Creep and shrinkage models for railway prestressed concrete sleepers: A review

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CREEP AND SHRINKAGE MODELS FOR RAILWAY PRESTRESSED CONCRETE SLEEPERS: A REVIEW

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ABSTRACT

Creep and shrinkage of railway prestressed concrete sleepers play vital role in serviceability performance required for safe and reliable operations of a railway line. The time-dependent effects depend largely on various environmental and loading condition factors. Many investigators in the past have proposed various material models to predict creep and shrinkage effects but those were mostly applied to general reinforced concrete members. In contrast, prestressed concrete design needs a suitable model for predicting the time dependent behaviour of prestressed concrete structures such as long span bridges, stadiums, silos and confined nuclear power plants, etc. This paper highlights the constitutive models, which have led to predictive models that could be realistically applied to prestressed concrete. This paper presents a critical review of creep and shrinkage effects on railway prestressed concrete sleepers. Three common design codes have been considered, including European Standard EUROCODE2, American Standard ACI and Australian Standard AS3600-2009. The study results show that EUROCODE2 and AS3600 are very coherent and consistent. The paper also highlights the construction and practical issues as a result of undesirable creep and shrinkage effects at different time frames.

Keywords: railway, prestressed concrete, sleepers, creep, shrinkage.

1. INTRODUCTION

Development of railway transportation system is dramatically and continuously around the world. Train is the safest transportation which the accidents are the minimum in comparison to other transportations. Railway transportation is also very economic because of its large capacity, especially for heavy haul transportation. Nowadays, high-speed train is developed rapidly which becomes the best choice for long distance traffic due to the fact that train travels at high speed over long distance. In the environmental aspect, railway transportation has less carbon emissions than airplanes and road vehicles.

Traditional ballasted railway structure consists of superstructure and substructure. The superstructure is made up of rails, fastening system, rail pads, and sleepers. The substructure consists of ballast, sub-ballast and formation. Railway sleepers are transverse beam located on ballast used to support the rail and maintain rail gauge. Railway sleepers can be traditionally manufactured by timber, concrete, and steel. Nowadays, some new engineered materials can also be used to produce railway sleepers like rubber crumb. The use of new materials has improved efficiency of recycling of waste material. Furthermore, they also optimize structural functions. There are 3 types of sleepers commonly in use: monoblock sleeper, twinblock sleeper, and railblock. Monoblock sleeper is the most commonly used in the conventional track. It's a one piece sleeper which may be manufactured from timber, concrete or steel. Twinblock sleeper consists of two concrete blocks tied together by a steel bar. Rail block is usually made of concrete or stone which supports a single rail (Taylor, H., 1993). Rail block is frequently used in the non-ballasted track.

Most of the sleepers are currently produced by prestressed concrete which is the most commonly used type of sleepers. They play a vital role in track performance, behaviours and safety. Today, many prestressed concrete sleepers do not meet the intended design life. This can be attributed to the use of the railway system increases significantly. Therefore, previous prestressed concrete sleepers were not designed for durability and time-dependent performance of today's high speed and heavy haul train traffic. A large number of prestressed concrete sleepers are in need of repair or complete replacement. This paper presents a critical review of creep and shrinkage effects on railway prestressed concrete sleepers. Three common design codes have been considered, including European Standard EUROCODE2, American Standard ACI and Australian Standard AS3600-2009.

2. CREEP AND SHRINKAGE PREDICTION

For prestressed concrete sleepers with 50 years design service life, the serviceability limit state becomes very important. The accurate prediction of creep and shrinkage of prestressed concrete sleepers becomes essential when considering the serviceability limit state. During the design of a sleeper, the engineer must estimate the long-term behaviour of the prestressed concrete sleepers. Because concrete is not a homogeneous material, the prediction of creep and shrinkage at the beginning of service life is very difficult. In addition, creep and shrinkage also continually change with time. Therefore, to accomplish an accurate estimation of long-term behaviour is very difficult and complex.

2.1. Creep

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. Creep is a considerable factor in concrete structure (Neville, A. M, 1981).

The deformation of concrete is different from other materials like steel. When a load is applied to steel, the deformation won't change with time if the load is constant. Concrete deforms as soon as the load applied like steel. This is known as elastic deformation. However, the displacement of concrete gradually increases with time when the load left in place. The displacement reaches a value as large as three to four times of immediate elastic deformation. The inelastic deformation with constant load is known as creep deformation. "Creep is defined as the increase of strain with time when the stress is held constant." As the rule, creep increases when water/cement ratio increases or cement content increases. On the other hand, creep decreases when aggregate content increases in concrete mixture (Bhatt, P., 2011).

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:

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

Where (∞,$_0$) is the final creep coefficient, which the value of σ_c does not exceed 0.45f_{ck} (t_0). E_c is the tangent modulus.

$$\varphi(\infty, t_0) = \varphi_{RH} \times \frac{16.8}{\sqrt{f_{cm}}} \times \frac{1}{(0.1 + t_0^{0.20})} \tag{2}$$

$$\varphi_{RH} = 1 + \frac{1 - 0.01 \times RH}{0.1 + h_0^{0.333}}, \quad f_{cm} \leq 35MPa \tag{3}$$

$$\varphi_{RH} = (1 + \frac{1 - 0.01 \times RH}{0.1 + h_0^{0.333}} \alpha_1)\alpha_2, \quad f_{cm} > 35MPa \tag{4}$$

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

$$t_0 = t_{0,T}(\frac{9}{2 + t_{0,T}^{1.2}} + 1)^{\alpha} \geq 0.5, \tag{5}$$

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

Where: RH = relative humidity in %, $h_0 = 2A_c/u$ 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.

2.1.2. ACI

According to ACI 209-92, the predicted parameter is creep coefficient $\varphi(t, t_0)$ and the equation is given by:

$$\varphi(t, t_0) = \frac{(t - t_0)^{\psi}}{d + (t - t_0)^{\psi}} \varphi_u \tag{6}$$

where $\varphi(t, t_0)$ is creep coefficient at any time *t* when a load applied at age t_0.

d (days) and ψ are considered constants for a given member shape and size that define the time-ratio part. ACI-209R-92 recommends an average value of 10 and 0.60 for d and ψ respectively.

φ_u is the ultimate creep coefficient.

For the ultimate coefficient φ_u, the average value is given:

$$\varphi_u = 2.35$$

According to ACI-209R-92, the creep coefficient φ_u needs to be modified by correction factors. Therefore, φ_u should be multiplied by six factors.

$$\varphi_u = 2.35\gamma_c \tag{7}$$

$$\gamma_c = \gamma_{c,t0}\gamma_{c,RH}\gamma_{c,vs}\gamma_{c,s}\gamma_{c,\psi}\gamma_{c,\alpha} \tag{8}$$

Where $\gamma_{c,t0}$ = loading age coefficient

$\gamma_{c,RH}$ = ambient relative humidity coefficient

$\gamma_{c,vs}$ = the volume to surface ratio of the concrete section coefficient

$\gamma_{c,s}$ = slump coefficient

$\gamma_{c,\Psi}$ = fine aggregate coefficient

$\gamma_{c,\alpha}$ = air content coefficient

2.1.3. Australian Standard 3600-2009

The creep coefficient at any time φ_{cc} can be determined by:

$$\varphi_{cc} = k_2 k_3 k_4 k_5 \varphi_{cc.b} \tag{9}$$

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:

$$k_2 = \frac{\alpha_2 (t-\tau)^{0.8}}{(t-\tau)^{0.8} + 0.15t_h} \tag{10}$$

$$\alpha_2 = 1.0 + 1.12e^{-0.008t_h} \tag{11}$$

$$t_h = 2A_g/u_e \tag{12}$$

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:

$$k_3 = \frac{2.7}{1+\log(\tau)} \; (for\ \tau > 1\ day) \tag{13}$$

For the factor k_4 which accounts for the environment:

$k_4 = 0.7\ for\ an\ arid\ environment$

$k_4 = 0.65\ for\ an\ interior\ enviroment$

$k_4 = 0.60\ for\ a\ temperate\ enviroment$

$k_4 = 0.5\ for\ a\ tropical\ or\ near - coastal\ enviroment$

For the factor k_5 is given by:

$$k_5 = 1.0\ when\ f_c' \leq 50MPa \tag{14}$$

$$k_5 = (2.0 - \alpha_3) - 0.02(1.0 - \alpha_3)f_c'\ when\ 50MPa \leq f_c' \leq 100MPa \tag{15}$$

Where $\alpha_3 = 0.7/(k_4\alpha_2)$

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 (Bhatt, P., 2011):

(1) Plastic shrinkage: it happens in few hours after concrete placed.
(2) Dry shrinkage: evaporation leads to loss of water.

According to, plastic shrinkage is due to water loss from concrete in plastic state. It could happen during the hydration process or water evaporation in environmental conditions. The factors lead to autogenous shrinkage is chemical reactions between water and cement known as hydration. There is not environmental influence such as temperature and moisture. Chemical reactions between carbon dioxide and the hydration products of cement leads to carbonation shrinkage. The carbonation chemical reaction equation is shown as (Haranki, B., 2009):

$$Ca(OH)_2 + CO_2 \rightarrow CaCO_3 + H_2O$$

The effects of shrinkage include environmental condition, material properties, curing method and mix proportion. According to ACI, shrinkage is related to ratio of volume and surface area which shrinkage is inversely proportional to ratio of volume and surface area:

$$\text{Shrinkage} \propto \frac{1}{(\frac{V}{S})^2}$$

where V is volume and S is surface area

2.2.1. Eurocode 2

The total shrinkage strain ε_{cs} can be given by:

$$\varepsilon_{cs}=\varepsilon_{ds}+\varepsilon_{as} \quad (16)$$

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

2.2.2. ACI

The shrinkage stain $\varepsilon_{sh}(\text{t},t_c)$ at age of concrete t (days), predicted from the start of drying at t_c can be calculated by:

$$\varepsilon_{sh}(t) = \frac{(t-t_c)^\alpha}{f+(t-t_c)^\alpha}\varepsilon_{shu} \quad (17)$$

$$\varepsilon_{shu} = 780 \times 10^{-6}\ mm/mm\ (in/in)$$

Where f (in days) and α are considered constants for a given member shape and size that define the time-ratio factor

ε_{shu} is ultimate shrinkage strain

$(t - t_c)$ is the time between end of curing and any time after curing

2.2.3. Australian Standard 3600-2009

The total shrinkage strain ε_{cs} is shown below:

$$\varepsilon_{cs} = \varepsilon_{cse} + \varepsilon_{csd} \tag{18}$$

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

The autogenous shrinkage εcse is given by:

$$\varepsilon_{cse} = \varepsilon'_{cse}(1.0 - \exp\{-0.1t\}) \tag{19}$$

$$\varepsilon'_{cse} = (0.6f'_c - 1.0) \times 50 \times 10^{-6}\ (f'_c\ in\ MPa) \tag{20}$$

$$\varepsilon_{csd.b} = (1.0 - 0.008f'_c) \times \varepsilon'_{csd.b} \tag{21}$$

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:

$$\varepsilon_{csd} = k_1 k_4 \varepsilon_{csd.b} \tag{22}$$

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.

3. 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 behaviour of railway concrete sleepers due to their creep, shrinkage and elastic shortening responses of the materials affect significantly the rail gauge control. 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. This insight will improve material design and structural restraints, which are very critical to the durability of railway track components.

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