09	1,144.58	1,157.77



Pre-Stressing Wires						
Concrete Grade	Type	Nominal Diameter (mm)	Quantity	Area (mm ²)	Eccentricity (mm)	
					Rail seat	Center
C-40 to C-70	Single wire	6.00	12.00	339.29	17.90	1.9

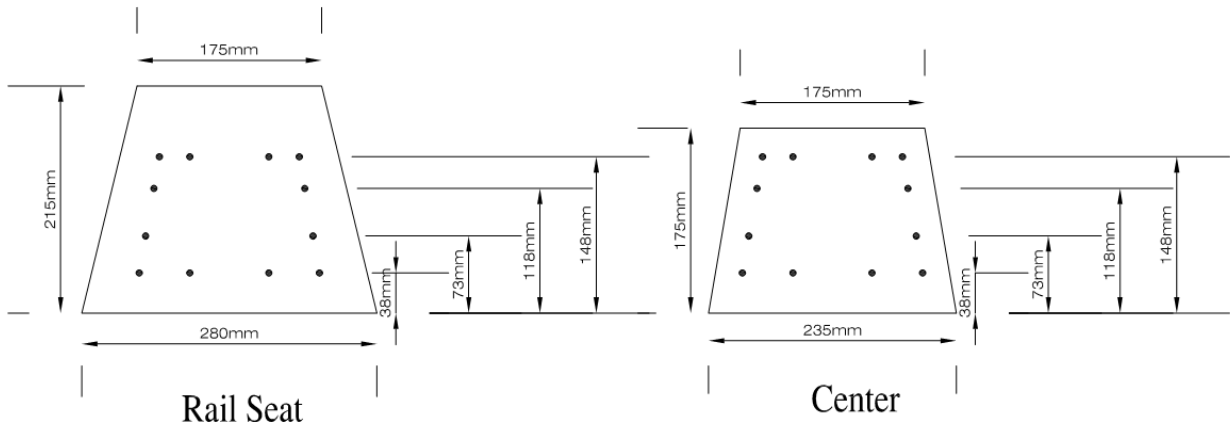
Pre-Stressing forces							
Concrete Grade	Jacking Force (kN)	Initial Pre-Stress (MPa)		Final Pre-Stress (MPa)		Pre-Stress force after loss (kN)	
		Rail seat	Center	Rail seat	Center	Rail seat	Center
C-40	450.41	1,267.76	1,253.16	1,045.15	1,008.67	354.61	342.23
C-45	450.41	1,271.08	1,257.14	1,053.38	1,018.69	357.40	345.63
C-50	450.41	1,273.74	1,260.46	1,060.21	1,027.16	359.72	348.51
C-55	450.41	1,276.39	1,263.12	1,066.45	1,034.28	361.84	350.92
C-60	450.41	1,278.38	1,265.77	1,071.60	1,040.82	363.59	353.14
C-65	450.41	1,280.37	1,268.43	1,076.38	1,046.89	365.21	355.20
C-70	450.41	1,281.70	1,270.42	1,080.22	1,051.97	366.51	356.93

Applied Stresses in Concrete (Mpa)														
Concrete Grade	At transfer						At service (M ⁻)				At service (M)			
	Rail seat		Center		Center		Rail seat		Center		Rail seat		Center	
	Top	Bottom	Top	Bottom	Top	Bottom	Top	Bottom	Top	Bottom	Top	Bottom	Top	Bottom
C-40	4.31	12.64	11.88	11.83	15.59	0.10	17.54	2.29	-4.41	17.24	-5.65	23.32		
C-45	4.32	12.67	11.92	11.87	15.61	0.19	17.62	2.39	-4.38	17.33	-5.36	23.42		
C-50	4.33	12.70	11.95	11.90	15.63	0.26	17.70	2.47	-4.36	17.40	-5.49	23.50		
C-55	4.34	12.72	11.97	11.93	15.65	0.32	17.76	2.54	-4.34	17.46	-5.43	23.57		
C-60	4.34	12.75	11.99	11.95	15.67	0.37	17.82	2.61	-4.33	17.51	-5.37	23.64		
C-65	4.35	12.77	12.02	11.98	15.68	0.42	17.87	2.67	-4.31	17.56	-5.31	23.70		
C-70	4.35	12.78	12.03	12.00	15.70	0.46	17.92	2.72	-4.30	17.60	-5.27	23.75		

Moment Capacity of the section (kN.m)								
Concrete Grade	Allowable				Ultimate			
	Rail seat		Center		Rail seat		Center	
	Positive	Negative	Positive	Negative	Positive	Negative	Positive	Negative
C-40	25.58	11.12	13.89	12.95	50.03	30.70	28.81	24.84
C-45	25.73	11.17	14.00	13.04	51.82	32.23	29.86	25.79
C-50	25.86	11.20	14.09	13.11	53.51	33.68	30.85	26.69
C-55	25.98	11.23	14.17	13.17	55.12	35.06	31.79	27.54
C-60	26.08	11.26	14.24	13.23	56.65	36.38	32.69	28.36
C-65	26.17	11.28	14.31	13.28	58.13	37.64	33.56	29.14
C-70	26.25	11.30	14.36	13.33	59.55	38.86	34.39	29.90

Allowable Stresses (MPa)						
Concrete Grade	Concrete				Pre-stressing tendon	
	At transfer		At Service		At transfer	At service
	Compression	Tension	Compression	Tension	Tension	Tension
C-40	11.90	0.00	18.00	-2.53	1,416.00	1,239.00
C-45	13.39	0.00	20.25	-2.68	1,416.00	1,239.00
C-50	14.88	0.00	22.50	-2.83	1,416.00	1,239.00
C-55	16.37	0.00	24.75	-2.97	1,416.00	1,239.00
C-60	17.86	0.00	27.00	-3.10	1,416.00	1,239.00
C-65	19.35	0.00	29.25	-3.22	1,416.00	1,239.00
C-70	20.83	0.00	31.50	-3.35	1,416.00	1,239.00

Concrete grade	Losses of Pre-stress (%)		Transfer Length (mm)		Bond Length (mm)		Development Length (mm)	
	Rail seat	Center	Rail seat	Center	Rail seat	Center	Rail seat	Center
C-40	21.27	24.02	518.78	518.78	572.25	601.05	1,091.03	1,119.83
C-45	20.65	23.26	534.28	534.28	565.76	593.14	1,100.04	1,127.42
C-50	20.13	22.62	548.54	548.54	560.36	586.46	1,108.90	1,135.00
C-55	19.66	22.09	561.77	561.77	555.43	580.83	1,117.20	1,142.60
C-60	19.28	21.60	574.12	574.12	551.37	575.67	1,125.49	1,149.79
C-65	18.92	21.14	585.73	585.73	547.60	570.87	1,133.33	1,156.60
C-70	18.63	20.76	596.68	596.68	544.57	566.86	1,141.25	1,163.54



Pre-Stressing Wires						
Concrete Grade	Type	Nominal Diameter (mm)	Quantity	Area (mm ²)	Eccentricity (mm)	
					Rail seat	Center
C-40 to C-70	Single wire	6.00	12.00	339.29	5.40	-10.60

Pre-Stressing forces							
Concrete Grade	Jacking Force (kN)	Initial Pre-Stress (MPa)		Final Pre-Stress (MPa)		Pre-Stress force after loss (kN)	
		Rail seat	Center	Rail seat	Center	Rail seat	Center
		C-40	450.41	1,271.75	1,250.51	1,055.23	1,001.48
C-45	450.41	1,274.40	1,253.16	1,062.50	1,010.53	360.50	342.87
C-50	450.41	1,275.73	1,257.14	1,067.80	1,019.81	362.29	346.01
C-55	450.41	1,278.38	1,261.13	1,073.79	1,028.33	364.33	348.91
C-60	450.41	1,281.04	1,263.12	1,079.35	1,034.42	366.21	350.97
C-65	450.41	1,283.69	1,265.77	1,084.56	1,040.64	367.98	353.08
C-70	450.41	1,285.68	1,268.43	1,088.86	1,046.46	369.44	355.05

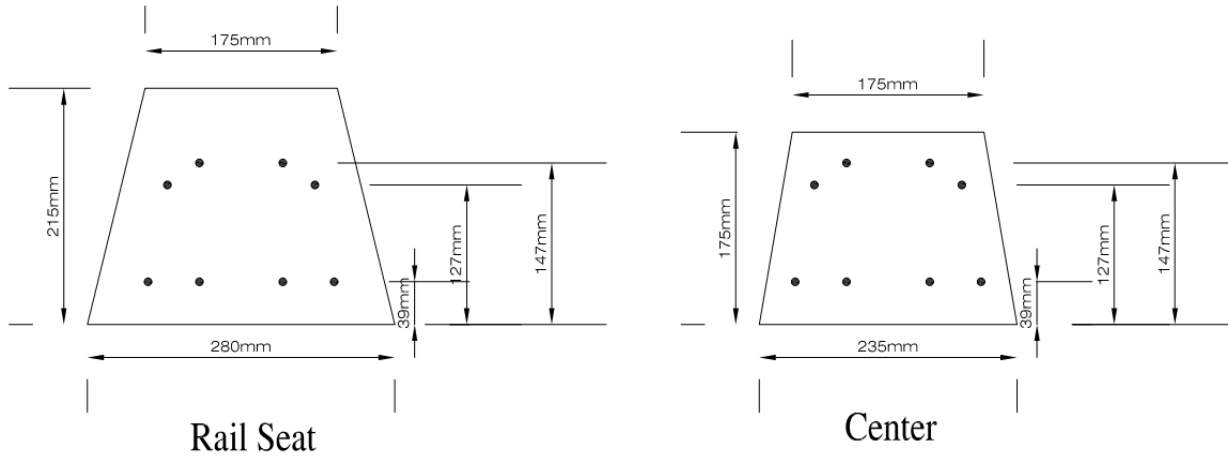
Applied Stresses in Concrete (Mpa)												
Concrete Grade	At transfer				At service (M+)				At service (M-)			
	Rail seat		Center		Rail seat		Center		Rail seat		Center	
	Top	Bottom	Top	Bottom	Top	Bottom	Top	Bottom	Top	Bottom	Top	Bottom
C-40	7.70	9.79	17.21	6.94	18.42	-2.19	21.76	-1.67	-1.58	14.95	-1.43	19.36
C-45	7.71	9.81	17.25	6.96	18.46	-2.14	21.88	-1.62	-1.54	15.01	-1.31	19.41
C-50	7.72	9.82	17.30	6.98	18.49	-2.09	22.00	-1.56	-1.51	15.05	-1.19	19.47
C-55	7.74	9.84	17.35	7.01	18.53	-2.05	22.11	-1.51	-1.47	15.09	-1.08	19.52
C-60	7.75	9.86	17.38	7.02	18.56	-2.00	22.19	-1.47	-1.44	15.14	-1.00	19.56
C-65	7.77	9.88	17.41	7.04	18.59	-1.96	22.27	-1.43	-1.41	15.18	-0.91	19.60
C-70	7.78	9.90	17.45	7.05	18.61	-1.93	22.35	-1.40	-1.38	15.21	-0.84	19.63

Moment Capacity of the section (kN.m)												
Concrete Grade	Allowable				Ultimate							
	Rail seat		Center		Rail seat		Center		Rail seat		Center	
	Positive	Negative	Positive	Negative	Positive	Negative	Positive	Negative	Positive	Negative	Positive	Negative
C-40	21.29	15.65	9.56	17.14	45.56	35.35	24.31	29.23				
C-45	21.40	15.72	9.62	17.25	47.35	36.88	25.36	30.18				
C-50	21.48	15.77	9.68	17.37	49.04	38.33	26.35	31.08				
C-55	21.57	15.82	9.74	17.48	50.65	39.71	27.29	31.93				
C-60	21.65	15.87	9.78	17.56	52.19	41.03	28.19	32.75				
C-65	21.73	15.92	9.82	17.64	53.66	42.29	29.06	33.53				
C-70	21.79	15.96	9.86	17.72	55.08	43.31	29.89	34.28				

Allowable Stresses (MPa)						
Concrete Grade	Concrete				Pre-stressing tendon	
	At transfer		At Service		At transfer	At service
	Compression	Tension	Compression	Tension	Tension	Tension
C-40	11.90	0.00	18.00	-2.53	1,416.00	1,239.00
C-45	13.39	0.00	20.25	-2.68	1,416.00	1,239.00
C-50	14.88	0.00	22.50	-2.83	1,416.00	1,239.00
C-55	16.37	0.00	24.75	-2.97	1,416.00	1,239.00
C-60	17.86	0.00	27.00	-3.10	1,416.00	1,239.00
C-65	19.35	0.00	29.25	-3.22	1,416.00	1,239.00
C-70	20.83	0.00	31.50	-3.35	1,416.00	1,239.00

Concrete grade	Losses of Pre-stress (%)		Transfer Length (mm)		Bond Length (mm)		Development Length (mm)	
	Rail seat	Center	Rail seat	Center	Rail seat	Center	Rail seat	Center
C-40	20.51	24.56	518.78	518.78	564.29	606.73	1,083.07	1,125.51
C-45	19.96	23.88	534.28	534.28	558.55	599.58	1,092.83	1,133.86
C-50	19.56	23.18	548.54	548.54	554.37	592.25	1,102.91	1,140.79
C-55	19.11	22.54	561.77	561.77	549.64	585.53	1,111.41	1,147.30
C-60	18.69	22.08	574.12	574.12	545.25	580.72	1,119.37	1,154.84
C-65	18.30	21.61	585.73	585.73	541.14	575.81	1,126.87	1,161.54
C-70	17.98	21.17	596.68	596.68	537.74	571.22	1,134.42	1,167.90

F.9 7mm diameter (wire)



Pre-Stressing Wires						
Concrete Grade	Type	Nominal Diameter (mm)	Quantity	Area (mm ²)	Eccentricity (mm)	
					Rail seat	Center
C-40 to C-70	Single-wire	7.00	8.00	307.88	11.23	-4.77

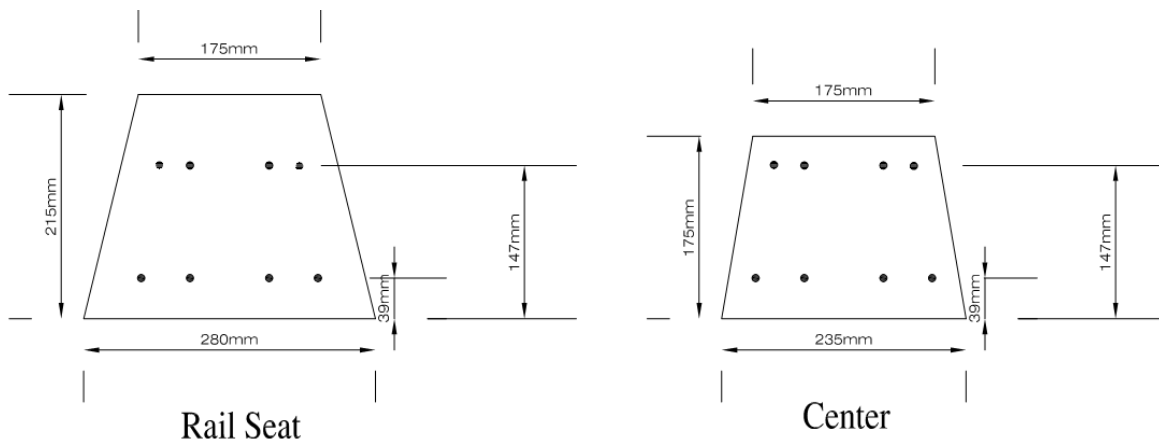
Pre-Stressing forces								
Concrete Grade	Jacking Force (kN)	Initial Pre-Stress (MPa)		Final Pre-Stress (MPa)		Pre-Stress force after loss (kN)		
		Rail seat	Center	Rail seat	Center	Rail seat	Center	
C-40	408.71	1,275.73	1,259.13	1,064.78	1,023.71	327.82	315.18	
C-45	408.71	1,278.38	1,263.12	1,071.74	1,033.25	329.96	318.11	
C-50	408.71	1,281.04	1,266.44	1,078.02	1,041.29	331.90	320.59	
C-55	408.71	1,283.03	1,269.09	1,083.17	1,048.05	333.48	322.67	
C-60	408.71	1,285.02	1,271.08	1,087.91	1,053.66	334.94	324.40	
C-65	408.71	1,286.35	1,273.07	1,091.69	1,058.83	336.10	325.99	
C-70	408.71	1,287.68	1,275.06	1,095.19	1,063.66	337.18	327.47	

Applied Stresses in Concrete (Mpa)												
Concrete Grade	At transfer				At service (M ⁺)				At service (M ⁻)			
	Rail seat		Center		Rail seat		Center		Rail seat		Center	
	Top	Bottom	Top	Bottom	Top	Bottom	Top	Bottom	Top	Bottom	Top	Bottom
C-40	5.60	10.11	13.52	8.35	16.71	-1.87	18.95	-0.44	-3.29	15.27	-4.23	20.59
C-45	5.61	10.13	13.56	8.38	16.73	-1.82	19.05	-0.37	-3.26	15.32	-4.14	20.66
C-50	5.62	10.15	13.59	8.40	16.76	-1.76	19.13	-0.31	-3.24	15.38	-4.06	20.72
C-55	5.63	10.17	13.62	8.42	16.78	-1.72	19.20	-0.26	-3.22	15.42	-3.99	20.77
C-60	5.64	10.19	13.64	8.43	16.80	-1.68	19.26	-0.22	-3.20	15.46	-3.93	20.81
C-65	5.65	10.20	13.66	8.45	16.82	-1.65	19.31	-0.18	-3.18	15.49	-3.88	20.85
C-70	5.65	10.21	13.68	8.46	16.83	-1.62	19.36	-0.15	-3.17	15.52	-3.83	20.88

Moment Capacity of the section (kN.m)								
Concrete Grade	Allowable				Ultimate			
	Rail seat		Center		Rail seat		Center	
	Positive	Negative	Positive	Negative	Positive	Negative	Positive	Negative
C-40	21.89	12.91	10.91	14.36	46.14	32.51	25.68	26.27
C-45	22.00	12.96	10.99	14.45	47.92	34.04	26.73	27.22
C-50	22.09	13.00	11.05	14.53	49.62	35.49	27.72	28.12
C-55	22.17	13.04	11.10	14.60	51.23	36.87	28.66	28.97
C-60	22.24	13.07	11.15	14.66	52.76	38.19	29.56	29.79
C-65	22.30	13.09	11.19	14.71	54.24	39.46	30.42	30.57
C-70	22.35	13.11	11.23	14.75	55.66	40.67	31.25	31.32

Allowable Stresses (MPa)							
Concrete Grade	Concrete				Pre-stressing tendon		
	At transfer		At Service		At transfer	At service	
	Compression	Tension	Compression	Tension	Tension	Tension	
C-40		11.90	0.00	18.00	-2.53	1,416.00	1,239.00
C-45		13.39	0.00	20.25	-2.68	1,416.00	1,239.00
C-50		14.88	0.00	22.50	-2.83	1,416.00	1,239.00
C-55		16.37	0.00	24.75	-2.97	1,416.00	1,239.00
C-60		17.86	0.00	27.00	-3.10	1,416.00	1,239.00
C-65		19.35	0.00	29.25	-3.22	1,416.00	1,239.00
C-70		20.83	0.00	31.50	-3.35	1,416.00	1,239.00

Concrete grade	Losses of Pre-stress (%)		Transfer Length (mm)		Bond Length (mm)		Development Length (mm)	
	Rail seat	Center	Rail seat	Center	Rail seat	Center	Rail seat	Center
C-40	19.79	22.88	518.78	518.78	649.55	687.37	1,168.33	1,206.15
C-45	19.27	22.17	534.28	534.28	643.14	678.59	1,177.42	1,212.87
C-50	18.79	21.56	548.54	548.54	637.35	671.18	1,185.89	1,219.72
C-55	18.41	21.05	561.77	561.77	632.61	664.95	1,194.38	1,226.72
C-60	18.05	20.63	574.12	574.12	628.24	659.79	1,202.36	1,233.91
C-65	17.76	20.24	585.73	585.73	624.76	655.02	1,210.49	1,240.75
C-70	17.50	19.88	596.68	596.68	621.53	650.58	1,218.21	1,247.26



Pre-Stressing Wires						
Concrete Grade	Type	Nominal Diameter (mm)	Quantity	Area (mm ²)	Eccentricity (mm)	
					Rail seat	Center
C-40 to C-70	Single-wire	7.00	8.00	307.88	6.23	-9.77

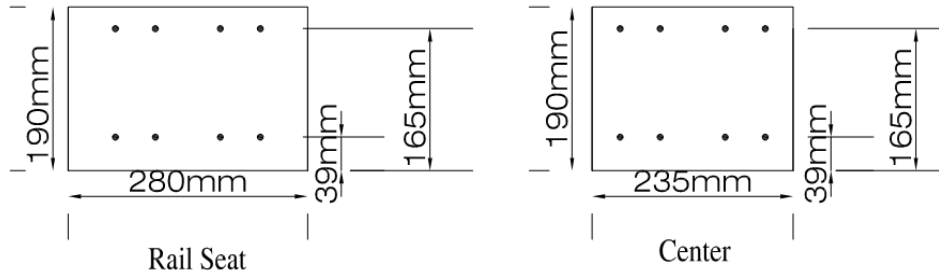
Pre-Stressing forces							
Concrete Grade	Jacking Force (kN)	Initial Pre-Stress (MPa)		Final Pre-Stress (MPa)		Pre-Stress force after loss (kN)	
		Rail seat	Center	Rail seat	Center	Rail seat	Center
C-40	408.71	1,275.73	1,259.13	1,066.52	1,020.80	328.35	314.28
C-45	408.71	1,278.38	1,263.12	1,073.38	1,030.49	330.47	317.26
C-50	408.71	1,281.04	1,266.44	1,079.59	1,038.68	332.38	319.78
C-55	408.71	1,283.03	1,269.09	1,084.66	1,045.55	333.94	321.90
C-60	408.71	1,285.02	1,271.08	1,089.34	1,051.26	335.38	323.66
C-65	408.71	1,286.35	1,273.07	1,093.06	1,056.53	336.53	325.28
C-70	408.71	1,287.68	1,275.06	1,096.52	1,061.43	337.59	326.79

Applied Stresses in Concrete (Mpa)												
Concrete Grade	At transfer				At service (M ⁺)				At service (M ⁻)			
	Rail seat		Center		Rail seat		Center		Rail seat		Center	
	Top	Bottom	Top	Bottom	Top	Bottom	Top	Bottom	Top	Bottom	Top	Bottom
C-40	6.83	9.06	15.47	6.57	17.74	-2.74	20.51	-1.90	-2.26	14.40	-2.68	19.13
C-45	6.84	9.08	15.52	6.60	17.78	-2.69	20.62	-1.84	-2.22	14.45	-2.56	19.19
C-50	6.86	9.10	15.56	6.62	17.81	-2.64	20.72	-1.79	-2.19	14.50	-2.47	19.24
C-55	6.87	9.11	15.59	6.63	17.83	-2.61	20.80	-1.75	-2.16	14.53	-2.39	19.28
C-60	6.88	9.13	15.61	6.64	17.86	-2.57	20.87	-1.72	-2.14	14.57	-2.32	19.31
C-65	6.89	9.14	15.63	6.65	17.88	-2.54	20.93	-1.69	-2.12	14.60	-2.26	19.34
C-70	6.89	9.14	15.66	6.67	17.89	-2.52	20.98	-1.66	-2.10	14.62	-2.20	19.37

Moment Capacity of the section (kN.m)										
Concrete Grade	Allowable				Ultimate					
	Rail seat		Center		Rail seat			Center		
	Positive	Negative	Positive	Negative	Positive	Negative	Positive	Negative	Positive	Negative
C-40	19.57	13.96	9.32	15.90	44.31	34.12	23.91	27.67		
C-45	19.66	14.01	9.38	16.01	46.10	35.65	24.96	28.62		
C-50	19.75	14.07	9.43	16.10	47.79	37.10	25.95	29.52		
C-55	19.82	14.11	9.47	16.18	49.40	38.48	26.89	30.38		
C-60	19.88	14.14	9.51	16.25	50.94	39.80	27.79	31.19		
C-65	19.93	14.18	9.54	16.31	52.42	41.06	28.66	31.98		
C-70	19.98	14.20	9.58	16.37	53.84	42.28	29.49	32.73		

Allowable Stresses (MPa)							
Concrete Grade	Concrete				Pre-stressing tendon		
	At transfer		At Service		At transfer		At service
	Compression	Tension	Compression	Tension	Tension	Tension	
C-40		11.90	0.00	18.00	-2.53	1,416.00	1,239.00
C-45		13.39	0.00	20.25	-2.68	1,416.00	1,239.00
C-50		14.88	0.00	22.50	-2.83	1,416.00	1,239.00
C-55		16.37	0.00	24.75	-2.97	1,416.00	1,239.00
C-60		17.86	0.00	27.00	-3.10	1,416.00	1,239.00
C-65		19.35	0.00	29.25	-3.22	1,416.00	1,239.00
C-70		20.83	0.00	31.50	-3.35	1,416.00	1,239.00

Concrete grade	Losses of Pre-stress (%)		Transfer Length (mm)		Bond Length (mm)		Development Length (mm)	
	Rail seat	Center	Rail seat	Center	Rail seat	Center	Rail seat	Center
C-40	19.66	23.10	518.78	518.78	647.95	690.05	1,166.73	1,208.83
C-45	19.14	22.37	534.28	534.28	641.62	681.12	1,175.90	1,215.40
C-50	18.68	21.76	548.54	548.54	635.91	673.59	1,184.45	1,222.13
C-55	18.29	21.24	561.77	561.77	631.23	667.26	1,193.00	1,229.03
C-60	17.94	20.81	574.12	574.12	626.93	662.00	1,201.05	1,236.12
C-65	17.66	20.41	585.73	585.73	623.50	657.15	1,209.23	1,242.88
C-70	17.40	20.04	596.68	596.68	620.31	652.63	1,216.99	1,249.31



Pre-Stressing Wires						
Concrete Grade	Type	Nominal Diameter (mm)	Quantity	Area (mm ²)	Eccentricity (mm)	
					Rail seat	Center
C-40 to C-70	Single-wire	7.00	8.00	307.88	-7.00	-7

Pre-Stressing forces							
Concrete Grade	Jacking Force (kN)	Initial Pre-Stress (MPa)		Final Pre-Stress (MPa)		Pre-Stress force after loss (kN)	
		Rail seat	Center	Rail seat	Center	Rail seat	Center
C-40	408.71	1,280.37	1,271.75	1,076.63	1,055.02	331.47	324.82
C-45	408.71	1,283.03	1,274.67	1,083.19	1,062.55	333.49	327.13
C-50	408.71	1,285.29	1,277.32	1,088.77	1,069.11	335.20	329.15
C-55	408.71	1,287.01	1,279.71	1,093.37	1,074.86	336.62	330.92
C-60	408.71	1,289.00	1,281.70	1,097.85	1,079.81	338.00	332.45
C-65	408.71	1,290.33	1,283.29	1,101.40	1,084.02	339.09	333.74
C-70	408.71	1,291.66	1,285.02	1,104.71	1,088.07	340.11	334.99

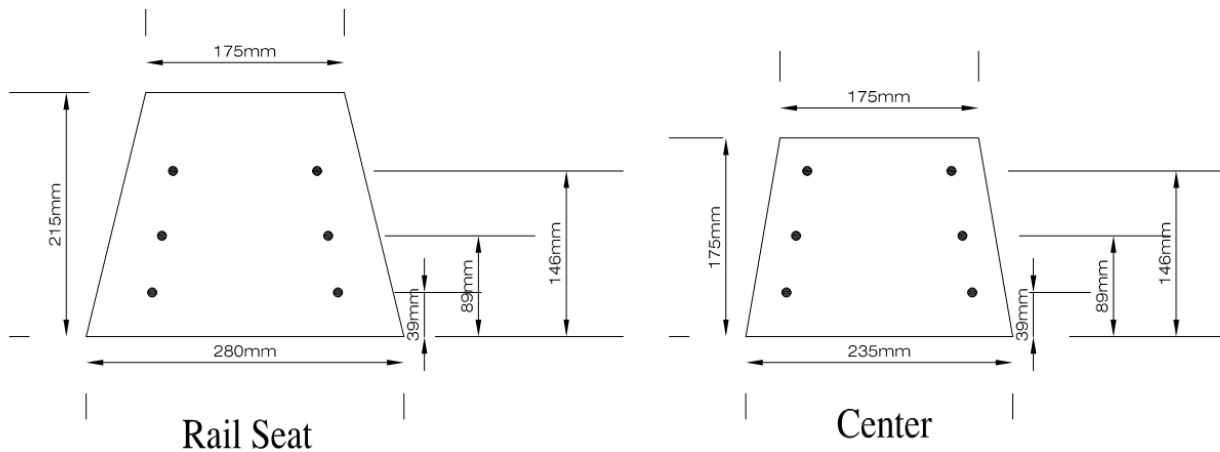
Applied Stresses in Concrete (Mpa)												
Concrete Grade	At transfer				At service (M+)				At service (M-)			
	Rail seat		Center		Rail seat		Center		Rail seat		Center	
	Top	Bottom	Top	Bottom	Top	Bottom	Top	Bottom	Top	Bottom	Top	Bottom
C-40	9.36	5.46	11.30	6.24	19.29	-6.82	14.94	-0.40	0.31	12.15	-1.30	15.85
C-45	9.38	5.47	11.32	6.25	19.33	-6.80	15.01	-0.35	0.36	12.18	-1.24	15.89
C-50	9.40	5.48	11.35	6.27	19.37	-6.77	15.06	-0.32	0.40	12.21	-1.18	15.93
C-55	9.41	5.49	11.37	6.28	19.40	-6.75	15.11	-0.29	0.43	12.23	-1.13	15.96
C-60	9.42	5.50	11.38	6.29	19.44	-6.73	15.15	-0.26	0.46	12.25	-1.09	15.98
C-65	9.43	5.50	11.40	6.30	19.46	-6.71	15.19	-0.24	0.49	12.26	-1.06	16.01
C-70	9.44	5.51	11.41	6.31	19.48	-6.70	15.22	-0.22	0.51	12.28	-1.02	16.03

Moment Capacity of the section (kN.m)									
Concrete Grade	Allowable					Ultimate			
	Rail seat		Center			Rail seat		Center	
	Positive	Negative	Positive	Negative	Positive	Negative	Positive	Negative	
C-40	11.91	17.61	10.75	16.97	34.81	39.45	30.36	34.90	
C-45	11.96	17.69	10.81	17.06	36.43	41.07	31.71	36.25	
C-50	12.00	17.75	10.86	17.14	37.96	42.60	33.00	37.54	
C-55	12.03	17.81	10.90	17.21	39.41	44.05	34.22	38.76	
C-60	12.07	17.86	10.94	17.27	40.80	45.44	35.38	39.92	
C-65	12.10	17.90	10.97	17.32	42.13	46.77	36.50	41.04	
C-70	12.12	17.94	11.00	17.37	43.41	48.05	37.57	42.12	

Allowable Stresses (MPa)						
Concrete Grade	Concrete				Pre-stressing tendon	
	At transfer		At Service		At transfer	At service
	Compression	Tension	Compression	Tension	Tension	Tension
C-40	11.90	0.00	18.00	-2.53	1,416.00	1,239.00
C-45	13.39	0.00	20.25	-2.68	1,416.00	1,239.00
C-50	14.88	0.00	22.50	-2.83	1,416.00	1,239.00
C-55	16.37	0.00	24.75	-2.97	1,416.00	1,239.00
C-60	17.86	0.00	27.00	-3.10	1,416.00	1,239.00
C-65	19.35	0.00	29.25	-3.22	1,416.00	1,239.00
C-70	20.83	0.00	31.50	-3.35	1,416.00	1,239.00

Concrete grade	Losses of Pre-stress (%)		Transfer Length (mm)		Bond Length (mm)		Development Length (mm)	
	Rail seat	Center	Rail seat	Center	Rail seat	Center	Rail seat	Center
C-40	18.90	20.53	518.78	518.78	638.63	658.53	1,157.41	1,177.31
C-45	18.40	19.96	534.28	534.28	632.59	651.60	1,166.87	1,185.88
C-50	17.98	19.46	548.54	548.54	627.45	645.56	1,175.99	1,194.10
C-55	17.64	19.03	561.77	561.77	623.22	640.26	1,184.99	1,202.03
C-60	17.30	18.66	574.12	574.12	619.09	635.71	1,193.21	1,209.83
C-65	17.03	18.34	585.73	585.73	615.82	631.82	1,201.55	1,217.55
C-70	16.78	18.04	596.68	596.68	612.77	628.09	1,209.45	1,224.77

F.10 8mm diameter (wire)



Pre-Stressing Wires						
Concrete Grade	Type	Nominal Diameter (mm)	Quantity	Area (mm ²)	Eccentricity (mm)	
					Rail seat	Center
C-40 to C-70	Single-wire	8.00	6.00	301.59	7.56	-7.65

Pre-Stressing forces							
Concrete Grade	Jacking Force (kN)	Initial Pre-Stress (MPa)		Final Pre-Stress (MPa)		Pre-Stress force after loss (kN)	
		Rail seat	Center	Rail seat	Center	Rail seat	Center
		C-40	377.75	1,204.91	1,186.74	1,005.18	958.98
C-45	377.75	1,208.04	1,189.88	1,012.19	967.52	305.27	291.80
C-50	377.75	1,209.92	1,193.01	1,017.40	975.21	306.84	294.12
C-55	377.75	1,211.79	1,195.51	1,022.15	981.68	308.27	296.07
C-60	377.75	1,213.67	1,198.02	1,026.52	987.63	309.59	297.86
C-65	377.75	1,214.93	1,199.90	1,030.00	992.58	310.64	299.36
C-70	377.75	1,216.18	1,202.40	1,033.24	997.78	311.62	300.92

Applied Stresses in Concrete (Mpa)												
Concrete Grade	At transfer				At service (M+)				At service (M-)			
	Rail seat		Center		Rail seat		Center		Rail seat		Center	
	Top	Bottom	Top	Bottom	Top	Bottom	Top	Bottom	Top	Bottom	Top	Bottom
C-40	6.04	8.62	13.97	6.89	17.07	-3.12	19.42	-1.94	-2.93	14.02	-4.23	19.90
C-45	6.06	8.64	14.01	6.91	17.10	-3.07	19.52	-1.89	-2.89	14.07	-4.14	19.96
C-50	6.07	8.66	14.04	6.93	17.13	-3.03	19.60	-1.84	-2.87	14.11	-4.05	20.01
C-55	6.07	8.67	14.07	6.95	17.15	-3.00	19.67	-1.79	-2.85	14.14	-3.98	20.03
C-60	6.08	8.68	14.10	6.96	17.17	-2.96	19.74	-1.75	-2.83	14.18	-3.92	20.09
C-65	6.09	8.69	14.12	6.97	17.19	-2.94	19.79	-1.72	-2.81	14.20	-3.86	20.12
C-70	6.10	8.70	14.15	6.99	17.20	-2.91	19.85	-1.69	-2.79	14.23	-3.80	20.15

Moment Capacity of the section (kN.m)										
Concrete Grade	Allowable				Ultimate					
	Rail seat		Center		Rail seat			Center		
	Positive	Negative	Positive	Negative	Positive	Negative	Positive	Negative	Positive	Negative
C-40	19.56	13.50	9.21	14.37	43.73	33.11	23.42	26.05		
C-45	19.66	13.55	9.27	14.46	45.52	34.64	24.43	26.98		
C-50	19.73	13.59	9.32	14.55	47.21	36.09	25.38	27.86		
C-55	19.80	13.62	9.37	14.62	48.82	37.47	26.29	28.70		
C-60	19.86	13.66	9.41	14.68	50.36	38.79	27.16	29.50		
C-65	19.91	13.68	9.44	14.73	51.83	40.05	27.99	30.27		
C-70	19.95	13.71	9.48	14.79	53.25	41.27	28.79	31.01		

Allowable Stresses (MPa)						
Concrete Grade	Concrete				Pre-stressing tendon	
	At transfer		At Service		At transfer	At service
	Compression	Tension	Compression	Tension	Tension	Tension
C-40	11.90	0.00	18.00	-2.53	1,336.00	1,169.00
C-45	13.39	0.00	20.25	-2.68	1,336.00	1,169.00
C-50	14.88	0.00	22.50	-2.83	1,336.00	1,169.00
C-55	16.37	0.00	24.75	-2.97	1,336.00	1,169.00
C-60	17.86	0.00	27.00	-3.10	1,336.00	1,169.00
C-65	19.35	0.00	29.25	-3.22	1,336.00	1,169.00
C-70	20.83	0.00	31.50	-3.35	1,336.00	1,169.00

Concrete grade	Losses of Pre-stress (%)		Transfer Length (mm)		Bond Length (mm)		Development Length (mm)	
	Rail seat	Center	Rail seat	Center	Rail seat	Center	Rail seat	Center
C-40	19.75	23.43	518.78	518.78	699.81	748.44	1,218.59	1,267.22
C-45	19.19	22.75	534.28	534.28	692.43	739.46	1,226.71	1,273.74
C-50	18.77	22.14	548.54	548.54	686.94	731.36	1,235.48	1,279.90
C-55	18.39	21.62	561.77	561.77	681.95	724.55	1,243.72	1,286.32
C-60	18.04	21.15	574.12	574.12	677.34	718.29	1,251.46	1,292.41
C-65	17.76	20.75	585.73	585.73	673.68	713.07	1,259.41	1,298.80
C-70	17.51	20.34	596.68	596.68	670.27	707.60	1,266.95	1,304.28