Influence of vertical holes on creep and shrinkage of railway prestressed concrete sleepers

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Abstract. Railway prestressed concrete sleepers (or railroad ties) must successfully perform two critical duties: first, to carry wheel loads from the rails to the ground; and second, to secure rail gauge for dynamic safe movements of trains. The second duty is often fouled by inappropriate design of the time-dependent behaviors due to their creep, shrinkage and elastic shortening responses of the materials. In addition, the concrete sleepers are often modified on construction sites to fit in other systems such as cables, signalling gears, drainage pipes, etc. Accordingly, this study is the world first to investigate creep and shrinkage effects on the railway prestressed concrete sleepers with vertical holes. This paper will highlight constitutive models of concrete materials within the railway sleepers under different environmental conditions over time. It will present a comparative investigation using a variety of methods to evaluate shortening effects in railway prestressed concrete sleepers. The outcome of this study will improve material design, which is very critical to the durability of railway track components.

1. Introduction

The railway sleepers (or called ‘railroad ties’) are a main structural and safety-critical component of railway track structures. The sleepers can be manufactured using timber, concrete, steel or other engineered materials [1]. Concrete sleepers were initially installed on track for many decades ago and at present are being used in almost everywhere in the world. Their major role is to redistribute wheel loads from the rail feet to the supporting ballast bed. Railway track structures are often subjected to impact loading conditions owing to wheel/rail interactions with common defects in either a wheel or a rail [2-5]. Durability and long term behaviours of railway prestressed concrete sleepers depend largely on their creep and shrinkage response. Many investigators have proposed various material models to predict creep and shrinkage but those were mostly based on general reinforced concrete concept. The popular uses of prestressed concrete in long span bridges, stadiums, silos and confined nuclear power plants have led to a concern of practitioners whether those predictive models could be realistically applied to prestressed concrete. Due to high initial elastic shortening in prestressed concrete, the creep and shrinkage effects should be critically re-evaluated in flexural members. This study will investigate methods to evaluate creep and shrinkage effects in railway prestressed concrete sleepers. Comparison between design codes of EUROCODE2 and AS2009-3600 will provide the insight into 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 [6].

This research aims at providing a principle understanding of creep and shrinkage effects in railway prestressed concrete sleepers. It will review the design criteria of prestressed concrete in Eurocode 2 and Australian Standard 2009-3600 and evaluate creep and shrinkage effects in railway prestressed concrete [7]. Furthermore, the effects among design method above should be compared in order to develop existing codes.

2. Prediction for creep and shrinkage

2.1. Methodology

There are three approaches in order to meet the objectives of the research. The initial step is to review the codes to understand the principles of prestressed concrete design, calculation processes of creep, shrinkage strain, loss of prestress and deflection. Before the calculation, the difference between codes should be known. Then all the calculation will be carried out analytically.

Second step is to analyse obtained data. To investigate the creep and shrinkage effects, sensitivity analysis has been carried out. Comparative study among different codes of practice will be performed.

The final step is to establish the loss of prestress and to calculate shortening of prestressed concrete sleeper.

2.2. Creep Prediction

Neville, A. M (1981) stated 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 [8]. Creep is a considerable factor in concrete structure. According to Martin, L, creep occurs very slowly after immediate elastic strain has happened[9]. The factors influence creep coefficient following:

1. Original water content
2. Effective age at transfer
3. Effective section thickness
4. Ambient relative humidity
5. Ambient temperature

If the load is removed, the strain decreases immediately due to elastic recovery and a gradual incomplete recovery due to creep. This behavior is shown in Figure 1.

![Figure 1 Time dependent creep.](image-url)
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.

2.2.1. Eurocode 2

The total creep strain $\varepsilon_{cc}(\infty, t_0)$ of concrete due to the constant compressive stress of $\sigma_c$ applied at the concrete age of $t_0$ is given by:

$$\varepsilon_{cc}(\infty, t_0) = \varphi(\infty, t_0) \times \frac{\sigma_c}{E_c}$$  \hspace{1cm} (1)

Where $(\infty, t_0)$ is the final creep coefficient, which the value of $\sigma_c$ does not exceed $0.45f_{ck}(t_0)$. $E_c$ is the tangent modulus.

$$\varphi(\infty, t_0) = \varphi_{RH} \times \frac{168}{\sqrt{f_{cm}}} \times \frac{1}{(0.1 + \frac{t_0}{28})}$$  \hspace{1cm} (2)

$$\varphi_{RH} = 1 + \frac{1 - 0.01 \times RH}{0.1 + h_0^{0.33}}, \quad f_{cm} \leq 35\text{MPa}$$  \hspace{1cm} (3)

$$\varphi_{RH} = (1 + \frac{1 - 0.01 \times RH}{0.1 + h_0^{0.33}}) \alpha_1 \alpha_2, \quad f_{cm} > 35\text{MPa}$$  \hspace{1cm} (4)

$$\alpha_1 = \left(\frac{35}{f_{cm}}\right)^{0.7}, \quad \alpha_2 = \left(\frac{35}{f_{cm}}\right)^{0.2}, \quad f_{cm} = f_{ck} + 8\text{MPa}$$

$$t_0 = t_{0,T} \left(\frac{9}{2 + t_{0,T}} + 1\right)^{\alpha} \geq 0.5, \quad \alpha = \{-1(S), 0(N), 1(R)\}$$  \hspace{1cm} (5)

Where: RH = relative humidity in %, $h_0 = 2A_c/u \text{mm}$, $A_c$ = 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 $(\infty, t_0)$ is multiplied by a factor $k_\sigma$ if the compressive stress applied at the age of $t_0$ exceeds $0.45f_{ck}(t_0)$ as can happen during prestress transfer process. The Table 1 shows the value of $k_\sigma$. The factor $k_\sigma$ is given by:

$$k_\sigma = \exp[1.5 \times \left(\frac{\sigma_c}{f_{ck}(t_0)} - 0.45\right)]$$  \hspace{1cm} (6)

**Table 1. Value of $k_\sigma$ in terms of $f_{ck}$.**

| $\frac{\sigma_c}{f_{ck}(t_0)}$ | $k_\sigma$ |
|-----------------------------|---------|
| 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].
2.2.2. *Australian Standard 3600-2009*

The creep coefficient at any time $\varphi_{cc}$ can be determined by:

$$\varphi_{cc} = k_2k_3k_4k_5\varphi_{cc,b}$$ (7)

Where $k_2$ is the development of creep with time; $k_3$ is the factor which depends on the age at first loading $\tau$ (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:

$$k_2 = \frac{\alpha_2(t-\tau)^{0.8}}{(t-\tau)^{0.8}+0.15t_h}$$ (8)

$$\alpha_2 = 1.0 + 1.12e^{-0.008t_h}, \quad t_h = \frac{A_g}{u_e}$$

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 $\tau$ can be shown as:

$$k_3 = \frac{2.7}{1+\log(t)} \quad (\text{for } \tau > 1 \text{ day})$$ (9)

For the factor $k_4$ which accounts for the environment:

- $k_4 = 0.7$ for an arid environment
- $k_4 = 0.65$ for an interior environment
- $k_4 = 0.60$ for a temperate environment
- $k_4 = 0.5$ for a tropical or near-coastal environment

For the factor $k_5$ is given by:

- $k_5 = 1.0 \quad \text{when } f'c \leq 50MPa$
- $k_5 = (2.0-\alpha_3)-0.02(1.0-\alpha_3)f'c \quad \text{when } 50MPa \leq f'c \leq 100MPa$

Where $\alpha_3=0.7/(k_4\alpha_2)$. The basic creep coefficient $\varphi_{cc,b}$ is shown Table 2 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 |

2.3. *Shrinkage Prediction*

Bhatt, P (2011) stated that 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 [11]:

(1) Plastic shrinkage: it happens in few hours after concrete placed.
(2) Dry shrinkage: evaporation leads to loss of water.
2.3.1. Eurocode 2
The total shrinkage strain $\varepsilon_{cs}$ can be given by:

$$\varepsilon_{cs} = \varepsilon_{ds} + \varepsilon_{as}$$ \hspace{1cm} (10)

Where $\varepsilon_{ds}$ is drying shrinkage strain; and $\varepsilon_{as}$ is autogenous shrinkage strain.

2.3.2. Australian Standard 3600-2009
The total shrinkage strain $\varepsilon_{cs}$ is shown below:

$$\varepsilon_{cs} = \varepsilon_{cse} + \varepsilon_{csd}$$ \hspace{1cm} (11)

Where $\varepsilon_{cse}$ is autogenous shrinkage strain; $\varepsilon_{csd}$ is drying shrinkage strain.

The autogenous shrinkage $\varepsilon_{cse}$ is given by:

$$\varepsilon_{cse} = \varepsilon'_{cse}(1.0 - \exp(-0.1t))$$ \hspace{1cm} (12)

$$\varepsilon'_{cse} = (0.6f'_c - 1.0) \times 50 \times 10^{-6} \ (f'_c \ in \ MPa)$$ \hspace{1cm} (13)

$$\varepsilon_{csd,b} = (1.0 - 0.008f'_c) \times \varepsilon'_{csd,b}$$ \hspace{1cm} (14)

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

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

$$\varepsilon_{csd} = k_1k_4\varepsilon_{csd,b}$$ \hspace{1cm} (15)

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 [6, 10-12].

3. Material Properties
The effects of various proposed holes used 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. [2]. The parametric 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.

![Figure 2. Cross section of railway sleepers.](image-url)
4. Creep and Shrinkage Evaluations

4.1. Creep evaluations
To investigate relationship between hole size and creep, the 5 cases have been analysed using different characteristic strength (no hole, 20mm dia., 30mm dia., 40mm dia. and 50mm dia.), which are plotted in Figure 3. The data of creep coefficient are calculated by EC2 and AS codes respectively. All the cases are estimated from 1 day up to 36500 days (100 years) in the same conditions (uniform dimension of sleepers, 70% relative humidity, curing for 7 days and first loading at 14 days etc.).

![Figure 3. Hole-creep effect.](image)

4.2. Shrinkage evaluations
Figure 4 shows five cases of different size of holes on the shrinkage effect. The data of shrinkage stains are calculated by EC2 and AS3600-2009 codes respectively.

![Figure 4. Hole-shrinkage effect.](image)

Based on the sensitive analysis, we found that long-term performance in prestressed concrete sleeper largely depends on geometry. Both of creep and shrinkage are proportional to hole sizes. Furthermore, larger strains result in more loss of prestress in sleeper.

5. Conclusions
There are two main duties for railway prestressed concrete sleepers (or railroad ties) that must successfully perform: first, to carry wheel loads from the rails to the ground; and second, to secure rail gauge for dynamic safe movements of trains. In many cases, inappropriate design of the time-
dependent behaviours of railway concrete sleepers due to their creep, shrinkage and elastic shortening responses of the materials affect significantly the rail gauge control. In addition, the concrete sleepers are often modified on construction sites to fit in other systems such as cables, signalling gears, drainage pipes, etc. Accordingly, this study is the world first to investigate creep and shrinkage effects on the railway prestressed concrete sleepers with vertical holes. This paper highlights constitutive models of concrete materials within the railway sleepers under different environmental conditions over time. Comparison has been carried out among a variety of reputable methods to evaluate shortening effects in railway prestressed concrete sleepers. Based on the sensitivity analyses, we found that creep and shrinkage in railway sleeper depends largely on the cross-section. According to the obtained data, the both of creep and shrinkage stains depend on holes’ size, which means large diameter of hole could result in more stain in prestressed concrete sleeper. This insight will improve material design and structural restraints, which are very critical to the durability of railway track components.

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