Hybrid FRP-concrete railway sleeper

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ABSTRACT

The aim of this research was to investigate the feasibility of a hybrid FRP-concrete beam as a rail sleeper. It was hoped that the new design would overcome some of the sustainability issues associated with traditional sleepers. The hybrid system consisted of a Rectangular Hollow Section (RHS) pultruded profile filled with geo-polymer concrete. The specimens were tested in a four-point bending setup to determine the flexural properties such as the bending modulus (E) and modulus of rupture (MOR). It was found that the proposed composite beam satisfied the minimum flexural requirements for composite railway sleepers as stated in the American Railway Engineering and Maintenance-of-way Association (AREMA) and the Chicago Transit Authority (CTA) standards. In many aspects, the novel system exhibited equal or better performance when compared with existing railway sleepers.

INTRODUCTION

These days, the most commonly used materials for railway sleepers are timber, steel and concrete. High maintenance cost, installation issues, deterioration of materials, and environmental considerations are among the factors that prompt research and industry to seek a different and more efficient system. Approximately three billion sleepers are currently used in rail networks around the world [1]. The big problem inherent in timber sleepers is their susceptibility to mechanical and biological degradation, including rotting, splitting, insect infestation, plate-cutting (abrasive damage to a sleeper due to lateral motion of its plate) and spike-pull (when a spike is gradually loosened from a sleeper) which lead to their failure. Although preservatives are used to prevent timber sleepers rotting and splitting, this protection is unable to improve their overall performances [2]. Recently environmental agencies have also become concerned about the application of chemical preservatives in timber sleepers and their proper disposal when the sleepers’ removal [3]. Around the 1880s, due to the scarcity of timber and the sensitivity towards its use, steel railway sleepers, which are much stronger than timber and less expensive than pre-stressed concrete, were introduced. Observations of rail deflections under imposed vehicle track loadings have shown that steel sleepers deflect more greatly than timber ones, which indicates that steel and adjacent timber sleepers do not carry even proportions of an imposed wheel loading [4]. Another worrying aspect is their fatigue cracking at the rail seat region, which leads to their failure. As the good conductivity of steel sleepers creates problems for signalling, special care is required in track-circuited areas. Also, their acceptance is decreasing due to their risks of corrosion and other chemical attacks [5]. The advantages of concrete technology led to the use of concrete for sleepers in the 1950s. Now-a-days, approximately 500 million railway sleepers in the world’s railway networks are made from concrete and, every year, the demand for them constitutes more than 50% of total demand [1, 6]. However, the heavy weight, high initial cost, low impact resistance and susceptibility to chemical attack (delayed ettringite formation, alkali-aggregate reaction, etc.) of mono-block prestressed concrete sleepers are major problems [7-9].

Recently, there has been a growing tendency among civil engineering material researchers to replace existing materials for sleepers with alternative environmentally friendly substances, e.g: Palomo in Spain [10] and Uhera in Japan [11] are testing geopolymer concrete; Manalo [12], Sckisui [13], Pattamaprom [14], Hoger [15], Cromberge [16], Lampo [17] and some other companies [18, 19] are trying to develop composite sleeper; and other researchers [20-22] are investigating retrofitting existing timber sleepers to make them more suitable. Nonetheless, the railway industry is using mainly the three old materials instead of the recently invented composite sleeper which cannot be manufactured within the allowable cost range and has not produced results from long-term performance testing.

Many advantages of pultruded FRP composites [23, 24] and fly ash-based geopolymer concrete [25-27] favour their application in composite railway sleepers. To date, very limited attempts have been
made to use these materials independently in civil engineering infrastructure but combining them for application in railway sleepers has not yet been examined. Researchers [21, 22, 28, 29] are now thinking of using fibre composites as alternative materials for railway sleepers. Successful achievements may come by combining a fibre composite with a geopolymer concrete as both have good characteristic properties.

MATERIALS

Aggregates

Three different sizes of coarse aggregates (14 mm, 10 mm and 7 mm) obtained in crushed rock form and fine aggregate in uncrushed form were used to prepare concrete in the laboratory. The specific gravity of aggregate was measured according to relevant ASTM standard.

Cement

Cement was used to prepare normal concrete composite beam for the comparison with fly ash based geopolymer composite beam. ASTM C188 was followed to measure the specific gravity.

Fly Ash

Fly ash was obtained from the Boral Company, Australia, and used in this research as the main constituent of the binding materials in geopolymer concrete. Its specific gravity was measured using the same procedure described in ASTM C188 for cement. The XRF analysis showed that the percentage sum of SiO₂, Al₂O₃ and Fe₂O₃ in the fly ash was around 93% which ensured that the fly ash used was a Class F type. Chemical compositions of cement and fly ash are given in Table 1.

<table>
<thead>
<tr>
<th>Oxide (%)</th>
<th>SiO₂</th>
<th>CaO</th>
<th>Al₂O₃</th>
<th>MgO</th>
<th>Fe₂O₃</th>
<th>SO₃</th>
<th>TiO₂</th>
<th>Na₂O</th>
<th>K₂O</th>
<th>L.O.I</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fly ash</td>
<td>62.19</td>
<td>1.97</td>
<td>27.15</td>
<td>0.40</td>
<td>3.23</td>
<td>0.07</td>
<td>1.06</td>
<td>0.30</td>
<td>0.89</td>
<td>1.75</td>
</tr>
<tr>
<td>Cement</td>
<td>20.18</td>
<td>65.94</td>
<td>4.14</td>
<td>1.77</td>
<td>3.65</td>
<td>2.61</td>
<td>0.19</td>
<td>0.06</td>
<td>0.62</td>
<td>0.56</td>
</tr>
</tbody>
</table>

Alkaline Liquid

In the present experimental work, a combination of sodium silicate (Na₂SiO₃) and sodium hydroxide (NaOH) solutions with molarity 16M was chosen as the alkaline liquid. The sodium silicate solution was obtained from IMCD Australia Limited and the sodium hydroxide solution was prepared in the laboratory by dissolving sodium hydroxide pellets in water.

Super-plasticiser

A super-plasticiser was used to improve the workability of fresh geopolymer concrete. A carboxylic ether polymer-based super-plasticiser under the brand name ADVA 142 was applied in the concrete mix.

Pultruded FRP Composite

In this research, a glass-fibre pultruded rectangular composite profile having dimensions of 190 mm × 100 mm × 2 m was selected to manufacture the beams. Three beams using geopolymer concrete filler and three other using normal concrete were cast for comparison purposes. The necessary properties of materials used in this research are given in Table 2.
Table 2. Properties of beam constituents

<table>
<thead>
<tr>
<th>Types of material</th>
<th>Cross section, (mm)</th>
<th>Modulus of elasticity, $E_p$ (MPa)</th>
<th>Ultimate strength, (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pultruded FRP composites</td>
<td>$190\times100\times10$</td>
<td>$E_p = 28870$</td>
<td>301</td>
</tr>
<tr>
<td>Normal cement concrete</td>
<td>-</td>
<td>$E_{nc} = 30000$</td>
<td>57</td>
</tr>
<tr>
<td>Geopolymer concrete</td>
<td>-</td>
<td>$E_{gc} = 19000$</td>
<td>40</td>
</tr>
</tbody>
</table>

EXPERIMENTAL PROGRAMS

Preparation of Composite Beams

To facilitate the pouring of the concrete, three pultruded hollow profiles were placed on a base-plate to provide better support at the bottom of the beam as shown in Fig. 1. The normal concrete beams were cast on the same day using the same mix to minimise variations. A similar process was also used for the geopolymer concrete beams.

Curing of Beams

Since a pultruded FRP profile can encapsulate the moisture within the concrete inside the beam, it was not necessary to keep the normal concrete beams in a highly moisturised room. However, as geopolymer concrete requires heating to accelerate its polymerisation process, a power blanket able to be heated up to 71°C, was used to heat the geopolymer beams as shown in Fig. 2. All the three geopolymer concrete beams were wrapped in this blanket and placed vertically for heating. This heating lasted for 3 days from the day after casting. After hardening, all the beams were stored in a temperature controlled room at 23°C with 50% humidity. The beams shown in Fig.2 were specifically marked and their corresponding cylinders stored in the same room under sealed conditions until testing.
**Test Set-Up and Procedure**

The six beams were tested along the weak axis in a four-point bending setup to determine the flexural properties such as the bending modulus (E) and modulus of rupture (MOR). All the beams have the same span length of 1440 mm that is slightly higher than 1435 mm, which is the standard gauge length of railways in Australia. To measure the mid-span deflection, two linear variable differential transformers’ (LVDT) were placed on each side of the beams. The beams were tested under displacement control at a constant rate of 1 mm/min. The schematic test setup arrangements are shown in Fig. 3.

![Figure 3. Schematic diagram of test setup](image)

**RESULTS AND DISCUSSION**

**Load-Displacement Behaviour**

The load-deflection responses at the mid-spans of the tested composite beams are given in Fig. 4.

![Figure 4. Load-displacement curves for four point bending](image)

The curves are slightly nonlinear. Ultimate failures of the geopolymer composite beams occurred at loads 91, 99 and 96 kN but, for the normal concrete composite beams, it happened at loads 120, 111 and 115 kN. This was due to the lower strength of 40 MPa of the geopolymer concrete obtained after heat curing using the power blanket. On the other hand, the compressive strength of the portland cement concrete was 57 MPa. As the load increased, failure was initiated in the pultruded FRP composites along the longitudinal direction of the beams and their stiffness slightly decreased from the first stage. Similar observations were noticed by other researchers [30, 31] who studied the behaviour.
of the concrete-filled Glass-FRP tubes under four-point bending. At the time of failure, composite profile split with the concrete protruding out by up to 1 mm at both ends of the beam shown in Fig. 5.

![Fig 5. Failure of beams: (a) normal concrete; and (b) geopolymer concrete](image)

**Effective Modulus of Rupture (MOR) of Sleepers**

The MOR is defined as the maximum capacity of a member in bending and can be computed by the bending stress equation given in Eq. (1) [32]. This estimation is essential as the sleepers’ bending performance depends on it.

\[
\text{MOR} = \frac{MC}{I_z}
\]  

(1)

Where \( M \), \( C \) and \( I_z \) are the bending moment, distance of the neutral axis from the outer most fibre of FRP composite calculated using Eq. (2) and the transformed moment of inertia with respect to neutral axis respectively.

\[
C = \begin{cases} 
\frac{h}{2} & \text{before tension cracking of concrete} \\
(h-y) & \text{after tension cracking of concrete}
\end{cases}
\]  

(2)

Here, ‘\( h \)’ is the depth of the section and the distance of the neutral axis from the top of the section is represented by ‘\( y \)’.

The fundamental assumptions relating to flexure stated that the material of beam should be homogeneous. But in the present case, the beams are non-homogeneous in that they are made of two entirely different materials. Therefore, the flexural analysis should be different from those used in homogeneous beams. The section of beam is considered as a virtual equivalent homogeneous section where the actual area of the FRP composite is replaced with an equivalent concrete area depending on the modulus of elasticity of these two materials depicted in Fig. 6.
Flexural Performance of Composite Sleeper

Performance Compared With Existing Composite Sleeper

The minimum requirements for the MOR recommended by the AREMA and CTA, and those of other existing composite railway sleepers [18, 32-34] are presented in Fig. 7 together with the average obtained for the present tests. It can be seen that the proposed composite sleeper satisfies the minimum requirements of the AREMA and CTA standards, and also performed better in terms of MOR than the other existing composite sleepers.
Performance Compared With Traditional Timber Sleeper

The MORs of traditional timber sleepers under different conditions measured by Duckworth [35] and Reid [36] are compared with that of the present composite sleeper and shown in Fig. 8, which indicates that the flexural strength of the proposed composite sleeper is above the lower value of traditional timber sleepers.

<table>
<thead>
<tr>
<th>Traditional Sleeper Conditions</th>
<th>Measured by Duckworth</th>
<th>Measured by Reid</th>
<th>Alternative</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hardwood dry untreated</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Hardwood green untreated</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Hardwood green treated and incised</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Hardwood dry treated</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Hardwood green treated</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Hardwood timber sleeper</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Softwood timber sleeper</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Proposed composite sleeper</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Figure 8. Comparison of MORs of different timber sleepers

Performance Compared With Prestressed Concrete Sleeper

Eq. (3) represented the rail seat load for the design of prestressed concrete sleeper according to Australian standard AS 1085.14.

\[
R = j \times Q \times \frac{DF}{100}
\]  \hspace{1cm} (3)

Where \(j\) is the design load factor (2.5), \(Q\) is static wheel load (125 kN), and \(DF\) is the axle load distribution factor (52% for 610mm spacing [37]) which estimates the design rail seat load \((R)\), 163 kN. If the proposed composite railway sleepers are placed in the real track with standard gauge length (1435 mm) and a sleeper spacing of 610 mm, the bending moment developed at the mid section of sleeper can be obtained from the uniformly distributed ballast pressure under the sleeper according to AS 1085.14 presented in Fig. 9 and Eq. (4).

\[
M = \frac{R(2g-I)}{4}
\]  \hspace{1cm} (4)

Figure 9. Load diagram of concrete sleeper for centre bending moment
This provided 15.08 kN-m moments at the centre of the sleeper. Where ‘$g$’ and ‘$M_c$’ are the gauge length and moment developed at centre of the sleeper due to rail seat load respectively. Now, let’s check the sectional moment capacity of the proposed composite sleeper.

Sectional moment capacity of the proposed composite sleeper

The sectional analysis is based on the following assumptions:

(a) A cross section that was plane before bending remains plane after bending;
(b) Concrete in tension is ignored and the concrete above the neutral axis is under a uniform compression stress as depicted in Fig. 10.

![Figure 10. Stress distribution at ultimate load](image)

Strain at different level can be calculated as

$\varepsilon_1 = \frac{\varepsilon_c y}{y - t}$

$\varepsilon_2 = \frac{\varepsilon_c}{y - t}(h - y - t)$

$\varepsilon_3 = \frac{\varepsilon_c}{y - t}(h - y)$

Where, the force can be represented by

$F_{p1} = \frac{E_p(\varepsilon_c + \varepsilon_1)bt}{2}$

$F_{p2} = \frac{E_p\varepsilon_c}{2}[2(y - t)t]$  

$F_{p3} = \frac{E_p\varepsilon_2}{2}[2(h - y - t)t]$  

$F_{p4} = \frac{E_p(\varepsilon_2 + \varepsilon_3)bt}{2}$  

$F_c = \alpha f'c \beta(y - t)(b - 2t)$

Here, ‘$y$’ is the depth of neutral axis from the top which can be calculated from the static equilibrium condition.

$\Sigma F_{tension} = \Sigma F_{compression}$

Now, it is obtained that, $\varepsilon_1$, and $\varepsilon_3$ both are less than the ultimate tensile strain of pultruded FRP composite, $\varepsilon_p = 0.011$. The location of each force from the top of the section is obtained as follows:

$y_{p1} = \frac{(\varepsilon_1 + 2\varepsilon_c)t}{3(\varepsilon_1 + \varepsilon_c)}$  

$y_{p2} = t + \frac{3(\varepsilon_1 + \varepsilon_c)}{(y - t)}$  

$y_{p3} = y + \frac{2}{3}(h - y - t)$
\[ y_{Fp4} = h - \frac{(\varepsilon_2 + 2\varepsilon_2)t}{3(\varepsilon_3 + \varepsilon_2)} \]

\[ y_{Fc} = t + \frac{\beta(y - t)}{2} \]

The internal moment developed at the failure of concrete in compression can be calculated as:

\[ M_{int} = -F_{p1}(y_{Fc} - y_{Fp1}) - F_{p2}(y_{Fc} - y_{Fp2}) + F_{p3}(y_{Fp3} - y_{Fc}) + F_{p4}(y_{Fp4} - y_{Fc}) \]

Mertol et al. [38] used the following relationship for \( \alpha \) and \( \beta \) depending on 28-day compressive strength of concrete.

\[ \alpha = \begin{cases} 0.85 & \text{for } f'_c \leq 69 \text{ MPa} \\ 0.85 - 0.0129(f'_c - 69) & \text{for } f'_c > 69 \text{ MPa} \end{cases} \]

\[ \beta = \begin{cases} 0.85 & \text{for } f'_c \leq 28 \text{ MPa} \\ 0.85 - 0.007252(f'_c - 28) & \text{for } f'_c > 28 \text{ MPa} \end{cases} \]

The moment developed in the real track (15.08 kN-m) is well below the theoretical sectional moment capacity (21.25 kN-m). The failure load predicted from sectional analysis showed good correlation with the experimental results given in Table 3.

**Table 3. Predicted and experimental failure load of composite beam**

<table>
<thead>
<tr>
<th>Properties</th>
<th>Theoretical</th>
<th>Experimental (Ave.)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>( P_1 ) (kN)</td>
<td>( M_{u1} ) (kN-m)</td>
</tr>
<tr>
<td>Normal concrete beam</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
| \( b = 190 \text{ mm}; h = 100 \text{ mm}; t = 10 \text{ mm}; \)  
\( \varepsilon_c = 0.003; f'_c = 57 \text{ MPa}; E_p = 28870 \text{ MPa.} \) | 100.14       | 24.03               | 115.33         | 27.68          |
| Geopolymer concrete beam          |             |                     |
| \( b = 190 \text{ mm}; h = 100 \text{ mm}; t = 10 \text{ mm}; \)  
\( \varepsilon_c = 0.003; f'_c = 40 \text{ MPa}; E_p = 28870 \text{ MPa.} \) | 88.53        | 21.25               | 95.33          | 22.88          |

**Effective Modulus of Elasticity (E) of Sleepers**

In the design of a composite structure, stiffness is considered one of its important parameters along with strength. Stiffness is measured in terms of an equivalent modulus of elasticity of the structure in the elastic ranges of stress and strain. It is calculated using the static mechanics of the four-point bending test represented in Eq. (5):

\[
E = \frac{23\Sigma F \times L^3}{648 \times I_x \times \Delta_m}
\] (5)

Where \( E \), \( P \), \( L \), \( I_x \) and \( \Delta_m \) are the flexural modulus of elasticity of the beam (MPa), total load on the beam acting in both load points (N), span length between the two supports (mm), transformed moment of inertia with respect to neutral axis and the deflection at the mid-span (mm) respectively. Before concrete cracking, the transformed moment of inertia was calculated with respect to the centroidal axis while it was computed about the shifted neutral axis after tension cracking. Variations in its flexural rigidity (EI) with displacement is plotted after getting stabilized the beam which given in Fig. 11.
Fig. 12 compares the equivalent modulus of elasticity of the proposed alternative composite sleeper with those of the other existing composite sleepers [18, 32-34] which shows that it satisfied the minimum requirements of the CTA standard and was well above those of the other existing composite sleepers.

CONCLUSIONS
The theoretical prediction to estimate the failure load of the composite beam showed a good agreement with the experimental results. The technical procedure and testing methods for determining the static performances of composite railway sleepers were studied experimentally, and it was shown that the proposed composite beam satisfied the minimum flexural requirements for composite railway sleepers stated in the AREMA and CTA standards and also showed satisfactory performance when compared with existing railway sleepers. Finally, this study concluded that introducing this novel, environmentally friendly, composite railway sleeper to the railway industry may prove to be a viable alternative.
REFERENCES

5. ARTC, TCS 10: Steel Sleepers – Usage and Installation Standards 2009, Australian Rail Track Corporation
13. Sckisui FFU Synthetic Railway Sleepers. SEKISUI Chemical GmbH.


