Article:

Whittle, J.W. orcid.org/0000-0001-5792-1140, Słodczyk, I.A., Danks, S. et al. (2 more authors) (2025) Investigating the effect of railway track ballast and bed conditions on the lateral resistance of timber, concrete, steel, and composite sleepers using a novel test methodology. Engineering Structures, 340. 120769. ISSN 0141-0296

https://doi.org/10.1016/j.engstruct.2025.120769

Author accepted manuscript for the following research, published in *Engineering Structures, Volume 340* on *1 October 2025*. Originally accepted for publication on *8 June 2025*. DOI: https://doi.org/10.1016/j.engstruct.2025.120769

Title:

Investigating the effect of railway track ballast and bed conditions on the lateral resistance of timber, concrete, steel, and composite sleepers using a novel test methodology

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Attribution:

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Abstract:

This study investigates the effect of sleeper (tie) type, ballast condition, and vertical rail restraint forces on sleeper-ballast interaction, which is responsible for lateral resistance behaviour, to support track safety management. Lateral resistance, principally dictated by the sleeper-ballast interaction is a property of ballasted railway track critical to overall track stability, and to the reduction of track buckling risk. Previous investigations of this property have overlooked the restraining effect of the rail which limits the uplift of sleepers during sleeper push tests. A novel single sleeper push tests (SSPT) methodology, utilising a kinematic restraint, has been used to test the lateral resistance of five sleeper types including timber, concrete, steel, and composite. The tests were performed for a range of ballast dimensions and consolidations, with lateral resistance values up to 40mm displacements presented. The percentage contribution of the sleeper base is calculated for each sleeper, finding reasonable agreement with values found in existing literature. This study has found that for small displacements, concrete and steel sleepers generate similar levels of lateral resistance, with steel sleepers exhibiting increased resistance for extended push distances. Steel sleepers have a concave structure and are found to generate much of their lateral resistance through internal ballast interaction, making them suitable for use in circumstances where the cribs or shoulders are damaged or reduced. Timber and composite sleepers were found to provide lower resistances, approximately 50% of the peak resistance of concrete sleepers. As railways worldwide are re-engineered to avoid climate change driven infrastructure failures these findings contribute to track safety management by improving buckling mitigation strategies, whilst aiding the selection of more suitable and effective components to alleviate the effects of climate change on the railway track system.

Keywords:

sleeper, ballast, lateral resistance, single sleeper push test, full-scale test, railway track, climate change

Highlights:

- Novel test method used to assess five sleeper types under varied ballast conditions.
- Concrete and steel sleepers behave similarly at small lateral displacements.
- Steel sleepers exhibit increased resistance at greater push distances.
- Timber and composite sleepers provide similar levels of lateral resistance.

1. Introduction

The railway track system is principally constructed from rails, sleepers, and ballast [1]. A key role of railway sleepers (ties) is to provide lateral stability to the rails, enabling them to provide stability and resist lateral movement [2, 3]. Climate change driven phenomenon, including higher temperatures and increased rainfall, are increasing track stability risks (e.g. through track buckles) through raised rail stress, ballast washout, and failure of drainage systems [4-7]. Real world failure of track system infrastructure, and its impacts, due to weather events including landslides [8], flooding [9], and heatwaves [10, 11] is well documented [12]. To reduce risk, to the demonstrably vulnerable rail, sleeper, and ballast track system, it is essential to quantify performance of track components. This allows design codes and standards to be updated and to ensure the implications of infrastructure modifications are understood. Focusing on lateral resistance of sleepers in ballast this paper reports the application of a recently developed test method [13] for timber, concrete, steel, and composite sleeper types. This first comparative study using the new test method in which uplift of the sleepers is restrained (as it is by the rail in installed track) shows important differences in behaviour which can guide application of the most appropriate sleeper material for particular conditions to enable improved system resilience.

1.1. Lateral Resistance

Lateral resistance, principally dictated by sleeper-ballast interaction, is a property of ballasted railway track critical to overall track stability, and ultimately reducing track buckling risk [2, 3]. The resistance available at the interface between sleeper and ballast can be characterised by a force-displacement curve, which typically consists of a rapid rise in force followed by a near constant plateau after a short lateral displacement (usually less than 5 mm) [14]. This property is called lateral resistance (R_t) and can be considered as the sum of the three components acting on the bottom (R_b), side (R_s) and end (R_e) of the sleeper. The R_b and R_s components are a result of frictional forces of the ballast against the sleeper as it moves, while R_e results from reaction forces of the ballast on the sleeper end. Lateral resistance can be influenced by several factors including ballast consolidation [15-19], ballast condition [20, 21], ballast dimensions [22, 23], ballast particle size distribution [24], sleeper dimensions, sleeper cross-section, and sleeper material [25]. Reported lateral resistance values can also be influenced by the test method used [26-28]. These factors can alter the shape of the defining curve (e.g. producing a slower rise or a lower resistance following a peak). Achieving large values of lateral resistance (e.g. through ballast consolidation, ballast gluing, using lateral resistance plates (sleeper anchors), or using different sleeper types [29-34]) is highly desirable and is one of the main strategies of improving track safety when considering buckling resistance [2]. Global railway networks employ several types of sleepers situated in varying service conditions, making an investigation of the combinations of sleeper types and ballast conditions a key interest.

1.2. Lateral Resistance Testing Methods

Within existing literature, two main methods are used in a laboratory environment to test lateral resistance. The first is a single sleeper push test (SSPT), where a sleeper is positioned in ballast and pushed toward the shoulder whilst the load required to move the sleeper and displacement are recorded [22, 35]. Alternatively, a track panel of several sleepers, connected by fasteners and rail, can be displaced in a track panel push test (TPPT) [36]. Each method has advantages, with the former being simpler to complete but the latter generally being more representative of the real track system due to the summation of areas of influence from each individual sleeper [37, 38]. Application of each test methodology usually requires adaptations for track or laboratory conditions. For example, on track it is typical to unfasten a sleeper from the rail and use a ram to displace the sleeper whilst anchoring on the opposing rail for a SSPT [39]. There are a number of standardised test methods including UIC [40], SNCF [40], TUM [40], and BS [15], but adoption varies widely between countries and studies as outlined in Table 1 of the Supplementary Material (SM).

1.3. Lateral Resistance Values

A detailed overview of lateral resistance tests found within existing literature considering different sleeper types, test method (including standard methods), ballast conditions, and the lateral resistance values reported can be found in the SM. Within existing literature, three main categories of investigation can be seen: laboratory experiments [13, 26, 41-48], field experiments [17, 27, 31, 36, 47, 49-56], and computational simulations [26, 57, 58]. Occasionally, a study makes use of one or more of these techniques (e.g. to validate simulation investigation). Approximately half of existing studies report values at 2 mm of displacement, whilst the remainder report either peak lateral resistance or the 'breakaway' displacement. Fig. 1 shows an analysis of all existing literature and the lateral resistance results presented.

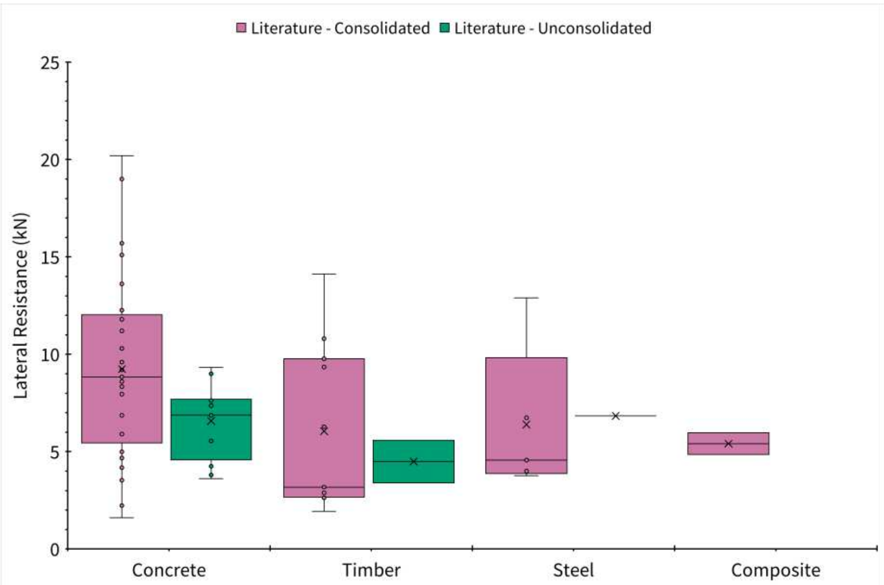


Fig. 1: Lateral resistance values taken from existing literature, synthesised by sleeper type and ballast consolidation level.

This analysis shows a significant range of reported lateral resistance values across both sleeper type and ballast consolidation level. This variation is caused by several factors including the chosen test methodology, implementation of that methodology (with respect to displacement values and ballast consolidation), environmental conditions, variation in chosen components, and a lack of methodology standardisation between studies. This variation in implementation makes true comparison between studies and utilisation of results difficult. Additionally, even for tests within which the sleeper type, ballast condition, and reported displacement are nominally identical, the resultant lateral resistance values seen can vary widely. For example, in the case of consolidated timber tests, this is by up to as much as four standard deviations (SDs).

Furthermore, a majority of previous work focuses on only one type of sleeper with very few investigating two or more within the same study. Additionally, most research focusses on either timber or concrete sleeper variants; leaving a significant gap in accurately quantifying how alternative sleeper types (including steel and composite) behave under near identical conditions. As shown in Fig. 1, steel and composite are almost completely unstudied in the unconsolidated ballast regime.

Therefore, this paper aims to quantify the lateral resistance behaviour of common railway sleepers; hardwood timber [59], concrete (G44) [60], concrete (EG47) [60], steel (W560H) [61], and composite [62]. The tests are performed under four distinct bed and ballast conditions utilising the novel laboratory-based methodology developed in Słodczyk et al. [13], which applies a kinematic restraint to the sleeper during testing to better represent a real track system. This is the first time all major types of sleepers have been tested under such a varied set of conditions in a directly comparable way. This methodology also allows tests to be completed to greater lateral displacements which will help understand the potential outcome of a track buckle.

A further aim of this paper is to determine the contribution of the base of each sleeper compared to overall lateral resistance, to understand the potential effect of extreme weather driven failure mechanisms (e.g. ballast washout). The findings of this research will enhance the understanding of lateral resistance performance characteristics of railway sleepers under different ballast and bed conditions, enabling objective decisions to be made about overall system resilience, track buckling risk and wider track safety both now and in the future.

This paper is structured as follows: Section 2 describes the study methodology, Section 3 presents study results and findings, Section 4 discusses the results presented in Section 3, and Section 5 summarises key insights and their implications.

2. Methodology

2.1. Experimental Apparatus

In order to achieve the aims of this paper, full-scale laboratory experiments were carried out in a ballast box based on BS 500:2000 [15]. The box contained approximately 9 tonnes of ballast graded in accordance with NR/L2/TRK/8100 [63]. The dimensions of the box, ballast and shoulder can be seen in Fig. 2a. The rail section at each end of the sleeper was fixed using the standard fasteners, and is equivalent to the weight supported by a single sleeper in a track of standard 650 mm sleeper spacing [15, 64]. This sleeper test rig includes the novel use of a kinematic vertical restraint made from two right angle steel sections of length several times that of the maximum push length secured to the frame, supporting the actuator. This restraint enables an improved lateral resistance test across a greater displacement range by enforcing conditions that are more representative of track than existing methods [13], which is not normally possible using existing test methodologies. The effect of the rail resisting upwards movement of sleepers during lateral shift is achieved by the aforementioned steel sections remaining in constant contact throughout the test, thereby generating results which are more representative of in-service behaviour for all types of railway sleeper. The experimental configuration does not include additional active downward force on the sleeper (e.g. a representation of downward vehicle forces) in this instance.

The lateral load was applied using a Thomson 60 kN (item 7) linear actuator which was placed at the end of the sleeper furthest from the ballast shoulder with its centreline 75 mm above the top face of the sleeper end to minimise the rotational force applied to the sleeper. An angled wedge, not rigidly attached to the sleeper, was used an interface between the actuator plate and the sleeper to transfer force through the fastener [13]. As shown in Fig. 2a and Fig. 2b, the horizontal and vertical sleeper displacements were monitored directly by a Penny & Giles SLS130 (item 3) and a Caldaro S1SF (item 4) linear variable differential transducers (LVDTs) respectively, with the 'free' distance between the rail and the restraint (item 8) minimised to within 1 mm. The horizontal and vertical loads generated by the sleeper were measured by a VPG 50 kN (item 2) and two GLBM 20 kN (item 5) load cells respectively.

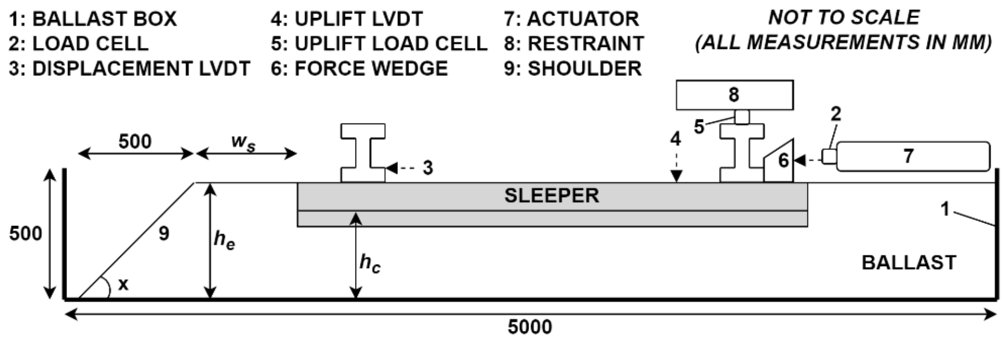


Fig. 2a: Sleeper test rig schematic [13].

Fig. 2b: Sleeper test rig experimental arrangement showing load cell (2), displacement LVDT (3), uplift LVDT (4), wedge (6), actuator (7), restraint (8).

2.2. Test Procedure and Program

Within the test program each sleeper type was tested under two different ballast conditions; consolidated (ballast density of approximately 1750 kgm^{-3}) and unconsolidated (ballast density of approximately 1250 kgm^{-3}) and bed conditions; no ends or cribs, and full. Under the no ends or cribs condition (herein described as open), the crib height (h_c) and end height (h_e), as shown in Fig. 2a, were reduced to be coplanar with the base of the sleeper. Under the full condition, the heights of h_c and h_e were formed coplanar to the top of the sleeper, where the maximum ballast layer thickness was 380 mm. The ballast shoulder angle (x) was set to 45 degrees (the angle of material natural repose), with the shoulder width (w_s) set to 500 mm from the end of the sleeper; as shown in Fig 2a. It should be noted that the physical and descriptive transition point between the ballast shoulder and end varies across the world. In this paper shoulder and end both refer to all ballast beyond the end of the sleeper.

Under each of these conditions three repeats were performed, resulting in sixty tests. This program, including sleeper specification, is summarised in Table 1. Each SSPT followed a strict procedure, as previously developed by Słodczyk et al. [13], but with a greater range of ballast conditions assessed. However, small differences in the experimental apparatus and research aims necessitate additional steps as described in Section 2.2.1 and Section 2.2.2.

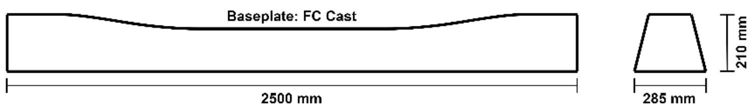
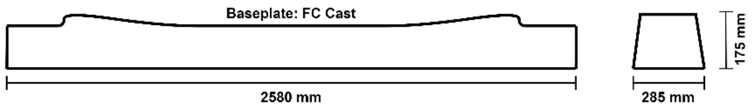
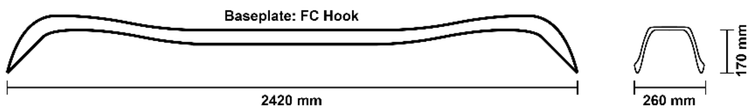
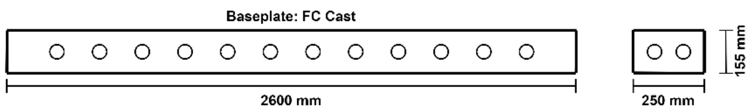
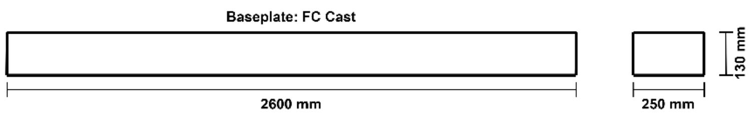
Test No.	Ballast Condition	Bed Condition	Sleeper Type	Sleeper Specification: Dimensions*	Sleeper Specification: Mass (kg)
1-3	U	O	Concrete (G44)		299
4-6		F			
7-9	C	O			
10-12		F			
13-15	U	O	Concrete (EG47)		286
16-18		F			
19-21	C	O			
22-24		F			
25-27	U	O	Steel (W560H)		93
28-30		F			
31-33	C	O			
34-36		F			
37-39	U	O	Composite		121
40-42		F			
43-45	C	O			
46-48		F			
49-51	U	O	Timber		143.5
52-54		F			
55-57	C	O			
58-60		F			

Table 1: Test program (three repeats under each condition) and sleeper specification summary (*dimensions not to scale). Where U = Unconsolidated, C = Consolidated, O = Open, F = Full.

2.2.1. Ballast Preparation (a)

To ensure a consistency across the test program, the ballast was prepared pre- and post-test: (i[a]) First, the sleeper was positioned in the box and the ballast formed co-planar with the sleeper top. (ii[a]) The ballast around and underneath the sleeper was agitated using a Robel hand tamper. In the case of the steel sleeper, ballast was manually pushed up into the hollow section of the sleeper. This was done to reduce voiding around and beneath the sleepers and to meet manufacturer's installation specifications [16]. In the unconsolidated condition, the ballast was not compacted beyond manually pushing the ballast to eliminate voids and ensuring contact with the sides and leading face of the sleeper - this represents a freshly tamped condition found in the field (see Section 2.2). (iii[a]) In the consolidated condition, between each test, the bed was compacted using a Hulk Electro H320 wacker plate of 5 kN force in predetermined alternating clockwise and anticlockwise patterns around the sleeper for approximately 10 minutes (see Section 2.2). (iv[a]) Ballast was then removed or reinstated from the cribs and shoulder, depending on whether the required bed condition was open or full. It should be noted that the ballast bed was broken up (i.e. unconsolidated) in between each sleeper type using a JCB 8030ZTS excavator to prevent cumulative consolidation of the ballast bed. To mitigate against ballast degradation, regular inspections were conducted to ensure that the condition of the ballast remained consistent and within specification.

2.2.2. SSPT Methodology (b)

For all test conditions, each SSPT was performed in the same manner: (i[b]) The sleeper was pushed towards the shoulder using the actuator whilst recording the displacement of both the sleeper and restraint, as well as both the force exerted on the load cell (item 2), and uplift load cells (item 5). The sleeper was displaced at a constant rate of 10 mm/min [15] up to 40mm. All force and position data were acquired at a frequency of 10 Hz. (ii[b]) The steps starting from (i[b]) were repeated three times for each test condition, with ballast (re)prepared depending on condition as outlined in Section 2.2.1. (iii[b]) Finally, the actuator and sleeper were returned to their initial position and steps repeated starting from (i[a]).

3. Results

The sections below present the results of tests 1-60 (as summarised in Table 1). Each result presented is the average of the three repeats completed under each condition. This is done to better represent aggregate behaviour of a bulk track system, where each sleeper may exhibit different behaviour due to local conditions. A numerical summary of each test is shown in Table 2. The lateral resistance values presented are at the displacements of 2 mm, 25/30 mm, and 40 mm; where 25/30 mm is the average of the values at 25 mm and 30 mm as described by BS500:2000 [15]. The value of peak lateral resistance and associated displacement are also shown. The standard deviation (SD) of the lateral resistance value at each discrete displacement is also reported. At each reported displacement point, the SD across the entire dataset is 0.51, 0.70, 0.71, and 0.68 respectively, indicating strong repeatability between each bed and ballast condition as well as sleeper type. The highest and lowest SD values for each sleeper type do not occur under the same bed and ballast conditions, indicating that inter-test variation is the result of natural sleeper-ballast interaction not systematic error resulting from test procedure.

Test No.	Sleeper Type	Lateral Resistance ± SD (kN)				
		2 mm	25 / 30 mm	40 mm	Peak	Peak Displacement at Peak Lateral Resistance (mm)
1-3	Concrete (G44)	1.83 ± 0.53	2.31 ± 0.18	2.23 ± 0.36	2.44 ± 0.43	13.28
4-6		1.30 ± 0.75	4.97 ± 0.31	5.24 ± 0.05	5.25 ± 0.12	39.34
7-9		1.39 ± 0.61	2.80 ± 0.50	2.90 ± 0.84	3.13 ± 0.72	36.94
10-12		6.66 ± 0.84	9.26 ± 1.82	8.62 ± 0.45	9.52 ± 0.65	25.61
13-15	Concrete (EG47)	1.49 ± 1.05	2.59 ± 0.88	2.50 ± 0.61	2.81 ± 0.91	28.19
16-18		2.12 ± 0.50	4.72 ± 0.21	5.17 ± 0.28	5.19 ± 0.19	39.85
19-21		1.60 ± 0.67	2.25 ± 0.80	2.42 ± 0.74	2.66 ± 1.01	26.02
22-24		5.83 ± 0.81	8.82 ± 1.53	8.87 ± 1.06	9.20 ± 0.93	35.82
25-27	Steel (W560H)	2.32 ± 0.20	6.48 ± 0.76	6.74 ± 0.89	6.81 ± 0.85	37.30
28-30		3.52 ± 0.98	5.92 ± 0.96	6.73 ± 0.67	6.86 ± 0.58	38.92
31-33		1.98 ± 0.05	6.20 ± 0.34	8.83 ± 1.10	9.26 ± 1.15	38.86
34-36		6.89 ± 0.40	14.73 ± 1.41	19.02 ± 2.29	20.92 ± 1.41	39.85
37-39	Composite	0.59 ± 0.24	1.10 ± 0.27	1.23 ± 0.29	1.25 ± 0.34	39.89
40-42		1.64 ± 0.37	2.63 ± 0.33	2.73 ± 0.17	2.92 ± 0.11	22.47
43-45		1.21 ± 0.34	1.77 ± 0.66	1.68 ± 0.42	2.13 ± 0.70	23.30
46-48		3.49 ± 0.56	5.39 ± 1.09	5.29 ± 1.64	5.58 ± 1.39	24.70
49-51	Timber	1.26 ± 0.29	2.21 ± 0.73	2.55 ± 1.19	2.67 ± 1.10	37.08
52-54		2.01 ± 0.46	3.40 ± 0.14	3.55 ± 0.30	3.6 ± 0.21	35.00
55-57		1.18 ± 0.34	1.88 ± 0.88	2.13 ± 0.77	2.13 ± 0.73	39.99
58-60		3.75 ± 0.25	5.73 ± 0.20	5.78 ± 0.25	5.89 ± 0.09	18.68

Table 2: Lateral resistance values at a given displacement for tested sleepers, presented as an average (±standard deviation) of the three repeats completed under each condition.

3.1. Individual Force-Displacement Plots

Lateral resistance values for tests 1 – 12 can be seen in Fig. 3a, completed using a G44 concrete sleeper. The tests completed within a full, consolidated bed (tests 10-12) show a characteristic shape of a peak value which remains approximately constant beyond 10 mm lateral displacement. The value recorded 25/30 mm displacement of 9.26 kN (which corresponds to the effective lateral resistance peak) respectively is similar to those reported by other authors including Pucilio et al. [53]. Additionally, the value recorded at 2 mm displacement of 6.66 kN is broadly consistent to those reported by Aela et al. [26] but is slightly lower. The tests completed under the other bed and ballast conditions, as expected, show much lower peak values. Furthermore, despite differences in consolidation levels, both tests completed with an open bed exhibit very similar behaviour and reported values. The curves generated indicate that the consolidation regime used did not have any effect during the open bed tests which highlights that ballast is unlikely to 'lock' into a sleeper which is made of a smooth, hard material (e.g. concrete) without significant consolidation frequency which could only be achieved on track.

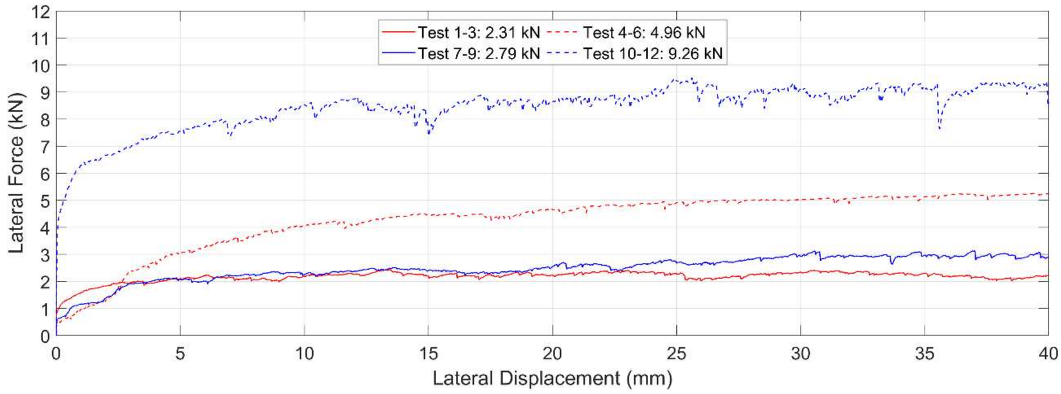


Fig. 3a: Concrete (G44) sleeper, force-displacement plot under unconsolidated (red) and consolidated (blue) conditions, presented as an average of the three repeats completed under each condition.

Lateral resistance values for tests 13 – 24 can be seen in Fig. 3b, completed using an EG47 concrete sleeper. As expected, the tests completed within a full, consolidated bed (tests 22-24) exhibit a very similar curve profile compared to the larger G44 concrete sleeper. However, contrary to expectations, the lateral resistance values across all displacements are similar to the G44 concrete. The values recorded at 2 mm and 25/30 mm displacements of 5.83 kN and 8.82 kN respectively are a 12 % and 5 % reduction in lateral resistance when compared to the larger sleeper. The values and behaviour of the other tests completed show much lower peak values and are very similar in profile to those of the G44 concrete sleeper. Similarly to the G44 concrete sleeper, the curves generated indicate that the consolidation regime used did not have any effect during the open bed tests.

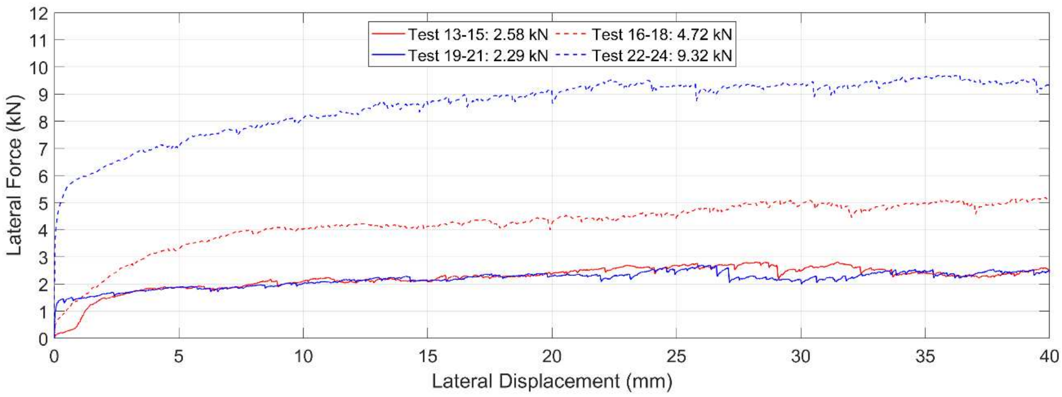


Fig. 3b: Concrete (EG47) sleeper, force-displacement plot under unconsolidated (red) and consolidated (blue) conditions, presented as an average of the three repeats completed under each condition.

Lateral resistance values for tests 49 – 60 can be seen in Fig. 3c, completed using a hardwood timber sleeper. The tests completed within a full, consolidated bed (tests 58-60) are characterised by a similar profile to both concrete sleepers but with a much lower peak lateral resistance value. The values recorded at 2 mm and 25/30 mm displacements of 3.75 kN and 5.73 kN. Similarly to the results generated by both concrete sleepers, both tests completed with an open bed exhibit very similar behaviour and reported values despite differences in consolidation levels. The reported values fall into the middle of the range of values found in existing work, where some are lower such as those found by Reiner [54] and some higher such as those found by Zakeri and Bakhtiary [46].

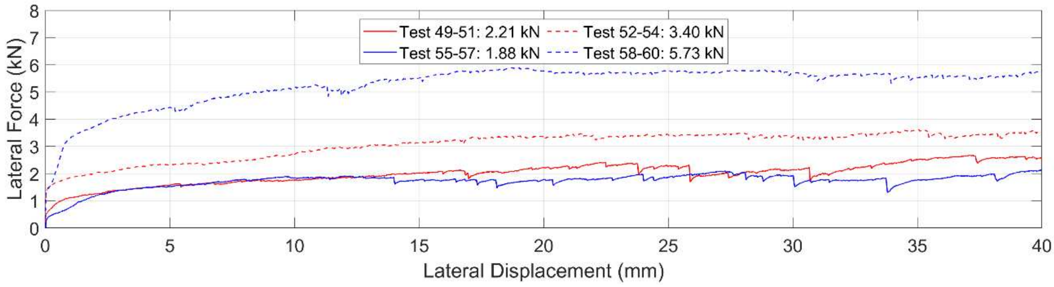


Fig. 3c: Timber sleeper, force-displacement plot under unconsolidated (red) and consolidated (blue) conditions, presented as an average of the three repeats completed under each condition.

Lateral resistance values for tests 37 – 48 can be seen in Fig. 3d, completed using a composite sleeper. Unexpectedly, the tests completed within a full, consolidated bed (tests 46-48) are characterised by a similar profile to the directly comparable timber sleeper but with a lower peak lateral resistance value. The values recorded at 2 mm and 25/30 mm displacements of 3.49 kN and 5.39 kN respectively are a 7 % and 6 % reduction in lateral resistance when compared to the timber sleeper. The reported values are slightly lower than the values found in limited existing work at 2 mm but are higher than Liu et al. [44] and lower than Jing et al. [51] once extended displacements are reached.

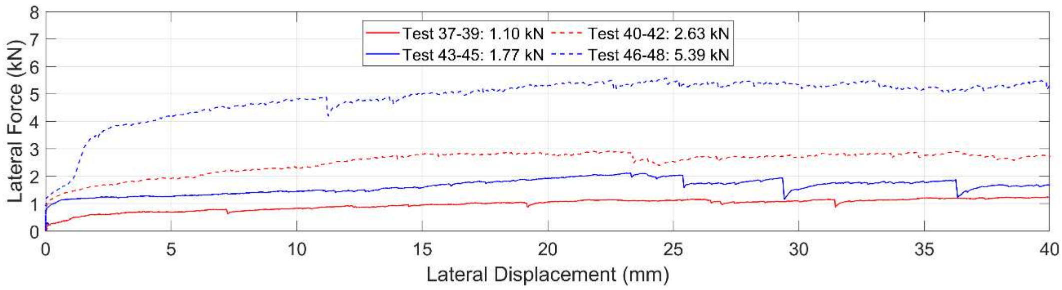


Fig. 3d: Composite sleeper, force-displacement plot under unconsolidated (red) and consolidated (blue) conditions, presented as an average of the three repeats completed under each condition.

Lateral resistance values for tests 25 – 36 can be seen in Fig. 3e, completed using a W560H steel sleeper. As has been found by other authors, the steel sleeper is characterised by a very different curve when tested under a restrained regime compared to monoblock style sleepers. The values recorded at 2 mm and 25/30 mm displacements of 6.89 kN and 14.72 kN, with a rising load under each of the conditions tested. These values are greater than those reported by authors including Zakeri et al. [56] and Jing et al. [43] but comparable to those found by other authors including Zakeri and Bakhtiary [46] and Słodczyk et al. [13]. The latter of these results was generated using a similar experimental configuration.

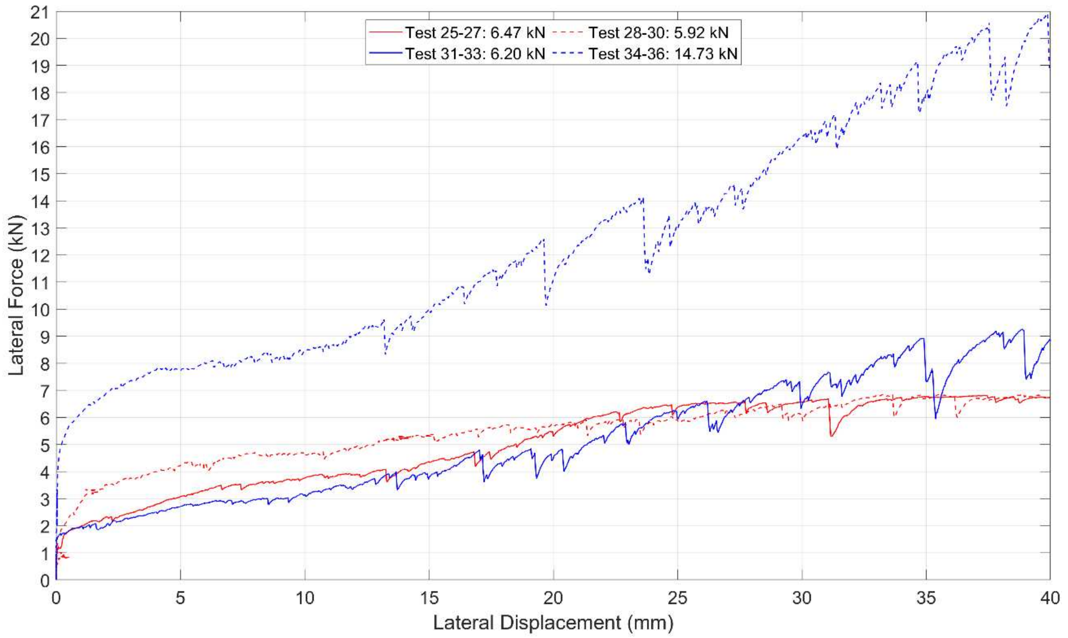


Fig. 3e: Steel (W560H) sleeper, force-displacement plot under unconsolidated (red) and consolidated (blue) conditions, presented as an average of the three repeats completed under each condition.

3.2. Combined Force-Displacement Plot

A combined force-displacement of each sleeper type completed within a full, consolidated bed is shown in Fig. 4. This graph shows that until a lateral displacement of approximately 10 mm, the W560H steel and G44 concrete sleeper have a near identical force-displacement characteristic; after which the steel sleeper begins to deviate. The EG47 concrete sleeper has a lower initial maximum force than the G44 concrete but both reach a very similar eventual plateau. Additionally, although the maximum value of lateral resistance is lower, both timber and composite sleepers have very similar force-displacement curves. This behaviour is explored further in Section 4.

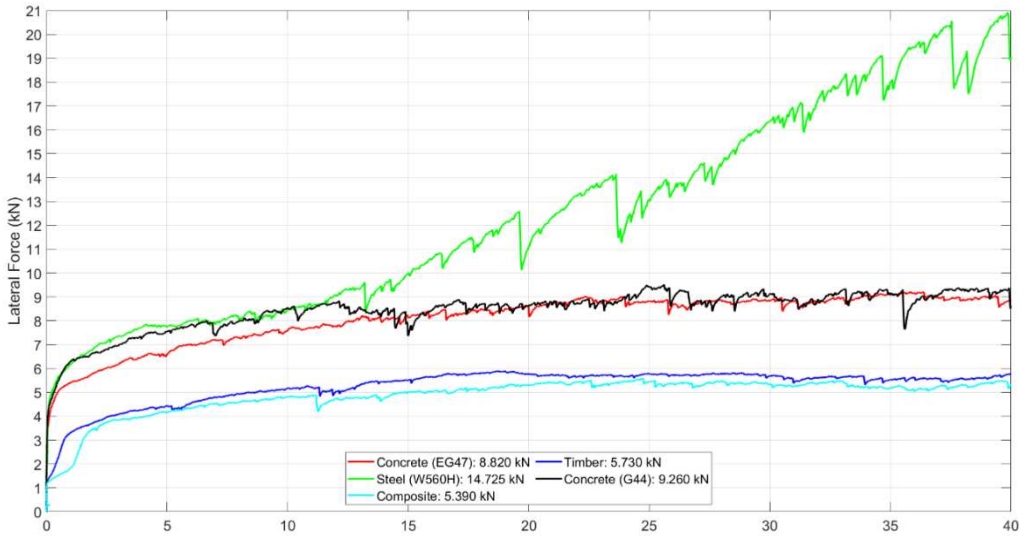


Fig. 4: Combined force-displacement plot under full, consolidated conditions, presented as an average of the three repeats completed under each condition.

3.3. Contribution of base and crib to overall lateral resistance values

Within this test program only open or full ballast conditions were tested, as described in Section 2. Based on the data presented in Table 2, values for R_b have been derived under both unconsolidated and consolidated ballast conditions using

$$R_b = \frac{\bar{\gamma}}{\bar{\delta}}, \text{ Eqn. 1}$$

where

$$\bar{\gamma} = \frac{\sum_i^n R_t}{3}, \text{ Eqn. 2}$$

$$\bar{\delta} = \frac{\sum_j^m R_t}{3}, \text{ Eqn. 3}$$

for which (where not already defined) n is the final test in an open bed condition test (i.e. test 3), i is the first test in an open bed condition test (i.e. test 1), m is the final test in an full bed condition test (i.e. test 6), j is the first test in an full bed condition test (i.e. test 4). The terms γ and δ represent the average R_t value under open and full bed conditions respectively.

These are presented in Table 3, alongside values found in existing literature. It should be noted that the derived contributions from this study are only at 25/30 mm, which is the point of steady lateral resistance. The derived values of R_b in this study, given the established range of experimental methods, are in broad agreement with those found in existing literature, particularly those in the consolidated ballast condition as this most closely reflects the work done in those other studies. This behaviour is explored further in Section 4.

Sleeper Type	**Contribution of base (%)**							
	R_b							
	This Study (U)	**This Study (C)**	**[31] (C)**	**[46] (C)**	**[22] (C)**	**[65] (C)**	**[52] (C)**	**[36] (C)**
Concrete (G44 or equivalent)	47	30	24.3	62.2	26 - 35	-	26.6	-
Concrete (EG47 or equivalent)	55	26	-	-	-	-	-	27.2
Steel (W560H or equivalent)	109	42	-	55.7	-	-	-	-
Composite	42	33	-	-	-	-	-	-
Timber	65	33	-	50.6	-	50 - 60	-	-

Table 3: Contribution of base to lateral resistance, arranged by sleeper type. Where U = Unconsolidated, C = Consolidated.

4. Discussion

4.1. Comparison to existing literature

To better understand the individual and comparative performance of different sleeper types, the lateral resistance has been examined under four distinct bed and ballast conditions utilising a novel SSPT methodology which limits the uplift displacement a sleeper can experience during a test to better reflect the conditions that would be found in track. These tests were completed to lateral displacement distances greater than many existing studies have reported. Across all values for lateral resistance generated during this study, all sleeper types were found to agree broadly with the values reported for both laboratory and simulation experiments. However, as expected, all values were lower than those found during field experiments where the track had been subject to vehicle traffic or dynamic track stabilisation. This reflects how difficult it is to replicate real world consolidation techniques, at full scale, in a laboratory, and how much lateral resistance a track system can increase following significant volumes of traffic. However, the ballast densities used under each bed condition in this study are in broad agreement with existing literature therefore a strong degree of confidence can be placed on a comparability of results to other studies in this regard [26, 31, 66, 67].

4.2. Comparison between sleeper types

When compared to each other at different displacement distances and test conditions, the G44 concrete and EG47 concrete generated very similar force-displacement curves as shown in Fig. 4. As expected, the G44 variant produced higher lateral resistance values under nearly all test conditions. However contrary to expectation, the values are much closer than expected. It is typically thought that the G44 (and sleepers in general) generates its lateral resistance ability from its mass [68]. However as shown in Table 2, the smaller and lighter EG47 has far exceeded its relative expected performance by matching the G44 in the full, consolidated tests. This is likely due to a closer than expected mass difference (EG47 is only 4.4% lighter) and sleeper profile (shown in Table 1).

When compared to each other across the range of tested displacements and conditions, the timber and composite sleepers generated similar maximum lateral resistance values as shown in Fig. 4. Given the design similarities, this finding is not surprising. However, the composite sleeper had significantly lower lateral resistance in the open and unconsolidated ballast test, which are representative of poor track conditions. This is likely indicative of the fact that the composite sleeper is made from a smooth, hard plastic material which has a much lower coefficient of friction than the more fibrous timber. The sleeper has an additional ‘dimple’ profile along the length which is designed to increase overall surface area thus increasing lateral resistance performance, however, as shown in Fig. 5, the ballast was unable to effectively lock into the sleeper under the conditions achieved during these tests. The higher consolidation rates available in the field may change this behaviour, but this is beyond the scope of investigation in this work.

In contrast, the steel sleeper produced a considerably different force displacement curve to those previously discussed; not reaching a relatively early (in many cases less than 10 mm) peak lateral resistance followed by a plateau. Instead, it continues to climb until the maximum push distance, as shown in Fig. 4. Test 34 and test 35 were completed to an extended displacement, and show that the plateau begins at approximately 50 mm. This is most likely due to the hollow and angled spade ends of the steel sleeper resulting in a different interaction between the sleeper and the ballast compared to monoblock variants. Under consolidated conditions (where the effect is the most dramatic), it will cause the sleeper to simultaneously 'plough' through the ballast at the front whilst also trying to 'rise' over the ballast at the rear. This is likely due to an additional zone of contact at the rear spade which in turn further consolidates the ballast inside the hollow portion of the sleeper body, that generates a sleeper-ballast interaction which is more like monoblock variants.

All types of sleeper tested experienced dips and climbs in lateral resistance across the test distance, as shown in Fig. 4. It is likely that for monoblock type sleepers this was caused by 'ballast rolling' underneath and around the sleeper leading to temporary unlocking of the ballast. However, the behaviour was most pronounced with the steel sleeper; likely due to the rise and plough effect described which is caused by the sleeper geometry. Further preliminary tests with modified steel sleepers have also shown this behaviour.

Fig. 5: Sleeper-ballast interaction for the composite sleeper, showing surface 'scoring'. Note surface dimples.

4.3. Base contribution comparison between sleeper types

The derived contribution of the base for each sleeper type under both consolidated and unconsolidated conditions seen in Table 3 helps to make comparison of this work to that of other authors. Whilst unconsolidated, both concrete and composite can attribute approximately half of their resistance to the base sleeper-ballast interaction. The timber sleeper contribution is slightly higher at 65 %, whilst the steel sleeper operates at approximately 100 % of its full bed value. These higher values can be attributed to the mechanism by which each sleeper generates its lateral resistance. As previously discussed, the steel sleeper can generate most of its resistance from the internal sleeper-ballast interactions which due to the shape can be considered to involve pseudo-crib and pseudo-end contributions, even under poor conditions. Similarly, the fibrous composition of the timber sleeper means that ballast can, sometimes, lock into the sleeper and generate additional resistance. As expected, a consolidated ballast bed decreases the relative contribution of the base to approximately 30 % for all monoblock sleeper types compared to approximately 40 % for the steel sleeper. Again, this is likely to be due to the additional internal sleeper-ballast interactions previously described. The value derived for steel sleeper in the unconsolidated ballast condition can be considered the only outlier from this study in which the base contribution has been found to be greater than the same test for a full ballast bed. This can be explained by the fact that the majority contribution towards lateral resistance is generated through the internal interactions between the sleeper trough and ballast as well as the inherent variance between tests (e.g. tests 25 – 27 experience a small drop in the 25/30 mm region). It should be noted that no existing literature has reported on the base contribution of a composite sleeper.

4.4. Implications

The observations outlined above indicate that the sleepers tested can be grouped into two broad categories with respect to lateral resistance performance. Firstly, the timber and composite sleepers perform and behave in a very similar way and are suitable for lower lateral track loads. Secondly, the concrete and steel sleepers tested behave very similarly up to 10 mm displacement. Beyond this the steel sleeper climbs in lateral resistance as displacement increases. Furthermore, the steel sleeper can retain more of its resistance to movement when the bed and ballast conditions are poor (either due to consolidation levels or ballast dimensions) due to its unique geometry. This could have implications in the field, particularly in the case that track has been recently laid and renewed (and so has good bed conditions but low ballast consolidation), or where the track has been subject to significant traffic or other event (and so has poor bed conditions but good ballast conditions). In the case of the former, both concrete variants can generate approximately 50% of their best-case lateral resistance performance, whereas the steel sleeper retains close to its full resistance. However, the effects of installation differences between sleeper types (e.g. installing a steel sleeper in the field to the same state achieved in a laboratory can be difficult) are not accounted for. There are other practical differences between types (e.g. settlement effects and rates [67]) which may impact overall track system behaviour in the field. Although this is likely to be a secondary effect within the system, it should be investigated within future track trials (discussed further in Section 5).

5. Conclusion

The lateral resistance properties of railway sleepers in ballasted track are vital in ensuring track stability. They play a key role in mitigating the effects of extreme weather driven failure mechanisms on infrastructure (e.g. track buckles), which will become more frequent due to climate change.

In the work presented, the lateral resistance behaviour of a comprehensive range of railway sleepers (G44 concrete, EG47 concrete, composite, W560H steel, and timber) has been compared in a laboratory using a novel full scale SSPT methodology. This is the first study to make this comparison for a range of bed and ballast conditions using a newly developed test with constraint on vertical rail movement. It was found that for small (2 mm) displacements (including distance required for full ballast mobilisation), the G44 concrete, EG47 concrete and W560H steel sleeper perform in a similar manner whilst the timber and composite sleeper generate approximately 50 % of the peak lateral resistance. Similarly, it was found that at longer displacements (25 / 30 mm), the same three sleepers generate more than twice the lateral resistance force of the timber and composite sleepers. In contrast to other published work, at all measured displacements the steel sleeper matched or exceeded the performance of the concrete variants. It is thought this is due to the sleeper-restraint interaction being more representative of track conditions; no other published method applies this level of kinematic restraint. Furthermore, composite sleepers were similar but ultimately generated lower levels of lateral resistance at the displacements investigated. From this work it can also be concluded that steel sleepers generate a significant portion of their lateral resistance from internal ballast interaction within their unique concave structure.

This work, alongside existing literature, leaves single sleeper behaviour well characterised under a range of laboratory conditions, allowing for more effective prediction of system behaviour in track buckling scenarios. However, future studies would benefit from more accurate quantitative characterisation of ballast consolidation levels through recent advances in measurement techniques [69]. An opportunity exists to extend this work to quantify behaviour of multi-sleeper panels in the laboratory as well as understanding how different laboratory results equate to real world behaviour. This would also enable quantification of installation effects on different sleeper types. Additionally, further tests within the laboratory could be used to investigate more extreme conditions (i.e. wet beds, reduced ballast beds and profiles, fouled ballast) and the role of track construction in climate mitigation strategies and management within the railway industry.

Acknowledgements

The authors would like to thank Andy Trowsdale and Scott Dyball at British Steel Limited for their assistance in completing this work. The authors would also like to thank Darren Sharp at Network Rail and Roger Lewis at the University of Sheffield for additional support in-kind.

Funding

The authors would like to thank the Engineering and Physical Sciences Research Council (EPSRC) through the Advanced Metallic Systems Centre for Doctoral Training (EPSRC grant ref. EP/S022635/1), EPSRC (EPSRC grant ref. EP/T517835/1), British Steel Limited and Network Rail for providing the funding for this research.

Supplementary Material

Data supporting this publication can be freely downloaded from the University of Sheffield research data repository at https://doi.org/10.15131/shef.data.25592694.v1, under the terms of the Creative Commons Attribution (CC BY) licence.

Declaration of Conflicting Interest

The authors declare that there is no conflict of interest.

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