Mechanical Behaviour of a New Type of Fibre Composite Railway Sleeper

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ABSTRACT

This paper presents the results of an experimental investigation on the flexural and shear behaviour of a new type of fibre composite sleeper for railway turnout application. The building block of this innovative railway sleeper is a new generation composite sandwich structure made up of glass fibre composite skins and modified phenolic core material that has been specifically developed for civil engineering applications. Three different section configurations for railway sleepers were produced by gluing layers of fibre composite sandwich structure together in flatwise (horizontal) and in edgewise (vertical) orientations and tested under 4-point static bending and asymmetrical beam shear tests. The effects of the orientation of sandwich lamination on the mechanical behavior of sleepers were investigated. The capacity of the fibre composite sleepers in holding spike-screws was also evaluated. The results showed that the orientation of sandwich laminations has a significant effect on the mechanical behavior of fibre composite railway sleepers. The sleeper section with glued sandwich structures in the edgewise position presented appropriate strength and stiffness for railway sleeper application and has high resistance to hold screw spikes. The mechanical properties of the fibre composite sleeper are far better than most of the available composite railway sleepers and are comparable with the existing timber turnout sleepers demonstrating that the new fibre composite sleeper is a viable alternative sleeper material for railway turnouts.

KEYWORD

Fibre composites, sandwich structures, railway sleepers, flexure, shear
1. INTRODUCTION

Timber sleepers have a long history of effective and reliable performance in the railway environment [1]. As a sleeper material, timber deteriorates with time and needs appropriate replacement in order to maintain track quality to a specified service level and ensure a safe track operation. In recent years, hardwood timber for railway sleepers is becoming more expensive, less available and of inferior quality compared to the timber previously available. This problem is greater in specific locations of the railway track such as turnouts where hardwood timber continues to be the most widely used sleeper material. Turnout is a part of the railway where track crosses one another at an angle to divert a train from the original track [2]. The structure of a turnout is complicated and requires special sleepers with varying lengths and fastening locations [3]. The difficulty of obtaining large section and quality hardwood timber has resulted in most railway industries searching for alternative materials for replacement timber sleepers.

Significant efforts have been provided towards the development of composite sleeper alternatives. Several fibre composite sleeper technologies have been evolved from concept development to the construction and deployment of full-scale prototypes for trial testing. These earlier developments are for standard applications only which are not cost competitive with conventional sleeper materials. A review conducted by Manalo et al. [4] suggested that fibre composites are viable alternative sleeper materials in railway turnouts where stronger, larger and longer timber sleepers are required. Fibre composites can be produced with similar usability and design characteristics to that of hardwood sleepers and provide flexibility to be drilled in-situ for attachment of rail fasteners. This material can also provide longevity of 50 to 100 years, and become a carbon sink as well as being less of a pollutant than other alternatives.

The design of most structures using fibre composite materials has been driven by stiffness requirement rather than strength [5]. This drawback of fibre composite materials has been overcome with the development of innovative materials and structures utilising the inherent advantages of this material. An example of this efficient structure is the composite sandwich panel. Recently, a new type of composite sandwich panel has been developed for structural applications [6]. Extensive investigation have been completed to understand the behaviour of the individual sandwich structure. A study on the innovative concept using small-scale glued sandwich beams has indicated that the strength and stiffness of this sandwich structure is suitable for structural beam application [7]. However, the test of small specimens is most of the time not representative of the behavior of actual structures. More importantly, testing of full-scale specimens provides a broader representative of the structural behavior.

In this study, the mechanical behaviour of the full-size glue-laminated fibre composite sandwich structure is investigated and evaluated based on the performance requirements for a railway turnout sleeper. The effects of the orientation of sandwich laminations on the strength, stiffness and capacity to hold mechanical connections are investigated. It is anticipated that the results of this study will provide valuable information necessary to facilitate the actual application of this innovative beam concept in a railway turnout.

2. EXPERIMENTAL PROGRAM

2.1 Material properties

The fibre composite turnout sleeper is made up of structural composite sandwich panel manufactured by LOC Composites Pty Ltd., Australia. This novel sandwich panel is made up of glass fibre composite skins co-cured onto the phenolic core material using a toughened phenol formaldehyde resin [6] and has a nominal thickness of 18 mm. The skin is made up of 2 layers of bi-axial [0°/90°] glass fibre fabrics with a chopped strand mat and has a total thickness of 3 mm. The mechanical properties of the fibre composite skin and the phenolic core are listed in Table 1.

| Table 1 Properties of fibre skin and phenolic core |
|-----------------------------------------------|--------|--------|--------|
| Test              | Property   | Skin   | Core   |
| Flexure           | Modulus (MPa) | 14,280 | 1,330  |
|                  | Peak stress (MPa) | 317    | 14.3   |
|                  | Strain at peak (%) | 2.29   | 1.22   |
| Tensile           | Modulus (MPa) | 15,380 | 1,032  |
|                  | Peak stress (MPa) | 247    | 6      |
|                  | Strain at peak (%) | 1.87   | 0.61   |
| Compression       | Modulus (MPa) | 16,102 | 1,350  |
|                  | Peak stress (MPa) | 201    | 23     |
|                  | Strain at peak (%) | 1.56   | 3.51   |
| Shear             | Modulus (MPa) | 2465   | 520    |
|                  | Peak stress (MPa) | 27.8   | 4.5    |
|                  | Strain at peak (%) | 2.38   | 0.81   |
2.2 Manufacturing of full-scale sleepers

The turnout sleeper was fabricated by gluing together a number of fibre composite sandwich panels to form a uniform cross section of 150 mm deep and 230 mm wide for timber turnout sleepers as per required by AS 3818.2 [8]. To attain this dimension, the beam with edgewise lamination was produced by gluing 13 sandwich panels while the beam with flatwise lamination with 8 sandwich panels. Another beam with combined sandwich laminations was prepared. In this beam section, the topmost and bottommost laminations are oriented in the flatwise position while the middle portion is oriented in the edgewise position. Figure 1 shows the full-size composite turnout sleepers.

2.3 Test specimens

The full-scale specimens tested in flexure has a total length of 2400 mm while the specimens tested under asymmetrical beam shear are 600 mm long. Table 2 lists the description of the test specimens. In the specimen designation, 4F and AS correspond to beams tested under static 4-point bending and asymmetrical beam shear, respectively, TS for turnout sandwich, and F, E, and C represent the orientation of the laminations.

<table>
<thead>
<tr>
<th>Name</th>
<th>Orientation</th>
<th>Test</th>
</tr>
</thead>
<tbody>
<tr>
<td>4F-TS-F</td>
<td>Flatwise</td>
<td>Flexure</td>
</tr>
<tr>
<td>4F-TS-E</td>
<td>Edgewise</td>
<td>Flexure</td>
</tr>
<tr>
<td>4F-TS-C</td>
<td>Combined</td>
<td>Flexure</td>
</tr>
<tr>
<td>AS-TS-F</td>
<td>Flatwise</td>
<td>Shear</td>
</tr>
<tr>
<td>AS-TS-E</td>
<td>Edgewise</td>
<td>Shear</td>
</tr>
<tr>
<td>AS-TS-C</td>
<td>Combined</td>
<td>Shear</td>
</tr>
</tbody>
</table>

2.4 Test set-up and procedure

Figure 2 shows the test set-up for the 4-point static bending test of fibre composite turnout sleeper. The load was applied at 0.4 and at 0.6 of the span through a 2000 kN universal testing machine with a loading rate of 5 mm/min. The asymmetrical beam shear test was performed following the set-up in Figure 3. All the specimens were tested up to failure to determine the strength and the failure mechanisms. The applied load and displacement were recorded using a data logger.

2.5 Screw-spike withdrawal resistance

The low pull-out force of the mechanical connection in most fibre composite sleepers is considered the most likely reason for sudden catastrophic failure of the track system due to derailments [9]. Thus, the holding resistance of the composite sleepers to a 24 mm diameter and 165 mm long ‘R’ type screw-spike was evaluated through direct withdrawal test. Clearance holes measuring 17 mm in diameter were drilled and the screw spikes were then screwed into these holes until the clearance under the head was 45 mm. A loading head and jig was used to pull-out the spikes from the sleepers. Figure 4 shows the test set-up and the location of the holes in specimen.
3. RESULTS AND OBSERVATIONS

3.1 Failure load and mechanisms
Table 3 summarizes the failure load of the fibre composite sleepers under 4-point static bending and asymmetrical beam shear tests. The level of load where the compressive failure of the topmost skin was observed was taken as the failure load in flexure. For specimens tested under asymmetrical beam shear, the first drop in the load corresponds to the maximum load that the sleepers could carry.

Table 3. Failure load of composite turnout sleepers

<table>
<thead>
<tr>
<th>Specimen</th>
<th>Flexure, kN</th>
<th>Shear, kN</th>
</tr>
</thead>
<tbody>
<tr>
<td>TS-F</td>
<td>162</td>
<td>512</td>
</tr>
<tr>
<td>TS-E</td>
<td>225</td>
<td>1,314</td>
</tr>
<tr>
<td>TS-C</td>
<td>144</td>
<td>1,121</td>
</tr>
</tbody>
</table>

Based on the result of the investigation, the sleeper with laminations in the edgewise position has the highest failure load in both flexure and shear among the beam configurations considered.

3.2 Flexural behaviour

(a) Load-displacement relationship
The load and midspan deflection behaviour of the full-scale fibre composite sleepers is shown in Figure 5. The figure shows that the load of all the sleeper specimens increased almost linearly with deflection with a slight reduction in stiffness due to tensile cracking of the core. The specimens then continued to carry the load until final failure.

![Fig.5 Load and midspan deflection relationship](image)

Flexural cracks were developed in the core of the bottommost sandwich laminations in specimen 4F-TS-F wherein the cracks in the core propagated to the core of the next sandwich layers indicating continual stress redistribution among the sandwich laminations. The specimen then failed by compressive failure of the topmost skin and debonding of the skins near the loading plates outside the constant moment region (Figure 6a). Tensile cracks of the core were observed in specimen 4F-TS-E at 100 kN. The vertical skins prevented the tensile cracks in the core from widening to cause failure however, compressive failure on the outermost skins was then observed. The continuous application of the load caused the skin to debond from the core and made the detached skins to buckle. Simultaneously, tensile cracks in the core and the skin at the bottom of the beam developed. The final failure of the 4F-TS-E occurred only when compressive failure of the inner (and bonded), and crushing of the core were observed leading to its total collapse (Figure 6b).

(b) Failure behavior in flexure
Figure 6 shows the failure behaviour of fibre composite sleepers under the 4-point bending test. Flexural cracks were observed in the core of the bottommost sandwich laminations in specimen 4F-TS-F but this did not lead to failure. The increasing load caused the propagation of the cracks to the core of the next sandwich layers leading to the simultaneous compressive failure of the fibre composite skin, crushing of the core and tensile splitting of the skins.
3.3 Shear behaviour

(a) Load and crosshead displacement relationship
Figure 7 shows the load and crosshead displacement behaviour of the fibre composite sleepers under asymmetrical beam shear test. For specimen AS-TS-F, the load increased linearly with the displacement of the crosshead until final failure. A sudden drop in the applied load was observed which indicated the final failure of the specimen. For specimens AS-TS-F and AS-TS-C, the load increased linearly with the crosshead displacement but became non-linear at higher load. This non-linear behaviour is due to the initiation of shear failure in the vertical fibre composite skins with some indentation failure in the core under the loading point and at the support.

(b) Failure behavior in shear
Figure 8 shows the failure of fibre composite sleepers under asymmetrical beam shear test. The three section configurations showed different failure behaviours. The failure is typically initiated at the maximum shear region between the inner support and the loading points.
The specimen AS-TS-F failed abruptly due to shear failure of the core (Figure 8a). In contrast, the failure behaviour of specimens AS-TS-E and AS-TS-C is progressive. The specimen AS-TS-E failed due to shear failure of the skins and the core with some delamination between the sandwich laminations (Figure 8b). A shear failure in the outermost skins of the edgewise laminations in specimen AS-TS-C was observed. The continuous application of the load caused the debonding of both the top and bottom sandwich laminations (Figure 8c). This debonding failure can be attributed to the lower shear strength of the core compared to that of the skins and epoxy adhesives.

3.4 Screw-spike resistance
The screw-spikes remained in the specimens throughout the test; however the force simply decreased after reaching the maximum value as the spike started to pull out. Table 4 summarises the results of the pull-out test of screw spikes. The screw-spike withdrawal resistance in glued sandwich beams varies between 62 and 68 kN for specimen with edgewise laminations and between 60 and 64 kN with flatwise laminations. This shows that the presence of horizontal skins did not significantly contribute to the mechanical holding resistance of the beams. This can be due to the relative thinness of the skin compared to the core.

<table>
<thead>
<tr>
<th>Test no.</th>
<th>Orientation</th>
<th>Location</th>
<th>Peak load (kN)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Flatwise</td>
<td>Skin</td>
<td>63.91</td>
</tr>
<tr>
<td>2</td>
<td>Edgewise</td>
<td>Core</td>
<td>64.85</td>
</tr>
<tr>
<td>3</td>
<td>Flatwise</td>
<td>Skin</td>
<td>60.31</td>
</tr>
<tr>
<td>4</td>
<td>Edgewise</td>
<td>Skin</td>
<td>62.61</td>
</tr>
<tr>
<td>5</td>
<td>Edgewise</td>
<td>Skin</td>
<td>68.83</td>
</tr>
<tr>
<td>6</td>
<td>Edgewise</td>
<td>Core</td>
<td>62.47</td>
</tr>
</tbody>
</table>

4. DISCUSSION

4.1 Effect of sandwich orientation on stiffness
There is no significant difference in the bending stiffness of the full-scale sandwich beams with different section configurations in the linear elastic region as shown in Figure 5. However, an overall reduction in stiffness was observed when flexural cracking of the core occurred in sleepers 4F-TS-F and 4F-TS-C. On the other hand, the vertical skins in specimen 4F-TS-E prevented the formation of tensile cracks in the core resulting to an almost constant stiffness of the beam until final failure. This result suggests that the specimen with edgewise laminations offers a more constant stiffness throughout the whole loading regime among the different configurations investigated.

4.2 Effect of orientation on bending strength
The sandwich orientation has a remarkable effect on the flexural strength. Based on the results, the specimen 4F-TS-E failed with the highest bending moment among the different sections investigated. The high failure load of specimens with edgewise sandwich lamination is due to the presence of the vertical skins which increases the loading capacity of the beams. On the average, the specimens with edgewise sandwich laminations is 20% stronger than that of specimens with flatwise laminations only and with combined sandwich laminations.

The failure behaviour of all the specimens depends largely on the compressive strength of the skins. In specimens 4F-TS-F and 4F-TS-C, the sandwich laminations at the topmost and bottommost layers were subjected to the highest bending stresses. Since the skin has lower compressive strength than tensile strength, the topmost sandwich layer became the weakest link among the laminations which eventually controls the system strength. The specimen 4F-TS-E is the most reasonable beam configuration amongst the investigated sandwich beams when stiffness and maximum load are taken into account. This section configuration is also the easiest to manufacture especially if certain dimensions need to be followed like in spot replacement where the depth of the beams should match that of the existing sleepers.

4.3 Effect of orientation on shear strength
The orientation of sandwich laminations has a predominant effect on the shear behaviour of sleepers from glue-laminated sandwich beams. The results showed that the shear strength of specimens AS-TS-E and AS-TS-C is more than double that of specimen AS-TS-F (see Table 3). This is due to the contribution of the vertical skins in carrying the shear. The effectiveness of vertical fibre composite laminates to carry shear has already proven effective in increasing shear capacity of structures when Triantafillou [10] externally bonded CFRP laminates to structural timber in the critical shear zones. One of the requirements in producing fibre composite sleepers is that, it should not split or crack due to shear in any way requiring replacement of the sleeper [9]. This clearly shows that the fibre composite sleepers with edgewise sandwich laminations are very promising from a shear strength point of view.
4.4 Effect of orientation on spike resistance
The resistance to hold screw-spike was quite high for both sleeper configurations (with flatwise and with edgewise laminations) with the level of load to pull out the spike is almost the same. The main reason could be that this resistance to hold mechanical connections was provided mainly by the core with minimal contribution from the fibre composite skin as it is relatively thin compared to the core. It is also expected that the resistance of the sleeper section with combined sandwich laminations is also the same for specimen with either flatwise or edgewise lamination only. This shows that the phenolic core material has sufficient strength to hold mechanical connections as the screw-spike withdrawal resistance is higher compared to that of the usual Red Oak hardwood sleeper which has only around 38 kN [11]. Conversely, the high resistance to pull out screw spikes from glue-laminated sandwich beams can address the inability of most composite sleepers to meet the requirements for mechanical connections and shows that it can provide a comfort level to installing these sleepers in field trials. However, tests on other types of fastening inserts such as dog spikes and dog screw spikes should be conducted to determine the safest and most reliable railway fasteners to fibre composite sleepers. The method of installation and removal of these railway fasteners are different which may cause splitting and/or damage to the glue-laminated composite sandwich beams. Similarly, dynamic test on these different mechanical fasteners is necessary.

4.5 Comparison with other composite sleepers
Table 5 compares the mechanical properties of the new fibre composite turnout sleeper concepts to that of the existing timber sleepers and some of the available composite sleepers and the minimum performance requirements recommended by the American Railway Engineering and Maintenance-of-way Association (AREMA). In the table, sleeper A, B and C represent turnout sleeper made up of sandwich beam with flatwise, edgewise and combined laminations respectively, D for existing timber railway turnout sleepers [12], E for AREMA [11], F for Dynamic Composites LLC [13], G for IntegriCo [14], H for Tieteck™ [15] and I for Eslon Neo Lumber (Sekisui sleeper) [16]. On the other hand, the \( MOE, \sigma_b \) and \( \tau \) correspond to the modulus of elasticity, bending strength, shear strength (in MPa), and SSW is the screw-spike withdrawal resistance in kN of the fibre composite railway sleepers, respectively.

Table 5 Properties of composite railway sleepers

<table>
<thead>
<tr>
<th>Sleeper</th>
<th>MOE</th>
<th>( \sigma_b )</th>
<th>( \tau )</th>
<th>SSW</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>5.01</td>
<td>75.48</td>
<td>7.32</td>
<td>62.21</td>
</tr>
<tr>
<td>B</td>
<td>5.19</td>
<td>103.19</td>
<td>18.74</td>
<td>63.76</td>
</tr>
<tr>
<td>C</td>
<td>5.05</td>
<td>66.76</td>
<td>16.82</td>
<td>--</td>
</tr>
<tr>
<td>D</td>
<td>7-26</td>
<td>64-160</td>
<td>2-7</td>
<td>38</td>
</tr>
<tr>
<td>E</td>
<td>1.17</td>
<td>13.81</td>
<td>6.22</td>
<td>22.21</td>
</tr>
<tr>
<td>F</td>
<td>1.73</td>
<td>17.92</td>
<td>--</td>
<td>17.82</td>
</tr>
<tr>
<td>G</td>
<td>2.00</td>
<td>24.21</td>
<td>--</td>
<td>16.63</td>
</tr>
<tr>
<td>H</td>
<td>1.24</td>
<td>13.86</td>
<td>--</td>
<td>17.80</td>
</tr>
<tr>
<td>I</td>
<td>8.10</td>
<td>142.03</td>
<td>10.22</td>
<td>65.00</td>
</tr>
</tbody>
</table>

The comparison shows that all the composite sleeper configurations made from glued sandwich beams have mechanical properties comparable to that of the existing timber turnout sleepers. The mechanical properties of these new composite sleepers are also higher than the recommended values by AREMA and the available composite sleepers, except for one with higher strength and stiffness. The low mechanical properties of most of the currently available fibre composite sleepers indicate that these sleepers are not suitable for turnout application. This further justifies the need to develop a cost effective fibre composite turnout sleeper with an approved structural performance.

5. CONCLUSIONS

This paper presented the investigation onto the mechanical behavior of sleepers made from glue-laminated fibre composite sandwich beams and evaluation against the performance requirements for a railway turnout application. Based on the results of this study, the following conclusions can be drawn:

1. The orientation of sandwich laminations has a significant effect on the behaviour of the railway sleepers made from glue-laminated fibre composite sandwich beams.
2. Composite sleepers with edgewise sandwich laminations showed the most efficient section among the investigated beam configurations.
3. Glue-laminated fibre composite sandwich beam has strength and stiffness suitable for railway turnout sleeper application.
4. The phenolic core material provides the composite sleepers with a high resistance to pull out screw spikes.
5. The new composite turnout sleeper has better mechanical properties than most of the commercially available composite sleepers.
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