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PERFORMANCE OF AN INNOVATIVE COMPOSITE RAILWAY SLEEPER

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Abstract

The high maintenance cost and scarcity of the hardwood timber promote alternative technologies for replacing the timber railway sleepers. The advantages of composites in high strength-to-weight ratio, durability, reliability, longer life and less maintenance are of great interest for their application in railway sleepers. This study investigated the performance of an innovative composite railway sleeper manufactured from sandwich panels and bonded with the epoxy polymer matrix. The performance including rail-seat vertical load, centre bending moment, shear strength, screw holding capacity and electrical resistance have been investigated and compared with the timber sleepers. Results showed that the new composite sleeper can maintain the minimum performance requirements and showed a very similar behaviour to the timber ones. This innovative composite technology could be a suitable replacement to the existing timber sleepers.

Keywords: Composite railway sleepers, performance, alternative technology

Introduction

The Australian rail networks, one of the longest in the world, consists of more than 40 thousand kilometres in length and the primary sleeper materials are timber, steel and concrete. In Queensland, 57% of the railway tracks are constructed using timber sleepers that equates about 10 million in total and requires over 400,000 timber sleepers per year to maintain them [1]. Approximately 100,000 mature hardwood trees need to be cut down to supply this sleeper demand which have a severe impact to the environment. Moreover, the supply of high quality hardwood for timber sleepers is becoming scarcer. In order to address these issues, the Queensland Railway (QR) has adopted a strategy of replacing timber sleepers by the alternative sleepers on a substantial basis to meet demands. This strategic plan is not only taken by the QR but it is also the current approach for sleeper maintenance all over the world.

The University of Southern Queensland has a long history of composite sleeper development which started in early 2000 to address the high demand for alternative timber sleeper replacements. The early developments produced an alternative sleeper with similar depth, stiffness and weight to that of the existing timber sleepers with the additional benefits of excellent durability, environmentally friendly and cost effectivity [2]. This sleeper was produced from polymer concrete reinforced with fibre composite materials wherein the amount of resin in the polymer concrete was higher in the tension zones comparing with the other parts. More recently, an innovative sleeper technology was developed using fibre composite sandwich panels and polymer concrete [3]. In addition to these novel composite sleepers, sleeper technologies made from recycled plastic materials are also available. The challenges of using these composite sleeper technologies are presented in [4]. This comprehensive review found that the recycled plastics are struggling to meet the minimum performance requirements for a railway sleeper although they have a reasonable price. On the other hand, the fibre reinforced polymer sleepers can meet the performance requirements satisfactorily, however, they are up to 10 times more expensive than the traditional timber sleepers. The inferior strength and stiffness properties of recycled plastic sleepers and the prohibitive cost of currently available fibre reinforced technologies have been identified as the primary reasons for their slow uptake in the market. There is a continuous need therefore to further engineer the composite sleepers to achieve reasonably priced sleepers without compromising their structural performance. This study investigated the performance of an alternative sleeper manufactured from composite sandwich panels and bonded with epoxy polymer matrix to replace the existing timber sleepers.

Materials

Composite sandwich panels and epoxy polymer matrix are the two materials that were employed in manufacturing the new composite railway sleepers. The sandwich panels were made up of 1.8 mm thick GFRP skins and 16.4 mm thick phenolic core with fibre volume ratio of 45%. The fibres were oriented in longitudinal (4 layers), transverse (2 layers) and $\pm 45^0$ angular (2 layers in each) directions that provide necessary strength and stiffness in different directions. The phenolic core material came from non-food based natural plant products derived from vegetable oils and plant extracts [5]. On the other hand, polymer concrete consists of filler bonded together with polymeric resin. Previous study by the authors [6] has suggested that the optimal polymer matrix can be achieved by mixing 40% filler with 60% resin (by volume). The two main constituents of resin systems named a DGEBA type epoxy resin and amine-based curing agent, three different filler materials a Fire Retardant Filler (FRF), Hollow Microsphere (HM) and Fly Ash (FA). The diameter of the round shaped filler materials were 75 to 95 microns for FRF, 20 to 300 microns for HM, and 0.1 to 30 microns for FA while the maximum size of coarse aggregate was 5 mm. The properties of the sandwich panels and epoxy polymer matrix are given in Table 1. The detail investigation of those properties can be found in [7] for sandwich panels and [6, 8] for epoxy polymer matrix.

Table 1: Properties of sandwich panels and epoxy polymer matrix

Test	Properties	Sandwich panels		Polymer matrix
		GFRP skin	Phenolic core	
Flexure	Elastic modulus (GPa)	14.28	1.33	-
	Peak stress (MPa)	450.39	14.32	45.09
	Strain at peak (%)	2.29	1.22	-
Tensile	Elastic modulus (GPa)	15.38	1.03	-
	Peak stress (MPa)	291.20	5.97	14.74
	Strain at peak (%)	1.61	0.61	-
	Poisson's ratio	0.25	-	-
Compressive	Elastic modulus (GPa)	16.10	1.33	1.66
	Peak stress (MPa)	238.04	21.35	65.56
	Strain at peak (%)	1.24	4.04	-
	Poisson's ratio	-	0.29	0.25
Shear	Shear modulus (GPa)	2.47	0.53	0.66
	Peak stress (MPa)	23.19	4.25	4.90
	Strain at peak (%)	3.08	0.81	-

Performance of Sleepers

The strength and stiffness of the composite sleeper should be compatible with those of timber during railway maintenance works. This compatibility is necessary to avoid the differential settlement of rail track. Prototype sleepers with optimal section were manufactured and their structural performance was evaluated experimentally and compared with those timber and standard requirements. The results of which are presented in the following sub-sections.

Rail seat vertical load and centre bending moment

Rail seat vertical load and centre bending moment tests are some of the most important performance characteristics required for the approval of new sleeper technology. Figure 1 shows the set-up for the rail-seat vertical load and centre bending moment tests in accordance with relevant Australian standard [9]. The experimental investigation was carried out in two rail seats and centre part of sleeper over 400 mm span at a load rate of 2 mm/min using 2000 kN capacity of SANS machine. Rubber pads were placed under loading and support points to prevent localised failure and then the experimental capacity of the sleeper was measured when the first crack occurred.

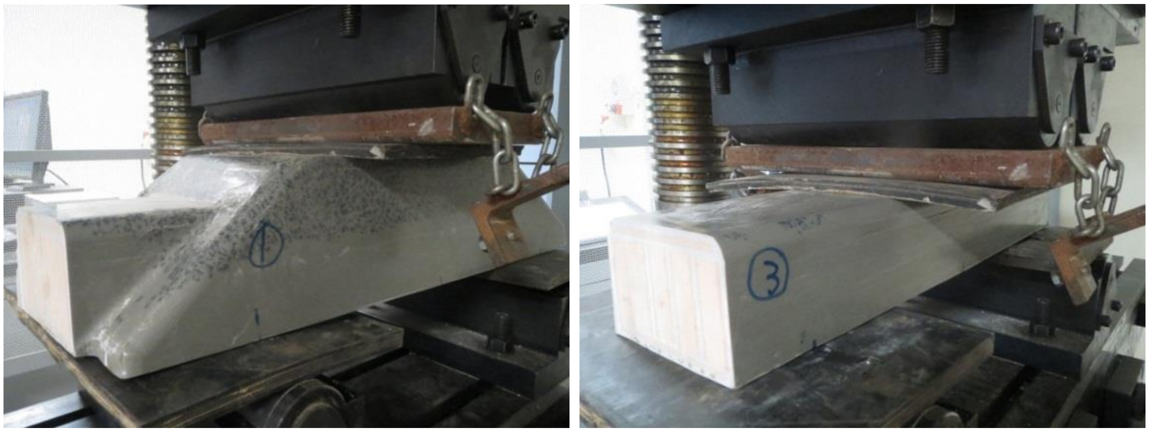

(a) vertical load test at rail seat (b) centre bending moment test

Fig. 1: Flexural capacity tests at rail seat and centre position

The results of the test are summarised in Table 2. As indicated, the first cracking in the rail seat of composite sleeper occurred at an applied moment of 24.02 kN-m. The load at which the first structural cracking occurs should be considered as a measure of the capacity of sleepers to avoid any cracks. However, it is worth noting that the sleeper continued to carry load up to an applied moment of 41.01 kN-m. The observed failures is due to compressive and shear failure of the fibre composite sandwich panel, the main structural component of the composite sleeper promoted flexural tensile cracking in the polymer matrix. On the other hand, the first sign of structural cracking was observed at the centre of the sleeper at a bending moment of 5.37 kN-m. Similarly, the specimen continued to carry load and failed at an applied moment of 19.97 kN-m. The maximum bending moment for narrow gauge sleeper occurred at the rail-seat (M_r) and the centre (M_c) of the sleeper can be determined from the rail-seat load ($R = 72\ kN$), distance between rail centres ($g = 1130\ mm$) and total sleeper length ($l = 2130\ mm$) by Eq. (1) and Eq. (2), respectively [10]. From Table 2 it can be seen that the first cracking moment capacity at the rail-seat and centre of the proposed composite sleepers are 3-times and 2-times higher than the maximum developed moment of 9 kN-m and 2.34 kN-m at the respective sections.

$$M_r = R\,\frac{(l-g)}{8} \tag{1}$$

$$M_c = R\left[\frac{g}{2} - \frac{l}{4}\right] \tag{2}$$

Table 2: Experimental results of rail seat vertical load and centre bending moment tests

Segment	First crack		Ultimate capacity		Maximum developed
	Load (kN)	Moment (kN-m)	Load (kN)	Moment (kN-m)	Moment (kN-m)
Rail-seat	240.2	24.02	410.1	41.01	9
Centre	53.7	5.37	199.7	19.97	2.34

Shear strength

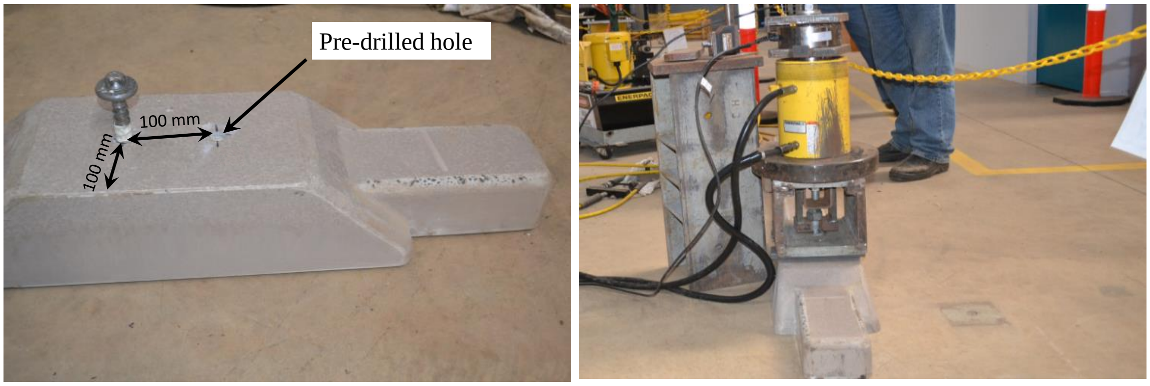
The shear strength of the composite sleeper was evaluated by asymmetrical beam shear test. The beams was eccentrically loaded at two trisected points and the supports were applied at the other two points with a shear span of 100 mm (Fig. 2a). This type of test method promote shear failure of the specimen by reducing the bending effect. Figure 2(b) shows the shear crack of the tested beam at 305 kN load. As the position of load cell was above the mid-section of the sleeper, the maximum shear force experienced by the sleeper is only half of the failure load. Therefore, the shear strength of 120 mm × 80 mm section was obtained 15.89 MPa which is approximately 4-times greater than the shear strength of the softwood timber of 4 MPa [4]. This results further show the effectiveness of using the sandwich panels in the vertical position to achieve a high shear strength sleepers.

(a) asymmetrical beam shear test setup (b) shear test of the beam

Fig. 2: Shear capacity test of the composite sleeper

Screw holding capacity

The low anchorage capacity of the composite sleepers is identified a major challenge for their slow uptake in the market [4]. The screw is primarily used to hold down the baseplates that attach sleepers to the rails and prevent lateral and vertical movements between them. The screw holding capacity of the composite railway sleepers are evaluated through direct withdrawal test. The screw used in the fastening system has a diameter of 16 mm with 125 mm of length and can be inserted into a pre-drilled hole using petrol driven rattle-gun. Two screws were inserted in the rail-seat area at a distance of 100 mm from the edge and 100 mm between the two holes (Fig. 3a). A loading head and jig (Fig. 3b) was used to pull-out the screw using a 500 kN hydraulic jack at a rate of 2 mm/min and the maximum value of pulling force was determined. The average screw withdrawal resistance of the composite railway sleeper was found to be 74 kN and showed a reasonably consistent results between two locations at rail-seat region with a maximum variation of 10%. This magnitude is well above 40 kN pulling force which is the minimum required screw holding capacity for timber sleepers according to AS1085.18 [11]. Similarly, the consistent results indicate that the proximity of the holes will not affect the screw spike resistance. These results demonstrated that the innovative composite sleepers can overcome the limitations of low screw holding capacity of most the existing plastic sleepers.



(a) Screw inserted at different locations (b) direct pull-out test

Fig. 3: Pulling strength test of screw

Electrical resistance

The railway sleepers should have sufficient electrical resistance to minimise the problems for signalling, particularly in track-circuited areas. Resistance was measured in both dry and wet conditions of sleeper. The rain was simulated by sprinkling water on the sleepers as shown in Figure 4(a). After preparing the sleepers for testing, a 26 volts and 13 volts AC 50 Hertz potential was applied between the two screws at rail seat location (Fig. 4b). This range of voltage and frequency is within the limit of 10 to 40 volts AC at 50 Hertz according to AS 1085.19 [12]. The magnitude of current flow was measured after 15 minutes of applying the voltage for getting a stable dial reading. The electrical impedance was determined from the applied voltage divided by the current flow through sleeper from one end to another as provided in Table 3. According to the American Railway Engineering and Maintenance-of-way Association (AREMA) specification, the minimum required impedance is 10 kilo-ohms when a wetted sleeper is subjected to 10 volts AC 60 Hz between two rails for a period of 15 minutes [13]. The impedance of dry and wet sleepers shall not be less than 1000 kilo-ohms and 4 kilo-ohms, respectively according to the Australian Standard AS 1085.19. This indicates the proposed composite sleeper satisfactorily meet the electrical impedance requirements.

Table 3: Electrical impedance determination in dry and wet conditions

Test condition	Performance of composite sleeper			Minimum requirements, kΩ	
	Voltage, V	Current, μA	Resistance, kΩ	AS 1085.19	AREMA
Dry	26.00	4.6	5650	1000	-
	12.98	2.3	5640		
Wet	26.03	7.7	3380	4	10


(a) spraying water on the sleeper (b) applying voltage between rail-seats

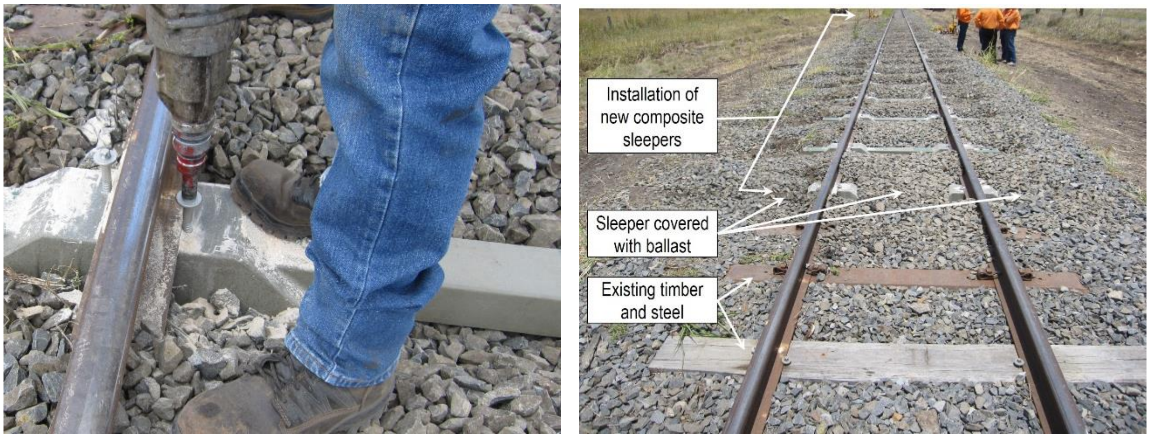
Fig. 4: Electrical impedance test

In-track Installation and Performance

A total of 50 sleepers have been installed on a trial basis in the Southern line rail track at Nobby, Queensland as shown in Figure 5 to investigate the in-track performance of the new composite sleeper. The existing track was constructed with timber and steel sleepers (Fig. 5a) where timber was only replaced by the alternative composite sleeper. The conventional machineries for timber sleepers were used (Fig. 5b). After removing the existing timber sleeper from the rail-track, the composite one was inserted below the rail using the installation machineries. The screw fastening system inserted into the sleeper at two opposite sides of the rail that can hold the rail and sleeper in correct gauge (Fig. 5c). The installation process and fastening systems of composite sleeper are similar to the installation of timber sleepers.

Report has been published on the derailment failures of sleeper and in this case the damaged sleepers need to be replaced which increases the track maintenance costs [14]. The non-uniform optimal shape of the composite sleepers usually covered by the ballast when installed in the track as shown in Figure 5(d). This ballast cover not only protects the sleeper from the potential damage caused by derailment but also keep lower the surface temperature from the extreme heat by sun. The non-uniform shape of composite sleepers increase the lateral stability of track by creating superior interlock between sleeper and ballast. However, the handling and installation of the sleeper requires careful attention due to this non-uniform shape. The long term performance, particularly fatigue needs to be investigated to increase the confidence of using this new technology. A high durability against the environment is expected due to its outer polymer coating which is able to resist moisture ingression, ultraviolet radiation and chemical attack [8]. Moreover, it is also expected a high resistance against fire during welding of joints adjacent to sleeper due to the use of fire retardant filler in polymer concrete. As the new composite sleepers can maintain the standard performance requirements and showed a very similar behaviour to the timber, this technology could be a suitable replacement to the existing timber sleepers.

(a) existing track with timber and steel (b) composite sleeper installation



(c) fastening system installation (d) timber replaced by composite sleepers

Fig. 5: Installation of composite sleepers replacing existing timber

Conclusions and Recommendations

This study evaluated the performance of an innovative composite railway sleeper for a possible replacement of existing timber sleepers from which the following conclusions are drawn:

- The first cracking moment capacity at the rail-seat and centre of the composite sleepers are 3-times and 2-times higher than the maximum developed moment in the respective sections. Moreover, the shear strength of the composite sleeper is approximately 4-times greater than the softwood timber.
- The screw withdrawal resistance of the composite railway sleeper is obtained 74 kN which is well above 40 kN, the minimum requirements of timber sleeper.
- The composite sleeper satisfactorily meet the minimum electrical impedance requirements in both dry and wet conditions.
- The installation process and fastening systems of the composite sleepers are similar to timber sleepers and compatible with the conventional machineries.

The innovative composite sleeper could be a suitable replacement to the existing timber sleepers due to their very similar behaviour. To increase the confidence of using this innovative composite sleeper technology, the following studies need to be investigated.

- The tracks often induce high-magnitude impact loads and million cycles repeated loads, the impact resistance and fatigue behaviour of composite sleepers are inevitably required to define safety and reliability based design.
- The long-term performances of composite sleeper such as creep deformation and lateral track resistance are critical issues as their continuous service over time has a significant effect on their mechanical properties.
- Establishing design guidelines are important as it will provide instructions to the design engineers for a safe and reliable design of composite sleepers.

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