

# OPTIMAL DESIGN AND ANALYSIS OF PRE-STRESSED CONCRETE SLEEPERS

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## ABSTRACT

*The track system consists of structural components like a sleeper that has to be designed to accommodate the maximum tonnage. The main function of a sleeper is to transfer the load from the rail to the ballast via the rail pad and to the under laid 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 and moment calculations at critical sections. In this paper a pre-stressed pre-tensioned concrete sleeper having an optimal shape, strength and tendon type and profile with reference to the existing sleeper type that is used by the Ethiopian Railways Corporation (ERC), which is the new type II Chinese sleeper, was analyzed and designed. Moreover, FEM modeling of pre-stressed concrete sleepers was conducted. The optimal design output of this research 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. The final optimized design outputs and analysis result of the existing sleepers are compared with respect to raw material consumption for production and its capacity.*

**Keywords:** Analysis, design, sleeper, FEM modeling, optimization, pre-stressed concrete

## INTRODUCTION

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 [10, 11]. 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 [17-20].

This research focused on the analysis and design 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 that will be used in the construction of ballasted track in Ethiopia. The suitable shape, cross-section, concrete grade and the type and position of pre-stressing wires have been selected. Before the sleeper is 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 [16].

The finite element software SAFE and ANSYS have been employed to model and analyze the sleeper to verify the design result obtained from design codes.

There are two types of pre-stressing systems: pre-tensioning and post-tensioning systems. In pre-tensioning systems the strands are tensioned before the concrete is placed. This method is generally used for mass production of pre-tensioned members. The cables are anchored to a strengthened mold. Once the concrete has hardened, the cables are released, and maintain their tension by their adherence to the concrete. The pre-compression is transmitted from steel to concrete through bond over the transmission length near the ends.

In post-tensioning systems the tendons are tensioned after concrete has reached with specified strength. The tension is applied to the tendons (located in a duct) after hardening of the concrete. This technique is often used in projects with very large elements. The pre-compression is transmitted from steel to concrete by the anchorage device (at the end blocks). The main advantage of post-tensioning is its ability to post-tension both precast and cast-in-place members. [14, 15, 21].

This research is principally concerned with the design of pre-tensioned structures (sleepers), although mention is made of the option of post-tensioning when appropriate.

## RESEARCH METHODOLOGY

The research methodology starts with literature review and the required data are collected from Ethiopian Railways Corporation (ERC). Analysis of existing new type II concrete sleeper has been made as a base line of the research. Modeling and optimization of new type sleeper with respect to concrete grade, geometry, number and position of pre-stressing wires have been done with an iterative process. FE Software's SAFE and ANSYS, and theory of mechanics have been used for modeling and optimization of the design and analysis.

## DATA COLLECTION AND ANALYSIS

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. Thus includes the service life, sleeper spacing, loading in MGT (Million gross tons annually), design speed, axel load and others [12]. The geometrical dimension of the existing sleeper is shown in Fig 1.

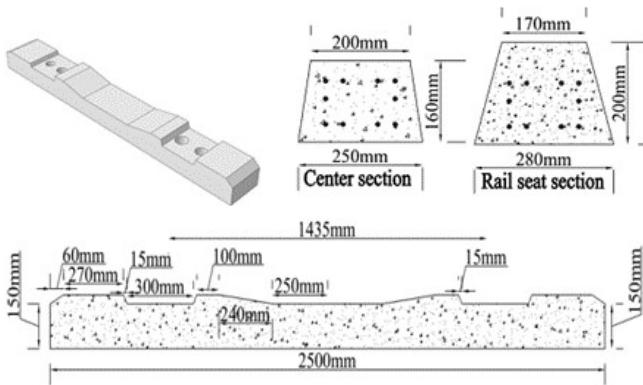


Figure 1 Typical sleeper geometry and dimensions

Loads considered for the analysis and design of sleepers in this research include rail seat loads and the ballast pressure. The flexural capacity of the sleeper is determined by the rail seat and ballast pressure loads [13].

Typical track design with concrete sleepers utilizes sleeper spacing of 60 cm. 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 having an axel load 25 tons. Quasi-static, dynamic and combined vertical design load factor are: 140% to 160%, 150% and 250% of the static load, according to Australian Standards (AS) 1085.14 [1-3, 5-6]. The load carried by a single sleeper is the product of the distribution factor (D.F) and static wheel load.

$$R = \frac{Qj(D.F)}{100} \quad (1)$$

**LOAD ON THE SLEEPER**  $R = 156.25kN$  **DISTRIBUTION BALLAST**

It is practically impossible to predict the exact distribution for a sleeper in the in-track condition; there are many hypothetical distributions of sleeper bearing pressure and bending moment diagrams (Talbot, 1920). 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 [16]. In this analysis the effective length of a sleeper is defined as the distance of 990 mm from the end of the sleeper. 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. AS (1085.14) uniform ballast pressure is assumed and the maximum ballast pressure is estimated by taking three different cases used in sleeper design [5-6]. The center binding coefficient  $\alpha$  covering 520 mm length at the mid-span of the sleeper varies from 0 to 1.0; and the defined values in this research include 0, 0.75 and 1.0 which are depicted in Fig. 2, 3 and 4 below.

Figure 2 Ballast pressure distribution with zero centre binding coefficient

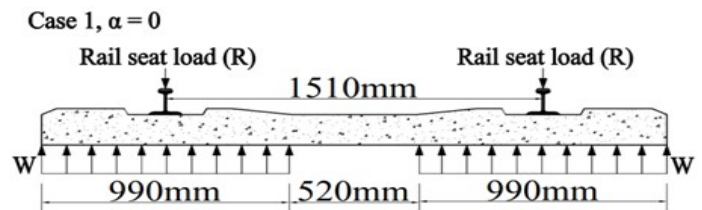


Figure 3 Ballast pressure distribution with 75% centre binding coefficient

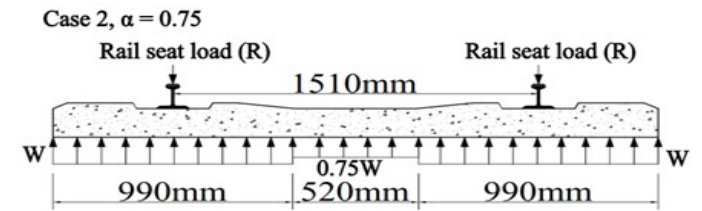
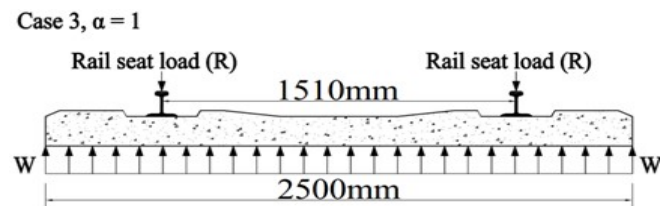


Figure 4 Ballast pressure distribution with 100% centre binding coefficient



The above two cases shown in Fig 2 and 3 are practical for design. The design moments at rail seat and centre section are determined according to AS 1085.14-2003 in both cases of positive and negative values. But the 3<sup>rd</sup> case is more of a theoretical character and applicable in old railway lines after repeated loading. The shear and moment loading diagrams due to the rail seat and ballast pressure are drawn by taking the upside down position via Figures 5-7.

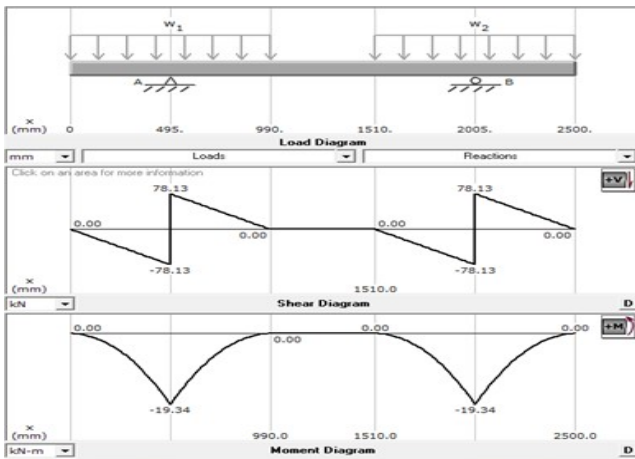


Figure 5 Shear force and bending moment diagrams for zero center binding coefficient

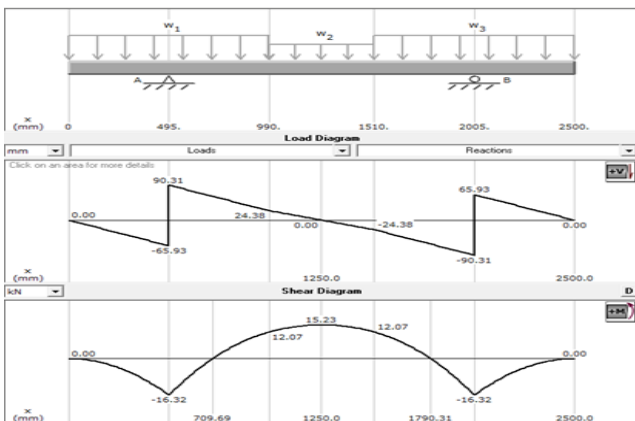


Figure 6 Shear force and bending moment diagrams for 75% centre binding coefficient

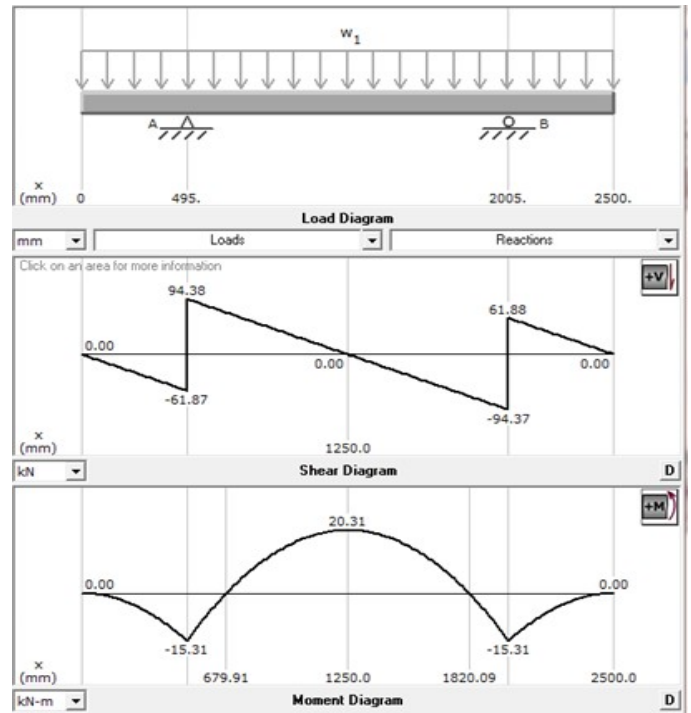
Australian standard accounts 50% uniform pressure and 75% in the case of China's standard. For this analysis the centre binding coefficient is taken 0.75 and the design bending moment is obtained 15.23kN.m as shown in figure 6.

### 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. A finite element software SAFE is used to show the interaction of the sleeper and the ballast in static loading case. Analysis of stresses are verified by using another finite element software AN-

SYS [9].

Figure 7 Shear force and bending moment diagrams



for 100% centre binding coefficient

### GEOMETRY OF THE SLEEPER

The geometry of the sleeper has an influence on the ballast pressure distribution and its flexural capacity. The cross-sectional geometry at critical sections (rail seat and centre) has been evaluated based on AS 1085.14.

### CONCRETE GRADE

In most design codes including the Ethiopian Building Code Standard (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. The iteration has been employed for the optimized geometry done based on the software SAFE. The limiting factors are the stress levels allowed during the transfer and service loads.

### 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 wires used for this optimal design includes the EN10138-BS5896 7-wire strands having 9.3 mm and 8 mm diameter and 1860MPa ultimate strength, 7 mm diameter and 2060MPa ultimate strength, 3-wire strands 5.2 mm and 6.5 mm diameter and 1960MPa and 1860MPa ultimate strength respectively, single wires of 4 mm, 5mm, 6mm, 7mm and 8 mm diameter with 1860MPa, 1860MPa, 1770MPa, 1770MPa and 1670MPa ultimate strength respectively [4, 7, 14-15].

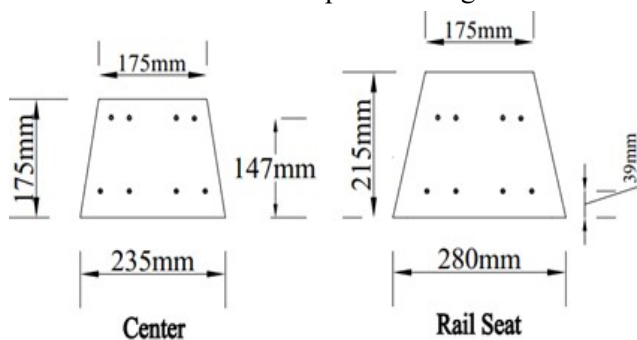
### SELECTION OF THE OPTIMIZED SLEEPER

Based on the result of the finite element software, SAFE, the distribution of the ballast pressure, increasing the width at the end beyond 310 mm did not result in reduction in ballast pressure over the effective length. The centre section bottom width is still possible to reduce further, but to avoid stress concentration; it is fixed to 235 mm, which is adequate for the imposed load.

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 35 mm. Elsewhere, the minimum clear concrete cover to tendons generally shall be 25 mm with exception that the tendon may be exposed at end faces. The minimum clear tendon cover to an insert hole of fitting shall be 12 mm [1-3, 5-6].

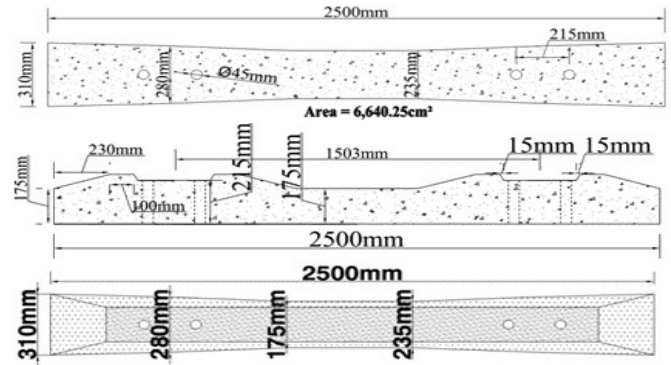
Figure 8 Cross-section of optimized sleeper

As the diameters of the pre-stressing wires are in-



creased, the losses at the critical sections are increased. More loss is encountered at the centre in both cases; losses are limited to 22% to 25% [6].

Figure 9 Geometry of the optimized sleeper



### FINITE ELEMENT ANALYSIS (FEA)

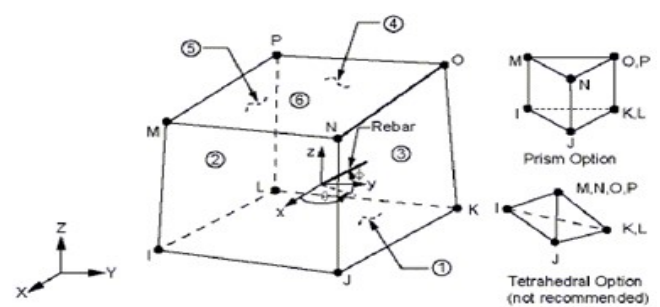
It is a powerful tool which can be applied to the design of irregular shaped members. For flexural members that are exposed to regions of high stress concentration or exhibit varying cross-sectional dimensions along with their length, the application of FEA modeling techniques is a valued addition to the analysis process [8]. In this study, the ANSYS finite element computer program was used to simulate the behavior of the pre-stressed concrete sleeper capacity. Three dimensional elements have been used to model pre-stressed concrete sleeper and reinforcement bar elements.

### ELEMENT SELECTION

#### I. SOLID ELEMENTS

The users start with the SOLID65 three-dimensional reinforced concrete solid element which is defined by eight nodes with three degrees of freedom. The SOLID65 is capable of cracking tension and crushing in compression due to built in algorithms.

Figure 10 SOLID65 Element



## II. BAR ELEMENTS

It is recommended starting with the LINK8 element. 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 that no bending of the element is considered.

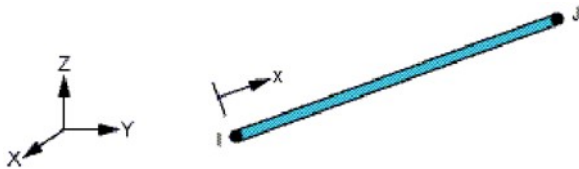


Figure 11 LINK8 Element

## III. ANALYSIS RESULT

Variation of Ballast Pressure distribution analyzed by the software, SAFE, Contour values are in  $\text{kN/mm}^2$ , e.g.  $-481 \times 10^{-6} \text{kN/mm}^2 = 481 \text{kPa}$ , compressive pressure. The total length of a sleeper is kept constant, i.e. 2.5m for all iterations.

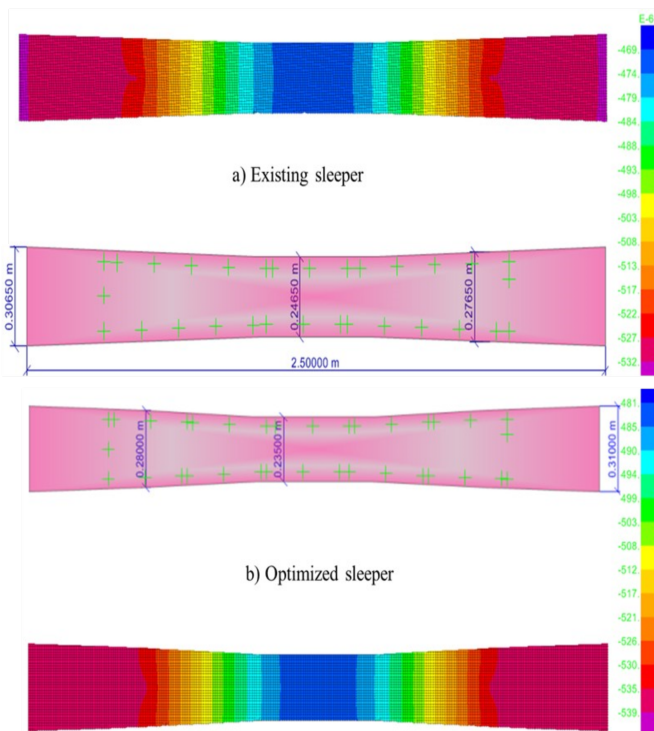


Figure 12 Ballast pressure responses of sleepers

In Fig. 12, the variation of stresses due to the ballast pressure obtained from the analysis of the software SAFE is shown for both the existing and optimized sleepers. The maximum ballast pressure in the optimized sleeper is relatively higher than the current sleeper due to reduction of the contact area of the ballast in optimized sleeper. The maximum pressure in case of optimized sleeper is 481kPa, whereas it is 469kPa in the current case which is lower than the maximum limiting value of 750kPa based on the Australian design code (AS 1085.14-2003). Analysis results obtained from ANSYS are depicted in Figures 13(a-d) and 14 (i-iv).

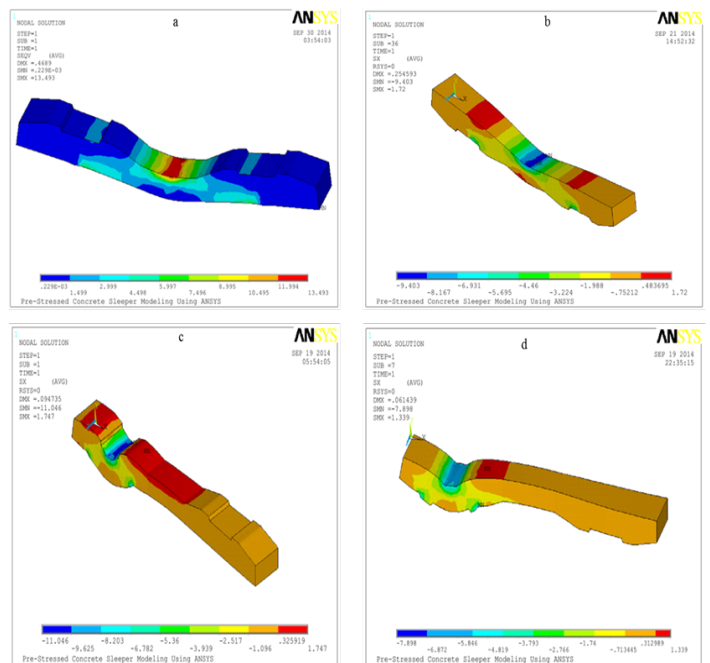


Figure 13 ANSYS analysis result for moment loading

The flexural capacity of the sleeper at the critical sections analyzed by ANSYS is indicated in Fig. 13a-d. 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, is based on a uniform ballast support beneath each rail seat. 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 design values of moment and stresses are summarized in the discussion part of Table 2. Stress intensities along the centre line of the sleeper via its length are quantified in Fig. 14 i-iv.

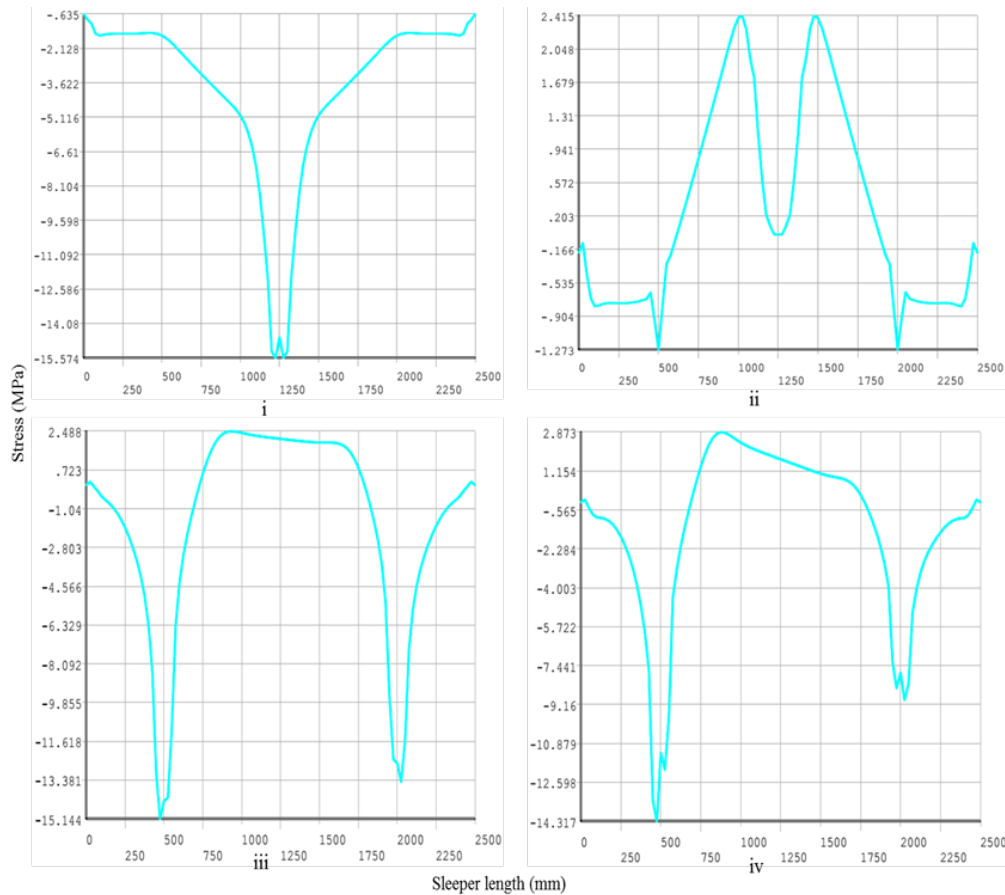


Figure 14 Stress distributions along the sleeper length

## DISCUSSION

This research focused on the analysis and design of pre-stressed concrete sleepers, but it has to be economical relative to the applied one, which has employed some optimization process during the analysis by adopting an iterative process, since the parameters are vast which cannot be shown with mathematical formulations with objective functions. From the optimal design the concrete grade is reduced from C-60 to C-55, tendon area from  $311.57 \text{ mm}^2$  to  $307.72 \text{ mm}^2$ , the profile of the tendon is rearranged with 2 layers, also the geometric shape has been modified by taking six different shapes (Figure 15). The results of the parametric optimization indicate that the capacity of an existing sleeper can be increased most efficiently by increasing the depth at rail seat section and decreasing at the centre section, increasing the diameter of the pre-stressing with lower concrete strength.

Design parameters which were considered in this study include geometry of a sleeper, concrete

strength, pre-stressing type, strength, size and profiles. First, the design and analysis of an existing sleeper was considered for reference to optimal design of the study. The validation of the analysis was done using FE software. The results of the parametric optimization indicates that an increase in the diameter of pre-stressing tendons and section depth with a lower concrete grade provide considerable increases in the sleeper capacity. Regarding pre-stressing centroids and eccentricities, variable eccentricity of pre-stressing along the length of a pre-stressed concrete member is not implemented in this pre-stressed design. Altering the depth of the pre-stressing and therefore the magnitude of the eccentricity with respect to the moment along the member using harped tendons is common practice for pre-stressed bridge girders and other flexural members. The existing sleeper design has eccentricities both above and below the neutral axis of the sleeper. In the rail seat section where positive bending governs, the pre-stressing is below the neutral axis cross-section. While in the sleeper centre, where bending is negative, the pre-stressing is above the neutral axis of the cross-section.

This transition of pre-stressing from below the neutral axis at the rail seat to above at the centre is not achieved by harped tendons. Instead, the cross-sectional dimensions of the sleeper centre change to move the neutral axis downward while the pre-stressing tendons maintain the same distance from

the bottom of the sleeper. Inputs required independent of the analysis procedure were the material and cross-sectional properties of the sleeper.

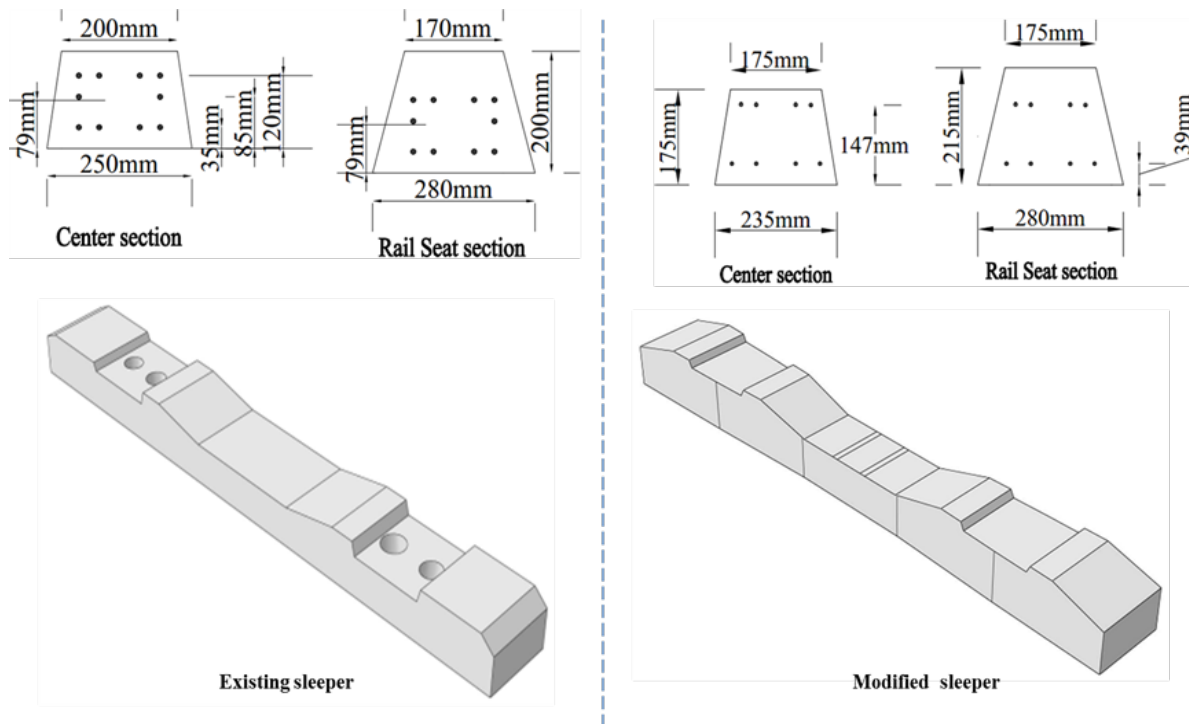


Figure 15 Comparison of profile and geometry of existing and modified sleepers

The profile of the sleeper is characterized by variation at the rail seat and centre section, but tendons are straight throughout the sleeper length since sleepers are produced in bulk. This variability of sleeper profile ensures the eccentricity of the tendon below CGC at the rail seat and above the CGC at the centre section to counteract the imposing loads. The Australian standard (AS1085.14) is adopted for the design of both the existing which is designed by China and new optimized sleepers. The capacity of the section and the applied

stresses are compared at transfer and service load, which shows that the critical section is adequate for the acting loads.

Table 1 Summary of the design moments and stresses (existing 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	14	15.2	1.61	27	3.1
Centre	12.55	2.51	14.13	27	3.1

The FEM analysis shows higher results than the theoretical values. This is due to the loading and boundary conditions which are based on Laboratory setups; and time dependent losses, the results after loss proximate to the theoretical values and the result is acceptable.

Table 2 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

## CONCLUSION

The analysis result of existing sleeper shows that its flexural capacity is adequate for the planned 25 tone axel load based on the design Code of AS 1085.14, 2003. 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 research. The result shows 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 to attain the flexural capacity requirements at critical sections. 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 centre. 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 force. The eccentricity of tendons at the rail seat is below the centroid of the section and above at the centre of a sleeper. From the optimized design, the diameter of 7 mm wire having 1770MPa ultimate tensile strength is selected considering the capacity and safety of the structure. 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 which are not accounted in case of ANSYS analysis. The analysis setup (model) is based on the laboratory setup which results in the maximum values for design purpose.

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