ASPECTS TO CONSIDER WHEN DESIGNING A RAILWAY TRACK SLAB

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ABSTRACT

Rail track slabs, also known as ballastless track systems, have gained prominence as a modern and efficient alternative to traditional ballasted tracks in railway infrastructure. This technical abstract provides an overview of rail track slab design, highlighting its structural components, benefits, design considerations, and key challenges.

Rail track slabs are engineered systems that consist of a concrete slab supported directly on the substructure, eliminating the need for traditional ballast and providing a stable and durable track foundation. The design of rail track slabs involves several critical components, including the concrete slab itself, rail fastening systems, insulation layers, drainage provisions, and the substructure.

Benefits of rail track slabs include improved track stability, reduced maintenance requirements, enhanced track geometry control, and the ability to accommodate higher train speeds and heavier axle loads. Additionally, the absence of ballast minimizes issues associated with ballast degradation, fouling, and track settlement. These advantages make rail track slabs particularly suitable for high-speed rail lines, heavy freight corridors, and areas with challenging geological conditions.

Design considerations for rail track slabs encompass various factors such as load distribution, thermal expansion and drainage management. The concrete slab must be designed to withstand static and dynamic loads from passing trains while maintaining dimensional stability under varying temperature conditions. Rail fastening systems play a crucial role in securing the rail to the slab while allowing for expansion and contraction.

Challenges in rail track slab design include addressing differential settlement in the substructure, managing the effects of dynamic loads on the slab, preventing rail creep and ensuring effective water drainage. Frame analysis and train wheel load simulation can be employed to model the behaviour of rail track slabs under various loading scenarios and environmental conditions.

In conclusion, rail track slabs offer a modern solution for railway track infrastructure with numerous advantages over traditional ballasted tracks. The design of rail track slabs involves intricate considerations of concrete slab composition, rail fastening systems, insulation, and drainage. While challenges persist, advances in engineering and simulation technologies continue to refine the design and implementation of rail track slabs, contributing to the efficiency and longevity of railway networks worldwide.

1. INTRODUCTION

Embedded track slabs are becoming increasing popular with the increased use of light transport systems and drive toward low maintenance rail system.

Track slabs provide a neater rail track solution in urban environments and are commonly used in rail depot yards especially in freight rail depot yards. This allows vehicles to traverse the slabs with little obstruction from the rails.

Track slabs can operate with very little maintenance for up to 15 years. The most common maintenance item is the booted system which joins the track to the slab.

The calculations provided in this paper are extracts from some of the calculations and models used for the expansion of Depot 82 for Transport Canberra Light Rail project. The Australian loading code AS 5100.2 2017 and concrete design code AS 5100.5 2017 were used. A similar approach can be used using other design codes. A typical embedded track slab is shown below.

Figure 1: Typical embedded track slabs

1.1 Aim of Paper

The aim of the paper is to explain the steps required to design rail track slab.

2. MAIN CONSIDERATIONS FOR TRACK SLAB DESIGN

The main considerations required for track slab design are listed below.

2.1 Basic Design Concept

The following aspects play a major role for the design of a rail track slab:

- Underlying supporting strata modulus.
- Rail Vehicle axle loads.
- Transverse vehicle crossing loads.
- Length between expansion joints.
- Differential temperature between rails and track slab.
- Connection between the rails and slab.
- Concrete Shrinkage.

The embedded track slabs must withstand co-existent:

- Moments
- Shear forces
- Axial forces (tension is undesirable).

2.2 Basic Modelling

Two models are used:

- Longitudinal model
- Transverse model

The longitudinal model is used to calculate the longitudinal reinforcement:

- Longitudinal bending
- Longitudinal tension and compression

The transverse model is used to calculate:

- Transverse reinforcement

The longitudinal model is shown below.

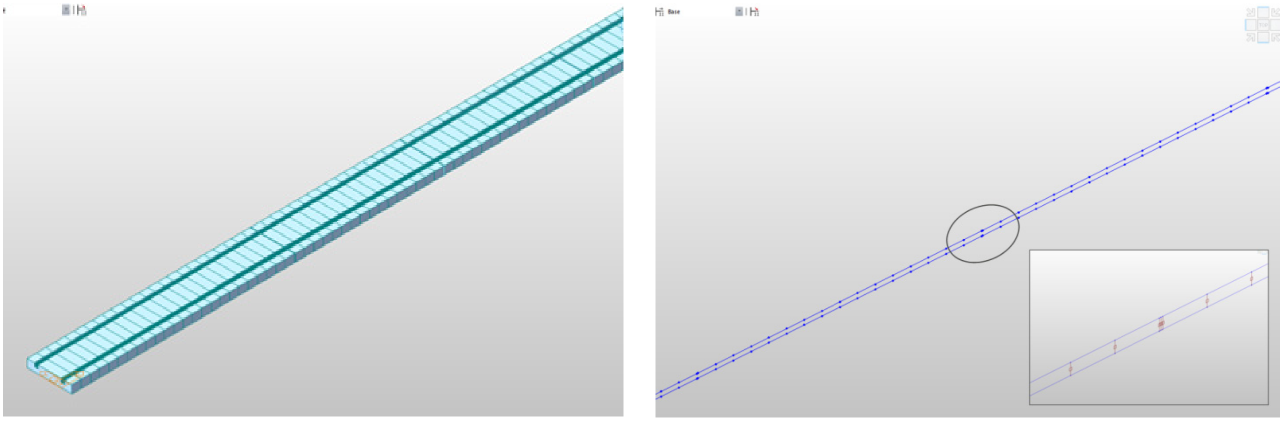


Figure 2: Track slab longitudinal model. Solid model shown left and line model shown right. Springs connecting slab and rail are shown on the right insert

The transverse model is shown below.

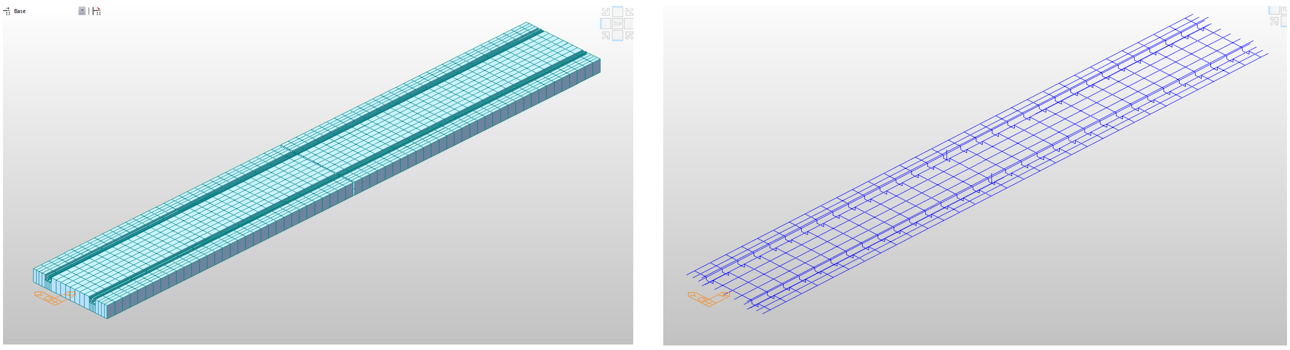


Figure 3: Track slab transverse model

The track slab cross-section and transverse model cross section used are shown below.

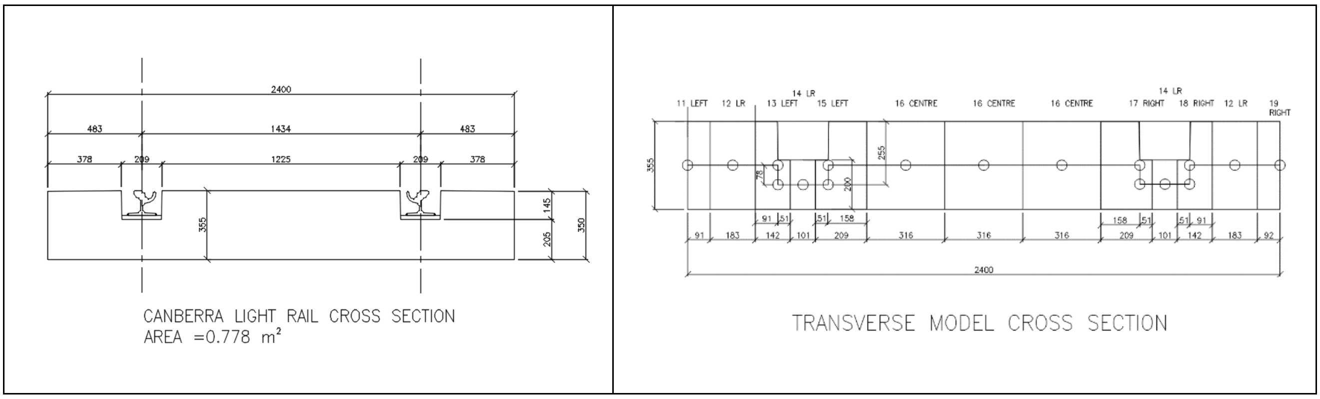


Figure 4: Track slab cross section and transverse model cross section

The main considerations for track slab design are listed and described below.

2.3 Underlying sub-strata modulus

The stiffness of the underlying strata plays an important role regarding the design of the embedded track slab.

A stiffer sub-strata will support a larger proportion of the applied loads directly under the slab resulting in smaller moments being applied to the structure.

2.3.1 Calculation of Sub-Strata Modulus

The worst-case subgrade support condition is realised assuming a subgrade CBR of 3% immediately beneath the proposed subbase. Using the following chart a correlation between subgrade CBR and modulus of subgrade support can be identified. The graphs used are taken from Austroads Guide to Pavement Technology to determine the Modulus of subgrade reaction are shown below.

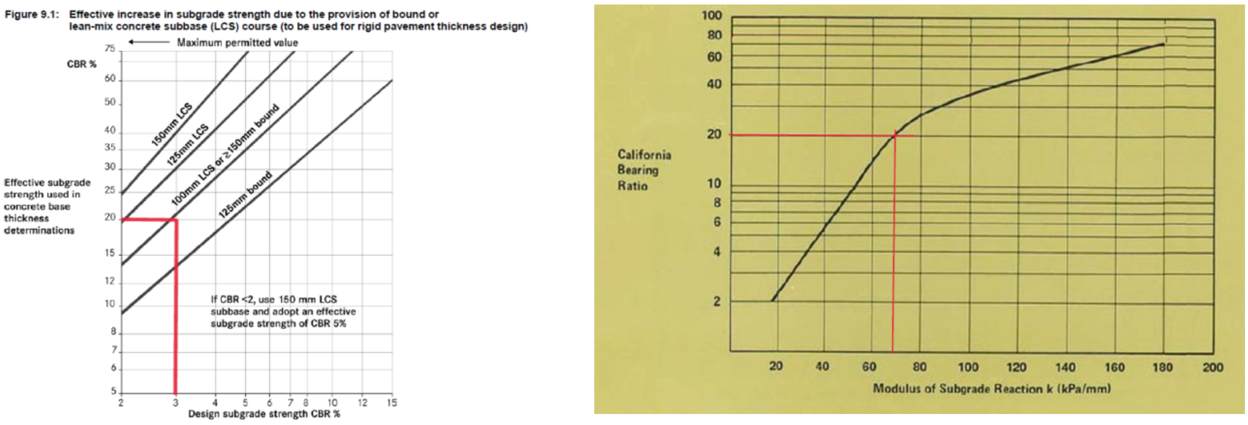


Figure 5: Estimating effective subgrade strength when combining a cemented subbase over subgrade (Austroads Guide to Pavement Technology Part 2: Pavement Structural Design)

From the graph the Modulus of subgrade reaction = 70 kPa/mm

We would normally run 3 models:

1. Model with subgrade reaction = 100% x 70 kPa/mm
2. Model with subgrade reaction = 50% x 70 kPa/mm = 35 kPa/mm
3. Model with subgrade reaction = 200% x 70 kPa/mm = 140 kPa/mm

The calculations shown going forward are for a subgrade reaction 50% x 70 kPa/mm = 35 kPa/mm. (This was a very conservative approach – not the actual conditions on site).

From this we need to work out the spring constants to apply to the model.

The spring constants normally are given in the form kN/m

For the line model:
The section width = 2.4 m
Element length = 0.5 m
Element area (central elements) = 1.2 m^2

The force required to deflect the 1.2 m^2 element 1 mm = 35 x 1.2 = 42 kN.

Spring constant k for 1.2 m^2 element = 42 / 0.001
= 42000 kN/m
Edge units with half the area have k = 21000 kN/m

2.4 Connection Between Rails and Concrete

The embedded track slab requires a connection between the track slab and the rails. This can take the form of a booted system or resin as shown below.

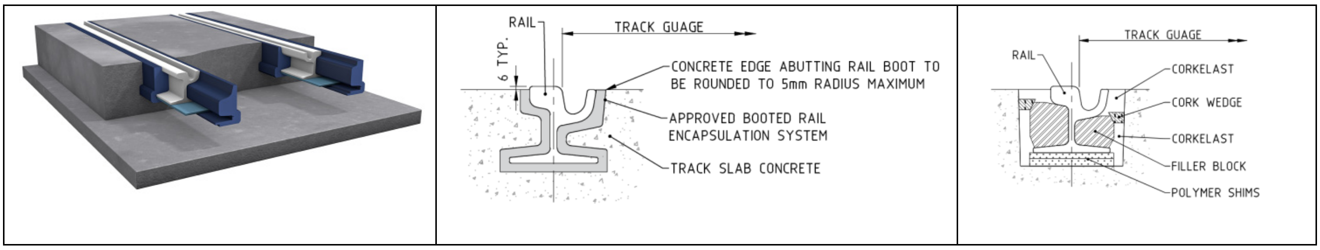


Figure 6: Typical embedded track systems

2.4.1 Longitudinal Relationship Between Concrete and Rails in Embedded Track Slab

Typically for an unloaded track according to International Union of Railways UIC 774-3R the horizontal spring coefficient is given below:

k = 19 kN/m for a maximum displacement of u_o = 7 mm.

For a displacement larger than 7 mm the rail will slide horizontally in its slot.

The forces are large.

Before the rail slides the maximum horizontal force = 133.0 kN/m.

This is very large and can even cause the whole concrete slab to slide along the ground. Consider 400 m of rail track.

Assume the rail is heated 20°C hotter than the concrete slab on a hot day.

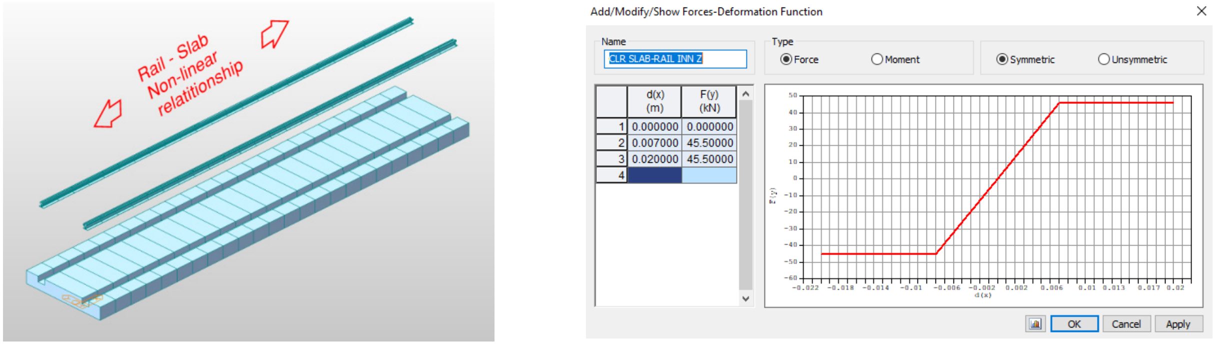
The extension of the track for each 200 m of track from the centre:

Extension = 20 x 100 000 x 1.17 x E-5 = 46.8 mm.

Either of the following conditions can occur:

- The rail will slide relative to the track.
- The track will slide along the ground.
- The rail will stretch / compress.
- The concrete slab will stretch / compress.
- Combinations of all of the above.

The non-linear longitudinal relationship between rail and slab is shown below.



Name: CLR SLAB-RAIL INN Z

Type: ● Force ○ Moment

● Symmetric ○ Unsymmetric

	d(x) (m)	F(y) (kN)
1	0.000000	0.000000
2	0.007000	45.50000
3	0.020000	45.50000
4		

Figure 7: Non-linear longitudinal relationship between rail and slab with track beginning to slide after 7 mm movement

2.4.2 *Vertical Relationship Between Concrete and Rails in Embedded Track Slab*

For an embedded track slab there is normally a thin layer of rubber between the rail and the slab. When the rail presses down on the slab the load is transferred to the slab and the slab transfers the load to the soil.

If a large load like a truck is placed on the slab the slab might settle but the rail will remain straight. If the slab settles more than 2 mm more than the rails the bond between the rail and the slab can be damaged. This is more prone to happen at the expansion joints and can be solved using dowels. Weak underlying substrata can worsen the problem. Non-linear vertical springs are needed between the slab and the rails.

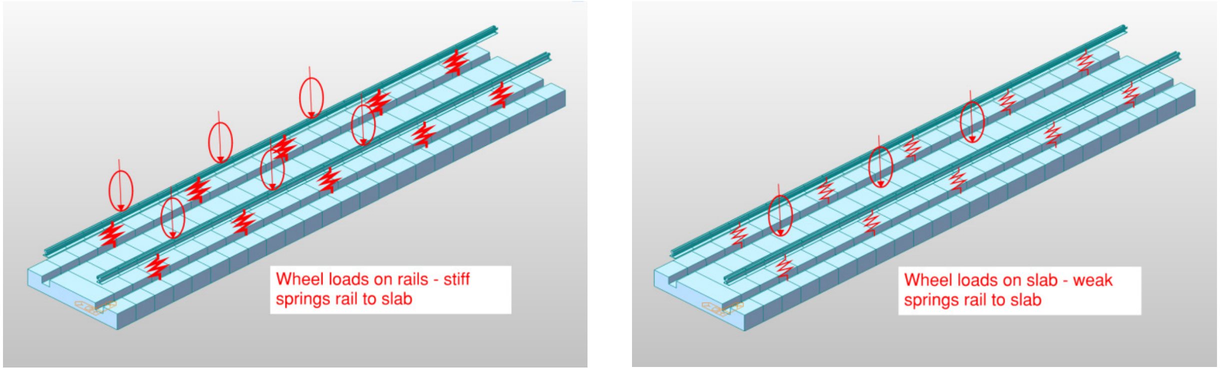


Figure 8: Non-linear vertical relationship between rail and slab

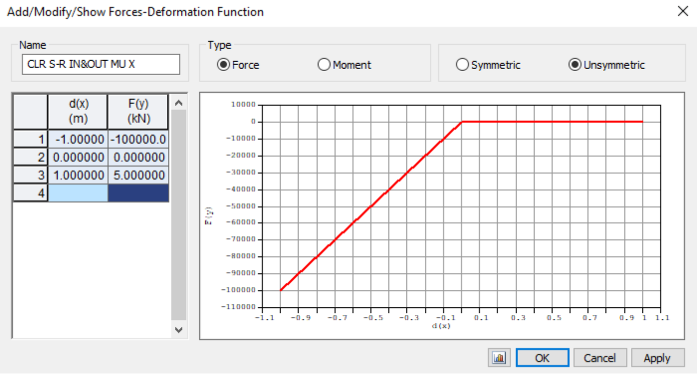
When loads are applied directly to the rails stiff springs are used between the rain and the slab.

When loads are applied directly to the slab weak springs are used between the rail and the slab. The slab can go down locally but the rails will remain straight. The springs between the rail and the slab must provide a high level of resistance to compression loads but a low resistance to tension loads.

A non-linear spring is used to model this aspect.

The compression resistance of the spring = 10.0 kN/mm
The tension resistance of the spring = 0.005 kN/mm

The non-linear spring is shown below:


Add/Modify/Show Forces-Deformation Function

Name: CLR S-R IN&OUT MU X

Type: ● Force ○ Moment

○ Symmetric ● Unsymmetric

	d(x) (m)	F(y) (kN)
1	-1.00000	-100000.0
2	0.000000	0.000000
3	1.000000	5.000000
4		

Figure 9: Non-linear vertical spring used between the rail and slab

2.5 Connection Between Slab and Sub-Strata

A unique relationship exists between the track slab and the ground in the longitudinal direction and in the vertical direction.

2.5.1 Longitudinal Relationship Between Concrete Slab and Ground

A typical track slab will resist longitudinal movement due to the friction from the ground underneath and at the sides as shown below.

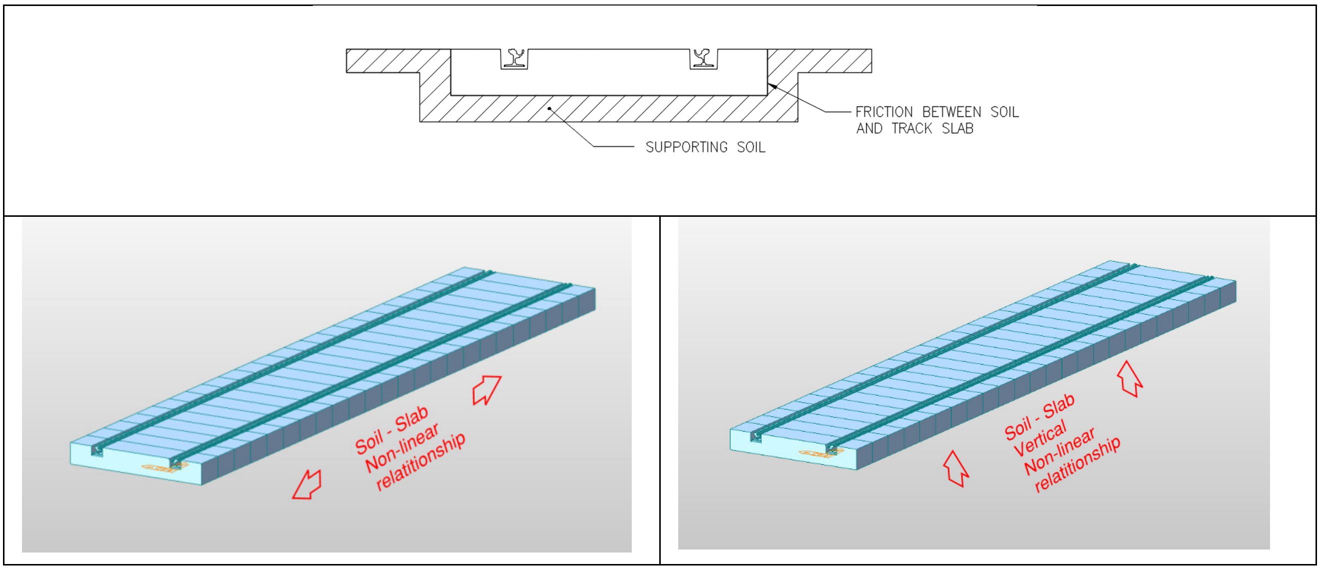


Figure 10: Cross section and non-linear longitudinal springs used between the soil and slab

The longitudinal resistance used = weight of rail and concrete per linear meter
= 0.78 m2 x 25 = 19.5 kN/m

k = 19.5 kN/m for a maximum displacement of u_0 = 5 mm.

2.5.2 Vertical Relationship Between Concrete Slab and Ground

As previously calculated for a vertical subgrade reaction = 35 kPa/mm

The vertical compression spring constant k for 1.2 m^2 (0.50 m long element):

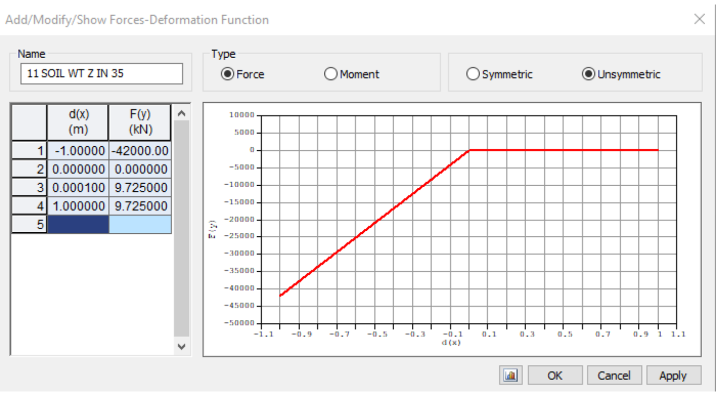
k = 42000 kN/m

Edge units with half the area have k = 21000 kN/m

A non-linear vertical spring is required.

The slab must be free to lift up but when it does so it must exert the force of gravity.

The weight of a 0.5 m long segment of slab = 0.78 (area) x 0.5 x 25 = 9.75 kN. The non-linear vertical relationship between the soil and the slab is shown below.



Add/Modify/Show Forces-Deformation Function

Name: 11 SOIL WT Z IN 35

Type: ● Force ○ Moment

○ Symmetric ● Unsymmetric

	d(x) (m)	F(y) (kN)
1	-1.00000	-42000.00
2	0.000000	0.000000
3	0.000100	9.725000
4	1.000000	9.725000
5		

Figure 11: Non-linear vertical spring used between the soil and slab

3. DESIGN LOADS

The design loads are listed and explained below.

<u>3.1 LC1 Dead Load of Slab</u>

<u>3.2 LC2 Light Rail Vehicle (LRV)</u>

The light rail vehicle loads are shown below.

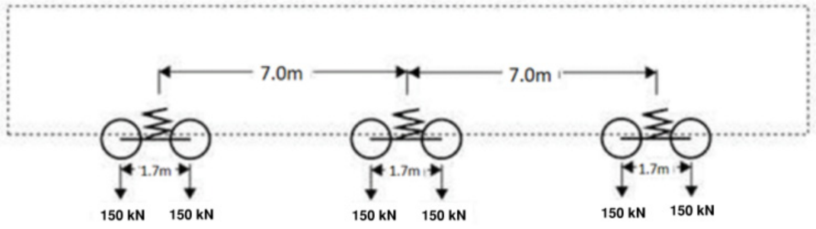


Figure 12: Light rail vehicle axle configuration

3.3 LC2 Nosing Load

The nosing loads are shown below.

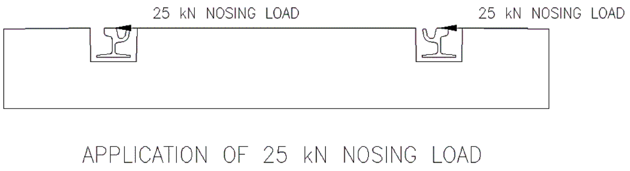


Figure 13: The nosing loads are shown below (33% of vertical wheel load)

3.4 LC4 Derailment Loads

There are 4 derailment load cases: The derailment load cases were applied as per AS 5100.2 – 2017. The derailment axle spacing is the same as for the light rail vehicle for LC4A and LC4B. The four derailment load cases are described below.

- LC 4A - Derailment case 1 - Load in centre
- LC 4B - Derailment case 2 - Two derailment wheel loads of each axle are applied
- LC 4C - Derailment case 3 - 200 kN point load in centre of track slab. Note: The loads of this case have been adjusted to 100 kN in proportion to the LRV axle load of 150 kN.
- LC 4D - Derailment case 4 - 200 kN point load at edge of track slab (reduced to 100 kN)

The four derailment cases are shown below.

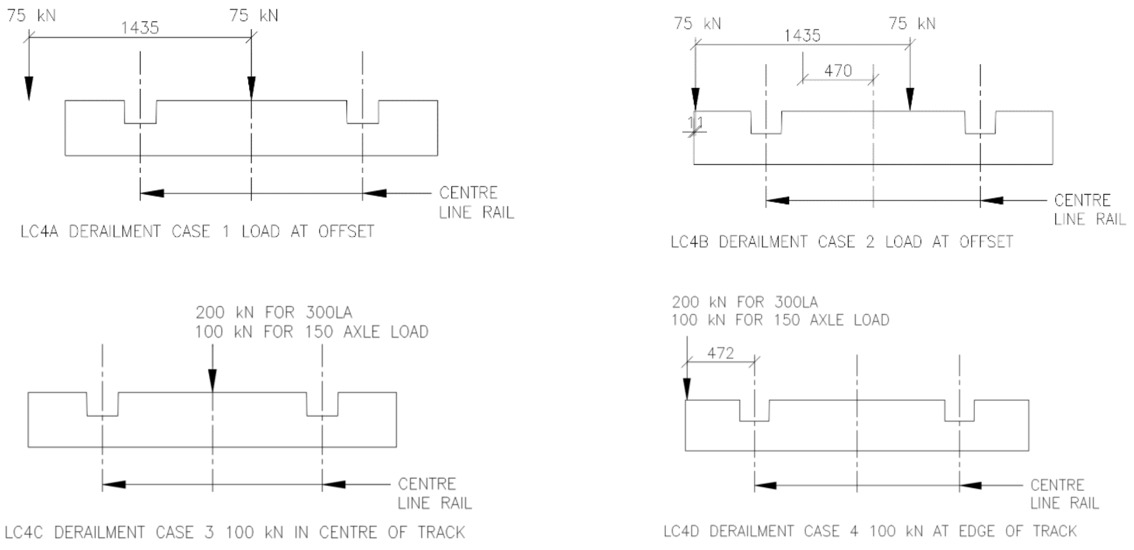


Figure 14: The four derailment load cases LC 4A, LC4B, LC4C and LC4D

3.5 LC5 T44 vehicle loading

The T44 represents a typical five axle truck. The axle loads are realistic but load factors of up to 2.8 overall are applied. The T44 is shown below.

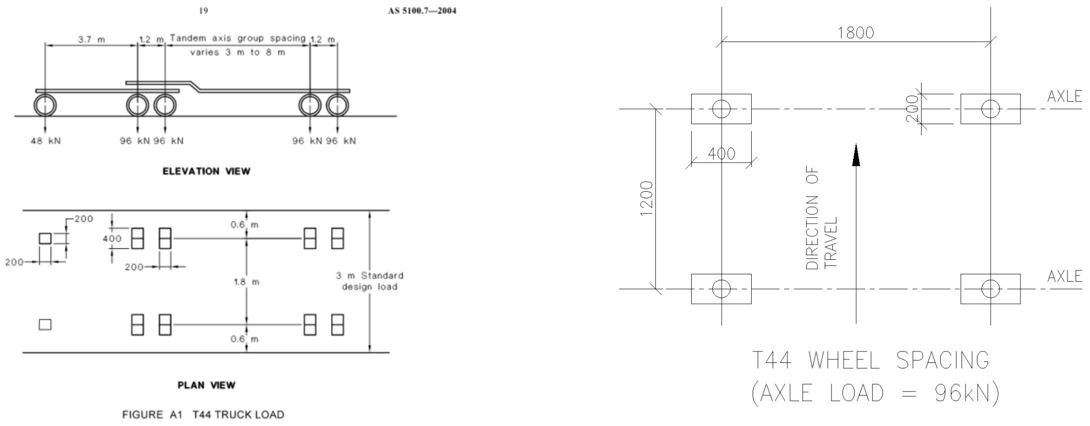


Figure 15: Details of the T44 load

The longitudinal application of the T44 vehicle is shown below:

- The T44 vehicle travels in a direction perpendicular to the LRV.
- The T44 crossing positions are shown for the longitudinal model below.

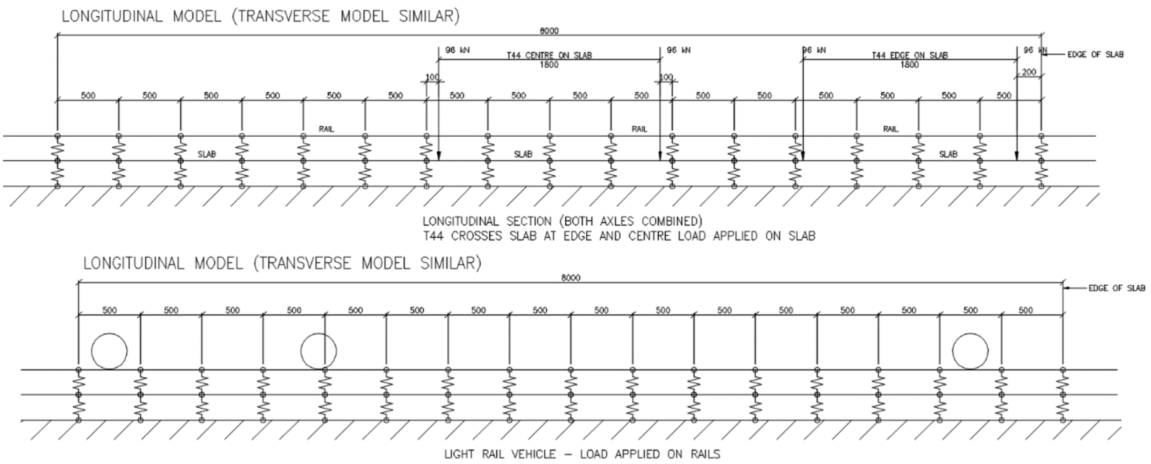


Figure 16: Longitudinal section. T44 load application on slab and LRV load on rails

3.6 LC6 Average Temperature Variation

The maximum and minimum temperatures after all adjustments are shown below:

- Max. temperature 49°C.
- Min. temperature = 3°C

The temperature range = (49 - 3) / 2 = ± 23.0°C.

3.6.1 LC 6A Maximum Uniform Temperature Variation

According to International Union of Railways UIC-774-3 clause 1.4.2 (Pg 12) the difference between the deck and the track does not deviate by more than ± 20°C

Three load cases are applied for the maximum uniform temperature variation as shown in the Table below.

Table 1: Maximum uniform temperature application

LC Name	Concrete temperature	Rail temperature
LC6A+++	+20	+40
LC6A++	+20	+20
LC6A+	+20	+0

3.6.2 LC 6A Min Uniform Temperature Variation

The minimum uniform temperature load cases are shown in the Table below.

Table 2: Maximum uniform temperature application

LC Name	Concrete temperature	Rail temperature
LC6A - - -	-20	-40
LC6A - -	-20	-20
LC6A -	-20	+0

3.7 LC7 Temperature Gradient

3.7.1 LC 7A Temperature gradient (MAX) 10^{o}C

The temperature gradient in the concrete slab was rationalized in the model as shown in the figure below. A temperature of T = 20ºC is applied to the concrete. 50% of 20^{o}C was used because the slab in insulated by the soil.

3.7.2 LC 7B Temperature gradient (MIN) -8^{o}C

The temperature gradient in the slab was rationalized in the model as shown below. A temperature of 0.4T is -8 ºC can be applied to the concrete. 50% of 20 ^{o}C was used because the slab in insulated by the soil.

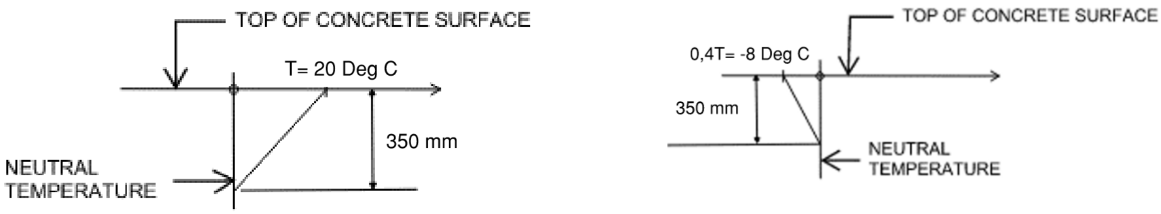


Figure 17: LC 7A Max. temperature gradient and LC 7B Min. temperature gradient

3.8 LC8 Shrinkage

The shrinkage between 60 days and 10950 days is equivalent to a temperature of -28ºC applied.

4. LOAD FACTORS

The load factors are applied to the loads to increase the design loads to build in safety. There are two load factors, the dynamic load factor (DLA) and load safety factor (LSF).

The DLA and LSF are multiplied together and both are different for ULS, SLS and fatigue loads.

4.1 Dynamic Load Allowance (DLA)

The two vehicles have load factors applied to their basic weights:

- Light rail vehicle (LRV)
- T44 vehicle

The dynamic allowance for fatigue is 50% of the ULS dynamic load allowance.

The dynamic load allowance factors are shown in the Table below.

Table 3: Vehicle dynamic load allowance (DLA)

Vehicle	DLA	DLA Effect ULS	DLA Effect SLS	DLA Effect fatigue
LRV	0.25	1.25	1.25	1.125
T44 vehicle	0.4	1.4	1.4	1.2

4.2 Vehicle Design Load Safety Factors (LSF)

The vehicle design load safety factors are shown in the Table below:

Table 4: Vehicle Design Load Safety Factors (LSF)

Vehicle	ULS	SLS	Fatigue
LRV straight track	1.5	1.0	1.0
T44	2.0	1.0	1.0

4.3 Vehicle DLA x LSA

The vehicle DLA x LSF (dynamic allowance x load safety factors) products are shown in the Table below for ULS, SLS and fatigue.

Table 5: DLA x LSF products

Vehicle	DLA	DLA Effect ULS	DLA Effect SLS	DLA Effect fatigue	SLS	ULS	DLAx ULS	DLAx SLS	DLAx LSF fatigue
LRV	0.25	1.25	1.25	1.125	1.0	1.5	1.875	1.25	1.125
T44 vehicle	0.4	1.4	1.4	1.2	1.0	2.00	2.8	1.4	1.2

5. LOAD COMBINATIONS

The general summary of design load combinations that need to be applied to the track slab are summarised in the Table below.

For modelling purposes, the load cases required for design purposes are shown below.:

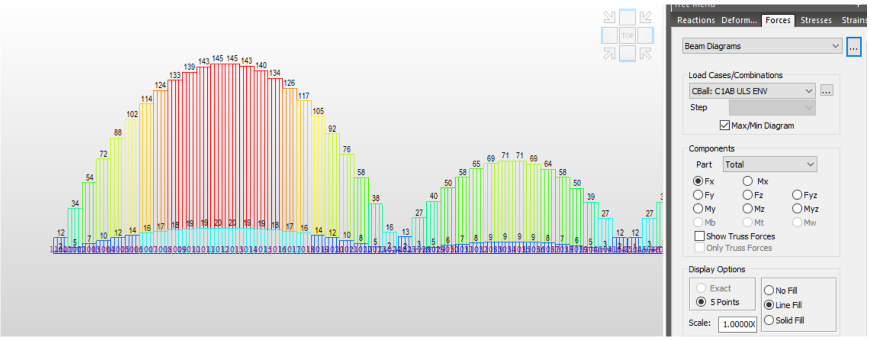
Table 6: Load combinations used for design

Load Case	Combination	Case
C ULS 1A	1.2xLC1 + 1.875xLC2 + 1.5xLC3 + 1.2xLC8	LRV vertical load + nosing + shrinkage
C ULS 1B	1.2xLC1 + 1.875xLC2 + 1.5xLC3 + 1.0xLC6 + 1.0xLC7 + 1.2xLC8	LRV vertical load + nosing + temp + shrinkage
C ULS 2	1.2xLC1 + 1.2/1.0xLC4 + 1.2xLC8	Vertical load + derailment envelope + shrinkage
C ULS 3	1.2xLC1 + 2.80xLC5 + 1.2xLC8	T44 crossing + shrinkage
C SLS 1A	1.0xLC1 + 1.25xLC2 + 1.0xLC3 + 1.0xLC8	Vertical load + nosing + shrinkage
C SLS 1B	1.0xLC1 + 1.25xLC2 + 1.0xLC3 + 0.5xLC6 +0.7xLC7 + 1.0xLC8	Vertical load + nosing + temp + shrinkage
C SLS 3	1.2xLC1 + 1.40xLC5 + 1.0xLC8	T44 crossing + shrinkage
C FAT 1A	1.125xLC2 + 1.0xLC3	Vertical load only + nosing
C FAT 3	1.20xLC5	T44 crossing

6. RESULTS

6.1 Slab Axial Load Envelope

The slab axial load envelope is shown below. The first slab is 12.0m long and the remaining slabs are 8.0 m long.



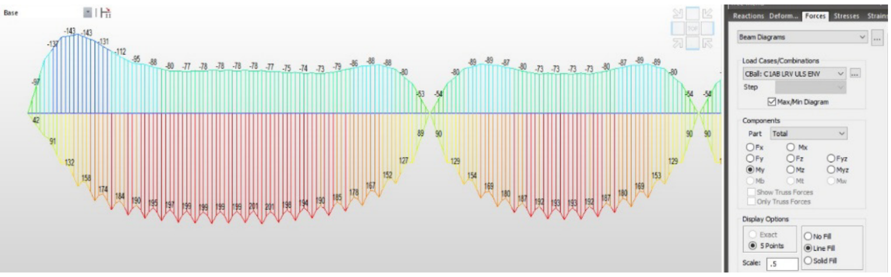
Beam Diagrams
Load Cases/Combinations: CBall: C1AB ULS ENV
Step
☑ Max/Min Diagram
Components
Part: Total
● Fx ○ Mx
○ Fy ○ Fz ○ Fyz
○ My ○ Mz ○ Myz
○ Mb ○ Mt ○ Mw
☐ Show Truss Forces
☐ Only Truss Forces
Display Options
○ Exact
● 5 Points
Scale: 1.00000(
○ No Fill
● Line Fill
○ Solid Fill

Figure 18: Slab axial loads

The maximum axial load = 145 kN tension.

6.2 Slab C1 AB ULS (LRV) Moment Envelope

The slab LRV ULS moment envelope is shown below:



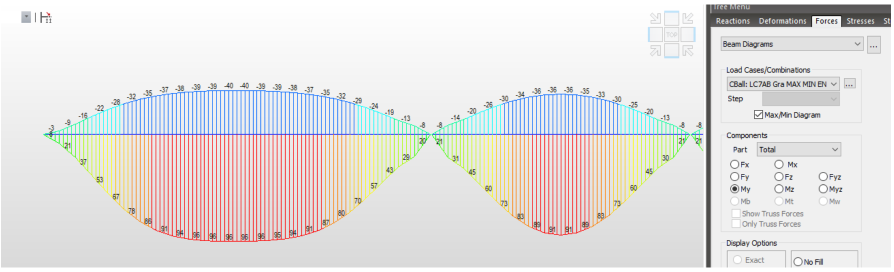
Beam Diagrams
Load Cases/Combinations: CBall: C1AB LRV ULS ENV
Step
☑ Max/Min Diagram
Components
Part: Total
○ Fx ○ Mx
○ Fy ○ Fz ○ Fyz
● My ○ Mz ○ Myz
○ Mb ○ Mt ○ Mw
☐ Show Truss Forces
☐ Only Truss Forces
Display Options
○ Exact
● 5 Points
Scale: .5
○ No Fill
● Line Fill
○ Solid Fill

Figure 19: Typical slab LRV ULS moments

The maximum sagging moment = 201 kN.m
The maximum hogging moment = 143 kN.m

6.3 Slab LC7 Max Min Temperature Gradient Unfactored Moment Envelope

The slab LC7 Max. Min. temperature gradient unfactored moment envelope is shown below.



Tree Menu

Reactions | Deformations | Forces | Stresses | St

Beam Diagrams

Load Cases/Combinations: CBall: LC7AB Gra MAX MIN EN

Step

☑ Max/Min Diagram

Components

Part: Total

○ Fx ○ Mx

○ Fy ○ Fz ○ Fyz

● My ○ Mz ○ Myz

○ Mb ○ Mt ○ Mw

☐ Show Truss Forces

☐ Only Truss Forces

Display Options

○ Exact ○ No Fill

Figure 20: Unfactored temperature gradient moments

The maximum sagging moment	= 96 kN.m
The maximum hogging moment	= 40 /36 kN.m

6.4 Longitudinal Section Checking

The maximum longitudinal design values are shown in the Table below. The longitudinal capacity needs to take into account the co-existent bending moment and axial forces in the slab. The shear capacity is influenced by the co-existent axial forces and bending moments.

Table 7: Longitudinal moment and shear design envelope

CLR Longitudinal design Max Values				
Force description	Load case name	Corresponding axial load	Corresponding Moment	Corresponding shear force
Max sagging moment	1 C5AB T44 ULS Sag	69.9	323.3	192.0
Max hogging moment	2 C5AB T44 ULS Hog	7.8	-184.2	200.2
Max shear force	3 C5AB T44 ULS Shear	69.9	291.0	367.2
Min shear force	4 C5AB T44 ULS Shear	12.3	89.0	-398.5

The bending results are shown below:

The maximum allowable rebar stress = Ø Fy = 0.8 x 500 = 400.0 MPa

The maximum stress = 384.5 MPa OK

The section reinforcement and bar longitudinal stresses are shown below. Bar stresses were calculated using the Midas General Section Designer

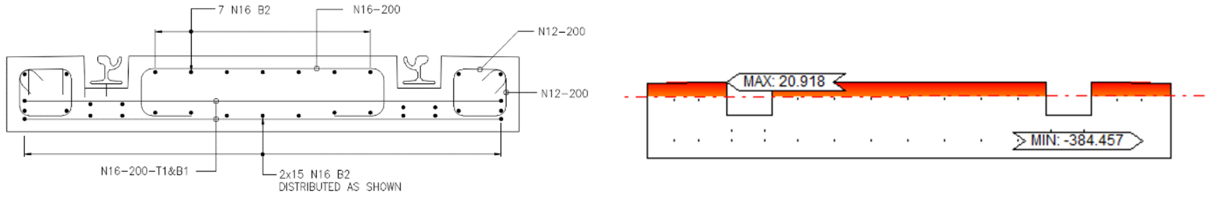


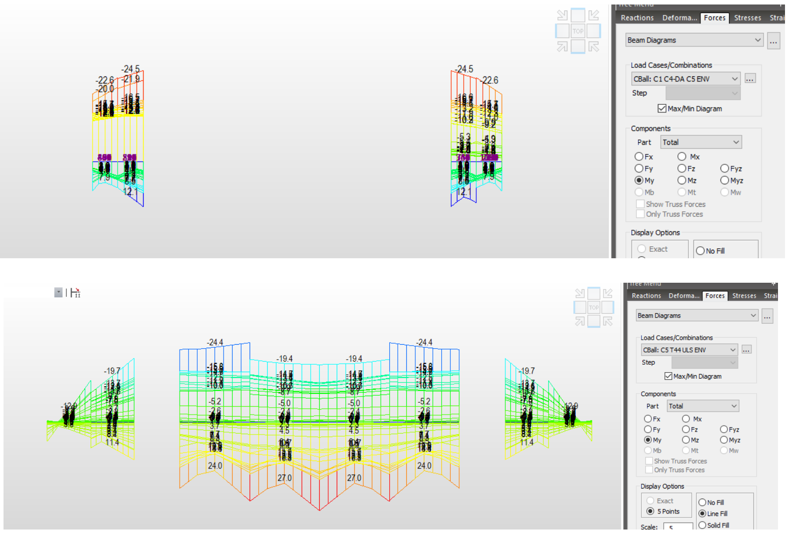
Figure 21: Left. Design reinforcement. Right – Midas General Section Designer results

6.5 Longitudinal SLS Design and Longitudinal Fatigue Design

The maximum longitudinal SLS and longitudinal fatigue stresses are checked in a similar manner to the ULS bar stresses.

6.6 Transverse ULS, Transverse SLS and Transverse fatigue

The transverse bending moment envelopes for the 200 mm deep and 355 mm deep sections are shown below. The slab transverse shear capacity is also checked transversely.



Beam Diagrams
Load Cases/Combinations: CBall: C1 C4-DA C5 ENV
☑ Max/Min Diagram
Components
Part: Total
● My

Beam Diagrams
Load Cases/Combinations: CBall: C5 T44 ULS ENV
☑ Max/Min Diagram
Components
Part: Total
● My
Display Options
● 5 Points
● Line Fill
Scale: 5

Figure 22: The bending moment envelopes for 200 thick and 355 thick transverse elements

7. TURN-OUT TRACK SLAB DESIGN

7.1 Basic Design Methodology

The longitudinal design is based on the longitudinal design of the standard track.

The transverse capacities are calculated using the following live loads:

- LRV
- Derailment loads and
- T44 crossing vehicle

The turn-out Midas (wire frame view) model and solid model is shown below.

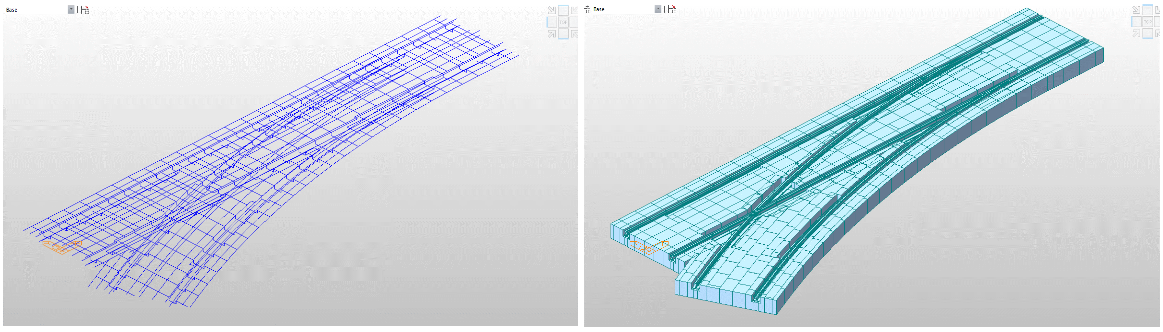


Figure 23: Midas turn-out grillage model – wire frame and solid frame view

The typical reinforcement for the turn-out is shown below.

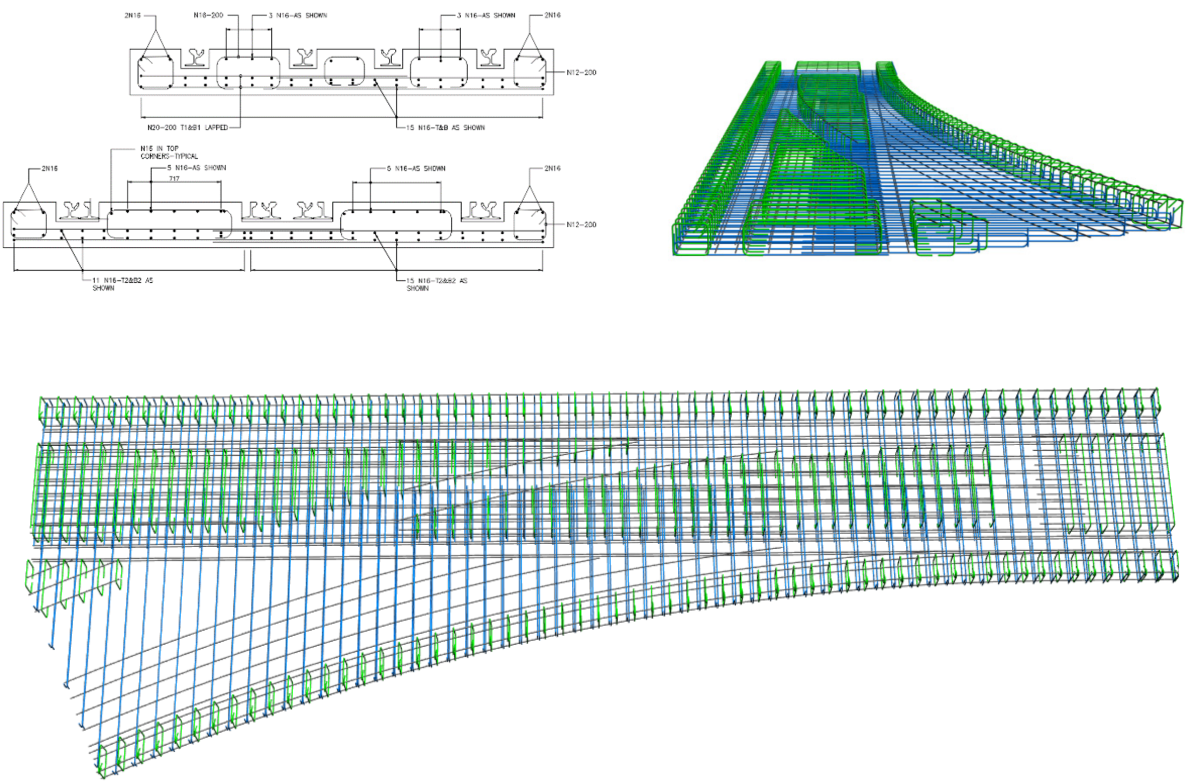


Figure 24: Turn-out typical cross-sectional reinforcement and typical bar placing

8. CONCLUSIONS

This paper has focussed on some of the aspects of track slab design. The following aspects have not been covered:

- SLS and fatigue design checks
- Detailed bending and shear calculations
- Design of dowels at expansion joints
- Design details where track slab joins a ballasted track

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