The influence of sleeper material characteristics on track behaviour

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ABSTRACT

Composite materials, typically consisting of polymers reinforced with steel or fibres, have been proposed by sleeper manufacturers as an effective and environmentally sustainable alternative to more traditional sleeper materials, such as timber and prestressed steel reinforced concrete. However, composite sleepers are significantly softer and more flexible than their concrete counterparts and may not be as stiff in bending as some hardwood sleepers.

To understand the effect of sleeper material properties on track mechanical response, laboratory tests have been carried out in the Southampton Railway Testing Facility using a fibre reinforced composite and a prestressed steel reinforced concrete sleeper. Tests showed that composite sleepers, being softer and more flexible, offer a more compliant sleeper/ballast interface, with more and larger ballast grain contacts, but are characterised by more exaggerated deflection profiles and greater propensity to become centre-bound. This should be taken into account in the design and selection of composite sleepers.

BACKGROUND

Railway sleepers are essential components of the railway track, whose mechanical properties have a significant effect on track performance, durability and safety.

On modern railways, timber sleepers have largely been replaced by prestressed steel reinforced concrete sleepers, which have greater durability and strength. However, compared with timber, concrete introduces a much harder interface between the sleeper and the ballast, potentially raising the contact stresses on the ballast grains and causing greater ballast damage.

Because of these disadvantages there are still locations along routes where timber sleepers may be preferred such as over susceptible older structures like bridges and at locations where impact loads may be present such as at S&C and at transitions. At locations where timber sleepers or bearers still offer advantages in the short term they suffer from a major disadvantage in that their design life is relatively short.

An alternative to the use of timber sleepers is the use of sleepers formed of composite materials. Composite sleepers are available from a number of suppliers but all generally offer a much more compliant sleeper/ballast interface similar to that provided by timber sleepers but with the advantage of a design life similar to that of prestressed steel reinforced concrete sleepers [1]. However, their bending stiffness is significantly less than concrete sleepers and only composite sleepers reinforced with steel or fibres have a bending stiffness similar to that of a hardwood timber sleeper [2].

The bending stiffness may potentially have a significant effect on stress transfer from the rails onto the ballast bed, influencing track resilient response, the development of ballast permanent deformation with train passage and, in turn, sleeper propensity to become centre-bound.

To better understand the role of sleeper bending stiffness on performance, laboratory tests were carried out in the Southampton Railway Testing Facility (SRTF) using a common steel prestressed concrete sleeper

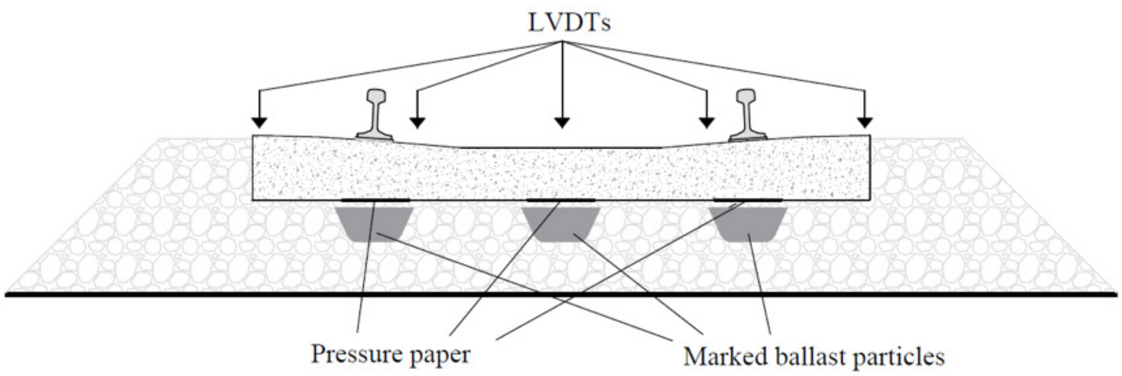

Figure 2. Schematics of samples and system used to acquire measurements

Figure 1: Photo of the testing rig

and a relatively soft and much more flexible composite sleeper. Numerical modelling was also carried out to gain insights into trackbed stress transfer for the initial case of a sleeper on a uniform support of varied bending stiffness.

TESTING MATERIALS AND METHODS

The testing rig is a laboratory representation of a single sleeper bay extended to the shoulders under plane strain conditions (figure 1). In each test, a cyclic sinusoidal load representative of a 20 tonne train axle was applied using a hydraulic actuator at a frequency of 3Hz to 3 million cycles, i.e. 60 MGT (million gross tonnes).

The sleepers were placed on a 300 mm thick layer of granite ballast, underlain by a 12 mm thick rubber mat designed to reproduce the resilient response of a good subgrade. The ballast was laid to form shoulders with slopes of approximately 45°, which is close to ballast's natural angle of repose and represents an extreme scenario for a single track route.

Fresh granite ballast representative of the material placed on UK mainlines was used in each test and compacted to provide an initially uniform support. Further details of the testing apparatus and a description of sample preparation protocols are given in [3,4].

The primary test outputs are sleeper resilient and permanent displacement, sleeper/ballast contact and ballast damage. The sleeper vertical displacements were monitored by means of linear variable displacement transducers (LVDTs) installed at both sleeper ends, near the rail seats and at mid-sleeper. Pressure sensitive paper was attached to the sleeper base.

This is marked by ballast grains applying a pressure greater than 10 MPa and was used to evaluate the number and area of the sleeper/ballast contacts accumulated throughout each test [5]. More than 300 marked ballast grains were placed under the sleepers in the top half of the ballast bed to assess ballast damage in terms of percentage mass loss, representative of grain wear and chipping, and number of broken grains. A schematic of the system used to acquire test data is shown in figure 2.

A standard type G44 prestressed steel reinforced concrete sleeper and a composite sleeper formed of long continuous longitudinal glass fibres in a polyurethane matrix [6] were tested. The latter is shown in figure 3. The sleepers were 2.5 m long and had similar widths (285 mm and 260 mm respectively). The composite sleeper was approximately 7 times more flexible in bending than its concrete counterpart and had a softer base that could be indented by the high localised sleeper/ballast contact stresses.

TEST RESULTS

The resilient deformed shapes at maximum load of the sleepers in the short term (after 10 cycles to allow for initial bedding in) and in the long term (after 3 million cycles) are shown in figure 4. At 10 loading cycles the composite sleeper showed a pronounced w-shaped deflection which contrasts with the slightly hogging deformed shape exhibited by the stiffer concrete sleeper.

With loading cycles, the composite sleeper showed a dramatic increase of sleeper end deflections, moving towards a centre-bound condition.

In both tests, the magnitudes of the resilient (i.e. recoverable) deflection of the sleeper ends increased with the number of loading cycles while the middle resilient deflections reduced (figure 3). This can be explained by the differential settlement of the ballast along the length of the sleeper. The ballast under the middle of the sleeper is well-confined and compacts/densifies under repeated loading, becoming stiffer and remaining in contact with the sleeper base. Beneath the rails and close to the sleeper ends, the ballast initially compacts/densifies but is more susceptible to lateral strain, owing to a combination of higher vertical contact stresses under the rails and light lateral confinement provided by the shoulders.

This allows the ballast to spread laterally developing gaps between the sleeper ends and the ballast for a portion of the load cycle. Figure 5 shows a conceptual impression of the primary mechanisms of sleeper settlement. In the region indicated by (a) the primary mechanism of settlement is ballast densification, in region (b) the more lightly confined ballast is able to strain laterally leaving the sleeper ends less supported as the test progresses. These mechanisms of sleeper settlement are an extreme case for a single track route with steep ballast shoulders on either side.

The different resilient behaviours observed for the composite and concrete sleepers at the beginning of the tests, when the ballast support is still substantially uniform, may be attributed to their significantly different flexibilities. The effect of sleeper bending stiffness on the resilient deflections in the short term, can be replicated numerically using a simple beam on elastic foundation (BOEF) model [7,8], where the sleeper is regarded as an Euler-Bernoulli beam of uniform flexural rigidity EI supported by a uniform distribution of elastic springs of modulus k_s, loaded at the rails (figure 6).

A BOEF model of a uniformly supported sleeper was implemented into a MATLAB finite difference code. This was used to investigate the effect of sleeper bending stiffness on the distribution of the resilient deflections and ballast pressure. The results are shown in figure 7 for a support modulus k_s = 50 MN/m^2 (this is approximately equivalent to a spring stiffness per sleeper end of 62.5 kN/mm), representative of good quality ballast and subgrade, and a 2.5 m long sleeper of width W=0.27 m, height H = 0.17 m and second moment of area I =$1.1{\cdot}10^{-4}$ m^4. The sleeper Young's modulus E was varied between 8 GPa and 36 GPa. The upper bound of this range is representative of concrete, the lower bound of reinforced composite.

Consistent with the laboratory test, the BOEF model showed a w-shaped sleeper deflection for Young's moduli typical of composite materials used for sleeper manufacture (Figure 7). According to the BOEF model, composite sleepers are also associated with greater peak ballast stresses under the rails (figure 7 secondary vertical axes). The greater unevenness of deflected shape and pressure distribution shown by the more flexible composite sleeper may have contributed to the mechanism of ballast lateral spreading that led to the sleeper becoming centre-bound in the longer term. However, while in the laboratory tests the ballast is prepared to provide an initially uniform sleeper support, on real tracks it is packed more densely under the rails during tamping operations, attenuating the tendency of the sleeper to become centre-bound.

The sleepers showed similar permanent settlement with increasing number of loading cycles, although the composite sleeper settled more rapidly (figure 8).

Figure 3. Photo of the composite sleeper tested (steel plates were attached to allow the installation of the LVDTs)

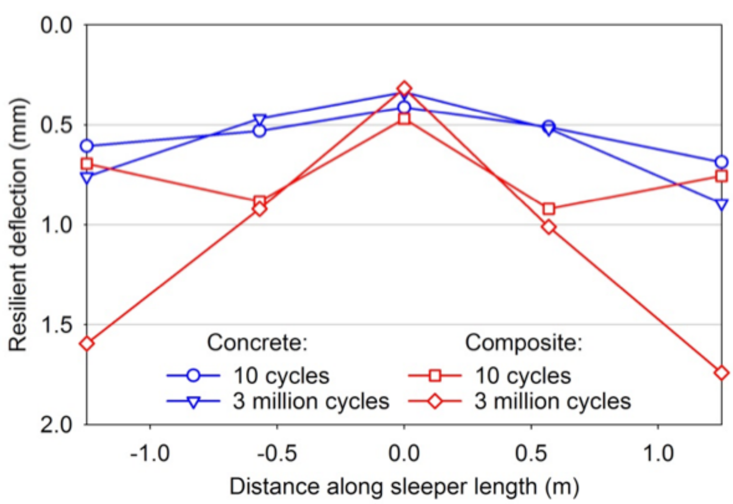

Figure 4. Distribution of sleeper resilient deflections at the beginning and at the end of the tests

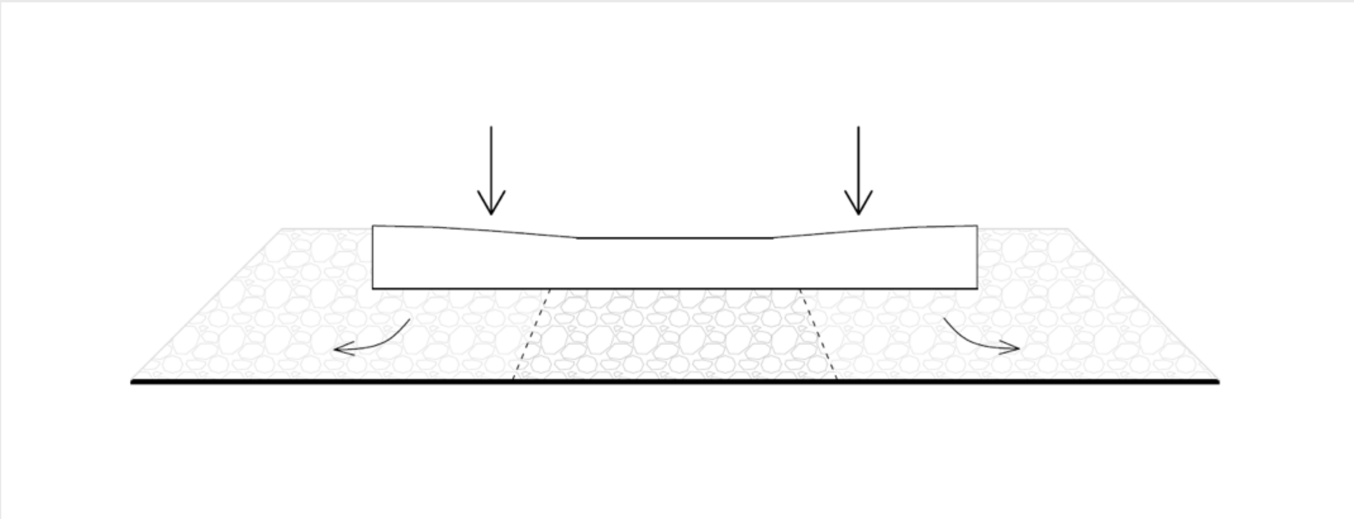

Figure 5. Conceptual representation of ballast long-term conditions; (a) region with well-confined ballast; (b) regions with lightly confined ballast and higher vertical load

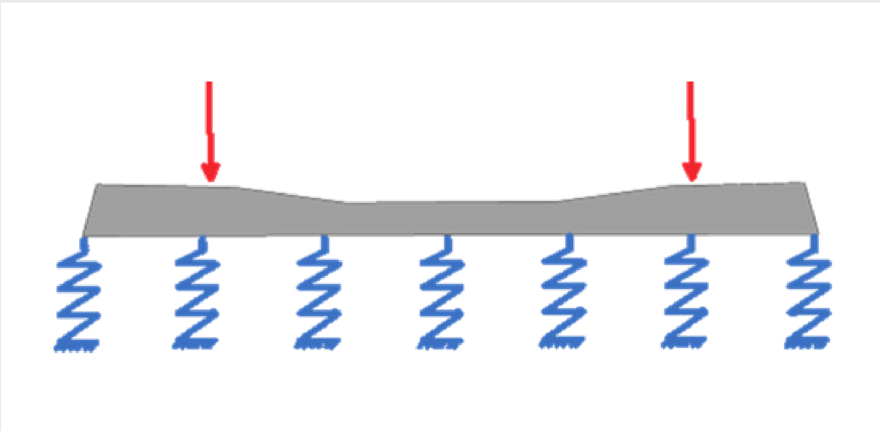

Figure 6. BOEF model applied to a single uniformly supported sleeper

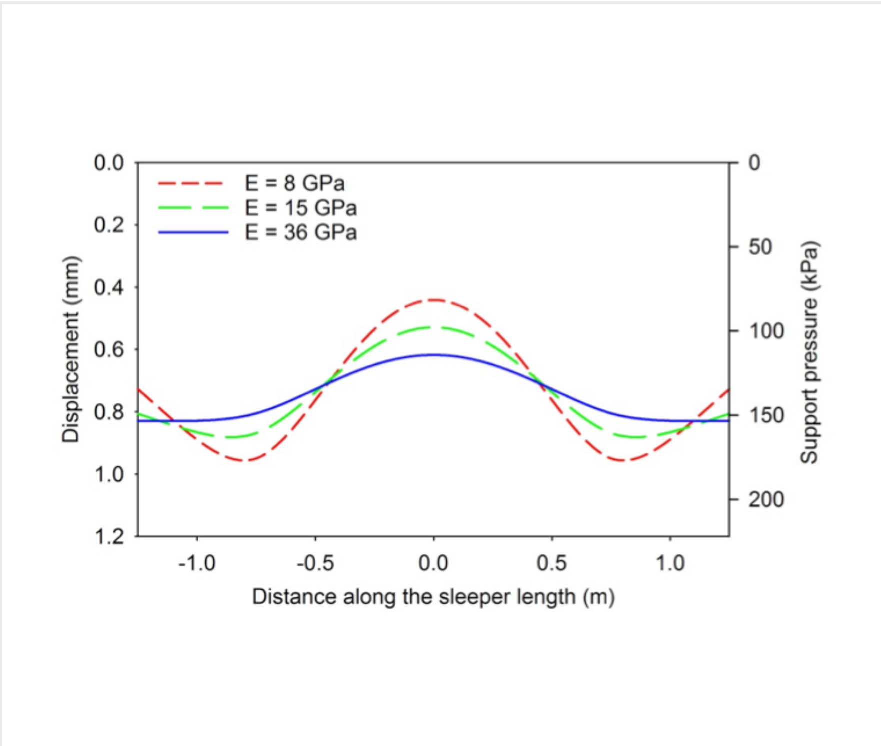

Figure 7. Effect of the bending stiffness on the distribution of the resilient deflections (BOEF)

The higher settlement rate exhibited by the composite sleeper might be attributed in part to its lower ability to spread uniformly the load over the ballast, but must at least partly be explained by the slightly smaller width of the composite sleeper (260 mm) compared with the concrete sleeper (285 mm).

The results from the analysis of the pressure sensitive paper and the assessment of ballast damage are summarised in table 1. The pressure exerted by the ballast grains on the soffit of the composite sleeper formed small plastic indentations that increased dramatically the overall sleeper/ballast area of contact and, to a lesser extent, the number of contacts. This is clear from figure 9, which shows the imprint left by the ballast grains on the base of the concrete and composite sleepers below one of the rails. In both tests the ballast suffered only marginal damage, as high quality crushed igneous rock (granite) ballast was used and the loading in the laboratory tests was not excessive. Although ballast damage under controlled laboratory conditions was not influenced by the sleeper material, composite sleepers might reduce ballast damage on real tracks, especially at locations subject to large dynamic loads such as S&C or transitions.

SUMMARY

Tests have shown that the bending stiffness of railway sleepers can significantly influence the mechanical behaviour of the railway track. This should be taken into account when designing or considering the potential use of composite sleepers, as they bring potential advantages but might also lead to less desirable track behaviours. When selecting a composite sleeper it should be considered that only those with reinforcement have comparable bending stiffness to timber hardwood sleepers. However, even reinforced composite sleepers are significantly less stiff than steel prestressed reinforced concrete sleepers and therefore, according to laboratory tests, might be more susceptible to centre binding.

The tests showed the potential of composite sleepers to attenuate the localised stresses at the sleeper/ballast interface and hence, ballast damage. Therefore, they are likely to be suitable at locations where large dynamic forces are present, e.g. S&Cs and transitions. Further work is needed to better understand the longer-term performance of composite sleepers in field installations. As the stock of field installed composite sleepers increases their performance can be assessed and specialised monitoring campaigns carried out. Although not previously discussed in this article, further work could also investigate the potential for changing the sleeper shape taking advantage of the freedoms offered by the use of composite construction methods.

ACKNOWLEDGEMENTS

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	Concrete	Composite
Average contact area at the sleeper/ballast interface	0.6%	2.8%
No. of contact points per pressure paper (270 mm x 200 mm)	19	24
Mass loss for the marked ballast grains	0.12%	0.12%
No. of broken grains within the marked ballast grains	3	2

Table 1. Sleeper/ballast contact (for stresses > 10 MPa) and ballast damage

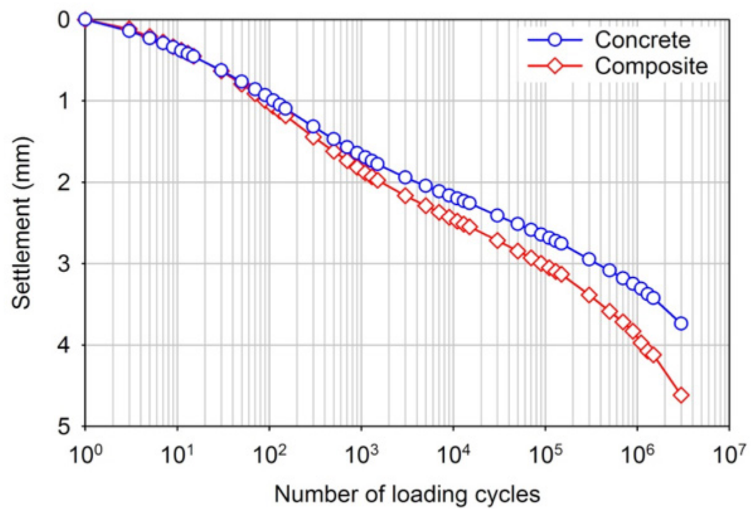

Figure 8. Sleeper settlement vs number of loading cycles

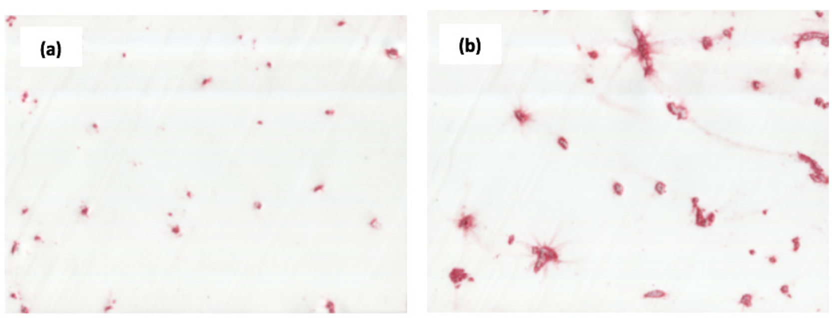

Figure 9. Pressure sensitive paper showing the cumulative ballast contact under one rail for the concrete (a) and composite (b) sleeper

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