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Structural response of macro-synthetic fibre reinforced concrete sleeper under multiple impacts

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Abstract

A high-performance concrete sleeper with increased crack resistance and service life is in high demand in the railway industry. Macro-synthetic fibre reinforced concrete (MSFRC) sleepers are sought out of such alternatives due to their higher structural performance, corrosion and electrical resistance. Nevertheless, the knowledge on dynamic impact behaviour of MSFRC sleepers is limited, which impedes the service life predictions. Accordingly, the study herein presented evaluates the impact response of MSFRC sleepers experimentally.
The sleepers were subjected to multiple impacts simulating the in-filed impact magnitudes corresponding to 3,10 and 2000 return year periods. The structural performance of the MSFRC sleepers was compared against the conventional pre-stressed (CPS) sleepers based on impact and reaction force, displacement and damage observed. Finally, the damage stiffness was evaluated analytically. The results concluded the beneficial adaptations of the MSFRC sleepers in the railway network due to their capacity to retain the integrity under ultimate impact loads. Correspondingly, higher service life can be expected from MSFRC sleepers than CPS sleepers.

Keywords: fibre reinforced concrete, railway sleeper, low-velocity impact, bending stiffness

1 Introduction

Currently, the pre-stressed concrete sleeper is in the highest demand due to the higher mechanical properties, adaptability, and availability than the other conventional sleeper materials; timber and steel [1]. However, the pre-stressed concrete sleepers are still replaced frequently due to severe cracking, which incurs a considerable cost to the railway industry. Consequently, alternative sleepers are entering to market, out of which fibre-reinforcement is proven efficient. Currently, the most popular in this category is the fibre-polymer composite (FPC) because of its' light-weight and improved mechanical performance compared to timber sleepers [2]. However, FPC sleepers are yet failing to compete with the structural properties of the concrete sleepers, especially the dynamic stability, thus leaving the modified concrete as an effective solution. Therefore, the study presented herein assesses the applicability of fibre-reinforced concrete sleepers as inclusion of fibre reportedly improves the flexural-tensile strength, ductility, and crack resistance of the concrete elements under both static and impact loads [3]. Even though steel fibres possess comparatively higher mechanical properties, the macro-synthetic fibres were selected considering the better corrosion and electrical resistance.

The main reason for premature failure in concrete sleepers is the dynamic impact loads caused by wheel-rail irregularities [1]. These irregularities result in high amplitude impacts associated with higher frequencies [4]. The magnitude of these impact forces varies from 200 kN to 750 kN (about six times the static load), where frequency ranges up to 2000 Hz [5]. Futhermore, the literature suggests a brittle cracking of the pre-stressing concrete sleepers under impacts[5], which can be prevented by enhancing the ductility of the sleeper. Thus, the inclusion of fibre seems a promising alternative owing to the crack-bridging capacity of the fibres [6]. Accordingly, the suggested macro-synthetic fibre reinforce concrete (MSFRC) sleepers were experimentally impacted to evaluate the impact, crack and damage resistance compared to conventional pre-stressed concrete sleepers.

During their service life, sleepers are subjected to multiple impacts with different magnitudes, progressively reducing their integrity. Therefore, the experiments should be carried out under similar impact forces for realistic predictions. However, it is difficult to calculate the magnitudes of such impacts because of the associated complexities such as, non-uniformity of the irregularities, track stiffness, axle loading and the speed at a given time. Therefore, a study, which specifies the reliable magnitudes, based on the return period was used to determine the experimental force regime [7].

2 Methods

The sleepers subjected to experiments follow a typical heavy-haul railway sleeper profile in New South Wales (Australia). The control specimen (PO) consists of 20 pre-stressing strands while an additional 1% volume fraction of Polypropylene fibres were incorporated in the MSFRC sleepers (PF). The fibres used have a length of 48 mm and possess yield strength and Young's modulus of 640 and 12000 MPa respectively. The concrete mix of PO and PF was designed to achieve a compressive strength and a spread above 50 MPa and 500 mm, respectively.

The experimental evaluation of the impacts on the sleeper was carried out using a drop hammer testing rig, consisting of a drop hammer weighing 592 kg (impactor) with a load cell attached, a guidepost and a mechanical hoist for the drop weight. The load cell mounted on the impactor was used to measure the impact load. The supports were positioned to have a 660 mm clear span similar to the static test according to AS 1085.14-2012 [8]. Each support was equipped with two load cells to measure the reaction force. A laser beam was used to record the rail seat deflection, and four strain gauges were placed to get the maximum tensile and compression strains (Figure 1). The sleepers were subjected to multiple impacts under two different loading protocols, as shown in Table 1. The drop heights of 300, 500 and 1000 mm were determined based on trial drops to simulate 3-year, 10-year and 2000-year return period impacts.

Afterwards, the results were analysed based on Lam's approach, assuming no rebounce during the impact event [9]. This approach uses the conservation of the momentum (Equations 1 and 2) and energy (Equation 3) to predict the relationship between the deflection and stiffness based on the energy imparted. Since the impactor's velocity (just before the impact), relative mass and deflection are known, the stiffness of the target is calculated, rearranging Equation 3. However, the stiffness obtained is the dynamic damaged stiffness of the yielded samples, which represents the stiffness of the cracked samples assuming an elastic behaviour.

$$mv_0 = (1+\alpha)mv_1 \tag{1}$$

$$v_1 = \frac{v_0}{1+\alpha} \tag{2}$$

$$\frac{m{v_0}^2}{2}\left[\frac{1}{1+\alpha}\right] + (1+\alpha)mg\Delta = \alpha mg\Delta + \frac{k\Delta^2}{2} \tag{3}$$

Where:

m = Weight of the impactor

αm = Weight of the target

v_0 = Velocity of the impactor just before the impact

v_1 = Velocity of the target just after the impact

v_2 = Velocity of the impactor just after the impact

k = Stiffness of the target

Δ = The maximum deflection

g = Acceleration

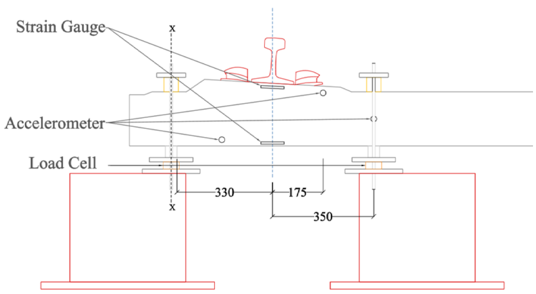

Figure 1: Experimental setup

	Loading Protocol 1			Loading Protocol 2		
	Drop Height (mm)	Energy Imparted (kJ)	Cumulative Energy Imparted (kJ)	Drop Height (mm)	Energy Imparted (kJ)	Cumulative Energy Imparted (kJ)
Drop 1	500	2.90	2.90	300	1.74	1.74
Drop 2	500	2.90	5.80	500	2.90	4.64
Drop 3	500	2.90	8.70	1000	5.80	10.44

Table 1: Energy imparted under multiple impact loading

3 Results

The impact and reaction force and displacement under each loading protocol for PO and PF are given in Table 2. The impact parameters under LP2 increased as the energy imparted on each drop increased. Contrary, under LP1, the parameters remained similar due to the constant energy imparted on each drop. According to the experimental results, no significant difference between PO and PF was observed under both protocols. The lesser PF reaction force under LP1 suggests that the stress transfer to the support is reduced with the incorporation of fibres. The deflection results for PO and PF are fairly consistent except for the final drop of LP2, which records a lesser deflection than PO. The last drop of LP2 is associated with a 2000-year return period which has caused severe damage in PO samples, as shown in Figure 2. Hence it can be concluded that the fibres delay the yield of the sleeper by improving the tension hardening properties of concrete. In addition, reduced crack propagation and damage evolution were observed in PF visibly. Consequently, the beneficial adaptation of MSFRC sleepers can be established qualitatively.

Loading Protocol	**Drop height (mm)**	**PO**			**PF**		
		Impact force (kN)	Reaction force (kN)	Deflection (mm)	Impact force (kN)	Reaction force (kN)	Deflection (mm)
LP1	500	447	310	6.1	462	347	5.3
	500	591	438	5.1	559	377	5.6
	500	588	466	5.8	564	414	5.2
LP2	300	420	273	3.6	373	270	5.6
	500	588	385	5.6	565	387	6.3
	1000	681	584	10.1	695	582	7.9

Table 2: Measured impact parameter of PO and PF under multiple impacts

Since the impact force or reaction force reading alone does not provide a comprehensive idea of the impact performance, the damage stiffness during an impact was calculated using Equation 3. Figure 3 shows the damage stiffness for each sample compared to static elastic bending stiffness, represented by a black dash line in each chart. A relatively lower bending stiffness was observed in PF samples for static and multiple impact loading, highlighting a possible increase in damping characteristics.

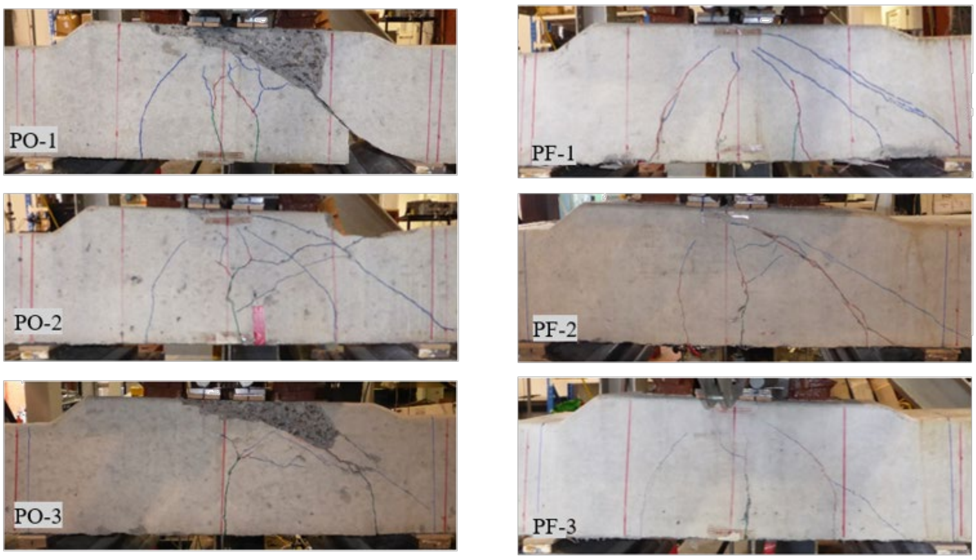

Figure 2: Damage of PO and PF samples under LP2

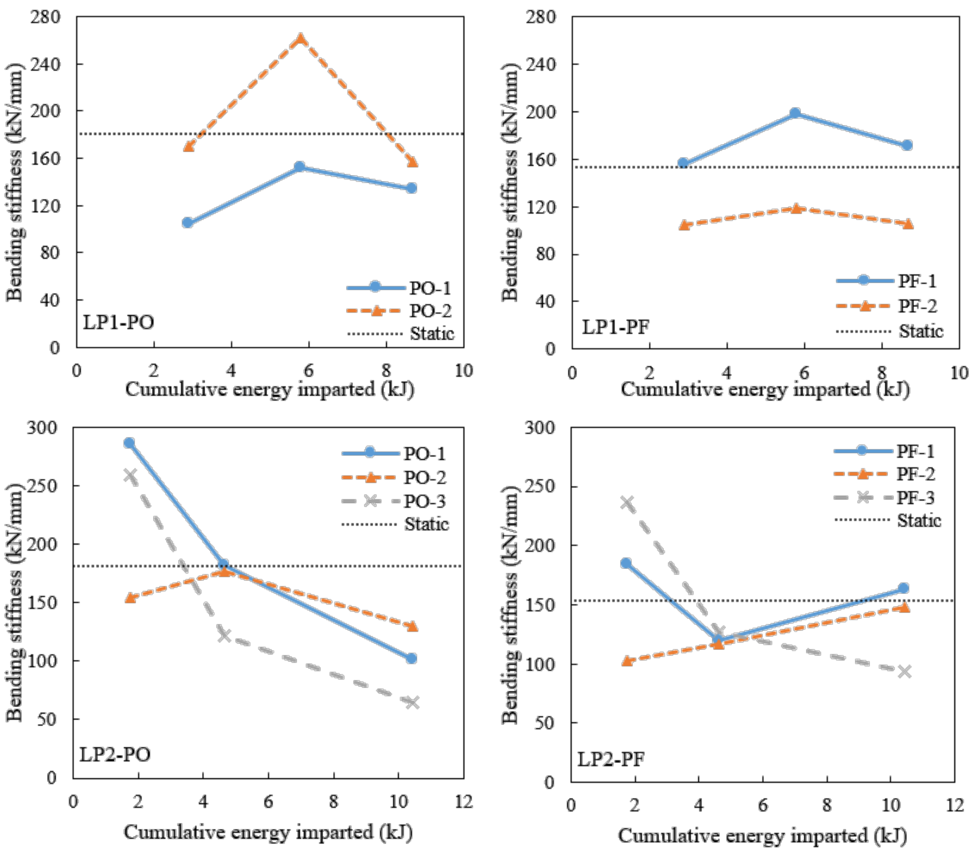

Figure 3: Calculated damage stiffness under multiple impacts

In LP2, PO stiffness has reduced with multiple impacts, in contrast to PF. Only PF-3 shows a stiffness reduction at the final drop, similar to PO. Larger flexural cracks at the bottom were apparent in all PO samples and PF-3, which is attributed to the stiffness reduction at the final impact. Contrary, both PF-1 and PF-2 showed significant flexural-shear cracks apart from the hair-line flexural cracks. Thus, in PF-1 and PF-2, bending stress has re-distributed, resulting in a stiffer behaviour. Consequently, fibres have prevented the formation of larger local cracks and damage. Such distributed cracks can improve the damping characteristics of the MSFRC sleepers.

4 Conclusions and Contributions

So far, no study predicts the fibre concrete impact behaviour under low strain rates and field measured impact forces. As a result, the direct application of such alternative sleepers has been delayed. Therefore, this study presented herein concludes the following beneficial adaptations of the synthetic fibre in concrete railway sleepers.

- Under multiple impacts, the fibre matrix distributes the stresses throughout the sleeper, reducing the fraction of the forces transferred to the support. Thus, MSFRC sleepers seem to provide a considerable advantage over conventional sleepers under multiple impacts associated with progressive failure.
- PO samples failed under multiple high-energy impacts, primarily having flexural-shear damage. However, the fibres have delayed the yielding of the PF samples by partially sharing the flexural stresses with the pre-stressing steel.
- The addition of fibres retained the sleeper integrity, preventing severe damages upon an impact of a 2000-year return period. Accordingly, higher service life can be expected from PF compared to PO.
- Higher stiffness in the damaged MSFRC samples was observed, concluding that the fibres effectively re-distribute the flexural stresses through the fibre matrix, thus causing distributed cracks rather than a localised macro-crack. A residual analysis, which is not presented in this paper, verifies this particular observation.

Most of the leading impact studies on pre-stressed and steel fibre reinforced concrete sleepers have only measured either the impact force or reaction force. The study presented herein further highlights that the impact force results alone do not represent the impact resistance of the sleeper. Therefore, additional evaluation based on the impact theories that use the reaction force and displacement is required in future impact studies on railway sleepers to quantify impact capacity.

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