TRACK STRUCTURE DESIGN ASSESSMENT

CRN-MAN-CVL-713026361-546

CRN CM 005

LINKING COMMUNITIES. CONNECTING CUSTOMERS.

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Document Control

Function	Position	Name	Date
Approver	A&E Manager	Lucio Favotto	24.01.2022

Revision	Issue Date	Revision Description
1.0	11.11.2021	UGLRL Operational Standards Template applied
2.0	29.11.2021	First full UGLRL issue
3.0	24.01.2022	Issued for publish to internet and webpage
4.0	24.03.2022	Two UGLRL references added – no other change

Summary of changes from previous version

Section	Summary of change
All	This document is based on the previous rail infrastructure maintainer (RIM). Full revision history is available on request from UGLRL

Chapter 1 Introduction

C1-1 Purpose

This manual provides empirically derived design methods for the assessment of UGLRL CRN track structure for the purpose of undertaking a value engineering solution as per CRN CS 200 Track Systems. This manual may also be used for guidance when undertaking assessment of the track structure as part of a Track Capability Assessment in CRN CM 004 Track Capability Assessment.

This manual also contains recommended parameters for the use on CRN track for:

- rail bending stress
- rail deflection
- contact stress
- shear stress
- ballast contact pressure, and
- subgrade pressure

This manual does not include assessment of track condition, maintenance requirement, track stability or economic assessment.

C1-2 Context

This manual is part of UGLRL CRN's engineering standards and procedures publications. More specifically, it is part of the Civil Engineering suite that comprises standards, installation and maintenance manuals and specifications.

C1-3 How to read the Manual

The best way to find information in this manual is to refer to the Table of Contents on page 3. There is no specific hierarchy of chapters, each one dealing with a separate topic. The Table of Contents is self-explanatory.

Reference is made to other CRN documents in which more detailed information or specific procedures are available.

C1-4 References

C1-4.1 Australian and International Standards

AS 1085

C1-4.2 CRN Documents

CRN CS 200 – Track System

CRN CS 210 – Track Geometry & Stability

CRN CM 202 – Track Fundamentals

CRN CP 231 – Timber Sleepers and Bearers

CRN CP 233 – Concrete Sleepers

CRN CP 233 – Steel Sleepers

CRN CM 004 – Track Capability Assessment

C1-4.3 Other

A Review of Track Design Procedures, Volume 1 Rails, G.P. Tew, S. Marich and P.J. Mutton, Railways of Australia, 1991

Track Geotechnology and Substructure Management, E.T. Selig, J. M. Waters, Railways of Australia, 1992

Railway Track Design A Review of Current Practice, N.F Doyle, BHP Melbourne Research Laboratories, 1980

Modern Railway Track, Second Edition, Coenraad Esveld, 2016

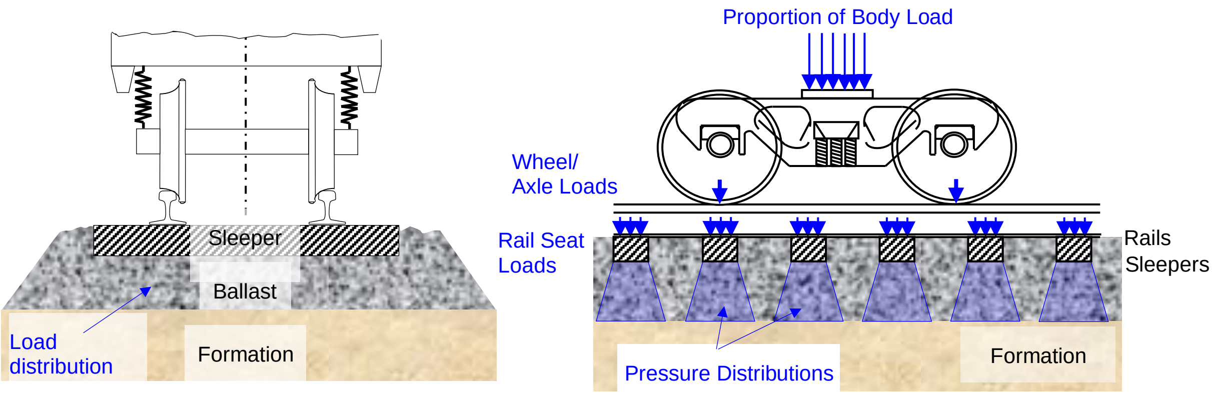
Chapter 2 Track Structure

C2-1 Introduction

As illustrated in Figure 1, the track structure consists of the following main components:

- Rails – whose main function is to provide support and guidance to the wheelsets/bogies/vehicles.
- Sleepers – whose main functions are to:
  - Support and anchor the rails.
  - Provide the required longitudinal, vertical and in particular, lateral track stability.
  - Provide a platform for distributing the applied loads into the ballast and formation.
- Ballast – whose main functions are to:
  - Support the sleepers, and hence support the vertical, lateral and longitudinal loads applied through the sleepers, with minimal plastic deformation and hence loss of track geometry.
  - Transfer the applied loads in an adequate manner to the formation.
  - Provide efficient drainage of water from the ballast bed.
- Formation – whose main function is to provide stable support for the overall track structure.

A more detailed description of these components is provided in *CRN CS 200 Track System and CRN CM 202 Track Fundamentals.*



Transverse Plane *Longitudinal Plane*

Figure 1 – Basic Representation of Vehicle/Track Components and Load Transfer

Chapter 3 Track structure design

C3-1 Introduction

The purpose of this chapter is to provide the reader with an understanding of the principle involved in designing a ballasted track structure.

Railways have developed over many years. The basic systems have evolved based on experience. Track design methodologies are empirically derived to reflect the requirements of a very complex reality.

Modern understanding of the railway track's response to static and dynamic vehicle loading has resulted in the development of engineering computer models such as GeoTrack and Kentrack, for the analysis of the track structure and should be used where practical.

C3-2 Track loading

The design of a railway track has followed an iterative process which commenced prior to the Industrial Revolution. Gradually, more science has been applied to the process which was, and to a large extent still is, an empirical method. The method is based on an understanding of the materials and the interaction of the materials in forming the permanent way.

It is recommended that anyone undertaking track design review the work by Jeffs and Tew in 1991 on behalf of the Railways of Australia and Modern Railway Track by Coenrad Esveld.

The railway track is an extremely elastic structure which is not readily analysed by simple design procedures. Under such circumstances traditional track structure design has been empirical, with economic considerations frequently dictating component selection and size. For example:

- The selection of rail size may be determined by the anticipated rail wear rate rather than by structural strength.
- Timber sleeper size may be governed by practical considerations like standardisation, adequate thickness for fastener requirements, or sleeper mass and sectional area to ensure adequate resistance to the lateral forces encountered, particularly on curves.

All of the design methods employed throughout the world have been derived from the work carried out by Hertz (1887). In his work Hertz described the deformation that occurs between two solid bodies when coming into contact, as is the case when the wheel and rail are brought together. When brought together an ellipse is formed and the dimensions of the ellipse are dictated by the material properties of the wheel and rail. These properties of hardness, elasticity and smoothness of the contact area are important in analysing how the load is transferred to the rail firstly, followed by the underlying layers of the railway system.

Figure 2 shows a flow chart presented by Prause et al in 1974 for a design process for conventional ballasted track structures. This general procedure is followed by many design engineers throughout the world to provide a fairly comprehensive first cut in the design of a railway track. The sections below provide a non rigorous first-cut method for each element in this design process. This document will follow this process generally from the top down. However, the process can commence at any level and proceed either upwards or downwards, as determined by key criteria for certain elements. For example:

- Design of a new track structure may begin with known vehicle loads and so would proceed top down using the process in Figure 2.
- Rating of an existing track structure may be governed by formation strength, so the process would be used in reverse to determine allowable traffic loadings.

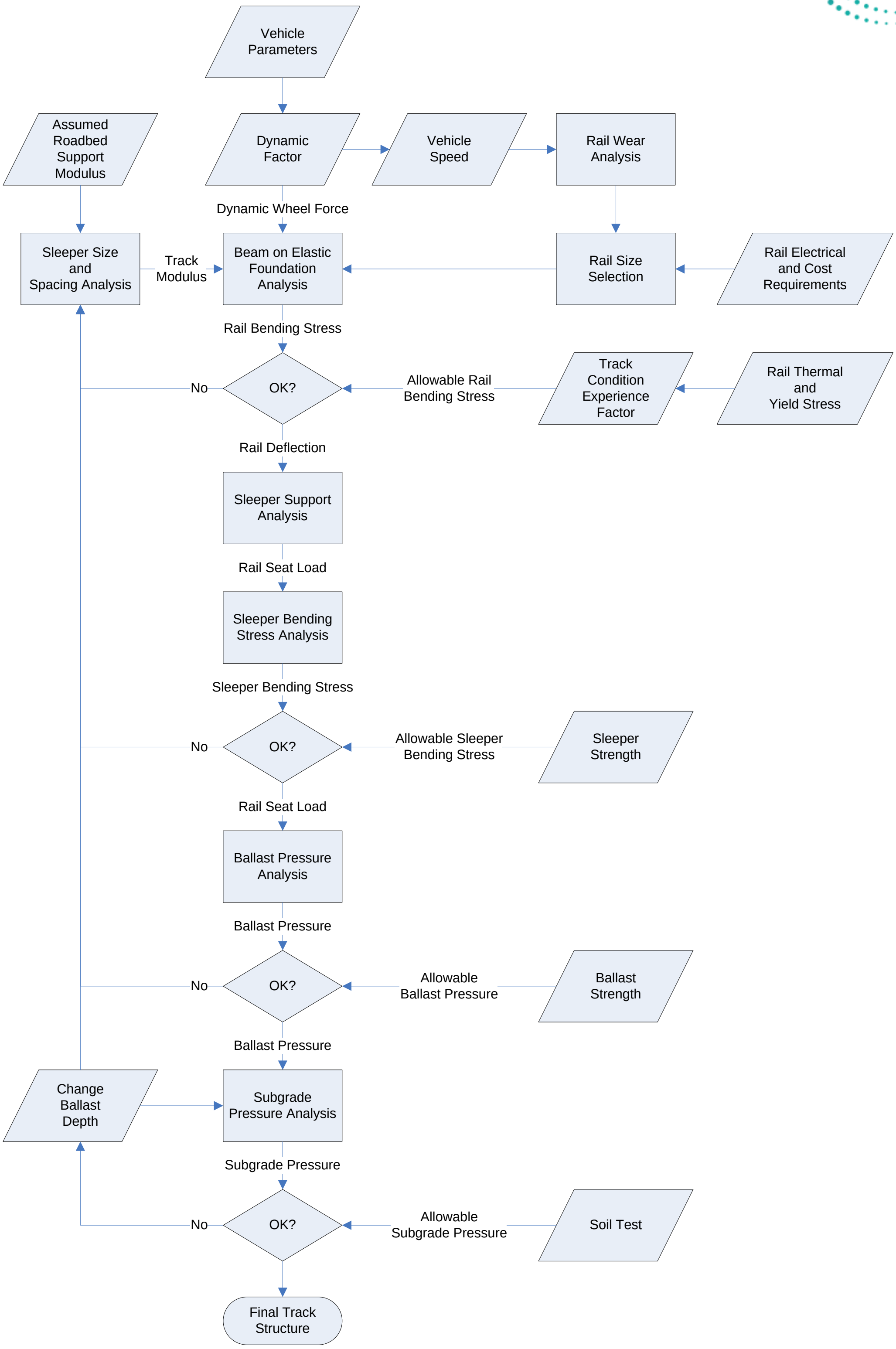


Figure 2 - Design Process for Conventional Ballasted Track Structures, Prause et al, 1974

The above design process provides an empirical design method using an allowable stress method of analysis to determine the applied loading.

Subsequent sections will lead you through the design process and elaborate on the background to the design process.

Dynamic impact factor

For general track conditions consisting of continuously welded rails, which typify all Class 1 and 2 tracks and some Class 3 tracks, the modified Eisenmann procedure, which has been validated by various field tests, can be used to determine the applied dynamic vertical loads. The procedure is statistical and specifies that the dynamic axle load, P_d, may be determined using the following relationship:

$$P_d = \phi P_0 \tag{1}$$

where: P_d = *design wheel load (N)*

P_0 = *static wheel load (N)*

ϕ = *dynamic impact factor*

= $1 + \delta n t$

δ = *0.1, for track in good condition (average TCI <=35)*

= *0.2, for track in average condition (average TCI between 35 & 45)*

= *0.3, for track in poor condition (average TCI between 46 & 55)*

= *0.4, for track in very poor condition (average TCI between 56 & 70)*

= *0.5, for track in extremely poor condition (average TCI >70)*

n = $1 + \frac{V-60}{140}$ *for* V *>60km/h*

= $\frac{V}{60}$, *for* V *≤60km/h*

t = *integer depending on the probability that the maximum applied load (or rail deflection) will not be exceeded*

= *0, for an upper confidence limit of 50%*

= *1, for an upper confidence limit of 84.1%*

= *2, for an upper confidence limit of 97.7%*

= *3, for an upper confidence limit of 99.9%*

V = *speed of the vehicle in km/h.*

The target TCI for use in determining δ, shall be as per maintenance targets in *CRN CS 210 Track Geometry and Stability.*

For the determination of t, an upper confidence limit of 84.1% should be assumed.

C3-4 Determining the Track Modulus

Track modulus is the term used to describe the vertical stiffness of the track structure below the rails. This forms part of the overall track stiffness which is the ratio of the load applied to the rail to the vertical rail deflection.

The most common method of assessing the track modulus is to use the beam on an elastic foundation method. In this, the structure below the rail is assumed to be a continuous elastic medium. This makes it easier to calculate the various forces in the system.

The main parameters that have a significant influencing effect on the track modulus are:

- Sleeper Type (timber, steel, concrete)
- Sleeper dimensions
- Sleeper quality/species (timber)
- Sleeper spacing
- Ballast durability
- Ballast stability
- Ballast compaction

- Ballast depth
- Sub-grade properties (as per ballast)
- Rail size.

Some other minor points worth considering on older track structures are:

- Degree of ballast fouling
- Moisture content of all layers of ballast and sub-grade.

It is important to note that the track modulus does not make any allowance for dynamic effects.

Each of the track components act as spring nests with specific stiffness and damping characteristics. These have a direct influence on the way in which the applied wheel loads are transferred and distributed throughout the track structure.

As illustrated in Figure 1, the loads applied by a wheelset influence not only the sleeper directly below the applied load, but also several of the adjoining sleepers. This occurs because the track system behaves essentially as two parallel infinite beams placed on discrete supports on a linear continuous elastic foundation (BOEF).

The concept is illustrated in Figure 3, for a single wheel load. It can be seen that in this case the rails are taken as a beam and the sleepers, ballast and formation have been taken as an elastic unit.

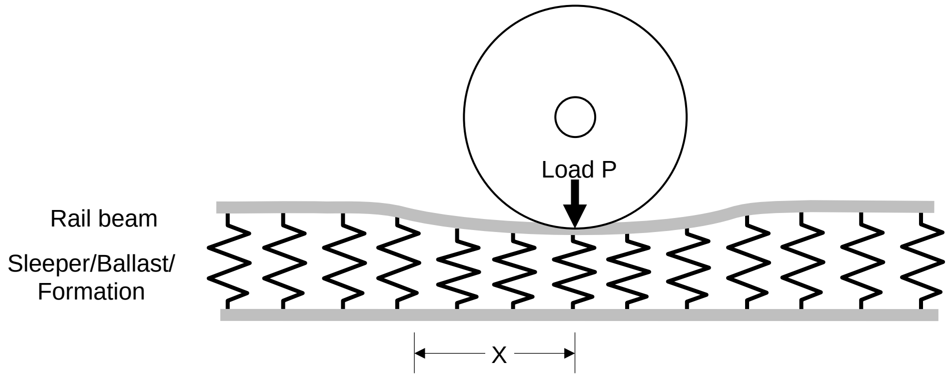


Figure 3 - Representation of track as a beam on elastic foundation (BOEF)

The track modulus can be determined for any section of track from experimental results using;

$$k = \left(\frac{P^4}{64EIy^4} \right)^{0.33} \qquad (2)$$

During the design phase, it may not be possible to accurately determine the track modulus from experimental results, as such, it may be permissible to approximate the track modulus.

$$\text{i.e. } k = \frac{K}{s} \qquad (3)$$

Where K = *Stiffness per sleeper (MPa)*

$$= \frac{1}{1/K_p + 1/K_{bs}}$$

K_p = *Rail pad stiffness*

K_{bs} = *Stiffness of ballast and subgrade layers (MPa)*

$$= \frac{1}{1/K_b + 1/K_{sub}}$$

K_b = *Stiffness of ballast layers (MPa)*

$$= \frac{1}{1/K_1 + 1/K_2}$$

K_1 = *Stiffness of upper layer of ballast (MPa)*

$$= \frac{C_1(l-b)E_{b1}}{ln\left(\frac{l/b\,(C_1Z_1+b)}{C_1Z_1+l}\right)}$$

K_2 = *Stiffness of lower layer of ballast (MPa)*

$$= \frac{C_2(l-b)E_{b2}}{ln\left(\frac{(C_1+Z_1+l)(C_2Z_2+C_1Z_1+b)}{(C_1Z_1+b)(C_2Z_2+C_1Z_1+l)}\right)}$$

K_{sub} = *Stiffness of subgrade (MPa)*

$$= \frac{K_s(C_2Z_2+C_1Z_1+l)}{C_2Z_2+C_1Z_1+b}$$

$$K_s = \frac{K_0(W_e+1)}{4W_e^2}$$

W_e = *effective width of subgrade (mm)*

$$= C_2Z_2 + C_1Z_1 + b$$

S = *Sleeper Spacing (mm)*

$C_1 = 2\tan\emptyset_1$

$C_2 = 2\tan\emptyset_2$

Z_1, Z_2 = *depth of the upper and lower ballast layers respectively (mm)*

θ_1, θ_2 = *internal friction angle of the upper and lower ballast layers respectively (mm)*

As a guide, the following are typical values of track modulus for standard gauge track. However, in practice there is considerable variation with location along the track and with seasonal conditions.

Rail Size (kg)	Ballast & Sleeper	Track Modulus k (MPa)
31	150mm, timber or steel	8
41	200mm, timber or steel	10
47 or 50	200mm, timber or steel	12
53	250mm, timber or steel	15
60	250mm, timber or steel	20
60	250mm, concrete	25
60	300mm, concrete	30

Table 1- Typical Values of Track Modulus k

C3-5 Calculation of Rail bending stress at the base of the rail

Using the beam on elastic foundation analysis under the action of a single wheel, the rail bending moment, M, can be found at any point x from the load point as

$$M_x = \frac{P_d e^{-\beta x}}{4\beta}\left(cos(\beta x) - sin(\beta x)\right) \text{ (Nmm)} \quad (4)$$

where: β = *track stiffness parameter*

$$= M_{r,max}\left(\frac{k}{4EI}\right)^{0.25} \quad (5)$$

k = *track Modulus (MPa)*

E = *Young's Modulus of rail steel*

= *207,000 MPa*

I = *Rail moment of inertia about the neutral axis (mm⁴)*

To determine the total bending moment in the rail at any point x, moments due to each load acting need to be summed.

$$M_{tot} = \sum_{i=1}^{n} M_x, \text{ (MPa)} \quad (6)$$

Where: n = *number of axles on the vehicle*

The stress in the rail due to rail bending can be determined by;

$$\sigma_r = \frac{M_{tot}}{Z_{bot}} \text{ (MPa)} \quad (7)$$

where: M_{tot} = *bending moment in the rail at point x from the load point (Nmm)*

Z_{bot} = *section modulus of the rail relative to the rail foot (mm^3)*

Rail is subject to both bending stress (due to the passing of rail traffic), and axial stress (due to the expansion and contraction of temperature changes). According to Hay, the maximum allowable bending stress is

$$\sigma_{max} = \frac{\sigma_y - \sigma_t}{(1+A)(1+B)(1+C)(1+D)} \text{ (MPa)} \quad (8)$$

where: σ_y = *yield strength of the rail section (MPa)*

σ_t = *48 MPa for jointed track, 90 MPa for CWR/JWR track*

A = *1, stress factor to account for lateral bending of the rail*

B = *1.15, stress factor to account for track condition*

C = *1.1, stress factor to account for rail wear and corrosion*

D = *1.15, stress factor to account for unbalanced superelevation*

C3-6 Calculation of Rail Deflection

Using the beam on elastic foundation analysis under the action of a single wheel, the rail deflection, y, can be found at any point x from the load point as

$$y_x = \frac{P_d \beta e^{-\beta x}}{2k}\left(\cos(\beta x) + sin(\beta x)\right) \quad (9)$$

To determine the total deflection in the rail at any point x, deflection due to each load acting need to be summed.

$$y_r = \sum_{i=1}^{n} y_x, \text{ (MPa)} \quad (10)$$

Where: n = *number of axles on the vehicle*

The less deflection in the rail, the less stresses are imparted on the entire track structure, and thus the track structure will require less maintenance per tonne. Guideline rail deflections for the rail industry are provided in Figure 4, and maximum allowable rail deflection for CRN track is detailed in Table 2. Relaxation of these limits may be considered where assessing locomotives, due to the number and frequency as opposed to a loaded wagon.

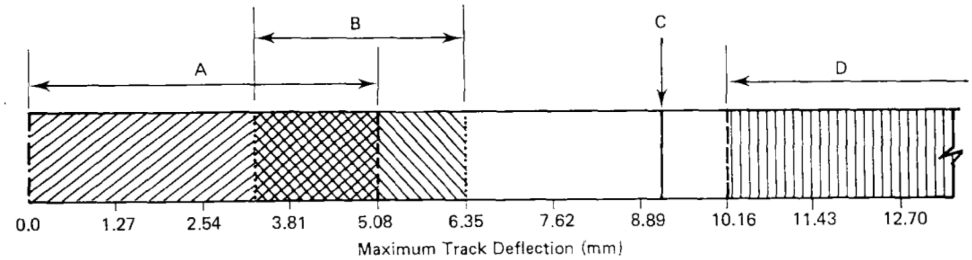


Figure 4 – Deflection limits for rail

Where A = *deflection range for track to last indefinitely*

B = *normal desirable deflection for heavy track to give requisite combination of flexibility and stiffness*

C = *limit of desirable deflection for track of light construction (i.e. ≤ 50kg/m rail)*

D = *Weak or poorly maintained track which will deteriorate quickly*

Track Class	Maximum Allowable Rail Deflection (mm)
Mainline	
1	4
2	5
3/3G	6
5	8
Siding	
1	5
2	6
3	7
5	*9*

Table 2 – Guideline maximum allowable rail deflection for CRN

C3-7 Calculation of contact stress and shear stress

Excess contact stress can lead to the development of corrugations, while excess shear stress can lead to the development of subsurface defects. As such these stresses should be designed to remain less than the limits discussed later in this section.

Contact stress acts over an oval contact area defined by $2a$ and $2b$ and estimated to be

$$\sigma_c = \frac{P_0.10^3}{2a.2b} \text{ (MPa)} \tag{11}$$

Where; $2a$ = *length of contact (mm)*

$= 3.04\sqrt{\frac{PR.10^3}{2bE}}$

$2b$ = *width of contact (mm)*

≈ *12mm*

P_0 = *static vertical wheel load (kN)*

R = *wheel radius (mm)*

E = *Youngs Modulus of rail steel*

=207,000 MPa

$\sigma_{ult'}$= *Ultimate tensile strength of rail steel*

The maximum shear stress, τ_{max} occurs at a depth of half the length of the contact area (ie $\frac{2a}{2}$), and can be approximated by

$$\tau_{max} = 410\sqrt{\frac{P_0}{R}} \text{ (MPa)} \tag{12}$$

For fatigue considerations the maximum allowable contact and shear stress should not be more than 50% and 30% respectively of the ultimate tensile stress for the material, $\sigma_{ult'}$, ie;

$$\sigma_c \leq 0.5\sigma_{ult'}$$

$$\tau_{max} \leq 0.3\sigma_{ult'}$$

C3-8 Calculation of P2 force

$P2$ force is a measure of the vertical impact force applied to the rail by the wheel at a dipped joint or vertical track defect. The estimated $P2$ force applied can be estimated by:

$$P2 = P_0 + 2\alpha.V\sqrt{\frac{M_u}{M_u+M_t}}.\left(1 - \frac{C_t\pi}{4\left(K_t\sqrt{M_u+M_t}\right)}\right).\sqrt{K_tM_u} \text{ (kN)} \tag{13}$$

Where M_u = *Vehicle unsprung mass*

2α = *total joint angle (radians)*

= *0.014 for track in reasonable condition*

= *0.028 for track with joints in poor condition, i.e. class 5 lines*

(may be increased due to track condition)

K_t = *Equivalent track stiffness (MN/m)*

$= \frac{2K}{\lambda}$

K' = *Track stiffness (MN/m)*

$= \frac{K}{bl}$

(note different units to the track modulus discussed in C3-4)

C_t = *Equivalent track damping (kNs/m)*

$= \frac{3C}{2\lambda}$

C = *Track damping (kNs/m)*

$= \frac{C_s}{S}$

C_s = *Ballast damping per sleeper end (kNs/m)*

= *30*

M_t = *Equivalent track mass (kg)*

$= \frac{3M}{2\lambda}$

M = *Track Mass (kg)*

$= \frac{M_s}{S} + M_r$

M_s = *Mass of sleeper (kg)*

M_r = *Mass of rail per one metre (kg)*

S = *Sleeper spacing (m)*

λ = *flexural rigidity of the track structure*

$= \beta$

The maximum allowable P2 force for various rail sizes typically found on the CRN are provided in Table 3.

Rail Size	Max P2 Force (kN)	
	Locomotive	**Freight Rolling Stock**
60kg **53kg** **50kg** **41kg** **107lb** **94lb**	295	230
100 lb **90 lb** **80lb**	200	200
60lb	130	130

Table 3 – P2 force limits for various rail sizes

C3-9 Sleeper capacity

Sleeper capacity shall be determined in accordance with CRN CP 231 Timber Sleepers and Bearers, CRN CP 233 Concrete Sleepers or CRN CP 233 Steel Sleepers, as applicable.

C3-10 Ballast contact pressure

It is important to understand the loading that is being transmitted from the sleepers to the ballast and underlying formation. Overloading of the sub-grade due to an inaccurate assessment of the loading or providing insufficient ballast depth for the bearing capacity of the sub-grade material, will lead to a rapid deterioration of the track geometry. In other words, the track quality and subsequent impacts and resulting degradation of all parts that comprise the track structure will be far greater than desired or economically sustainable.

The average contact pressure P_a a between the sleeper and the ballast is critical in the calculation of sleeper bending stresses and in assuring that the ballast structure is not over stressed. The calculation uses the assumption that the contact pressure is distributed uniformly across the effective sleeper length or bearing area.

i.e. $P_a = \frac{K y_{max}}{bl}$ (MPa) *(14)*

where K = *stiffness per sleeper (MPa) as per section C3-4*

b = *breadth of sleeper (mm)*

l = *effective length of sleeper under one rail (mm)*

$= (L - g)$

Where L = *the total sleeper length (mm)*

g = *distance between rail centres at the head of the rail (mm)*

The allowable average contact pressure between the sleeper and the ballast, P_a, should not exceed 350 kPa for manually tamped track, and 475 kPa for machine tamped track with high quality abrasion-resistant ballast.

C3-11 Subgrade pressure

The primary function of the ballast layer is to provide a layer that is sufficiently thick to reduce the contact pressure to an extent that is able to be accommodated by the sub-grade.

The average subgrade bearing pressure, σ_a, between the ballast and the subgrade uses the assumption that the pressure applied between the sleeper and the ballast, P_a, is distributed evenly over the subgrade.

i.e. $\sigma_a = \frac{P_a bl}{(C_1Z_1+C_2Z_2+b)(C_1Z_1+C_2Z_2+l)}$ (MPa) *(15)*

where b = *breadth of sleeper (mm)*

l = *effective length of sleeper under one rail (mm)*

C_1 = as per C3-4

C_2 = as per C3-4

Z_1, Z_2 = as per C3-4

θ_1, θ_2 = as per C3-4

Suggested safe average bearing pressures for sub-grades are typically those detailed in Table 4. However, detailed assessment of subgrade materials and suitability should be confirmed by an Authorised Geotechnical Engineer.

Soil description	Suggested safe bearing pressure (kPa)
Alluvial soil, non-compacted ground	70 - 105
Soft clay, firm sand, sandy clay	110 - 140
Dry clay, firm sand, sandy clay	145 - 210
Dry gravel soils	215 - 275
Compacted soils	280

Table 4 - Suggested safe bearing pressures