

A Review of Behaviour of Prestressed Concrete Sleepers

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ABSTRACT: Prestressed concrete sleepers (PCSs) are the most commonly used type of sleepers. They play an essential role in track performance, behaviour and safety. The focus of the published literature on PCSs has primarily been on quantification of dynamic load and resulting structural behaviour of sleepers, interaction with other components of track and failure mechanisms. While structural performance of PCSs is very important and researched as reflected by the large volume of published literature, concrete sleepers also need to meet the durability requirements. It is known that only a small percentage of concrete sleepers remain in service when reaching their intended design life, resulting in heavy maintenance and replacement costs. This paper reports a summary of the review of literature conducted as part of a broader investigation undertaken at the University of Melbourne. The aim of the investigation is to establish the material requirements of the concrete sleepers in order to meet the structural and durability requirements. A summary of the latest works on dynamic responses (including natural frequencies and mode shapes, damping, bending moments and strain rates), failure modes, fatigue and durability aspects of PCSs are presented. Moreover, design approach and dynamic loads are discussed briefly. It is established that a comprehensive research with a focus on material characterisation for concrete sleepers is currently lacking.

Keywords: Railway Concrete Sleepers, Strain Rate, High Performance Concrete

1 INTRODUCTION

Developing dramatically and continuously through the last decades, railway plays a vital role in transporting passengers and merchandise and provides the best and safest transportation option (Kaewunruen and Remennikov, 2008a). Conventional or ballasted track consists of superstructure and substructure. The rails, rail pads, fastening system and sleepers or ties make up the superstructure. The substructure consists of ballast, sub-ballast and formation (subgrade). Some different materials, such as timber, steel and concrete, have been employed as sleepers in railway construction to distribute the loads from rails to sub-structure and play major role in track performance and safety.

Although, different types of ballast-less track have been introduced and used in the last decades, the ballasted tracks have been known as the most popular even for use for high speed trains. Extensive use and development of ballast-less track, known as slab track, started 1980s, however, it dates back to the beginning of the 20th century (Michas, 2012). Research into ladder sleeper began in Japan, Soviet Union and France since the mid 20th century and their practical use began in late the century (Wakui et al. 1997). The efforts to combine the benefits of both ballasted and ballast-less tracks led to “frame-

tie-track” on high-density lines in Austria in 1999 (Riessberger, 2011).

Sleepers are transverse beams resting on ballast support. The main and important functions of sleepers are:

- to support the rail and maintain the track gauge;
- to withstand vertical and longitudinal movement of rails;
- to transfer and distribute loads from rail to ballast;
- to act as an anchorage platform for fastening systems; and,
- to provide insulation between parallel rails.

Restricted resources and rapid development of railway encouraged the use of steel and concrete as a replacement of timber which had traditionally been used. The twin-block and mono-block concrete sleepers have been developed and successfully employed. At the moment, mono-block PCSs, as the most commonly used types of sleepers (Okonta and Magagula, 2011), are popular and widely used in many countries such as North America, Europe, Asia and Australia. However, research efforts and trial applications of new materials such as polymer concrete and fibre composites in sleeper production form part of new developments (Manalo et al. 2010).

The reinforced concrete sleepers (RCSs) which have been used during the 1920s and 1930s in Italy and India, was found not to be effective because of poor structural performance and extensive damage (Hwang et al. 2011). Consequently, after some trials during the Second World War in the UK, PCSs were developed (Hwang et al. 2011). With longer life cycle and lower maintenance costs, PCSs brought many technical and economic advantages to the railway engineering. Besides, the large weight of PCSs provides stability for heavy-haul and high trains. Furthermore, PCSs are more sustainable than timber counterparts. It has been reported that the life cycle emissions of PCSs are two to six times less than that associated with timber sleepers (Crawford, 2009).

PCSs are expected to withstand high magnitude dynamic loads and harsh environments. Like other concrete elements and structures, the PCSs have their own failure modes. Although, structural engineers believe that there is a huge amount of untapped reserved strength in PCSs (Remennikov et al. 2007, Leong and Murray, 2008 and Nairn and Stevens, 2010), others, especially maintenance engineers, often encounter concrete damage, mostly in the form of cracks (Van Dyk et al. 2012 and Thun et al. 2008). To address the unresolved performance problems which considerably shorten the service life of PCSs, extensive research has been undertaken. The process has led to conclusions that in order to fully understand the behaviour of PCSs, their interaction with the other components of track must be considered. PCSs have been investigated using numerical models, field studies and experimental tests across the world. The nature of mechanical load being cyclic, dynamic behaviour of PCSs such as natural frequencies, mode shapes, damping, failure modes, residual strength and energy absorption capability have been scrutinized. Furthermore, as a significant component of the track, PCSs have generally been considered in the train-track models or wheel-rail models in order to estimate the dynamic loads imposed and to study the interactions of these with other components (Ahlbeck and Hadden, 1985, Ripke and Knothe, 1995, Lundqvist and Dahlberg, 2005 and Bian et al. 2013)

The main objective of this paper is to report on the latest developments reporting on the mechanical properties and dynamic responses of PCSs, as a part of a broader investigation undertaken at the University of Melbourne. The aim of the investigation is to establish the material requirements of the concrete sleepers in order to meet the structural and durability requirements. After introducing the current design approach, a brief overview of track loads is presented. Dynamic responses of PCSs including natural frequencies, mode shapes and damping are dis-

cussed. When subjected to external dynamic loads, PCSs undergo deformation both globally, (i.e., in the form of flexure) and locally. Bending moment and curvature of PCSs as a result of dynamic transverse load is discussed. Some investigations have reported localized stress concentrations where in some cases localized damage in the form of cracks or crushing of the concrete is observed. The strains at critical locations of the PCSs have been experimentally investigated. The strain rates of PCSs are calculated based on published information. Finally, the fatigue and durability aspects of PCSs are briefly discussed.

2 DESIGN APPROACH

An allowable stress approach which relies on simplistic impact factors is commonly used in design of PCSs and the railway track. The design of sleeper is based on vertical loads applied from train wheels and ballast support. Along with vertical loads, sleepers are subjected to lateral loads, especially, on a curved track. PCSs generally rely on bearing of the ends against ballast, gravity and friction between sleeper and ballast, to withstand lateral loads. Recently, to increase this resistance, haunches have been added to the sides of sleepers (Lutch et al. 2009).

Design of PCSs based on various design standards such as Australia (AS 1085.14, 2012), USA (AREMA, 2006) and Europe (EN 13230, 2009), follows a similar procedure 1. providing basic information on train and track by purchaser, 2. estimation of vertical design wheel load, 3. Assumption of a pattern for ballast load distribution, 4. calculation of sleeper bending moments, 5. computation of permissible stresses, 6. material selection, 7. manufacturing process and 8. testing of sleeper.

Here, the design procedure of PCSs is briefly presented based on Australia Standard (AS 1085.14, 2012). There are some minor differences between design standards. A discussion of these differences is beyond this paper. Some comparisons are available in Freudenstein (2007) and Sadeghi (2008).

According to AS 1085.14-2012 a wide range of information should be provided by the purchaser, for example, the maximum axle load, the maximum train speed, annual gross tonnes, track gauge and rail size. The vertical design wheel load is a product of maximum static wheel load and service factor, which is assumed 2.5, where in-field measurements are not available or there is no value specified by purchaser. This load is distributed on a certain number of sleepers depending on the rail weight, sleeper spacing and track stiffness. The distribution factor varies between 45% and 60% for the conventional track condition.

The load distribution under the sleeper and its variation with time significantly influence the structural design of the sleepers (Sadeghi and Barati, 2010). In freshly tamped track, the contact area occurs below each rail seat. This case is utilized to calculate the rail seat positive moment. After the track has been in service the centre of sleeper contributes in carrying distributed load. The negative moment at midspan of sleeper is calculated in such case. These two moments are used in the design of sleepers. Besides, the rail seat negative moment and midspan positive moment are calculated.

To ensure the performance and durability of the sleepers, some considerations are needed in material selection and manufacturing process of the sleepers. Further, to ensure the structural adequacy of the designed sleepers, a series of static bending tests, cyclic tests and fastener system tests are prescribed in the Australian Standard.

It is worthy to note that the allowable stress method has been criticised as an unrealistic and inadequate for design and evaluation (Leong and Murray, 2008). In an attempt to develop a limit state design methodology for railway track, Leong and Murray (2008) have analysed a large amount of data collected using a track monitoring system in Australia, and by using a modified and updated computer simulator (DTRACK). A model has been proposed to predict the impact force of wheel-rail as a function of wheel flat size, rolling speed and also impact return period (Leong, 2007).

3 LOADS

The dead load of sleepers is typically considered as negligible. Sleepers are, however, subjected to dynamic loads which are generated due to interactions between the wheels and the rail. In ideal conditions of the track and also trains wheels, these loads are lower in magnitude, but high repetition (high cycle). These dynamic loads may reach high magnitudes depending on the abnormalities of the wheels, the rail or even the support conditions and velocity of the train, but the repetition is low (low cycle). Nielsen and Johansson (2000) have classified the wheel tread irregularities into nine types which are eccentricity, discrete defect, periodic non-roundness, non-periodic non-roundness, corrugation, roughness, flat, spalling and shelling. The rail irregularities were categorised as rail corrugation, squats, rail welds and joints. This dynamic load can be represented in the form of cyclic impact load. Based on published data, Remennikov and Kaewunruen (2008) have concluded that the shape of impact load in time domain varies with the sources and the magnitude of the impact force itself, which occur repetitively and significant-

ly depends on the train speed. Further, it is reported that the magnitudes of the impact force are in the range of 100 to 750kN, with duration of between 1 and 12 ms and a frequency range of up to 2000Hz. Many numerical and finite element models are available to simulate wheel-rail dynamic interaction forces. Very recently, Correa et al. (2012) have introduced a full track numerical model to calculate wheel-rail interaction force. Figure 1 shows a sample impact due to the wheel flat. The impact forces could be simplified as a shock pulse. The static axle loads, however, vary from 50kN to 350kN (Esveld, 2001) or even to 392kN (Foan, 2011) depending on the train type and function.

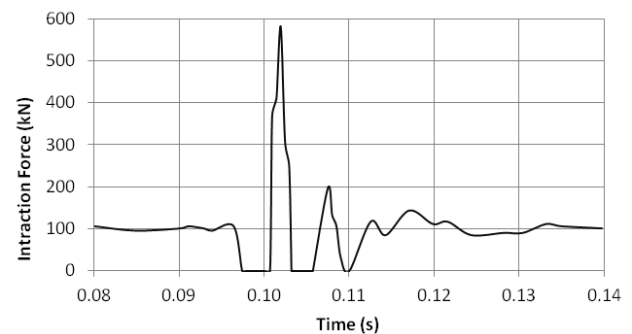


Figure 1: Wheel-rail force due to wheel flat at a speed of 24 m/s (Correa et al. 2012)

According to the Australian Standard, railway track material part 14: prestressed concrete sleepers (AS-1085.14 2003), while the size of low frequency loads depends on the rolling stock response to track geometry (design geometry, e.g. curvature and superelevation and incidental geometry i.e. track roughness) and support conditions (e.g. stiffness), high frequency loads occur as a result of irregular wheel and rail surface conditions (rail and wheel irregularities) or unsupported sleepers. Ripke and Knothe (1995) have mentioned that the track loads in higher frequencies, more than 30 Hz, are causes of deterioration of track components. Recent results of field observations have shown that high-frequency dynamic forces can intensify the deterioration rate of the fastening system and ballast and may cause the sleeper cracking, skewing, hanging and walking (Zhao et al. 2011).

4 DYNAMIC RESPONSE

As discussed above, sleepers are subjected to extremely high forces and strains under dynamic loading and also play an essential role in the dynamic response of global railway track, vibration damping and energy dissipating into the ballast (Barke and Chiu 2005). Dynamic responses of concrete sleepers are significantly affected by boundary conditions to which they are subject to. A review of literature in-

icates that there have been a number of studies related to the determination of static and dynamic responses of PCSs as briefly presented hereafter.

4.1 *Natural Frequencies and Mode Shapes*

As a cost effective and non-destructive method, modal analysis has been widely used to determine the natural frequencies and mode shapes of concrete sleepers. In this method the measurements from accelerometer and excitation hammer are analysed to extract the mode shapes and natural frequencies. Ahlbeck and Hadden (1985) have determined the first three bending mode shapes and related natural frequencies of concrete sleepers in free-free condition, as 108, 333 and 633Hz. The authors also have observed two torsional bending modes at 365 and 406Hz and the fourth bending at 1033 Hz. In addition, they reported that only the first bending mode shifts considerably from 108 Hz to 154Hz in track condition. Based on published data, Knothe and Grassie (1993) have shown that there is a good correlation between the measured and calculated (using Timoshenko beam model) eigenfrequencies. Other, commonly used methods to investigate to establish the dynamic behaviour of sleepers include finite element modeling, (e.g., works of Kaewunruen and Remennikov, 2008b, Gustavson and Gylltpft, 2002 Yu and Jeong, 2012).

Using modal analyse Remennikov and Kaewunruen (2005) measured the dynamic response of 4 Australian concrete sleepers. The results are reproduced in Table 1. It is worthy to mention that the first bending mode is corresponding to the fundamental bending mode. The results indicate that only the first resonant frequencies increased considerably, averaging 15.7% with a maximum of 33.4% for different ballast conditions. The results show that the effects of support condition are insignificant at the higher frequency range. This is in good agreement with the results of Ahlbeck and Hadden (1985).

Boundary conditions generally influence the natural frequencies. By analysing field measurements, Sadeghi (2010) investigated the effects of rail pad and ballast support conditions on PCSs responses. The results show that the influence of rail pad on the natural frequency reduction is negligible, especially, for the first mode. This confirms the Dahlberg's (2008) results which show negligible effects of rail pad and rail on natural frequencies (Dahlberg 2008). Sadeghi (2010) also reported a considerable reduction in natural frequencies due to ballast degradation during service load, a study which confirmed measured responses of concrete sleepers earlier by Vasil'ev and Dvornikov (2000). Further, induced damage to the concrete affects the dynamic response of the sleepers. The results of experimental work by

Salim et al. (2012) showed that the cracks, generated due to service loads, reduce the flexural stiffness of sleepers which, in turn, decreases the resonant frequencies. The damping coefficient tends to increase with crack propagation.

4.2 *Damping and Energy Absorption*

The vibration and noise from rolling wheels on rail are two important parameters in railway engineering, especially in high speed tracks. The capability of tracks to attenuate the vibration and noise depends on the damping ratio of its components. The damping properties of concrete sleepers vary depending on the boundary conditions to which they are subjected to. Grassie and Cox (1985) reported that the damping factor of PCS in free-free condition was only 0.3%, which was negligible compared to that in well supported sleeper by ballast. Damping properties of PCS have been measured in different track conditions by Sadeghi (1997). The author found that the Logarithmic Decrement varies between 0.043 and 0.091 depending on the method of measurement. Kaewunruen (2007) investigated the damping ratio of 4 different Australian type sleepers in free-free condition as well as in situ. The results have shown considerable variation, which was found to be depending on the sleeper type and support conditions. While the damping ratio for free-free condition has an average value of 0.26% and varies between 0.17% and 0.33%, the damping ratio for in-situ conditions increases to an average of 4.67%. The increase of the damping ratio is more than 50-fold in the first bending mode, and, for other modes, it is found to be between 5 to 10-fold. Consequently, it is concluded that the ballast plays a significant role in the damping and vibration reduction of railway tracks. The energy from impact loads between wheel and rail is absorbed by track component and train. Rail pads, sleepers and ballast bed play an extreme role in energy dissipation behaviour of the track. The concrete sleepers dissipate the imparted energy by vibration, deformation and fracture. The energy absorption mechanism of PCSs under dynamic loading has been investigated by Kaewunruen and Remennikov (2011) using the impact testing machine.

Kaewunruen and Remennikov (2011) have imparted impact forces to the specimens and measured the accelerations and displacements. They concluded that the energy balance theory can be applied to concrete sleepers and railway track. The results indicate that around 45% of the impact energy would be absorbed by the concrete sleeper as bending curvature and fracture. The remaining portion would accelerate the cracks in sleepers, break the ballast gravel, degrade the rail pad and damage the wheel.

Table 1: Natural frequencies of several sleepers (Kaewunruen and Remennikov, 2005)

Sleeper type	Length (m)	Mass (kg)	First (Hz)	Second (Hz)	Third (Hz)	Fourth (Hz)	Fifth (Hz)
Heavy Duty	2.5	206	B* - 135.71	B - 404.83	T - 481.36	B - 767.84	T - 1155.31
Medium Duty	2.47	198.1	B - 123.47	B - 349.49	T - 497.70	B - 651.50	B - 1026.15
Broad Gauge	2.85	299.5	B - 112.64	B - 312.50	T - 436.60	B - 605.51	T - 943.53
Narrow Gauge	2.15	283	B - 223.09	B - 561.62	B - 593.19	B - 1092.68	T - 1266.67
Mean	---	---	148.73	407.11	---	779.38	---

*Note: B – indicates bending mode; and, T- is for torsion

4.3 Bending Moments

Structural design of concrete sleepers is based on limiting the maximum quasi-static bending moments to permissible amounts. But, the wheel-rail force is a dynamic transient action. Consequently, the dynamic amplification factor (DAF) for bending moment is an important parameter in the design of PCSs. Using FE program NASTRAN, Kumaran et al. (2003) have modeled the track components to estimate the DAF at the critical sections (midspan and railseat) due to various excitations. The results show DAFs for both sections increase with increasing ballast elastic modulus, decreasing rail pad stiffness, increasing subgrade stiffness and loss of contact between ballast and sleeper at the centre. Also, a sharp peak has been reported when no rail pads are applied, corresponding to frequencies 215 and 160 Hz under full contact and loss of contact conditions, respectively. The results also indicate that the DAFs for deflection and ballast pressure on both sections follow similar trends in the frequency domain. However, the magnitudes are higher as shown in Figure 2. Kaewunruen and Remennikov (2008b) used the finite element package STRAND7 to investigate the DAF for bending moments of sleepers in different track conditions. The results show that the maximum positive dynamic bending moment at rail seats and the maximum negative dynamic moment at midspan are about 1.6 and 1.3 times the static moments, respectively. Also, they found that the first and the third bending modes essentially contribute to midspan and rail seat dynamic bending moments, respectively.

In addition to the bending moment, the deflection due to bending moment is affected by characteristics of dynamic loads (see Figure 2) and track components.

Sadeghi (2010) found that installation of rail pads results in less bending deflection in the first two modes. To investigate the influence of pad stiffness, Kaewunruen and Remennikov (2007) utilized a LS-DYNA model and found that deflection of sleepers at both rail seat and midspan increases significantly with increasing rail pad stiffness and ballast elasticity, particularly, when the magnitudes of the elastic modulus are below 1500 MPa. Further, from published literature, Barke and Chiu (2005) found that sleeper curvature increases with increasing frequen-

cy of excitation and larger accelerations are generated at the point of load application. The generation of large accelerations at both rail seat and midspan has been confirmed through experimental work by Kaewunruen and Remennikov (2009b). In their study the magnitude of acceleration reached over 600g at rail seat. Numerical modeling by Johansson et al. (2008) showed both acceleration and deflection decrease with increasing stiffness of under sleeper pad (USP). It should be noted that USP is an elastic layer used under the sleeper to reduce ballast damage and ground vibration.

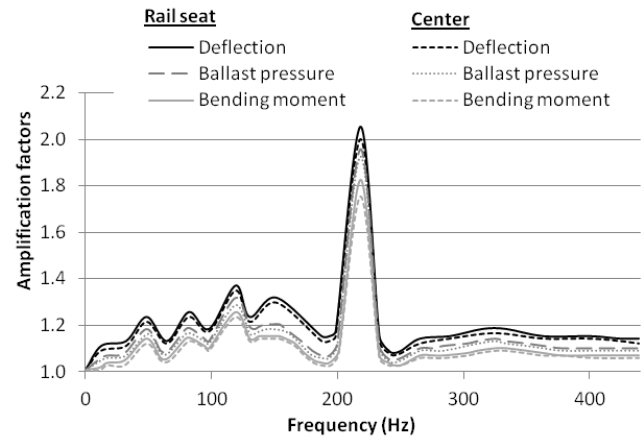


Figure 2: Amplification factor vs frequencies (Kumaran et al. 2003)

4.4. Strain Measurements

The strains and its variation in PCSs due to dynamic loads have been the subject of only few studies. There are no in-field measurements of PCSs strains, published in the literature. However, Kaewunruen and Remennikov (2009a) have conducted a series of impact tests on in situ PCS and measured the strains at both top and bottom fibres of rail seat and midspan to study the impact fatigue responses of the sleeper (Kaewunruen and Remennikov 2009a). To ensure simulation of the actual track conditions using this approach, the authors investigated the relationship between impact load and rail seat bending moment experimentally and compared their dynamic results with those of D-TRACK finite element model, which was developed by Cai (1992) for dynamic analyse of rail tracks. The capability of D-TRACK to perform a series of track analysis has been investigated by Steffens (2005). A comparison of the results confirms the suitability of the experimental test

approach to model the actual impact loading of sleepers.

Kaewunruen and Remennikov (2009a) used a high capacity impact test machine to impart 50 repeated impacts and the strains were measured after 1, 10, 20 and 50 impact loads of about 500 kN in both soft and hard track conditions (with less and more than 250 mm ballast bed, respectively). But only 16 measurements have been published. Four measurements are shown in Figure 3, as an example. It has been found that in hard track conditions the sleepers vibrate reasonably, resulting in small negative strains in positive zone. Also cracks could appear in the hard track more rapidly than in the soft track, cause that the strains fluctuate in the lower range.

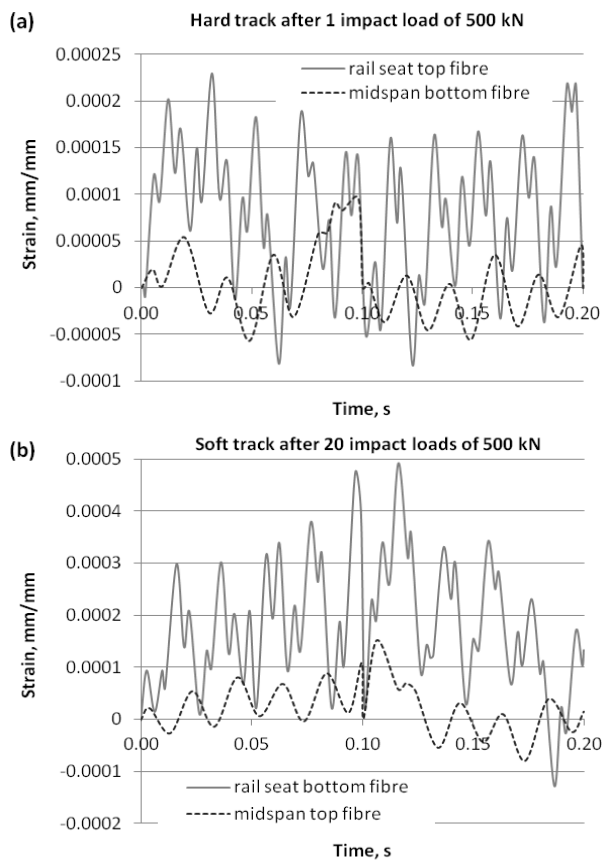


Figure 3: Dynamic strains of PCS under impact (Kaewunruen and Remennikov, 2009a)

4.5 Strain Rate

In general, the mechanical response of concrete members is dependent on the strain rate. By increasing the strain rate, the strength of concrete is significantly increased in both tension and compression (Ngo and Mendis, 2009 and Ngo et al, 2013). Strain rate is one of the important factors that affects the behaviour and performance of PCSs. The previous studies show the strength of concrete increases with increasing rate of strain, especially, for higher rates such as impact and blast loads. The magnitude of strain rate in PCSs due to the unusual high magni-

tude and low cycle loads has not been studied up to date.

To estimate the strain rate in PCSs, the strain measurements by Kaewunruen and Remennikov (2009a) are used. The graphs were digitized very precisely and the rates were calculated using spreadsheet for all 16 measurements. The calculated strain rates for measurements presented in Figure 3 are shown in Figure 4. Figure 4 shows high fluctuation in the strain rate at rail seat and midspan around time 0.1 s. Similar trend appears on 11 of the 16 calculated strain rates at both rail seat and midspan. Neglecting the high fluctuation, the strain rate varies in the range between 0.01 – 0.08 1/s at rail seat and 0.002 – 0.016 1/s at midspan, (see Figures 5 and 6).

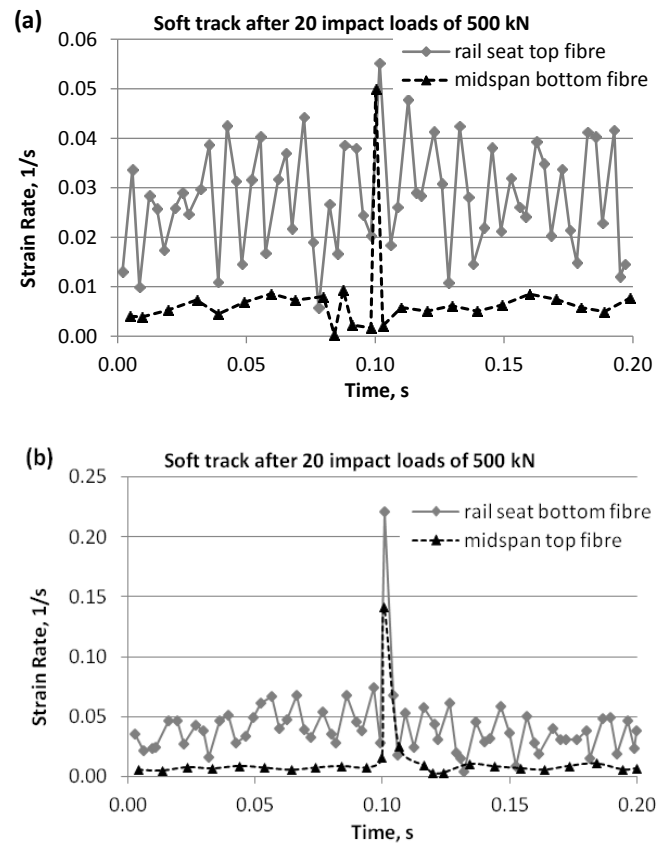


Figure 4: Strain rate of PCSs under impact loads

Ngo (2005) has shown the association of strain rates with different type of loading, (Figure 7). Comparing the calculated strain rates of sleeper with the values in Figure 7, it could be concluded that the dynamic loads of sleepers generate effects similar to those generated in concrete structures by earthquakes. The influence of strain rate on dynamic increase factor (DIF) of concrete strength seems to be insignificant. However, the investigations show both cracking and the ultimate bending moment capacity of PCSs at rail seat increase when subjected to impact loads, see Table 2 from Remennikov and Kaewunruen (2007). It is worthwhile to note that the sleeper has been put under ultimate impact and the true impact load has been measured by load cells.

Then, using this impact load they have calculated the relevant bending moment, based on simplified section analysis.

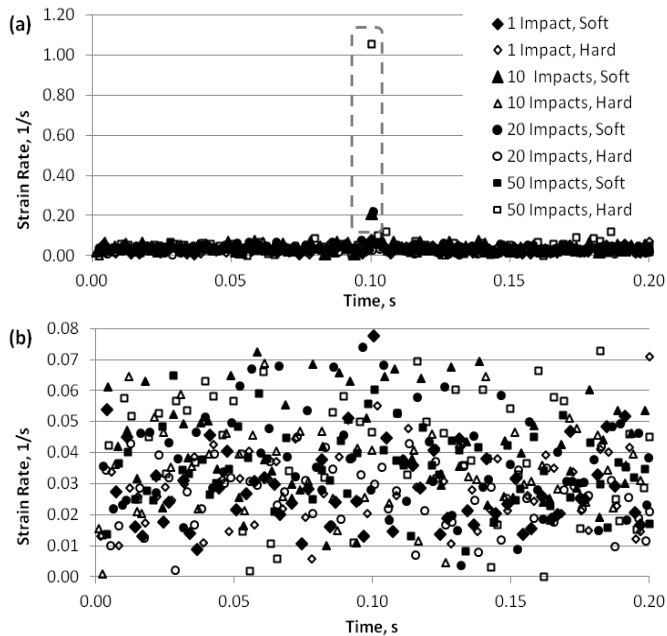


Figure 5: Strain rates at rail seat, (a) all calculations, (b) magnified up to strain rate 0.08 1/s

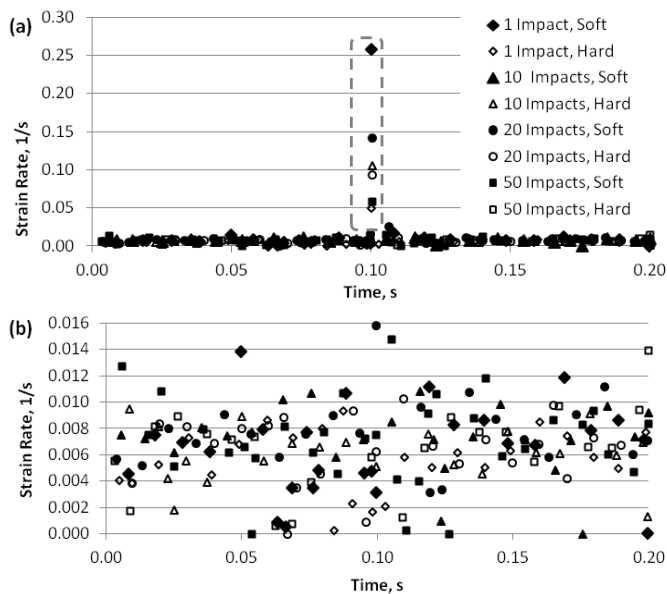


Figure 6: Strain rates at midspan, (a) all calculations, (b) magnified up to strain rate 0.016 1/s

5 FAILURE MODES

Due to the use of prestressing, the use of high strength concrete (HSC) is necessary in the production of PCSs. The minimum compressive strength of concrete is 50 MPa in Australia (AS-1085.14 2012) and 48.3 MPa (7,000 psi) in USA (Lutch et al. 2009). Additionally, HSC (compressive strength over 50 MPa) is mostly used to make sleepers in India (Kumaran et al. 2002), Iran (Rezaie et al. 2012) and many other countries. Even sleepers with com-

pressive strength over 100 MPa have been reported (Thun et al. 2008). So, the behaviour of concrete in sleepers should be investigated based on application of HSC. Owing to the variations in fracture modes, microstructure and differences, HSC is structurally a different material in comparison with normal strength concrete (NSC). The main concern regarding the use of HSC is the reduction in ductility with the increase in compressive strength (Mendis, 2003). Smooth fracture across micro-cracks and the lack of aggregate interlock are said to be the reasons for the brittle nature of HSC (Mendis, 2000). This brittleness may be the main cause of cracking, which has been ranked as the most common problem of concrete sleepers across the Globe, in the international survey conducted by Van Dyk et al. (2012), specifically when subjected to dynamic loads. Table 3 shows the main problems of PCSs and fasteners and their ranks. Also, the survey shows only a small percentage of concrete sleepers remain in service beyond their design life.

The failure modes of concrete sleepers in different track conditions are more varied than that occurs under standard tests. Through a literature review, Lutch et al. (2009) found that rail seat deterioration (RSD), flexural cracking from centre binding and rail fastener failure are the three primary failure mechanisms of PCSs. It should be noted that the RSD is a common type of failure in North America, ranked as the most important problem (Van Dyk et al. 2012). Considering results from inspection of 3 million sleepers, Thun et al. (2008) have observed that the first cracks appear on the upper side at the ends. Also, some sleepers had cracks on the sides towards the lower edge, which are not possible to detect by a visual inspection. Further, some cracks have been observed at the bottom of rail seat, the top of midspan, around the fastening. Longitudinal cracks were also observed along the sides, see Figure 8. Rezaie et al. (2012) have reported longitudinal cracks initiating from fastener locations and propagating to midspan during and even before track operation.

Surveying published literature indicates that the problems with fasteners, particularly those embedded in concrete, often are classified as problem of sleeper because in most cases these problems dictate the replacement of sleepers. But, they are not related to sleeper failure. Further, RSD is not reported as a main problem except in North America (for more information see Choros et al. 2007, Zeman et al. 2009 and Kernes et al. 2011). Consequently, the cracking could be the most important failure of PCSs in the world. However, other failures such as spalling, crashing, splitting and slippage between concrete matrix and strands have been reported, especially under events like derailment. Cracking of PCSs is a

crucial behaviour, not only in terms of mechanical and load carrying capacity, but also for durability and fatigue properties. Also, the pattern and severity of cracks are essential factors in the sleeper assessment. Rail seat and midspan static bending tests and impact tests have been used to identify cracking mechanism and propagation in concrete sleepers.

5.1 Cracking and Failure at Rail Seat

Rail seat positive bending moment is one of the main criteria in PCSs design. This moment can lead to flexural cracks initiating from the bottom of the

sleeper and propagating upward. Ye et al. (1994) carried out a series of rail seat positive bending static and impact tests to explore the influence of support conditions and loading rates on the cracking mode of PCSs. The sleeper has been subjected to rail seat static bending test until complete failure occurred. The flexural crack, flexural-shear cracks and shear cracks have appeared at the bottom of the sleeper around the rail seat due to load of about 355 kN, 489 kN and 613 kN, respectively, as shown in Figure 9. At this point, some slip of pretensioning wires, large deflections and crushing of the concrete on the upper surface occurred.

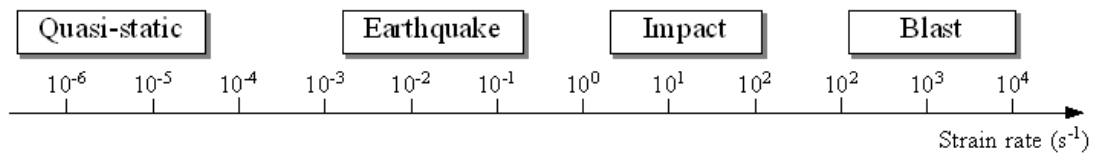


Figure 7: Strain rate association with different types of loading (Ngo, 2005)

Table 2: Experimental moment capacities of PCSs (Kaewunruen and Remennikov, 2007)

Loading	Target conditions	Tested moment at failure (kNm)	Type of damage
Static	Crack	34	First crack is due to bending
	Fail	84	Shear failure
Dynamic	Crack	44	First crack is due to bending
	Fail	95	Bending-shear failure

Table 3: The most critical concrete sleeper and fastening system problems, (adopted from Van Dyk et al. 2012)

Most critical concrete sleepers and fastening system problems	Average rank (from 8)		
	International (18)	USA (10)	Overall (28)
Shoulder/fastening system wear or fatigue	5.50	6.38	5.81
Tamping Damage	6.14	4.14	5.43
Cracking from dynamic loads	5.21	4.83	5.07
Cracking from centre binding	5.36	4.50	5.05
Derailment Damage	4.57	4.57	4.57
Deterioration of concrete material beneath the rail (RSD)	3.15	6.43	4.32
Cracking from environmental or chemical degradation	4.67	3.50	4.25
Other (e.g. manufactured defect)	4.09	3.57	3.90

(18), (10) and (28): Number of participants institutes and companies

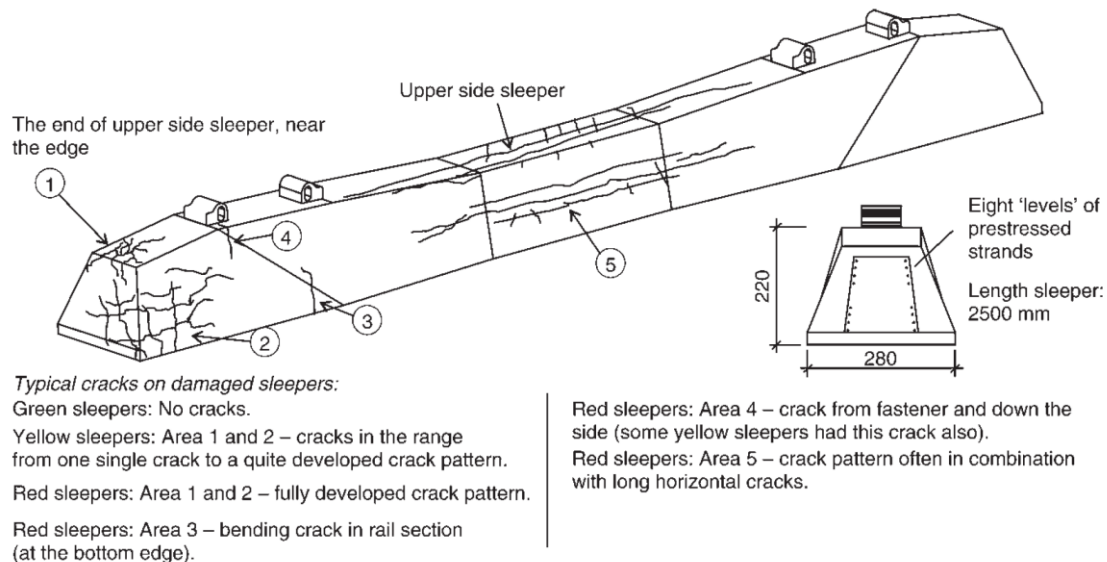


Figure 8: Classification of cracked sleepers (Thun et al. 2008)

The impact loading has been carried out using an impact machine with a drop height of 1.52 m and two masses of 345 kg and 504 kg (corrected impact velocity of 5.22 m/s). The results show that the cracking mode depends upon the magnitude of the impact force and the loading rate. The cracks have appeared in a sequence similar to that due to the static loading. It has also been observed that when the stiffness of the track system, which depends on support and the rail pad, increases the apparent rate of loading increases. This is because the sleeper responds more rapidly to the applied load. The distributed inertia forces increase the shear stiffness, and thus shear damage increases more significantly than the flexural damage. Consequently, increasing loading rate leads to change of the principal cracking mode from flexural to shear-flexural and then to shear. This cracking sequence has appeared in similar tests carried out by Kaewunruen and Remennikov (2009b). The authors have reported that the concrete failed by shear diagonal crushing and spalling without any appreciable deflection warning. No yielding or damage in pretensioning wires has been observed, (Figure 10).

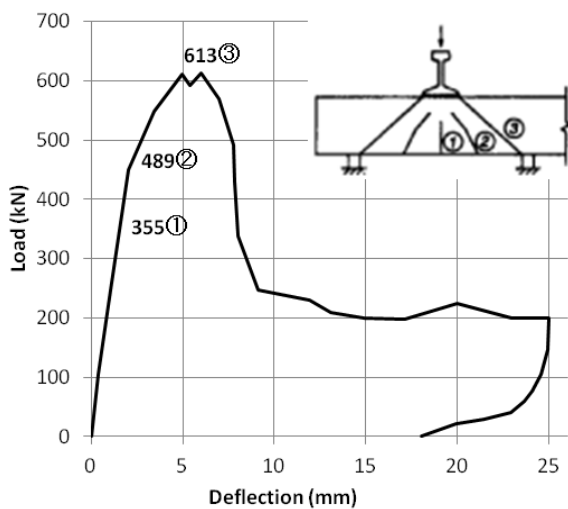


Figure 9: Load/deflection curve of sleeper in static loading (Ye et al. 1994)

Kaewunruen and Remennikov believe that the standard static testing evaluation does not provide realistic representation of the PCSs under the real-life loading condition. Consequently, they have investigated failure behaviour of PCSs at in situ conditions under impact loads. The magnitude and duration of impact forces depend on the drop height of falling mass (592 kg). The crack initiation and propagation have been detected visually during the test. The crack widths have been measured by means of a telescope magnifier (Kaewunruen and Remennikov 2009c). The observations and measurements are summarised in Table 4 for hard track condition. The magnitude of impacts increases until complete failure and degradation of concrete occurred at loads of

about 1640 and 1820 kN for soft and hard track conditions, respectively. Under ultimate impacts, sleepers experience extreme spalling and splitting in addition to shear cracks at rail seat and some bending cracks at midspan. Figure 11 shows the failure of a sleeper in hard track condition.



Figure 10: Behaviour of concrete sleepers under static loading (Kaewunruen and Remennikov, 2009b)



(a) Interfacial damage.



(b) Disintegration and top surface cracks.

Figure 11: Impact failure of sleepers at 1820 kN in hard track conditions (Kaewunruen and Remennikov, 2009c)

The same approach has been used in the investigation of dynamic crack propagation in PCSs under repeated impact loads (Kaewunruen and Remennikov, 2010). The PCSs have been subjected to impact loads of 500, 740 and 810 kN in simulated both hard and soft track conditions and the crack lengths have been recorded in different stages. The crack propagation due to repetitive impact loads on concrete sleepers in hard track condition is shown in Figure 12.

Table 4: Propagation of cracks in hard track, summarised and adopted from Kaewunruen and Remennikov (2009c)

Drop height (m)	Impact force (kN)	Return period	Crack type at rail seat	Crack length (mm)	Crack Width (mm)	Crack or failure description
0.10	400	9 months	bending	--	--	Flexural crack initiation
0.50–0.60	--	--	also diagonal	--	--	small cracks – no major failure
--	< 500	--	bending	200	0.01 – 0.02	Flexural cracks
--	500 - 850	--	bending	300	0.02 – 0.12	small concrete spalling at top
--	< 1200	--	bending	500	up to 0.3	significant spalling of concrete
--	1200-1800	--	also a few longitudinal	500	--	also more small cracks at top surface of midspan

The authors found that the cracks occurred faster and propagated longer in hard track conditions than the soft ones. The results show the probability of cracking of concrete sleepers at service condition is high and the reduction in sleeper stiffness and strength is unavoidable. However, the authors concluded that the damages in the sleepers are localized and do not have significant influence on serviceability of sleepers.

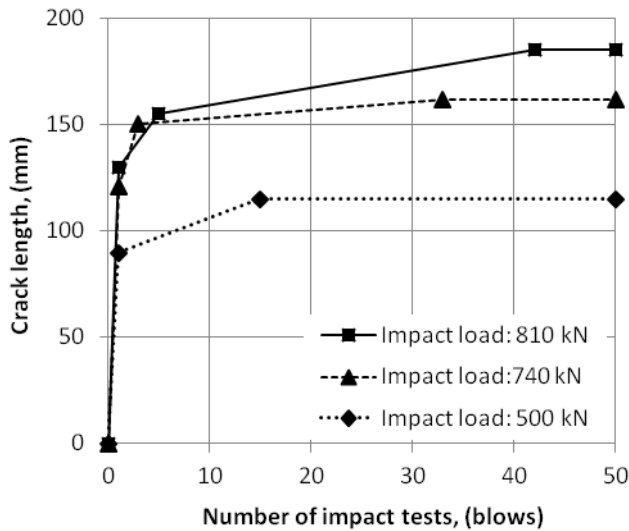


Figure 12: Crack propagation in sleeper under multi impact loads, hard track (Kaewunruen and Remennikov, 2010)

5.2 Cracking and Failure at Midspan

The cracking at the top of midspan is another kind of PCSs failure modes which occur due to midspan negative moment. Kaewunruen and Remennikov (2006a) have investigated the rotational capacity of concrete sleepers using a midspan bending test and have reported the crack initiation and the ultimate loads of the sleepers. The first flexural cracks were initiated at a load of around 75 kN and the sleeper was damaged at a load of 133.3 kN, equivalent to a bending moment of approximately 45 kNm. The authors believed a combined flexural and shear failure have occurred, explaining the crack behaviours. Similar crack propagation has been reported by Salim et al. (2012) with the first flexural cracks for the two specimens appearing at loads of 100.74 and

110.16 kN and the sleepers were damaged at loads of 398.93 and 389.71 kN due to shear cracks.

The same testing approach has been used by Kaewunruen and Remennikov (2006b) to investigate the post failure mechanism and residual load carrying capacity of PCSs. After concrete crushing the load tends to decrease while deflection tends to increase rapidly and at certain deflection, the damage of pretensioning wires starts one by one from the lowest layer. Damage of each wire results in a sudden vertical drop of load, approximately 10 kN. The load-deflection curve is depicted in Figure 13.

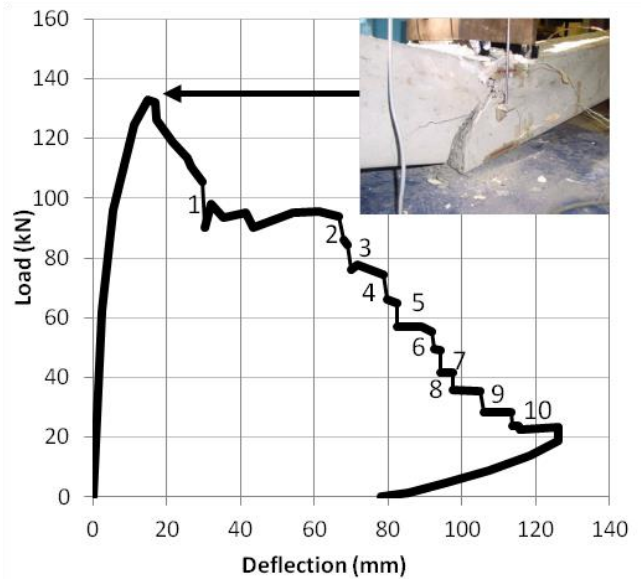


Figure 13: Residual load carrying capacity (Kaewunruen and Remennikov, 2006b)

6 FATIGUE AND DURABILITY

Fatigue damage of concrete is a significant issue in structural elements subjected to cyclic loading. Railway sleepers are subjected to both environmental and mechanical cyclic loads during their service life, though, it is not unreasonable to expect that the concrete sleepers are subjected to fatigue. Also, standard fatigue tests are prescribed in design standards to ensure that PCSs resist fatigue adequately.

The load carrying capacity and fatigue behaviour of PCSs under cyclic loads has been experimentally investigated by means of a three point midspan bending test (Salim et al. 2012). The sleeper has

been subjected to 3 million cycles of loading with an amplitude range of 16 to 166 kN and frequency of 5Hz. After cyclic loads no major cracks have been observed. Further, comparison of the results from static tests before and after cyclic tests have shown no reduction in the ultimate load capacity of the sleeper. The results are in good agreement with the study, which was carried out by Yu et al. (2010). They replaced 20% of cement with perlite admixture and investigated the fatigue behaviour and mechanical properties. By conducting a series of 2 million cycle fatigue test based on TB/T1879-2002 Chinese Standard, the authors reported that no cracks and no reduction in load carrying capacity were observed. Additionally, the results show while compressive strength at 1 day age was 49.0 MPa (18.3 % less than reference concrete) it passed the reference concrete and reached 65.4 MPa at 28 days age. However the elastic modulus was 31.2 GPa at age 28 days, 4.9% less than that for reference concrete. So, the authors concluded that concrete sleepers meet the fatigue requirements of the design standard.

As published results have shown no major crack and damage due to fatigue tests, some researchers such as Remennikov et al. (2007), Leong and Murray (2008) and Nairn and Stevens (2010) have stated that the current approach of standard codes, which overwhelmingly rely on permissible stress concepts, is conservative and have somewhat downplayed the role of fatigue. They believed that the fatigue life of concrete sleepers will be infinite because only compressive stress occurs at the sleeper sections due to service loads with low magnitude and high cycle.

To ensure adequate load carrying capacity, Thun et al. (2008) have investigated the fatigue behaviour of cracked PCSs. The authors have classified in-field cracked sleepers into green, yellow and red, based on severity of cracks, (see Figure 8). Then 13 red sleepers (extremely cracked) have been subjected to 2 million cycles of loading (rail seat bending) based on fatigue test of Swedish railway code. They have observed that the 7 sleepers have been failed while the 6 sleepers have passed through the test. According the results, the authors have found that the internal crack system is crucial for the load carrying capacity. However, no established relationship between visible crack pattern and fatigue capacity has been reported. Also, the authors have conducted series of other test (static bending test, fastener load capacity, compressive and tensile strength tests) on green and yellow sleepers and concluded that the sleepers are quite robust and small cracks do not significantly influence the load carrying capacity.

Kaewunruen and Remennikov (2010) have found that the high magnitude but low cycle impact fatigue is more significant than low magnitude but high cycle impact fatigue for PCSs. Also, it is well known

that the cumulative damage is the most likely cause to failure of concrete sleepers. Furthermore, they have believed that fatigue damage theory which is based on fatigue stress is not suitable for railway concrete sleepers subjected to periodic impacts (Kaewunruen and Remennikov 2009c). Consequently, they have adopted a hypothesis from Fryba (1996) and utilized the damage index, ratio of critical upward cracks length to the depth of a structural member, to evaluate the impact damage accumulation characteristics of concrete sleepers. Same authors (2009b) have investigated the residual strength of heavy haul PCSs with rail seat bending test before and after subjected to 50 identical impact load with 50 years return period and magnitude of about 500 kN. The results indicate that the sleepers subjected to impact loads tend to possess large amounts of reserved strength in spite of stiffness reduction due to “large cracks”. Therefore the authors concluded that the current permissible stress design concept is very conservative.

Using a fatigue damage function, Sýkorová et al. (2012) have calculated the stiffness reduction of concrete sleepers under cyclic loading. Figure 14 shows that the modulus of elasticity decreases sharply during the first few hundred thousands of load cycles and then at the end of life time. The authors have believed that fatigue of concrete results in progressive and permanent changes in the material and can cause microcracks within the sleeper, which, at times, appear as visible cracks on the surface. A reduction in stiffness of the member and in extreme cases fatigue may lead to structural failure. This is in good agreement with investigations of Gustavson and Gylltpt (2002) which show a 10% decrease in the flexural stiffness of sleepers due to cracking. The authors believed that while this stiffness reduction has only a small influence on the global sleeper response, cracks strongly affect the lifetime of concrete sleepers and may result in increased corrosion or fatigue failure of reinforcement.

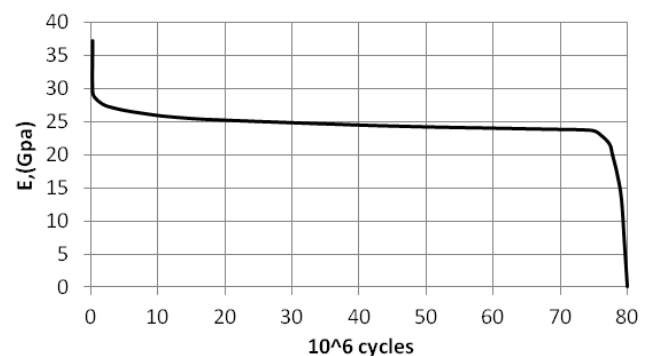


Figure 14: Reduction of elastic modulus of concrete sleeper during entire lifetime (Sýkorová, et al. 2012)

The published results of standard fatigue tests indicate that the in-service loads with high cycle and low magnitude have almost no significant influence

on PCSs load carrying capacity. But, it is demonstrated that occurring of microcracks in concrete sleepers due to service loads is unavoidable. Besides, the high magnitude dynamic loads even with a few years return period could lead to cracks propagating over half of sleeper height and cracks often are visible. The effect of microcracks and visible cracks on the durability of PCSs is the other concern.

The design and construction of concrete sleepers are based on the nominal resistance, while the life-time and durability are usually limited to material testing to avoid the risk of alkali silica reaction (Fib, 2006), curing process and concrete cover (AS-1085.14 2012). Generally, subjecting to various weather and environmental conditions make sleepers susceptible to penetration of water and chloride ions which can lead to corrosion of steel rebars. Corrosion of steel rebars influences the durability of reinforced concrete in two ways: decreasing load carrying capacity of rebars due to reduction in their cross section and the deterioration of the surrounding concrete because of increasing volume of rust products. The resistance of concrete to reinforcement corrosion significantly depends on water and chloride permeability. Uncracked HSC, which is commonly used to make sleepers, is expected to be less water permeable than NSC because of the more dense texture. But Aldea et al. (1999) have found that cracking changes the behaviour of material in terms of water and chloride permeability, and both NSC and HSC are affected by cracking. Corrosion of the strands under the influence of chloride ions is known as a significant factor that leads to deterioration of sleepers (Mohammadzadeh and Vahabi, 2011). Even concrete with compressive strengths over 60 MPa has been reported to be severely damaged within a couple of years by the combined effect of chemical reaction between calcium chloride and cement paste due to the mechanical and physical stress development (Berntsson and Chandra, 1982).

As demonstrated previously, the occurrence of micro-cracks in concrete sleepers due to service loads is unavoidable. Common sense and laboratory tests (Mohammed et al. 2001) show the presence of cracks can cause significant corrosion of steel bars in concrete, regardless of the size of the cracks. Further, microcracking due to service loads increases the penetration of chloride ions and leads to significant reduction in service life of reinforced concrete as Francois and Arliguie (1999) found through reviewing published literature. However, Wang et al. (1997) have shown that for crack opening displacement (COD) less than 50 microns under loading (≈ 15 microns after unloading), the crack width had little effect on concrete permeability. This limit is called "threshold crack width." With the COD be-

tween 50 and 200 microns under loading (≈ 15 and 65 microns after unloading), concrete permeability increased rapidly and for COD over 200 microns, the rate of permeability increase became steady and less rapid (Wang et al. 1997). Recently, Jang et al. (2011) found the threshold crack width is about 80 microns, for chloride ion diffusion.

Visible cracks, (COD > 50 microns) are known as macroscopic cracks (Francois and Arliguie, 1999). Addition to microcracks, macroscopic cracks are highly probable to occur in concrete sleepers. For example, several investigations in Sweden have indicated that approximately 500,000 of 3 million inspected sleepers had macroscopic cracks (Thun et al. 2008). Macroscopic cracks have a detrimental influence on corrosion of reinforcement in prestressed concrete and the test results show a doubling of crack width with time under cyclic loading can be expected (Nawy, 2010).

Besides microscopic and macroscopic cracks, there are other factors that influence the durability of concrete sleepers. For example Rail Seat Deterioration (RSD), which is relatively expensive to maintain, is produced by abrasion, freeze-thaw and hydraulic pressure (Bakharev and Stuble, 1997 and Zeman et al. 2009) and due to insufficient durability of the rail seat materials (Kernes et al. 2011). The durability of concrete sleepers largely depends on the ballast condition because it provides both support and drainage of water (Lutch et al. 2009). Additionally, the first three bending modes of sleepers significantly influence the durability of PCSs (Samuels and Palesano, 1987).

To ensure that the sleepers are durable enough, care and adjustment have to be exercised, from material selection, through production and curing process, handling, installation and maintenance. In this regard, using mineral and chemical additives, reinforcing fibres and various mix designs for concrete, some researchers have tried to increase the durability of sleepers.

To withstand the heavy load of torpedo car (common car in steel production plant), Hwang and colleagues have designed a Steel Fibre Reinforced Concrete (SFRC) with compressive strength 84 MPa (Hwang et al. 2011). They have used 234 kg/m³ of pozzolanic materials and 59 kg/m³ steel fibre in addition to superplasticizer to achieve the high strength. However the concrete reached higher than expected strength, 92 and 115 MPa at the ages of 28 and 133 days, respectively. The electrical resistivity of concrete at 28 days and 91 days were 44 and 128 k Ω -cm, respectively. The concrete has been categorised as one "with very low permeability" according to ASTM C1202 standard and with chloride ion penetration lower than 1,000 Coulombs. Furthermore, the concrete has shown neither failure nor

strength reduction after loading of 3 million cycles. Consequently, the authors have concluded that the SFRC may be considered to be durable concrete and suitable for sleeper construction.

The effects of different amounts of polypropylene fibre (PPF) on durability and other characteristic of concrete for application in sleepers have been experimentally studied by Ramezaniapour et al. (2013). By increasing the amount of PPF the compressive strength of concrete decreased, but both flexural and splitting strength increased first and then decreased with higher amounts. So they have concluded that the optimum amount of PPF was 0.7 kg/m³. With the addition of 0.7 kg/m³ PPF, the compressive strength of concrete has been found to decrease by 8.8%, however, both splitting tensile and flexural strength properties have been increased 39 % and 10 %, respectively. Further, the authors have conducted Scanning Electronic Microscope (SEM), X-ray Diffraction (XRD) analysis, Rapid Chloride Penetration Test (RCPT) and water penetration tests. They found that while the porosity of PPF concrete increases due to the amount of air trapped in the mixture in presence of the large fibres, the permeability and conductivity of concrete decrease because of blocking effect of PP fibres. The main conclusion is that adding PPF to concrete improves concrete resistance to penetration of ions which, in turn, may result in reduction of reinforcing corrosion. However, the application of the PPF concrete in sleepers has been ignored.

Rubberised Portland cement concrete is believed to improve the durability of concrete as well as mechanical properties such as impact resistance, sound insulation and damping ratio. The industrial production of rubberised Portland cement concrete sleepers has been started in the United States (Li et al. 2012). However, there are still many unsolved technical issues in the concrete design and construction of these sleepers.

Replacing cement with proper type and portion of fly ash can enhance the concrete durability. Curing conditions have been found to be the most important factor that affects the durability properties of fly ash concrete (Gopalan 1996). Although, replacement of cement with fly ash improves 90 days compressive and tensile strength of concrete, the replacement ratio is limited due to low early age strength which is important for demoulding requirements, especially, in steam-cured concrete sleepers. This issue may be solved by incorporating combination of 10% ground blast furnace slag (GBFS) and 20% fly ash that increases the compressive strength to the requirements of formwork removal after steam curing (He et al. 2010). The results from compressive tests that have been conducted by Liu and Xie (2012) show that the increase of fineness of Ultrafine Fly Ash Composite

(UFAC) has great influence on late strength, which indicates that the structure of concrete is densified and the durability of concrete is improved due to pozzolanic reaction at late age. In addition, Yu et al. (2010) have demonstrated that replacing of 20% of cement with perlite improved the durability of concrete sleepers.

7 CONCLUDING REMARKS

Increasingly used in railway track construction, especially, in high speed and heavy haul tracks, PCSs play an essential role in track performance and safety. Further, connecting the super-structure and sub-structure of the track, sleepers influence the track global behaviour. The behaviour of sleepers depends on the characteristics of other track components, especially, rail pads and ballast properties. This review demonstrates that some aspects of PCSs such as loading condition, static and dynamic responses of PCSs, energy absorption and interaction with track components have received widespread attention.

Cracks due to dynamic effects which appear on reel seat and mid-span are ranked as one of the prime concerns for PCSs. It is noted that they decrease the structural stiffness and make the PCSs susceptible to water and chloride ion penetration which may lead to a service life reduction. However, some researchers 'cautiously' believe the cracked sleepers have considerable residual strength and can withstand the intended loads while serving their design life.

To improve the durability aspects of PCSs, the effects of additional materials such as polypropylene fibre, rubberised cement, fly ash and ground blast furnace slag have been investigated. However, these investigations generally overlook the material performance under dynamic loads. This review establishes that further work needs to be done to better understand the requirements of PCSs in terms of high performance materials and their effects when subjected to high dynamic loads. This constitutes the research work which is currently continuing at the University of Melbourne.

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