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Time-dependent topology of railway prestressed concrete sleepers

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Abstract. The railway sleepers are very important component of railway track structure. The sleepers can be manufactured by using timber, concrete, steel or other engineered materials. Nowadays, prestressed concrete has become most commonly used type of sleepers. Prestressed concrete sleepers have longer life-cycle and lower maintenance cost than reinforced concrete sleepers. They are expected to withstand high dynamic loads and harsh environments. However, durability and long-term performance of prestressed concrete sleepers are largely dependent on creep and shrinkage responses. This study investigates the long-term behaviours of prestressed concrete sleepers and proposes the shortening and deflection diagrams. Comparison between design codes of Eurocode 2 and AS3600-2009 provides the insight into the time-dependent performance of prestressed concrete sleepers. The outcome of this paper will improve the rail maintenance and inspection criteria in order to establish appropriate sensible remote track condition monitor network in practice.

1. Introduction

The railway transportation system has been developed for decades, which is known as safest and most economic transportation system. The railway sleepers (or called 'railroad ties' in North America) are the main component of railway track structure. The use of materials in sleepers can be timber, concrete, steel, or other engineered materials [1]. The five main functions of sleepers are:

1. Support the rail and maintain the track gauge.
2. Transfer and distribute loads from rail to substructure
3. Withstand vertical and longitudinal movement of rails

Prestressed concrete sleepers are very popular used in railway system. They provide stability for heavy haul and high speed train [2]. Track components consist of superstructure and substructure. Superstructure includes rails, sleepers, fastening systems, sleeper pad, and ballast bed. Substructure includes subballast (or called 'capping layer'), formation and foundation. A number of previous papers have investigated durability and long-term behaviours of prestressed concrete in long span bridges, stadiums, nuclear power plants and silos. They have proposed various material models to predict creep and shrinkage but those were mostly based on general reinforced concrete concept. Due to high initial elastic shortening in prestressed concrete, the creep and shrinkage effects should be critically re-

evaluated in flexural members [3]. During the time interval, creep and shrinkage strains develop in the prestressed concrete sleepers and relaxation occurs in the tendons. The gradual change of concrete strain with time causes changes of stress in the reinforcement. The time-dependent deformation of a prestressed concrete sleeper is great affected by the quantity and location of the tendons. The tendons provide restraint to the time-dependent shortening of concrete caused by creep and shrinkage. As the concrete creep and shrinkage, the tendons are gradually compressed. An equal and opposite tensile force is applied to the concrete at level of the tendons, thereby reducing the compression caused by prestress. It is the tensile forces that are applied gradually at each level of tendons that result in significant time-dependent changes in curvature and deflection [4]. Long-term deflections due to creep and shrinkage are affected by many variables, including load intensity, mix proportions, member size, age at first loading, curing conditions, total quantity of compressive and tensile reinforcing steel, level of prestress, relative humidity and temperature. The change in curvature during any time of sustained load may be determined. The long-term deflection can be calculated when the final curvature has been determined [4].

This study will investigate methods to evaluate shortening and approximate deflection due to creep and shrinkage in railway prestressed concrete sleepers. Comparison between design codes of EUROCODE2 and AS2009-3600 will provide the insight into the durability of concrete sleepers. The outcome of the project will help rail track engineers to better design and maintain railway infrastructure, improving asset management efficacy.

2. Estimating long-term performance concept

2.1. Creep Prediction
The concrete under load that strain increases with time is due to creep. Therefore, creep can be defined as the increase in strain under the sustained stress and it can be several times as large as the initial strain [5]. If the load is removed, the strain decreases immediately due to elastic recovery and a gradual incomplete recovery due to creep. This behaviour is shown in Figure 1.
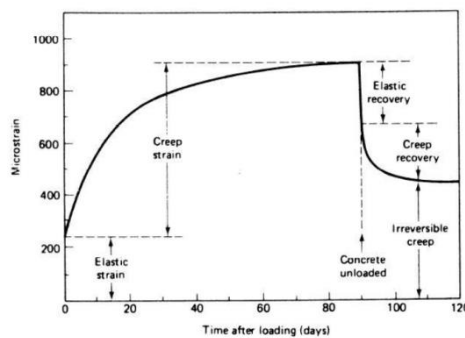
Figure 1: Time dependent creep

When creep is taken into account, its design effects are always evaluated under quasi-permanent combination of actions irrespective of the design situation considered, i.e. persistent, transient or accidental.

2.1.1. Eurocode 2
The total creep strain ε_{cc} (∞, t_0) of concrete due to the constant compressive stress of σ_c applied at the concrete age of t_0 is given by :

$$\varepsilon_{cc}(\infty, t_0) = \varphi(\infty, t_0) \times \frac{\sigma_c}{E_c}$$

Where $(\infty_{,0})$ is the final creep coefficient, which the value of σ_c does not exceed $0.45f_{ck}(t_0)$. Ec is the tangent modulus.

$$\varphi(\infty, t_0) = \varphi_{RH} \times \frac{16.8}{\sqrt{f_{cm}}} \times \frac{1}{(0.1 + t_0^{0.20})}$$

$$\varphi_{RH} = 1 + \frac{1 - 0.01 \times RH}{0.1 + h_0^{0.333}}, \quad f_{cm} \leq 35MPa$$

$$\varphi_{RH} = (1 + \frac{1 - 0.01 \times RH}{0.1 + h_0^{0.333}} \alpha_1)\alpha_2, \quad f_{cm} > 35MPa$$

$$\alpha_1 = (\frac{35}{f_{cm}})^{0.7}, \quad \alpha_1 = (\frac{35}{f_{cm}})^{0.2} \quad f_{cm} = f_{ck} + 8MPa$$

$$t_0 = t_{0,T}(\frac{9}{2 + t_{0,T}^{1.2}} + 1)^\alpha \geq 0.5,$$

$$\alpha = \{-1(S), 0(N), 1(R)\}$$

Where: RH = relative humidity in %, $h_0 = 2Ac/u$ mm, Ac = cross sectional area, u = perimeter of the member in contact with the atmosphere, S, R and N refer to different classes of cement.

The final creep will be larger and final creep coefficient $(\infty_{,0})$ is multiplied by a factor k_σ if the compressive stress applied at the age of t_0 exceeds $0.45f_{ck}(t0)$ as can happen during prestress transfer process. The Table 1 shows the value of k_σ. The factor k_σ is given by:

$$k_\sigma = \exp[1.5 \times \left(\frac{\sigma_c}{f_{ck}(t_0)} - 0.45\right)]$$

Table 1 Value of k_σ in terms of f$_{ck}$

$\dfrac{\sigma_c}{f_{ck}(t_0)}$	k_σ
0.5	1.078
0.6	1.252
0.7	1.455
0.8	1.691
0.9	1.964
1.0	2.282

The creep coefficient at any age t can be given by empirical solutions [6, 10-12].

2.1.2. Australian Standard 3600-2009
The creep coefficient at any time φ_{cc} can be determined by:

$$\varphi_{cc} = k_2 k_3 k_4 k_5 \varphi_{cc.b}$$

Where k_2 is the development of creep with time; k_3 is the factor which depends on the age at first loading τ (in days); k_4 is the factor which accounts for the environment; and k_5 is the factor which accounts for the reduced influence of both relative and humidity and specimen size.

For the development of creep with time k_2 can be calculated by:

$$k_2 = \frac{\alpha_2(t-\tau)^{0.8}}{(t-\tau)^{0.8} + 0.15t_h}$$

$$\alpha_2 = 1.0 + 1.12e^{-0.008t_h}$$

$$t_h = 2A_g/u_e$$

Where t is any time in days; t_h is the hypothetical thickness; A_g is the cross-sectional area of the member; u_e is the portion of the section perimeter exposed to the atmosphere plus half the total perimeter of any voids contained within the section.

For factor k_3 which depends on the age at first loading τ can be shown as:

$$k_3 = \frac{2.7}{1+\log(\tau)} \quad (for\ \tau > 1\ day)$$

For the factor k_4 which accounts for the environment:

$$
\begin{aligned}
k_4 \quad &= 0.7\ for\ an\ arid\ environment \\
&= 0.65\ for\ an\ interior\ enviroment \\
&= 0.60\ for\ a\ temperate\ enviroment \\
&= 0.5\ for\ a\ tropical\ or\ near{-}coastal\ enviroment
\end{aligned}
$$

For the factor k_5 is given by:

$$
\begin{aligned}
k_5 \quad &= 1.0 \quad when\ fc'{\leq}50MPa \\
k_5 \quad &= (2.0{-}\alpha3){-}0.02(1.0{-}\alpha3)f'c\ when \quad 50MPa \leq f'c \leq 100MPa
\end{aligned}
$$

Where $\alpha3=0.7/(k_4\alpha_2)$. The basic creep coefficient $\varphi cc.b$ is shown table below:

f_c' (MPa)	20	25	32	40	50	65	80	100
$\varphi_{cc.b}$	5.2	4.2	3.4	2.8	2.4	2.0	1.7	1.5

2.2. Shrinkage Prediction
Both of creep and shrinkage are influenced by the same parameters. Shrinkage is not an entirely reversible process like creep and it can be also influenced by relative humidity, surface exposed to atmosphere, compressive strength of concrete and types of cement. Shrinkage can be divided by two parts [5]:

(1) Plastic shrinkage: it happens in few hours after concrete placed.

(2) Dry shrinkage: evaporation leads to loss of water.

2.2.1. Eurocode 2
The total shrinkage strain εcs can be given by:

$$\varepsilon_{cs} = \varepsilon_{ds} + \varepsilon_{as}$$

Where ε_{ds} is drying shrinkage strain; and ε_{as} is autogenous shrinkage strain.

2.2.2. Australian Standard 3600-2009
The total shrinkage strain ε_{cs} is shown below:

$$\varepsilon_{cs} = \varepsilon_{cse} + \varepsilon_{csd}$$

Where ε_{cse} is autogenous shrinkage strain; ε_{csd} is drying shrinkage strain.

The autogenous shrinkage εcse is given by:

$$\varepsilon_{cse} = \varepsilon'_{cse}(1.0 - \exp\{-0.1t\})$$

$$\varepsilon'_{cse} = (0.6f'_c - 1.0) \times 50 \times 10^{-6} \ (f'_c \ in \ MPa)$$

$$\varepsilon_{csd.b} = (1.0 - 0.008f'_c) \times \varepsilon'_{csd.b}$$

Where $\varepsilon'_{csd.b}$ depends on the quality of the local aggregates and may be taken as 800×10^{-6} for concrete supplied in Sydney and Brisbane, 900×10^{-6} in Melbourne and 1000×10^{-6} in elsewhere.

The drying shrinkage strain ε_{csd} after the beginning of drying $(t - \tau_d)$ can be estimated:

$$\varepsilon_{csd} = k_1 k_4 \varepsilon_{csd.b}$$

Where k_1 is the factor which describes the development of drying shrinkage with time; and k_4 is the factor which accounts for the environment [4-6].

2.3. Deflection and shortening
In prestressed concrete construction, a large proportion of the sustained external load is often balanced by the transverse force exerted by the tendons. Under this balanced load, the short-term deflection may be zero, but the long-term deflection is not zero. The restraint to creep and shrinkage offered by non-symmetrically placed reinforcement on a section can cause significant time-dependent curvature and, hence, significant deflection of the member. The mid-span deflection can be determined by:

$$v_C = \frac{L^2}{96}(k_A + 10k_C + k_B)$$

2.3.1. Creep-induced curvature
The creep-induced curvature $\kappa_{cc}(t)$ of a particular cross-section at any time t due to a sustained service load first applied at age τ_0 may be obtained from:

$$k_{cc}(t) = k_{sus,0}\frac{\phi_{cc}(t,\tau_0)}{\alpha}$$

Where $\kappa_{sus,0}$ is the instantaneous curvature due to the sustained service loads,

$\varphi_{cc}(t, \tau_0)$ is the creep coefficient at time t due to load first applied at age τ_0

α is a creep modification factor

2.3.2. Shrinkage-induced curvature

The shrinkage-induced curvature on a reinforced or prestressed concrete section is approximated by:

$$k_{cs}(t) = -[\frac{k_r \varepsilon_{cs}(t)}{D}]$$

Where κ_r depends on quantity and location of tendons

$\varepsilon_{cs}(t)$ is the shrinkage strain

D is overall depth of the section

3. Case study: long-term performance assessment of prestresssed concrete sleeper

The effects of shortening and approximate deflections for estimating creep, shrinkage strain will be evaluated. The fundamental engineering properties of prestressed concrete sleeper used for calculation are based on previous research by Remennikov et al. The results are generated for comparisons between Eurocode 2 (EC2) and Australian standard 3600-2009 (AS). Figure 2 shows the cross section at rail seat of the prestressed concrete sleepers. The parameters of prestressed concrete sleeper are shown below [7]:

(1) Sleeper length: 2700mm

(2) Track gauge: 1600mm
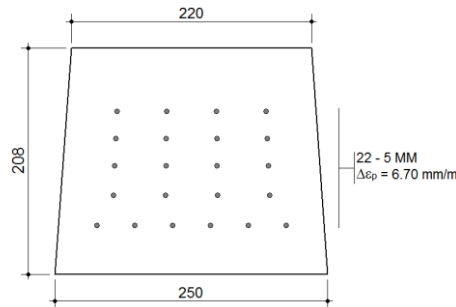
(3) Prestressing nominal force: 550kN

Figure 2: Cross section of railway sleepers

The case is estimated for 18250 days (50 years) in same conditions (uniform dimension of sleepers, 70% relative humidity, steam curing)

4. Shortening and Deflection Evaluations

4.1. Creep shortening

To investigate creep shortening, the 7 cases have been analysed using different characteristic strength (20MPa, 25MPa, 32MPa, 40MPa, 55MPa, 65MPa, 80MPa), which are plotted in Figure 3. The data of creep shortening are calculated by EC2 and AS codes respectively. All the cases are estimated from 1

day up to 18250 days (50 years) in the same conditions (uniform dimension of sleepers, 70% relative humidity, steam curing etc.).
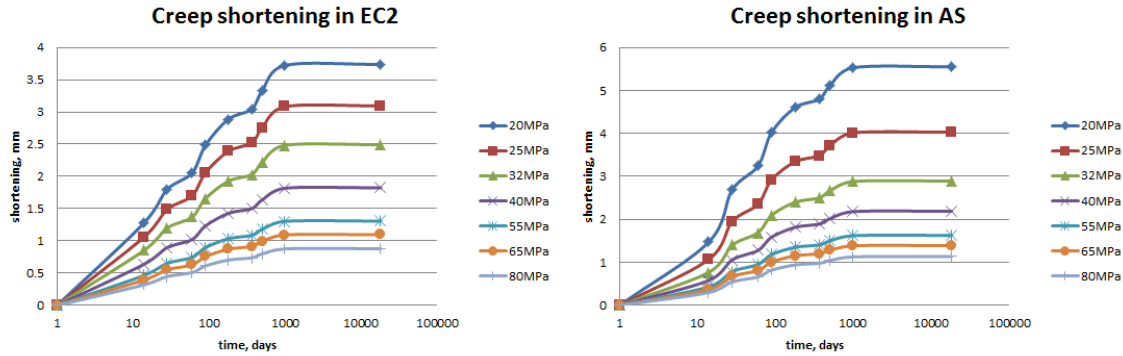

Figure 3 creep shortening

4.2. Shrinkage shortening

Figure 4 shows 7 cases of different strength of prestressed concrete sleepers on the shrinkage effect. The data of shrinkage shortening are calculated by EC2 and AS3600-2009 codes respectively.
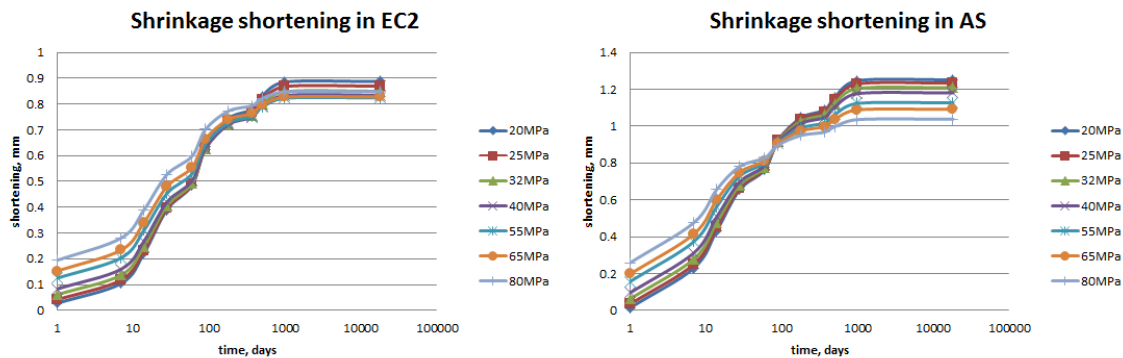

Figure 4 shrinkage shortening

Based on the sensitive analysis, we found that long-term performance in prestressed concrete sleeper depends on various factors. According to obtained data, the shortening and deflection depend on strain, which means large strain leads to more shortening and deflection in prestressed concrete sleeper. Previous research had stated that the higher strength of concrete has less loss of prestress and concrete strength less than 25MPa was not suitable for use in prestressed concrete sleepers [3]. Figure 5 and Figure 6 indicates total long-term shortening and approximate deflections (due to creep and shrinkage), which higher strength of concrete has less shortening and approximate deflection. However, in initial period, higher strength has more shortening than lower strength concrete due to autogenous shrinkage.
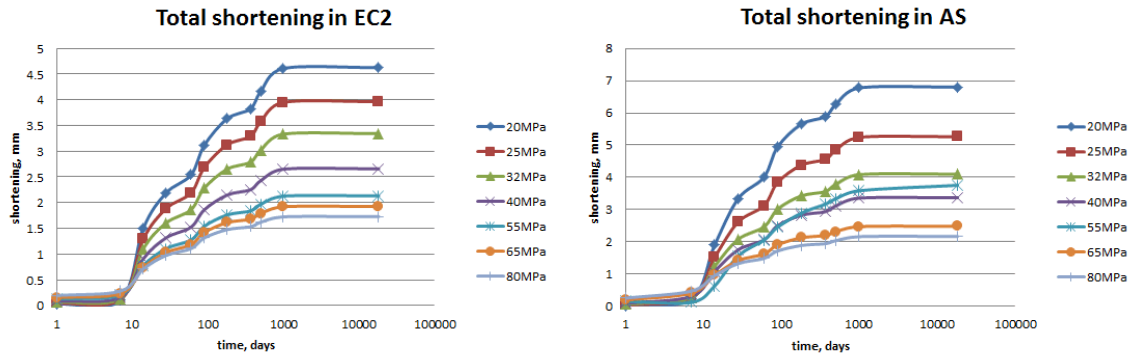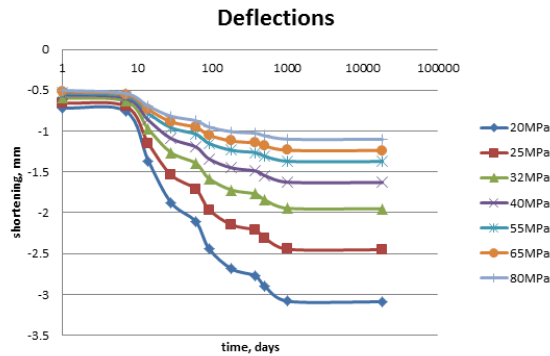
Figure 5 total long-term shortening

Figure 6 deflections

5. Conclusions

In real life, railway infrastructure experiences harsh environment and aggressive loading conditions from increased traffics and load demands, which means creep and shrinkage strains could have more significant influence for deformation of track components. When shortening and deflection occur in prestressed concrete sleepers, the track gauge could change with shortening and deflections. It is hazard that train derails because of track gauge change. Furthermore, there are many other factors to affect prestressed concrete sleepers shortening and deflections like relative humidity, curing conditions, age at first loading, temperature, abrasion etc. In this paper, Eurocode 2 and AS3600-2009 are used in predicting creep and shrinkage shortening and deflection. Comparison between design codes provides the insight into long-term performance of prestressed concrete sleepers. This paper presents shortening and deflections due to creep and shrinkage. It will improve the rail maintenance and inspection criteria in order to establish appropriate sensible remote track condition monitor network in practice.

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