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Reliability Assessment of Railway Prestressed Concrete Sleepers

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Abstract
This paper carries out the assessment of reliability indices of railway prestressed concrete sleepers designed in accordance with Australian Standard: AS1085.19. The current design approach of the prestressed concrete sleeper relies on the permissible stresses over cross-sectional area. Loading condition acting on railway sleepers is considered from axle burden and dynamic amplification factor. On the basis of Australian design of railway prestressed concrete sleepers, only service limit states are considered; however, the design challenge is to provide adequate resistance of certain cross sections to both positive and negative bending moments. In this paper, the service limit states functions are formulated taking into account the permissible compressive and tensile stresses at both initial and final stages, and applied positive and negative bending moments at railseat and middle sections. Random variables in the reliability analysis include railway track design parameters, axle load, material and geometrical properties, prestressing force and its losses, and model uncertainties regarded to the structural resistance and load effects. Statistical properties of related parameters are adopted from previous studies. Two analysis methods are used: first-order moment reliability method (FORM) and second-order moment reliability method (SORM). Sensitivity analyses of the reliability indices for flexural capacity according to the requirements of the limit states functions are also investigated, in order to evaluate the major influences of dynamic load factors, strengths of materials, track parameters, and model uncertainties.

Reliability assessment of railway prestressed concrete sleepers

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1. Introduction

Railway tracks are built to transport either passengers or merchandises across areas. The track structures are anticipated to guide and facilitate the safe, cost-effective, and smooth rides of any operation. Figure 1 shows the main components constituting typical railway tracks. Its components can be subdivided into the two main groups: superstructure and substructure. The most obvious components of the track such as the rails, rail pads, concrete sleepers, and fastening systems form a group that is referred to as the superstructure. The substructure is associated with a geotechnical system consisting of ballast, sub-ballast and subgrade (formation). Both superstructure and substructure are equally important in ensuring the safety and comfort of passengers and the quality ride of the passenger and freight trains. Note that in Australia, UK, and Europe, the common nomenclature for the structural element, which is a major component of ballasted railway tracks used to distribute the axle load on tracks from rails to foundation system is referred to 'railway sleeper', while the term 'railroad tie' is often called in the US and Canada (Esveld, 2001). This paper will adopt the former term to denote this component thereafter.

Railway sleepers are the cross-tie beams resting on ballast and support. Back to the past, wooden sleepers had been used because the timber could be easily found in the local area as the construction materials. Then, due to the higher durability and longer service life of concrete and steel materials, prestressed concrete (PC) sleepers and to a limited extent steel sleepers have been employed worldwide in modern railway tracks. Their main functions are to: (1) uniformly transfer and distribute loads from the rail foot to underlying ballast bed; (2) sustain and retain the rails at the proper gauge by keeping anchorage for the rail fastening system; (3) preserve rail inclination; and (4) provide support for rail by restraining longitudinal, lateral and vertical rail movements (Remennikov and Kaewunruen, 2007). Defined as concrete with a specified compressive strength greater than 50MPa, high strength concrete (HSC) is mostly used in Australian PC sleepers to facilitate and optimize the challenging design of their continuum sections (Standards Australia, 2003).

Current Australian and international design standards of PC sleepers (e.g. AREMA-US) are based on the permissible stress concept where various limited values or reduction factors are used in material strengths and load effects (AREMA, 2006; Leong, 2007). Recent findings among track engineers within Australian railway community show that railway tracks, especially railway PC sleepers, have untapped strength that could be the potential and economic advantages for track owners. Unfortunately, the allowable stress principle does not consider the ultimate strength of materials, probabilities of actual loads, and risks associated with failure, all of which could lead to the conclusion of cost-ineffective and over design of current PC sleepers. An effort to ascertain the actual reserved capacity has consequently initiated under a collaborative research project in the Australian Cooperative Research Centre for Railway Engineering and Technologies (Rail-CRC), including University of Wollongong (UoW), Queensland University of Technology (QUT), Queensland Rails, and RailCorp New South Wales.

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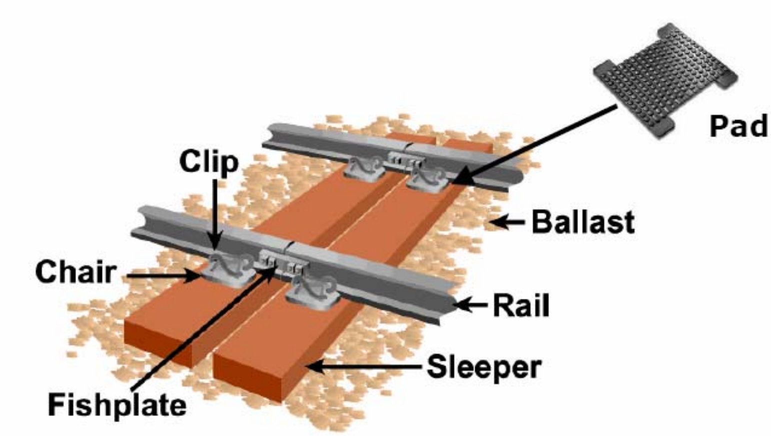

Figure 1 Typical rail track

This paper reports the assessment of reliability indices of railway prestressed concrete sleepers designed in accordance with current Australian Standard: AS1085.14-2003. Although the standard is presently under revision, the permissible stress, wheel load formula, and empirical method still remain almost the same (Standards Australia, 2006). The current design approach of the prestressed concrete sleeper controls the allowable stresses over cross-sectional area. Loading condition acting on railway sleepers is considered from axle burden and dynamic amplification factor. On the basis of Australian standard design of railway prestressed concrete sleepers, only service limit states are considered; however, the design challenge is to provide adequate resistance of certain cross sections to both positive and negative bending moments. In this paper, the service limit states functions are formulated taking into account the permissible compressive and tensile stresses at both initial and final stages, and applied positive and negative bending moments at railseat and middle sections. Random variables in the reliability analysis include railway track design parameters, axle load, material and geometrical properties, prestressing force and its losses, and model uncertainties regarded to the structural resistance and load effects. Statistical properties of related parameters are adopted from previous studies. Two analysis methods are used: first-order moment reliability method (FORM) and second-order moment reliability method (SORM). Sensitivity analyses of the reliability indices for flexural capacity according to the requirements of the limit states functions are also investigated, in order to evaluate the major influences of dynamic load factors, strengths of materials, track parameters, and model uncertainties.

2. Performance Levels

Lu and Gu (2004) described the context of performance-based design, which consists of five performance levels: fully operational, operational, life safety, near collapse, and collapse. In relation to Australian Standard AS1085.14-2003, the fully operational and operational stress level is the indicator for the sleeper performance-based design. Adopted for this study, the 2700mm long Austrak broad gauge sleeper was originally designed for both metropolitan and country tracks with the following parameters:

Track gauge	1600 mm
Rail size	53/60 kg
Maximum axle load	25 tonne
Maximum train speed	115 kph
Sleeper spacing	685 mm
Design rail seat load	187 kN

This sleeper was designed according to AS 1085.14 to satisfy permissible stresses at transfer (operational performance level) and at service (fully operational performance level). The sleeper design can be assessed using the reliability-based approach to calculate the safety index β. The limit state function $g(\mathbf{X})$ (see equation (1)) with respect to permissible stress criteria can be formulated as follows:

$$g(\mathbf{X}) = \textit{permissible stress} - \textit{fibre stress} \qquad (1)$$

The rail seat section is designed such that the extreme top and bottom fibres satisfy stress constraints as prescribed by AS 1085.14:

Concrete:
At transfer: f'_{cp} = 30 MPa; f_{ci} = 0.5 f'_{cp} = 15 MPa; f_{ti} = 0.25$\sqrt{f'_{cp}}$ = 1.37 MPa
At final: f'_c = 55 MPa; f_c = 0.45 f'_c = 24.8 MPa; f_t = 0.4$\sqrt{f'_c}$ = 2.97 MPa

Prestressing steel:
At transfer: f_p = 1700 MPa; $f_{pe@t}$ = 0.7 f_p = 1190 MPa
At final: f_p = 1700 MPa; $f_{pe@f}$ = 0.8 f_p = 1360 MPa

In general, the stresses at the top and bottom fibres (σ_t and σ_b, respectively) are

$$\sigma_t = -\frac{P}{A_g} \pm \frac{P \cdot e \cdot y_t}{I_g} \mp \frac{M \cdot y_t}{I_g} \qquad (2)$$

$$\sigma_b = -\frac{P}{A_g} \mp \frac{P \cdot e \cdot y_b}{I_g} \mp \frac{M \cdot y_b}{I_g} \qquad (3)$$

where P is the prestressing force, e is the effective eccentricity, M is the bending moment at the rail seat, A_g is the gross sectional area, I_g is the gross moment of inertia of the cross section, y_t is the distance between top fibre and neutral axis of the cross section, and y_b is the distance between bottom fibre and neutral axis of the cross section.

The current design procedure in AS1085.14-2001 (calculated using the QR PSC Design spreadsheet) provides the designed railseat section as shown in Figure 2 with fibre stresses at each stage. The design data is adopted from QR drawings. The sleeper is designed for the axle load of 25 tonne, sleeper spacing of 685mm, and the dynamic amplification factor (j) of 2.5. The length of sleeper L is 2.695m and the centre-centre gauge g is 1.680m.

The railseat load, R can be read: $R = j.Q\ (DF)/100$ where j is the design load factor (2.5), Q is static wheel load (125 kN), and DF is the axle load distribution factor (55% for 600mm spacing). For standard and broad gauge sleepers, at railseat, the positive moment $M_R^+ = R(L\text{-}g)/8$ while the negative moment $M_R^- = \max\{0.67\,M_R^+,\ 14\text{MPa}\}$. The wheel load is 125 kN and the designed railseat load is equal to 172 kN. Table 1 presents the sectional stresses of the Austrak broad gauge sleeper at the final stage. It should be noted that the stresses σ_t and σ_b are calculated using equations (2) and (3).

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Table 1 Design results for Austrak broad gauge sleeper using the QR PSC Design Spreadsheet

Moment	Value of Moment, kNm	Location	Total Stress, MPa	Allowable Stress, MPa	Performance Criteria
MR+	21.8	Top fibre	19.61	24.75	functional
		Bottom fibre	-1.71	-2.97	functional
MR-	14.6	Top fibre	-2.09	-2.97	functional
		Bottom fibre	18.97	24.75	functional

3. Basic Random Variables

The reliability model for each performance criteria considered contains a specified group of basic variables. The group represents the physical quantities characterizing actions and environmental influences, material and ballast properties, and imperfections and geometrical quantities. For each variable, if the uncertainty becomes important, it should be represented as a random variable, which is described by the probability distribution. The primary basic variables are those whose values are of primary importance for the design resistance results prescribed in AS5400-2005 (Standards Australia, 2005). In terms of the standard design of prestressed concrete sleepers based on AS1085.14, the strengths of concrete and wires, ballast properties or track stiffness, prestressing force in tendons, as well as action forces (wheel load & impact force) are primary basic variables (Kaewunruen and Remennikov, 2006). With regard to fatigue limit state, crack growth, load cycles/histories, and fatigue resistance are the primary basic variables.

The non-primary basic variables of railway prestressed concrete sleepers include the moduli of elasticity of concrete and wires, rail gauge length, sleeper geometry, sleeper spacing, vehicle profiles and characteristics, vehicle speeds, wheel/rail imperfections, type of rail pads and their properties, fastening systems, type of rails, subgrade condition, pressure distribution underneath a sleeper, track importance levels, maintenance levels (track & vehicle), and even the vehicle driver behavior (Murray and Leong, 2005; 2006; Leong, 2007). In addition, the non-primary basic variables for fatigue limit state are design working life, initial and critical crack sizes, uncertainties in materials and prestressing force levels, design decompression moments, loading paths, and inspected intervals and probability of crack detection.

In a particular concern of this study, the random variables associated with the uncertainties of basic resistance variables are concrete strength variations, losses in prestressing wires, changes in pressure distribution underneath a sleeper, different sleeper geometries, different track stiffness, various rail pads used, visual detection of initial crack size, and unpredictable major cracks and mode of failures. The random variables in terms of basic action variables include a variety of impact forces, different vehicle speeds, a variety of imperfections: sizes and types, return periods, and different static axle forces (passenger, coal, etc.). However, the random variables in the current reliability analysis are limited. Avaliable data include railway track design parameters, axle load, material and geometrical properties, prestressing force and its losses, and model uncertainties regarded to the structural resistance and load effects. Statistical properties of related parameters are adopted from previous studies as given in Table 2. It is assumed that these data produce a governing limit state over the service life of the sleepers. The time-dependent properties could also be found elsewhere (Darmawan and Stewart, 2007).

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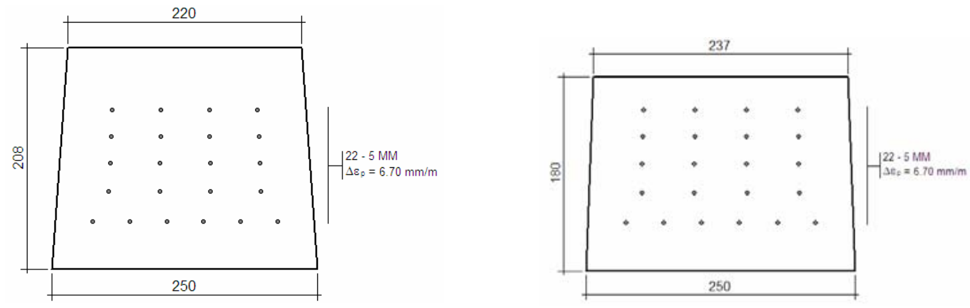

a) rail seat *b) mid span*

Figure 2 Rail seat and mid span cross sections of a PC sleeper

4. Limit State Functions and Reliability Analysis

Limit state functions for bending strength can be defined from Equations (1), (2), and (3) as

At the top fibre: $g_t(X) = \alpha_1 \bar{\sigma}_t - \alpha_2 \sigma_t$

At the bottom fibre: $g_b(X) = \alpha_1 \bar{\sigma}_b - \alpha_2 \sigma_b$

where $\bar{\sigma}_t$ and $\bar{\sigma}_b$ are the permissible stresses at the top and bottom fibres, respectively, at any stage (transfer/initial and final stages - f_{ci} , f_{ti} , f_c , f_t , $f_{pe@t}$, and $f_{pe@f}$), and α_1 and α_2 are the model variation coefficients with respect to the resistance and the action, respectively (Melchers, 1987). The rail seat and mid span sections are illustrated in Figure 2. Using the structural reliability analysis program COMREL (RCP GmbH, 2004), the reliability indices can be calculated for railseat and mid-span sections as provided in Tables 3 and 4, respectively. It should be noted that these safety indices are based on the design positive moment at railseat and the design negative moment at mid span for a specific sleeper only. Sensitivity of load and strength is illustrated in Figures 3 and 4. More information is required for further comprehensive study in the future.

The reliability index β can be obtained by using the stress limit functions:
β_{ti} = reliability index with respect to top fibre stress at initial stage;
β_{bi} = reliability index with respect to bottom fibre stress at initial stage;
β_{tf} = reliability index with respect to top fibre stress at final stage;
β_{bf} = reliability index with respect to bottom fibre stress at final stage;
β_{wi} = reliability index with respect to wire stress at initial stage;
β_{wf} = reliability index with respect to wire stress at final stage; and
β_{cf} = reliability index with respect to cross-sectional stress at final stage.
Where β = min $\{\beta_{ti}, \beta_{bi}, \beta_{tf}, \beta_{bf}, \beta_{wi}, \beta_{wf}, \beta_{cf}\}$

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Table 2 Statistical model of the selected PC sleeper.

Basic variables	**Symbol**	**Distribution type**	**Units**	**Mean value**	**Standard deviation**	**Coefficient of variation**
Loads						
Static wheel load	Qst	Log-normal	kN	125	31.25	0.25
Dynamic load factor	*j*	Log-normal		2.5	0.625	0.25
Axle load distribution factor	*DF*	Constant		0.55		
Resistances						
Permissible tension at transfer (f'_{cp} = 30 MPa)	f'_{ti}	Normal	MPa	1.37	0.2466	0.18
Permissible compression at transfer (f'_{cp} = 30 MPa)	f'_{ci}	Normal	MPa	15.0	2.25	0.15
Permissible tension at service (f'_c= 55 MPa)	f_t	Normal	MPa	2.97	0.5346	0.18
Permissible compression at service (f'_c= 55 MPa)	f_c	Normal	MPa	24.8	3.72	0.15
Concrete compressive strength	f'_c	Normal	MPa	66.0	9.9	0.15
Prestressing steel yield stress	f_p	Normal	MPa	1768	44.2	0.025
Area of prestressing steel	A_{ps}	Normal	m^2	432	5.4	0.0125
Prestressing nominal force	*P*	Normal	kN	550.0	33	0.06
Sleeper dimensions						
Length	*L*	Constant	m	2.7		
Depth (rail seat)	*h*	Constant	m	0.208		
Track parameters						
Track gauge	*g*	Constant	m	1.6		
Sleeper spacing	*S*	Constant	m	0.685		
Track stiffness	k_T	Constant	MN/m^2	100		
Railpad stiffness	k_P	Constant	MN/m^2	400		
Model uncertainties						
Uncertainty of resistance	Θ_R	Normal		0.99		0.06
Uncertainty of load effect	Θ_S	Normal		1.0		0.2

*Distribution patterns and coefficients of variation adopted from Al-Harthy (1992)

Table 3 Reliability indices of railseat section of AUS BG sleepers under design positive moment

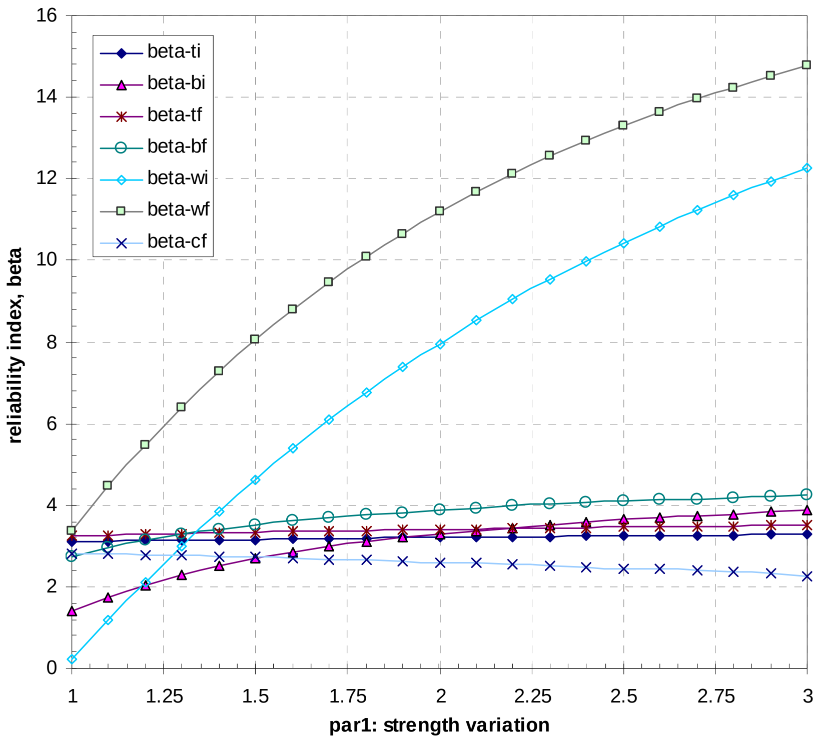
Reliability Index	**FORM[a]**	**SORM[b]**
β_{ti} (top fibre stress at initial stage)	3.101	3.105
β_{bi} (bottom fibre stress at initial stage)	1.524	1.403
β_{tf} (top fibre stress at final stage)	3.242	3.246
β_{bf} (bottom fibre stress at final stage)	2.750	2.730
β_{wi} (wire stress at initial stage)	0.221	0.221
β_{wf} (wire stress at final stage)	3.379	3.379
β_{cf} (cross-sectional stress at final stage)	2.825	2.818

[a]first-order reliability method; [b]second-order reliability method

Table 4 Reliability indices of middle section of AUS BG sleepers under design negative moment

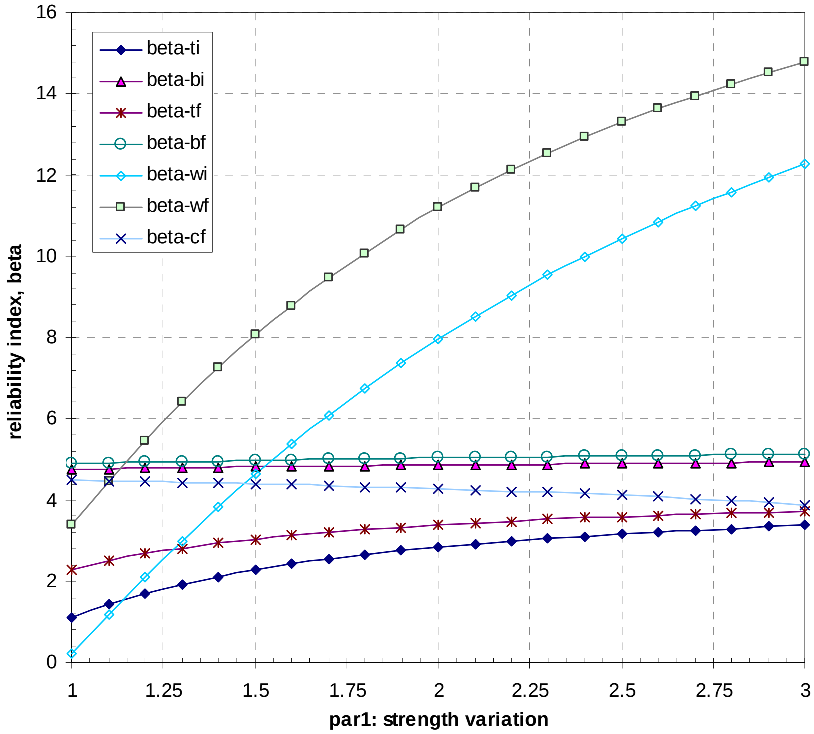
Reliability Index	**FORM[a]**	**SORM[b]**
β_{ti} (top fibre stress at initial stage)	1.122	1.104
β_{bi} (bottom fibre stress at initial stage)	4.760	4.763
β_{tf} (top fibre stress at final stage)	2.309	2.302
β_{bf} (bottom fibre stress at final stage)	4.886	4.892
β_{wi} (wire stress at initial stage)*	0.221	0.221
β_{wf} (wire stress at final stage)*	3.379	3.379
β_{cf} (cross-sectional stress at final stage)	4.501	4.494

[a]first-order reliability method; [b]second-order reliability method



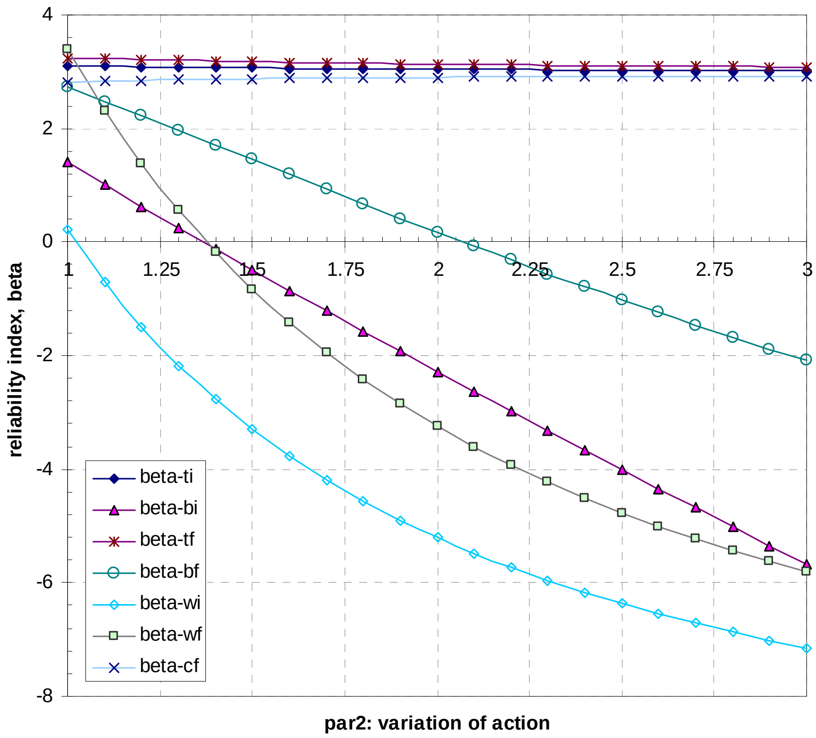
a) at rail seat

Figure 3 Effect of strength variation on reliability indices of PC sleepers



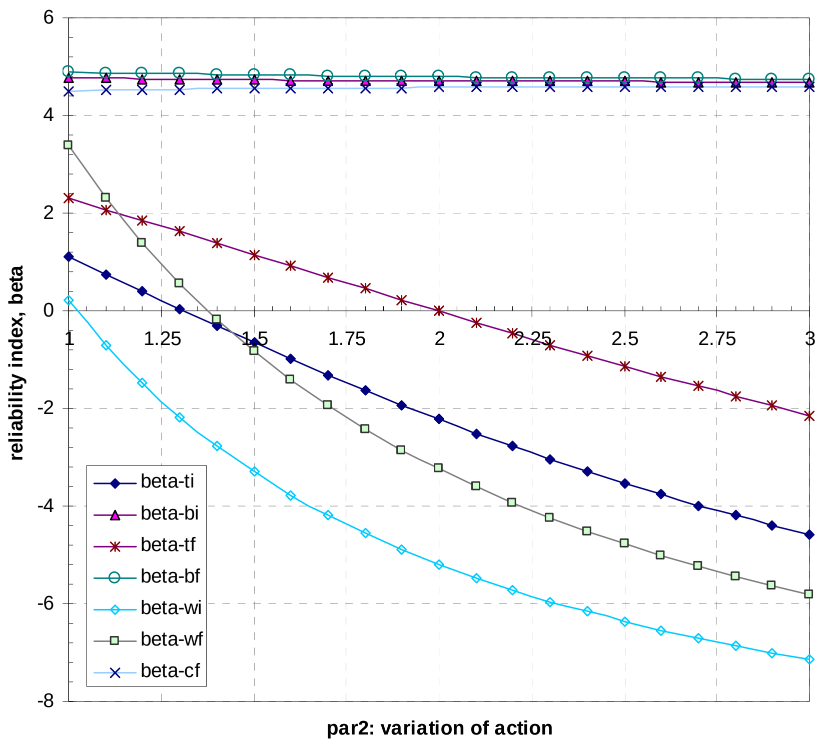
b) at mid spad

Figure 4 Effect of strength variation on reliability indices of PC sleepers



a) at rail seat

Figure 5 Effect of load action variation on reliability indices of PC sleepers



b) at mid spad

Figure 6 Effect of load action variation on reliability indices of PC sleepers

5. Conclusion

This paper investigated the reliability indices of a railway prestressed concrete sleeper designed and manufactured in Australia. The reliability assessment to attain the target reliability or safety indices of the PC sleeper was shown as well as the sensitivity analysis to study the effect of load action and strength variations on the target reliability indices. The target reliability will be used as the benchmark safety index for the reliability based approach for conversion of the permissible stress principle to limit state design concept for prestressed concrete sleepers. It is found that the shape of sleepers is optimized so that the sleepers tend to provide low to moderate safety indices at service performance level.

6. Acknowledgement

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