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Fatigue of steel-fibre-reinforced concrete prestressed railway sleepers

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ABSTRACT

Prestressed concrete sleepers are one of the major components in any railway track system that distributes wheel loads from the rails to the underlying ballast bed. Concrete sleepers are usually designed with an expected life of 50 years. However, during their life span, sleepers may experience extreme loading conditions from infrequent but high-magnitude wheel loads produced by a small percentage of "bad" wheels or rail abnormalities. These loads can initiate cracking in the sleepers that reduces durability and increases the risk of fatigue failure of prestressing strands through undergoing millions of cyclic loads. The physical performances of the concrete sleeper such as durability, energy absorption, fatigue and toughness can be improved with the inclusion of steel fibres. This study investigates the efficiency of using steel fibres to improve load carrying capacity and fatigue performance of rail sleepers. Eight prestressed concrete sleepers were tested with fibre contents of zero, 0.25% or 0.5%, by volume, under constant amplitude cyclic and static loading. The sleepers with 0.5% fibres demonstrated higher static capacity and extended fatigue life, lower deflections and finer crack widths than that of sleepers without fibres. The sleepers with 0.25% (20 kg/m^3) fibres showed variable results and, in some cases, a reduced fatigue performance. It is demonstrated that a minimum volume of fibres is essential to ensure enhanced performance.

1. Introduction

Prestressed concrete sleepers have been utilised in the railway industry for over 50 years [1]. Sleepers are a major part of ballasted railway tracks. They transfer the wheel loads from the rails to the underlying ballast foundation and transversely secure the rails to maintain the correct gauge-width. It has generally been concluded that the train speed, the wheel or rail irregularity and the stiffness of the rail pad are the three most significant parameters that control the dynamic responses of the concrete sleepers [2–4].

During their life cycles railway track structures experience static, dynamic and often impact loading conditions. In Australia, concrete sleepers are designed to withstand up to 40 tonne axle loads. The magnitude of the dynamic loads per rail seat can vary from 200 kN to 600 kN, while the design static wheel load per rail seat for a 40-tonne axle load is just 110 kN [5,6]. The level of the dynamic load depends on the type and speed of the train, the track geometry, the wheel-rail interactions associated with abnormalities in either the wheel or the rail and the ballast reaction on the sleepers [7]. Typically, a few hundred wheel axles act sequentially on each sleeper during the passage of a single train. This can create two dynamic effects: (i) resonance phenomenon caused by the build-up of the response induced by a wheel impact on the sleeper; and (ii) fatigue caused by the repetitively acting loads [8].

Fatigue of concrete is a progressive process of micro-crack initiation and propagation that leads to macro-cracks that grow to the point at which failure occurs. Under repeated cyclic loading, the mechanical properties of concrete change; permanent strains in the concrete increase and the stiffness decreases. Cyclic loading may also cause micro-cracking in the prestressing wires that initiates a stress concentration at the wire surface that may lead to sudden fracture [9]. The design life span of a prestressed concrete sleeper is usually considered to be around 50 years [10]. The current design approach for concrete sleepers is based on a permissible stress concept and elastic analysis [11–13]. The elastic models currently used in design, however, do not accurately capture the change in behaviour with time or the susceptibility of concrete sleepers to creep and fatigue problems. In these approaches, creep and fatigue are minimised as the repetitive wheel actions in service are of a comparatively low magnitude [8,14]. To ensure adequacy against fatigue failure, standard tests under repeated loadings are prescribed in design standards [10,15,16]. However, significant deterioration has been observed in Sweden in some sleepers fabri-

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Notation

A_t	transformed area of nominal section	G_f	fracture energy
CMOD	crack mouth opening displacement	M_{cr}	cracking moment of the rail seat
e	eccentricity of the centroid of prestressing force	P	effective prestressing force
f'_c	characteristics compressive strength of concrete	P_{max}	maximum load level in load cycle
$f_{cm\ (28)}$	mean cylinder compressive strength (28 days)	P_{min}	minimum load level in load cycle
f_{cf}	flexural tensile strength	P_2	test load
$F_{R(j)}$	residual flexural tensile strength at CMOD, j mm	Z	transformed section modulus of un-cracked section

cated between 1992 and 1996, which were expected to have a service life of 50 years [17]. Testing was undertaken on 13 cracked sleepers subjected to 2 million load cycles, following the fatigue test procedure of the Swedish railway code. Seven of the thirteen sleepers failed the test, with just 6 passing surviving. It was concluded that understanding the system of internal cracking is crucial for determining the fatigue resistance of sleepers.

As long as the prestressed concrete sleeper remains uncracked, the probability of fatigue failure is low. However, if cracking occurs, fatigue resistance can become critical [18]. In practice, cracks in the concrete sleepers have been visually observed by many railway organizations and the occurrence of micro-cracks in concrete sleepers under service load is unavoidable [2]. The problems of cracking of a sleeper, and subsequent fatigue related damage, are largely due to the high intensity impact loads from wheel or rail irregularities such as wheel burns, dipped joints, rail corrugation, or defective track stiffness. In addition to their high magnitude, short-duration impact loads can initiate resonance in track components. Wheel or rail irregularities with certain shapes combined with the train speed can excite the natural flexural modes of the concrete sleeper and magnify the vibration – another common cause of concrete sleeper cracking [2,3,5]. Cracks lead to large increases in the stress range in the prestressing wire and this may result in the need for maintenance, reduced sleeper life and early replacement of sleepers [5,19]. The Australian railway industry spends approximately 25–35% of its annual budget on rail track maintenance [20].

While research into the performance of structures fabricated from steel-fibre-reinforced concrete (SFRC) has been ongoing for more than 50 years, SFRC remains an emerging material in practice. New types of 'structural fibres' have become available in the marketplace that, for the first time, rely on the structural properties of the fibre (high-strength, high-ductility wire), in addition to the anchorage performance of the fibres in the concrete matrix. With on-going development, new, highly engineered, fibres products can be expected to appear in the marketplace. It is now well established that steel fibres enhance ductility, durability, energy absorption, fatigue and toughness of quasi-brittle materials like concrete. At the structural level, fibres have shown to improve fatigue performance of reinforced concrete beams and greatly improve crack control. Full scale fatigue tests were conducted on SFRC beams by Parvez and Foster [21]. They demonstrated that SFRC beams had a significantly higher fatigue life than conventional reinforced concrete beams.

The use of high strength concrete (HSC) has increased rapidly in construction practice, despite it having a relatively low tensile strength and reduced ductility. The reduced ductility manifests itself as a reduction of some of the desirable structural properties, such as fatigue strength [22]. The brittle nature of HSC can be readily modified and ductility improved by the addition of fibres [23–25]. This indicates that steel fibres could be a viable means to increase the durability and fatigue strength of HSC prestressed sleepers.

Sadeghi et al. [26] studied the effects of steel fibres on the mechanical behaviour of prestressed concrete sleepers with the variability in steel fibre contents (0, 0.3, 0.5, 0.7 and 1% by volume) and number of prestressing wires. The results indicate steel fibres improve the sleeper bending strength, energy absorption capacity, and increase cracking resistance; and reveals existence of an optimum fibre dosage for best structural performance. For their test, the sleeper with six prestressing wires reinforced with 0.5% by volume of hybrid steel fibres was determined to be optimal considering compressive strength, bending capacity, construction cost, energy absorption capacity and service life.

Hwang et al. [27] designed SFRC prestressed sleepers with 0.75% by volume of steel fibres, with 30 mm long fibres and aspect ratio of 55. Repeated loading tests were performed according to the test manual of AREMA [15]. The SFRC sleepers passed repeated loading of 3 million cycles without failure and showed improved toughness and durability. However, this investigation did not quantify the degree of improvement in fatigue performance achieved by SFRC prestressed sleepers compared to conventional concrete sleepers.

This paper examines the fatigue behaviour of SFRC prestressed sleepers subjected to repeated cyclic loading. The prestressed concrete sleepers were designed to comply with Australian Standard: AS 1085.14 [10]. A total of eight prestressed sleepers with two different fibre volumes were investigated. The loading range was selected such that the plain sleepers would fail at approximately 1 million cycles. All sleepers, plain and SFRC, were tested until failure or until 3 million loading cycles were achieved, whichever came first. The results of the study are reported herein.

2. Experimental program

2.1. Specimen geometry and materials

The experimental program consisted of eight prestressed sleepers with fibre volume fraction as the main variable. The sleepers were in three groups with different fibre contents of 0.0, 0.25 and 0.5% by volume (0, 20 kg/m^3 and 40 kg/m^3 of fibre, respectively). The eight specimens are identified as SF00-1, 2, 3; SF20-1, 2, 3; and SF40-1, 2. The first two letters "SF" stand for "steel fibre", next two digits indicating the amount of fibres in kg/m^3, followed by a specimen number. The test program is given in Table 1.

The dimensions and details of the sleepers are given in Fig. 1. All the sleepers had identical geometry and prestress level. The sleepers had overall length of 2134 mm with nominal gauge length of 1067 mm. The cross sections varied over the length of the sleeper. At the edge, the cross section was 190 mm height and 254 mm width, then tapered down towards center with 183 $\times$ 254 mm section at the rail seat and 162 $\times$ 254 mm at the center. Each sleeper consisted of 18 prestressing wires with 26.4 kN prestressing force per wire; the sleepers comply with the requirements of AS 1085.14 [10]. The prestressing wire had a nominal diameter of