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Case study

Effect of bending and compressive modulus of elasticity on the behaviour of timber-alternative railway sleepers supported by ballast

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ABSTRACT

Alternative railway sleeper technologies for replacement of timber are made of materials possessing a wide range of bending and compressive moduli. This poses a great challenge to railway authorities and engineers in designing a railway track supported by different sleeper technologies. This study evaluates the static behaviour of a railway track supported by different alternative railway sleeper technologies, i.e. recycled plastics (1.0 GPa), synthetic composites (7.4 GPa), timber (13.0 GPa), and low profile prestressed concrete sleepers (38.0 GPa), using a ballast box test representing a single sleeper section of a track. The deflection profiles along the length of the sleepers under a full service load was captured using Digital Image Correlation technique combined with the strain measurements at the top-centre of the sleepers. Three-dimensional Finite Element simulation of the sleepers' behaviour based on the Beam on Elastic Foundation theory was implemented and validated by the experimental results. The results show that sleepers with bending modulus of less than 13.0 GPa will have W-shape deflection profile and a high rail seat deflection while sleepers with a bending modulus of 38.0 GPa will show nearly flat behaviour. Local deformation at the rail seat region accounts for almost 6 % of the total deflection of sleepers on a low subgrade modulus and as high as 10 % for high subgrade modulus. The results of this study provide a better insight into the in-track behaviour of alternative sleeper technologies having distinctive material properties.

1. Introduction

Sleepers are one of the most important elements of a railway track [1]. The main functions of a sleeper are to transfer loads to the ballast and to hold and maintain track gauges. Timber has been the material of choice for railway sleepers for more than 150 years due to their ease of handling and installation, and excellent mechanical properties [2]. The major drawback of timber sleepers, however, is their short lifespan due to environmental deteriorations resulting in a high cost of maintenance and replacement [3]. The track maintenance cost in the UK and India during 2016–2017 was $775 million and $2.08 billion respectively [4], and it costs 37500–125000 $/km per year to maintain the European railway tracks [5] while 25–35% of the total operational cost is for

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maintaining the railway networks in Australia [6]. This high maintenance cost has led the industry to seek alternative cost-competitive materials, such as composite sleepers, that can perform similar to that of timber but with significantly longer service life.

In the last two decades, different alternative sleeper technologies have been introduced in the market for replacing deteriorating timber sleepers in existing railway tracks. These sleeper technologies include recycled plastics, synthetic composite (SC), and low profile prestressed concrete sleepers, which are made of materials possessing distinct physical and mechanical properties. A review of the literature indicated that the flexural modulus of elasticity (denoted as MOE or E_1) of available timber-replacement sleeper technologies vary significantly as shown in Fig. 1. Other researchers studied different aspects of these sleepers types such as the in-situ dynamic behaviour of SC sleepers [7], the deflection of concrete sleepers under different ballast conditions [8], and the effect of temperature variations on the behaviour of plastic sleepers [9]. A comparison of these studies indicates that the behaviour of these alternative sleepers is significantly different from each other that could be because of their stiffness variations. For example, Manalo et al. [10] found that the change in MOE of turnout railway sleepers from 1 GPa to 10 GPa would increase the bending moment by 75 %. Shokrieh and Rahmat [11] highlighted that deflection and bending moment are sensitive to change in the MOE of sleepers with lower values of MOE having a greater effect. It was shown that rail seat loads would reduce by 20 % while the deflection increases by 214 % for polymer sleepers compared to concrete sleepers [12]. These studies are however only conducted using numerical and analytical methods, and their results are not directly comparable because of the different assumptions and loading conditions used in their analyses. This limitation can be addressed by experimentally investigating the behaviour of different sleeper technologies with a range of MOE shown in Fig. 1 under similar support and loading conditions so that the obtained data is comparable and to reach a meaningful and relative conclusion that will help in the effective, safe and reliable design of a railway track.

The rail seat load depends on the track stiffness, rail deflection, and sleeper spacing [13,14]. The track or rail support modulus (k) is an important parameter that is often evaluated in the design of sleepers because it has direct implications on the rail deflections and hence on the load distribution of the sleepers. Kerr [15] indicated that both the sleeper bending and compressibility in the rail seat affect the track stiffness. The determination of k value is complex and traditionally involves the use of a loading vehicle because track modulus changes from one place to another along the track [15]. Conventionally, k is found through the relationships of the rail stiffness, rail deflection, and applied load. This means that other important parameters such as rail pad stiffness (if there is any), sleeper material type, ballast and sub-ballast stiffness, and subgrade stiffness are collectively incorporated in the traditional methods of k measurement. Recent developments in railway engineering also add new parameters such as under sleeper pad and ballast mat. A few researchers attempted to evaluate the contribution of each parameter to the rail support modulus individually. Studies on the effect of rail pad stiffness [16–18], the effect of under sleeper pads (USPs) [19,20], and the effect of ballast condition [21,22] found that each of these elements affects the performance of a railway track. Thompson et al. [17] indicated that softer rail pads attenuate track forces more than the stiffer pads, and Gräbe et al. [20] found that the USPs reduce the stress on the ballast while it increases the contact area in the sleeper-ballast interface. Nevertheless, the effect of sleeper material type on the behaviour of ballasted railway tracks has been investigated on a very limited scale. Shokrieh and Rahmat [11] studied the effect of bending MOE on the behaviour of railways sleepers through analytical investigations. The results of their theoretical study showed that the change in MOE greatly affects the behaviour of sleepers. The review of previous research indicated that the simultaneous effect of varying bending and compression moduli on the behaviour railway sleepers have not been studied in detail. There is clearly a lack of experimental investigation of different sleeper types (different materials) on the same testing configurations (ballast box for example). Moreover, the contribution to the change in rail seat deflection due to variation in the compressive modulus of sleepers is still not addressed in the literature, which can be evaluated experimentally using sleepers having different compression properties.

The evaluation tests according to the alternative sleeper materials standards [23–26] are based on rail seat and centre bending tests that do not accurately represent sleepers in-track since the sleepers are supported by the ballast. It was shown that the deflection due to bending evaluated according to the existing standards do not represent how a sleeper bends in the field [27] and the current test methods do not represent the behaviour of sleeper on ballast [28]. Some researchers evaluated the behaviour of railway sleepers using the ballast box test including the static deflection behaviour of Brazillian glulam wood sleepers [29], the effect of under-sleeper pads on the behaviour of tracks [19,20,30], simulation of flooded ballast [31], and ballast performance under cyclic loadings [32]. While these

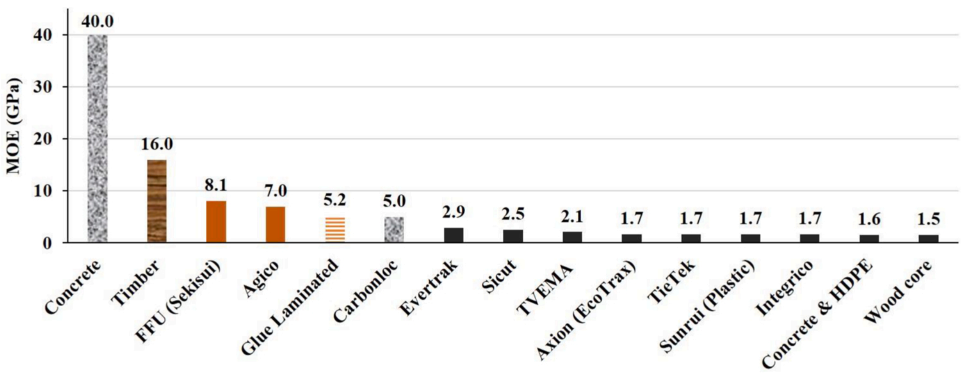


Fig. 1. MOE of different sleeper technologies [8,34–42].

studies employed tests under different conditions, they all showed that the ballast box is a suitable test method of mimicking actual railway tracks for the evaluation purpose. However, there was no attempt to evaluate how the type of sleeper materials affects the behaviour of a railway track. Moreover, the findings from these reported works cannot be adopted for Australian railway tracks due to the difference in gauge width. Experimental research about the full profile bending shape of sleepers is limited. The only reported works were by Carrasco et al. [29] wherein they used only five displacement transducers (TD) to capture the W-shaped profile of only a glulam sleeper and by Ferro et al. [33] wherein they used Linear Variable Differential Transformers (LVDTs) at five different locations of their sleeper samples. A more precise deflection profile of sleepers can be captured using non-contact Digital Image Correlation (DIC) technology, making it possible to track the whole sleeper settlement. Hence, there is a need to study the behaviour of different sleeper types (with a range of MOEs) supported by ballast representing an Australian track configuration.

This study investigates the effect of bending and compressive modulus of different timber alternative sleeper technologies on the behaviour of railway track using a ballast box. This investigation considers four sleeper types, namely hardwood timber, recycled plastic, synthetic composite and low-profile prestressed concrete (referred to as concrete hereafter) sleepers. The bending and compressive moduli of these sleepers were measured experimentally and their effect on track deflection behaviour was demonstrated through a ballast box test simulating narrow-gauge track static loading condition. The Digital Image Correlation technique (DIC) was used to capture the full deflection profile of the sleepers and Finite Element Analysis (FEA) of sleepers on ballast was also carried out to validate the experimental work. The results of this work are anticipated to broaden the view on the deflection behaviour and its effect on railway tracks for timber alternative sleepers made of different materials.

2. Experimental program

2.1. Evaluation of bending and compressive moduli of railway sleepers

All the sleeper technologies considered are designed following the requirements for narrow-gauge track configuration in Queensland, Australia where typical gauge width is 1067 mm (rail centres 1130 mm apart) and sleepers are 2125 mm–2175 mm long [43]. The hardwood timber sleeper was obtained from a local sawmill in Queensland and was identified as Grade 1 other species (spotted gum species) according to the Queensland Rail's material supply specification CT.169 [44]. The concrete sleeper is a low-profile prestressed concrete sleeper designed according to the rational design method [45] and uses concrete with a compressive strength of 60 MPa (28 days) and reinforced with 20 tendons (low relaxed with chevron pattern indentations) of 5.03 mm diameter each. The synthetic composite is a glass fibre-reinforced (continuous in the longitudinal direction) polyurethane foam type sleeper while the plastic sleeper is made out of post-consumer recycled plastics.

The flexural modulus of the sleepers was determined under a three-point bending by following the test method described in ASTM D790:2017 [46,47] and EN 408:2003 standards [46,47]. Full-scale samples were tested non-destructively up to 75 kN load on a test span of 1200 mm with a shear span-to-depth ratio between 5.2 and 4.4. The flexural modulus was calculated using the classical deflection equation (Eq. (1)) [48]. In Eq. (1), E_1 is the longitudinal bending modulus, P is the applied load, L is the test span, I is the second moment of area, and δ is the deflection measured at the centre.

$$E_1 = \frac{PL^3}{48I\delta} \tag{1}$$

The compressive modulus E_2 (also known as perpendicular to the grain for timber and similar materials; and, sometimes denoted as $E_{c,90}$) was determined using a local compression test following the EN 408:2003 standard [48]. This approach was also followed by other researchers when evaluating the mechanical performance of timber in the compression perpendicular to grain [49]. In this test, the rail seat was loaded up to 75 kN using a 150 mm wide by 25 mm thick steel plate and was fully supported at the bottom as shown in Fig. 2. The compression modulus of only timber, SC and plastic sleepers was evaluated as prestressed concrete has a high compression modulus and hence rail seat compression is not a concern for this type of sleepers. Besides, the compression modulus of the concrete

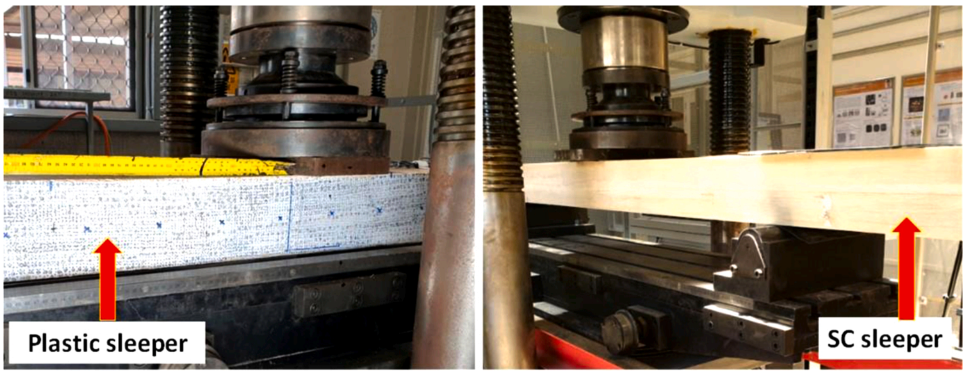


Fig. 2. Local compression (left) and flexural bending (right) test setup.

sleeper can be calculated directly following the methods described in Section 3.1.2 of AS3600:2018 standard [50] ($E_2 = 37{,}400$ MPa). Eq. (2) was used to determine the E_2 of the sleepers [48]. In Eq. (2), **m** is the slope of the load-displacement curve, **h** is the thickness of the sleeper, and A is the loaded area (considering the width of the loading plate and the sleeper).

$$E_2 = \frac{m\,h}{A} \tag{2}$$

Fig. 2 shows the actual test setup for the flexural bending and local compression tests while Fig. 3 shows the load-displacement behaviour of the sleepers tested under compression. Table 1 summarises the important properties of sleepers used in this research.

2.2. Ballast box, properties, and tamping

Several researchers have used a ballast box to simulate the behaviour of railway sleepers in actual field conditions. For this purpose, a steel box of 400 mm in depth, 1000 mm in width and 3000 mm in length was built to simulate a single sleeper layout of a railway track. The 1000 mm width of the ballast box ensures that the ballast coverage of at least one actual sleeper can be obtained because sleepers in the narrow-gauge tracks in Queensland are usually 685 mm apart. This extra width of ballast reduces the effect of confining of the ballast because ballast in actual tracks is continuous whereas in the laboratory it is confined within the box. Some researchers considered a soft layer between the wall of the box and the ballast [22,30,51,52] but, these softer layers are not usually a reflection of in-situ ballast pressure perpendicular to the rail. Different elastic layers (rubber and plywood for example) between the ballast and the bottom of the box were utilized by different researchers to represent the softness of the subgrade [19,22,51–53]. The effect of the elasticity of the subgrade is however very small [53] that can be neglected. In the current study, all the sleepers were tested in the same ballast and support condition to capture the effect of the sleeper material type. Notwithstanding, the effect of ballast disturbance was considered (if there is any form one test to another) by measuring the ballast stiffness using a plate load test and carrying out at least 3 tests for each type of sleeper; the results of which are discussed in the next section.

The ballast provides an elastic layer that supports the sleepers and helps transfer the wheel load from the rails and the sleepers to the subgrade The type of ballast used in this study is crushed rock from quarries usually used in QR tracks with specifications meeting the Australian Standard AS 2758.7 and the QR requirements [54]. The aggregates have a maximum particle size of 63 mm (graded) and have a size distribution shown in Table 2.

Ballast depths of 150–500 mm were reported in the literature for Australian railway tracks [43,55] with QR limiting the maximum depth to 600 mm due to track instability [56]. In this research, a ballast depth of 300 mm (measured from the bottom of the sleeper) was considered. A ballast depth of 300 mm was also considered in some track simulations [22,29] showing the acceptability of this ballast depth in supporting a railway track. The ballast was laid in two layers of 150 mm with manual tamping using a 10 kg sledgehammer and a 400 mm long piece of a timber sleeper as shown in Fig. 4. After levelling of each layer, the hammer was freely dropped (from 2.5 m height) onto the timber piece resting on the ballast for four times; and repeating the process until the whole surface was covered. The sleepers were not covered by ballast from the sides to make the deflection measurement at various depths of the sleeper possible. It is assumed that this will not affect the behaviour since the sleepers are only loaded vertically with no lateral loads.

2.3. Evaluation of sleeper support stiffness

Ballast stiffness is one of the parameters of a track stiffness (k) as shown in Eq. (3) [15].

$$k = \frac{1}{1/k_p + 1/k_s + 1/k_b + 1/k_{sb}} \tag{3}$$

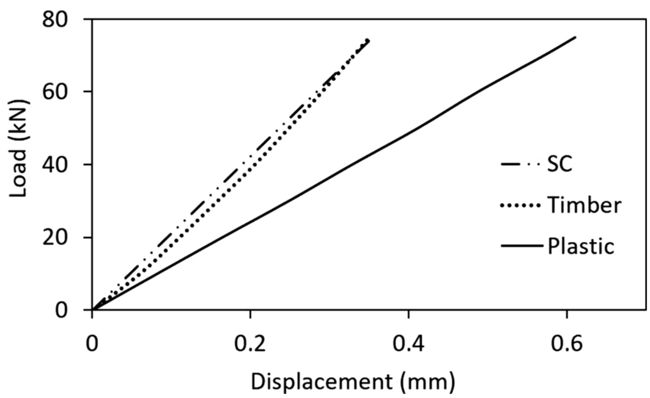


Fig. 3. Load-displacement behaviour of sleeper under local compression test.

Table 1
Sleeper sample properties.

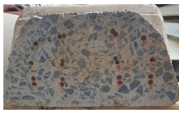
Sleeper type	Cross-section	Length (mm)	I (mm^4)	E_1 (GPa)	E_2 (MPa)
Timber		2130	29150104	13.0	800
Recycled plastic		2050	36621094	10.0	450
Synthetic composite		2120	28389667	7.40	750
Prestressed concrete		2130	48699500	38.0	37400

Table 2
Ballast size distribution and properties [54].

Photo	Sieve size (mm)	% passing	Bulk density (kg/m^3)	Particle density (kg/m^3)
	63.0	100	> 1350 according to AS 1141.4	> 2500 according to AS 1141.4
	53.0	85 to 100		
	37.5	50 to 70		
	26.5	20 to 35		
	19.0	10 to 20		
	13.2	2 to 10		
	9.5	0 to 5		
	4.75	0 to 2		

where k_p is the stiffness of the rail pad (if used), k_s is the stiffness of the sleepers (compressibility at the rail seat and sleeper bending), k_b is the vertical stiffness of the ballast, and k_{sb} is the stiffness the subgrade. Since any change in k changes rail deflection, and hence the distribution of sleeper loads, it is important to quantify the k parameters to understand the precise effect of each parameter. To obtain the pure effects of the compressive and bending modulus of the sleepers, rail pads have not been considered in this research. This situation can also represent an extreme in-track condition when worn or damaged rail pads do not provide much resilience [57]. In this

(a) (b)

Fig. 4. (a) Ballast tamping using a sledgehammer; (b) Plate load test on the ballast.

study, the sleepers are continuously supported by ballast in a steel box placed on a rigid concrete surface. Therefore, the stiffness of the ballast and subgrade can be combined into one parameter. This is referred to as sleeper support stiffness in this research (it is also called ballast modulus). Accordingly, any change in behaviour (settlement) from one test to another depends on the properties of the sleeper and its support as illustrated in Fig. 5. Hence, evaluation of the support stiffness for each test is important to indicate if there is any contribution from the change in the stiffness of the ballast. The values of the support stiffness were also used for comparison and verification of the sleepers behaviour according to the FEA in Ansys Software [58].

The sleeper support stiffness was evaluated using a plate load test as shown in Fig. 4. A 285 mm diameter steel plate was loaded until a contact pressure of at least 300 kPa was obtained, as also followed by Abadi et al. [52]. The displacement was measured using an LVDT attached to the head of the loading ram. The stiffness of the ballast was calculated from the slope of the pressure-displacement curve using Eq. (4) [32,59]. In Eq. (4), $\sigma_{max} - \sigma_{min}$ is the change in the applied stress, and $\delta_{max} - \delta_{min}$ represents the difference in the maximum and minimum displacement.

$$k_b = \frac{\sigma_{max} - \sigma_{min}}{\delta_{max} - \delta_{min}} \tag{4}$$

The test was carried out four times, i.e. the sleeper support modulus was measured before testing each type of sleeper to ensure consistent results and that any changes in the sleeper behaviour were only affected by changes in the bending and compressive moduli of the sleepers. This approach will also show whether the ballast becomes stiffer due to repetitive loads

2.4. Test of sleepers on ballast

The full profile bending of the sleepers and local compression around the rail seat area was captured by using the Digital Image Correlation (DIC) technique. Previous research has shown that the DIC is a powerful and precise non-contact full-field measurement technique [60,61] capable of accurately measuring submillimeter changes using only one camera [62,63]. In recent years, the use of DIC in the field of railway sleepers has been increased such as the deflection of railway sleepers [64,65], turnout sleepers [66] and the crack width measurement of concrete sleepers [67]. Hence the DIC technique was chosen for this research to not only capture the full profile deflection but also the local compression under the sleepers. These behaviours are very difficult to capture using traditional gauges which also highlights the advantages and novelty of using the DIC for this investigation.

The DIC system came from iMetrum Ltd. based in the UK, comprises an industrial PC, a digital video recording camera, low distortion lens, lighting, and tripods. It uses an advanced recording and data analysing software called the Video Gauge software [68] which uses complex algorithms to recognise changes in the sub-pixel patterns. This means it can measure high-resolution deflections of objects ranging in size from microns to hundreds of meters, depending on the lens selection [69]. The video (a series of images) from the DIC uses 256 shades of grey (0–255) to track changes in the material (displacements, distortions, etc) which means a good level of contrast is needed on the surface to be measured. This was achieved by randomly applying black speckles (the plastic and timber sleepers were painted white to obtain the best contrast) on the side of the sleepers. Black marks were also drawn every 100 mm along the length of the sleepers and at 50 mm intervals around the rail seats to capture full-profile deflection at these points. The use of the DIC enabled deflections to be captured in at least 25 points along the length to obtain a more realistic and accurate bending shape of the sleepers. One strain gauge was also attached to the top-centre of the sleepers. Data from the strain gauge was used as an indicator of the bending shape where positive strain represents W-shape while negative strain represents U-shape. After the ballast and the sleeper preparations, a sleeper was laid at the centre of the box, on the ballast, and the box was placed under a structural testing frame. A hydraulic load ram of 444 kN capacity with an LVDT for deflection verification from the DIC was used. The load was applied to two rail pieces sitting on the rail seats (1130 mm apart) through a spreader beam (Fig. 6). Several preloading tests were run using a timber sleeper to ensure the ballast is well compacted. At least three tests were performed for each sleeper type and the deflections were measured for each test. The final deflection measurement was taken when the difference in rail seat deflection between two successive tests was less than 0.1 mm.

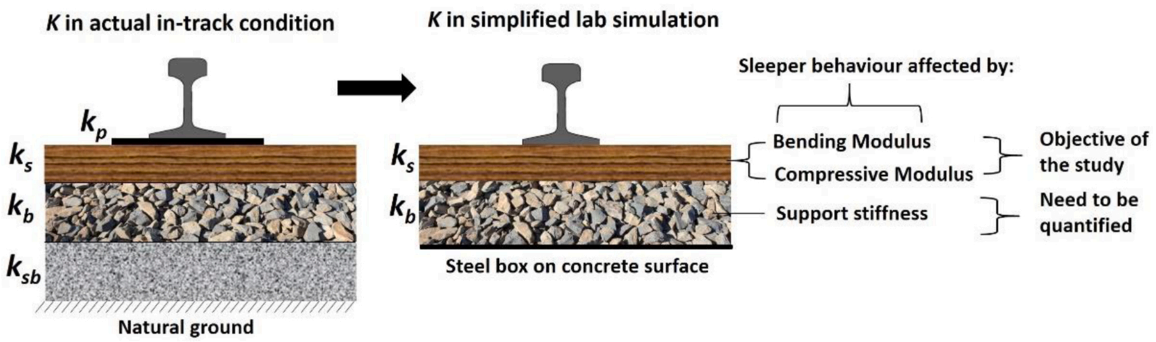


Fig. 5. Simplification made in the laboratory track simulation.

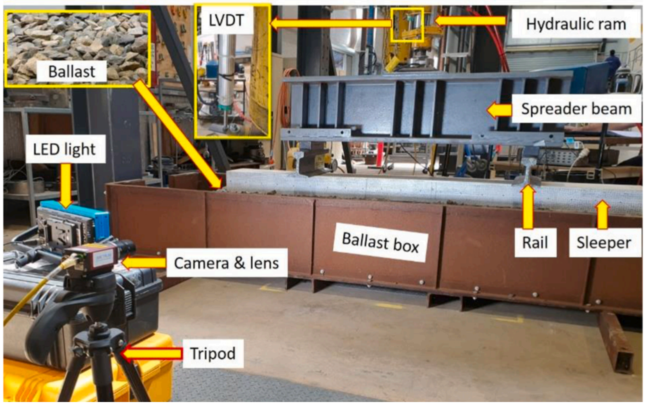


Fig. 6. Sleeper on ballast test.

3. Numerical simulation and validation

FE models of the sleepers using Ansys Workbench software version 2020 R1 [58] was created using the Solid186 element type. This type of element is a 20-node 3D structural element that has three degrees of freedom allowing deflections in the longitudinal (x), vertical (y), and lateral (z) directions. The properties of the sleepers in Table 1 were used to construct 3D models of the sleepers. As explained in Section 2.3, the ballast (k_b) and subgrade (k_{sb}) layers can be represented as one elastic layer resting on a rigid foundation in the ballast box test. The Elastic Support function in Ansys Workbench software was used to introduce the support stiffness of the sleepers (applied at the bottom face of the sleepers) as shown in Fig. 7. The definition of the Elastic Support in Ansys Workbench software coincides with the definitions used to describe the sleeper support stiffness which is the pressure (or force) required to produce a unit of normal deflection of the foundation. A wheel load of 72 kN was applied to each rail seat on an area equal to the contact area between the AS 41 kg rail and the sleeper, i.e. 127 mm times the width of the sleeper. The distance between the centre of the rail seats is 1130 mm. The movement of the sleepers was restrained in the z and x directions while allowing rotations around the z-axis to allow for bending of the sleepers. The vertical movement of the sleeper is only restrained by the elastic support as it is also the case in the experiment. Realistic support stiffnesses reported in Section 3.3 (presented in Section 5.1) were used for each type of sleeper (in N/mm^3 as shown in Table 3).

The FEA was validated with the experimental tests which will be discussed in Section 4.3. To ensure the FE models represent the sleeper on elastic foundation, the Beam on Elastic Foundation (BOEF) theory was used to validate the models in the development stage. The BOEF theory was introduced by Winkler in 1867 and by Zimmermann in 1888 [14]. A century later, Heteneyi [70] presented the full derivation of the deflection equation for a finite beam (sleeper) resting on an elastic foundation and loaded by two equal concentrated forces at the centre of the rail seats [14]. BOEF was used to validate the deflection profile of the sleepers as this analysis approach is based on beam on elastic foundation, which is very similar to an actual sleeper on ballast and an approach that has been used by many researchers for studies on sleeper on ballast [33]. Moreover, this analysis method has also been accepted in the

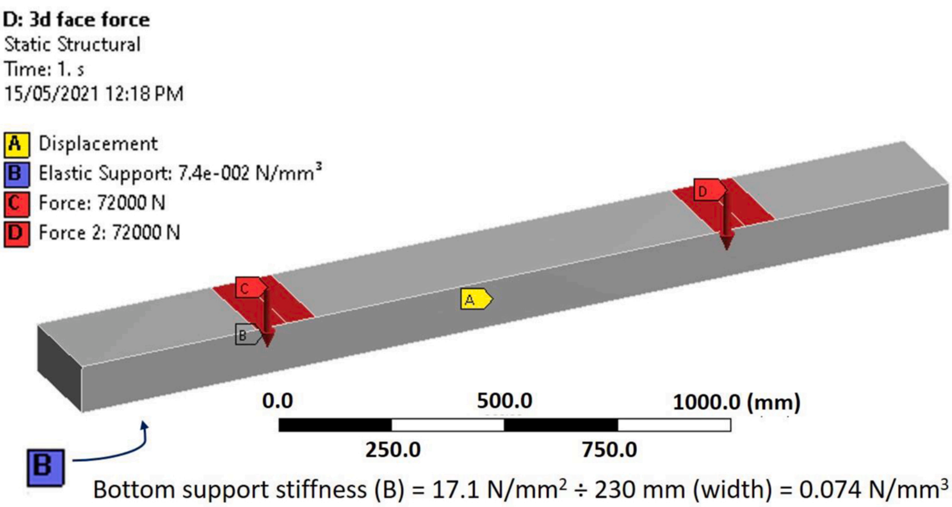


Fig. 7. FE model of the sleeper in Ansys software.

Table 3
Results of plate load test for sleeper support stiffness evaluation.

Sleeper type	Maximum stress applied (MPa)	Max deflection (mm)	Support stiffness (N/mm^3)	Sleeper width (mm)	Support stiffness (MPa)
Timber	0.386	5.2	0.074	230	17.1
Plastic	0.405	5.5	0.073	225	16.6
SC	0.357	4.9	0.073	225	16.4
Concrete	0.398	5.3	0.075	240	18.0

Australian standard for prestressed concrete sleepers AS 1085.14 [23] and steel sleepers AS 1085.17 [71]. According to this model, the deflection of the sleeper is affected by the condition of the ballast (sleeper support stiffness), gauge width/sleeper length, and the MOE of the sleeper. In this model, the sleeper is represented with a finite one-dimensional beam resting on an elastic foundation. The analytical equation according to BOEF (also in AS 1085.14 [28]) may be used directly to predict the vertical displacement of the sleeper at the rail seats only, but the W-shape of the sleepers cannot be predicted with only rail seat deflection data. Besides, the BOEF model only considers the bending modulus of the sleeper which assumes there is no deformation under the rail seat. This means that the effect of the compressive modulus on the rail seat compression of the sleepers cannot be captured by the BOEF theory. Therefore, Finite Element Analysis (FEA), that considers both the bending and compression properties of the sleepers, is a necessity to find out the effects of the sleeper material changes.

The sleepers were first modelled as constant compression modulus with varying the bending modulus in the range provided in Table 1. A support stiffness range of 10−40 MPa (typical for Australian tracks) was used in the comparison to ensure the model is accurate in various sleeper and support conditions. Excel spreadsheet was used to solve Eq. (4).3(2) (BOEF) in the AS 1085.14 [23] with varying sleeper and support stiffness, similar to the FEA. The results of the analytical (AS 1085.14) and the FEA were in very good agreement with almost no difference in the bottom rail seat deflections between the two methods (difference of around 0.01 mm for the range of the bending modulus presented in Table 1). The realistic sleeper support stiffness and sleeper bending, and compression modulus where then applied to the models to validate the experimental tests. The results are discussed in Section 4.3.

4. Results and discussion

4.1. Support stiffness of different sleepers

The results of the plate load test are tabulated in Table 3. Eq. (4) was used to calculate the support stiffness.

The obtained support stiffness is very consistent from one test to another with an average value of 0.074 N/mm^3. This indicates minimal ballast disturbance from one test to another, and the sufficient compaction of the ballast. The obtained average stiffness of the support in this research is 17 MPa which is also very close to the stiffness value (16.9 MPa) obtained by Baghsorkhi et al. [19] using a box test. Besides, the obtained values are within the typical ballast modulus values (10–40 MPa) for Australian tracks reported by Jeff and Tew [14]. It can, therefore, be said that the difference in the deflection behaviours of the sleepers is due to the difference in the bending and compressive modulus of the sleepers. The values of support stiffness highlighted in Table 3 are also those used in the FEA.

4.2. Strain behaviour at midspan of different sleepers

There is a slight increase in the strain reading from the first to the third test as shown in Fig. 8. This is because of the seating of the samples on the ballast as it was also confirmed from the rail seat deflections of test 1 and test 3 (Section 5.3). This change, although very small, is a reflection of the bending modulus of the sleepers. For example, the plastic sleeper showed almost no change in the strain and exhibited a positive strain for all three tests. This also shows that the plastic sleeper sits well on the ballast. The timber and the SC

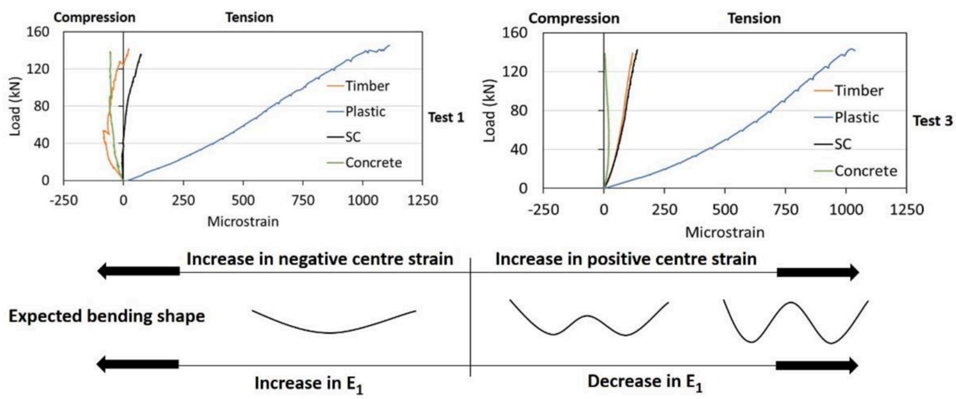


Fig. 8. Test 1 and test 3 top-centre strain data with expected bending shape illustration.

sleepers showed a negative strain up to around 50 kN and then leaned towards the positive side in the first test, but the SC sleeper showed a higher positive strain which is a reflection of its lower bending modulus than a timber. The concrete sleeper showed completely negative strain behaviour in the first test which indicates a U-shaped bending behaviour as was also noticed from DIC deflection measurements. In the third test, the plastic, SC, and timber sleepers showed a positive strain at the centre of the sleeper with values reflecting their bending modulus (a lower bending modulus sleeper has a higher strain). As a result, apparent W-shape bending behaviour is expected for these types of sleepers. The concrete sleeper, on the other hand, showed a positive strain but with values close to zero which indicates that the sleeper had almost flat centre when loaded. The above discussion can be further validated with the full-length deflection graphs presented in the next section.

4.3. *Effect of bending modulus*

All sleepers showed higher overall deflection in the first test with almost no difference between the second and last tests. Accordingly, the data from the third test is considered as the true sleeper behaviour on ballast and was used for comparison. A similar trend was also reported by Carrasco et al. [29] when they related the first test as ballast compaction and the second test as data acquisition for Citriodora glulam timber sleeper. In addition to the ballast compaction, sleeper settlement into the ballast was observed especially for softer sleepers. There is no permanent ballast settlement after the third test of the first sleeper type (i.e. the test of timber sleeper). Also, a consistent ballast modulus of 17 MPa $\pm$ 0.71 MPa was obtained for all tests, indicating that the ballast condition has not been disturbed after each test even at service load conditions. This was further confirmed with the condition of the ballast grain after the test wherein no crushed edges or broken pieces were observed. However, limitations should be recognised that manual tamping is different to that of the field tamping with a special equipment.

Fig. 9 shows a full profile behaviour of the sleepers measured at the bottom of the sleepers using the DIC (experimental) and the behaviour according to the FEA model implementing similar boundary conditions as explained in Section 3. It is worth noting that the deflection on the left and right-hand side of the sleepers as measured from the experiment are very identical from each other. This showed that a good ballast distribution, equal load application, and compaction along the sleeper length were achieved. This may however not be the case in reality as a slight change from left-to-right rail seat deflection was measured for timber and plastic sleepers [72]. As shown in Fig. 9, a good agreement between the FEA and the experimental results was obtained with slight differences in the deflection behaviour for plastic and the SC sleepers. This is justifiable because of the simplifications made in the FEA wherein the sleepers were modelled as anisotropic materials with solid bodies having different properties in x and y direction. In reality, however, the sleepers are slightly different and are more complex. The plastic sleeper has random pores in the centre of its cross-section that may compress during loading. These voids are created by adding foaming agents in the manufacturing process to minimise weight and the cost of material used [73]. Moreover, the ballast in the FEA model is represented as one elastic layer while it is a contribution of the interaction of many particles, in reality. This explains the slight shift (around 0.1 mm) in the experimental results versus the FEA results which were shown to be the limitation of this kind of simulation (BOEF) [74]. It can be said that the experimental results are in good agreement to that of the FEA model and hence the Australian standard AS 1085.14 [23] with only slight differences that can be neglected.

The expected W-shape deflection of the sleepers supported continuously on a ballast was successfully captured using the DIC. The plastic sleeper has the highest magnitude of deflection (5.8 mm at the rail seat) while the concrete sleeper has the least deflection (3.5 mm at rail seat). This was due to the much lower bending modulus of the plastic sleeper compared to the concrete sleeper. Since the SC sleeper had a lower bending modulus than the timber sleeper, its rail seat deflection of 4.9 mm was higher than the 4.1 mm of the timber sleeper. It is obvious that the change in vertical rail seat deflection is not proportional to the change in the sleeper bending modulus. The FEA of sleepers with support stiffness of 17 MPa also shows this behaviour (Fig. 10). By considering timber sleeper as the benchmark (MOE = 13.0 GPa), the plastic sleeper with a MOE of 1.0 GPa exhibited 42 % higher rail seat deflection while the SC with a MOE of 7.4 GPa had a 20 % higher rail seat deflection. On the other hand, the concrete sleeper (38.0 GPa) had only 13 % less rail seat deflection despite having MOE of three times that of timber sleepers. It follows that sleepers with MOE of around 13.0 GPa and higher do not show much difference in the rail seat deflection. In fact, the W-shape bending profile of these sleepers become less noticeable, with the centre part being almost flat as shown in the case of concrete sleepers in Figs. 9 and 8 (according to the strain data). This finding agrees with the theoretical findings in [11] wherein the researchers indicated that the effect of changing MOE on the deflection

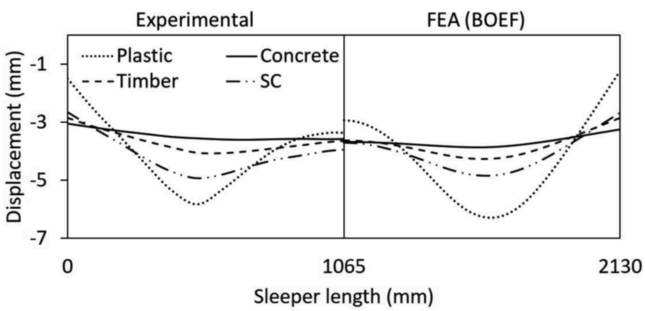


Fig. 9. Sleeper deflection shapes (experimental and FEA investigations).

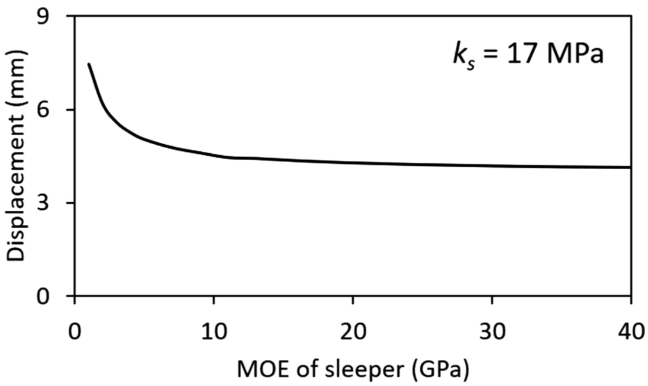


Fig. 10. Rail seat deflection for different sleeper MOE according to BOEF in AS1085.14.

of sleepers is more apparent on low bending modulus (1–15 GPa) sleepers than the higher ones.

Fig. 9 shows that stiffer sleepers exhibited overall lower deflections and the W-shape of these sleepers was less apparent; the concrete sleeper showed almost flat profile. As a result, softer sleepers experience higher stress at the rail seat and the centre due to the higher bending shape. This finding is supported by the higher strain readings at the top-centre of the sleepers (Fig. 8). Another consequence would be on the ballast pressure such that the softer sleepers, i.e. plastic sleepers, experience higher ballast pressure in the rail seat area than the stiffer sleepers (prestressed concrete sleepers). This higher deflection of the softer sleepers in the rail seat region means that these sleepers will be subjected to higher bending stress at service load which may result in material failure if not considered in the design. This agrees with the theoretical and graphical illustrations by Jeffs and Tew [14] wherein they indicated that the increase of the sleeper stiffness may lead to a more uniform pressure distribution under the sleeper. This could be because the bending modulus of these sleepers is much higher than that of the support stiffness (ballast) that makes these sleepers more resistant to bending. This was observed with the concrete sleepers' settlement into the ballast along its length (Fig. 9) without experiencing obvious bending. In conclusion, the bending modulus affects the overall W-shape profile of the sleepers and hence the stress distribution, the vertical deflection of the sleepers especially at the rail seat, and the pressure distribution under the sleepers.

4.4. Effect of compressive modulus

As highlighted in Section 3, the BOEF does not consider the local deformation of sleepers under the rail seat as this analysis approach is considering the sleeper materials to be of isotropic material, i.e. similar modulus of elasticity in all directions. In contrast, most of the timber-alternative sleeper materials as well as hardwood timber have properties different in different directions. This was clearly observed in the experimental investigation wherein the compression properties in the transverse direction has a significant effect on the overall behaviour of the sleepers. From the three-dimensional FEA of the sleepers supported by ballast, local compression at the rail seat contributes to total deflection as revealed in Table 4. The amount of deflection increases with the increase in the support modulus due to the increasing resistance of the support. This finding is especially critical for soft sleepers as there is a high compression effect under and around the rail seat that may induce higher local deformation on the top than the bottom part of the sleepers. Moreover, the compression tests in the sleeper standards only deal with the permanent indentation at the rail seats after removing the load. As no permanent indentation is recorded for the service load applied in this research, the local compression measured under rail can be of concern for the designers of low compression modulus sleepers.

This behaviour was captured in the test using the DIC by measuring the top and bottom deflections along the length of the sleepers. Table 5 shows the difference in the top and bottom deflections of the sleepers due to compression under the rails. The concrete sleeper was the only sleeper type that did not show any local compressive deflection under the rail. This can be explained by the nature of concrete which has a very high stiffness (compression modulus = 37.4 GPa) and will compress very minimally under the level of load applied in this study. This lack of compressibility and higher bending modulus increases track stiffness which in turn attracts more load to the sleeper and it induces high ballast pressure under the sleeper. Since the railway industry started using concrete sleepers more than half a century ago, this lack of compressibility has been realised and has been addressed with the provision of elastic rail pads.

Table 4
The difference in top-bottom rail seat deflection for different k_s values.

Sleeper type	Local compression (mm)			
	$k_s = 10$ MPa	$k_s = 20$ MPa	$k_s = 30$ MPa	$k_s = 40$ MPa
Timber	0.168	0.17	0.171	0.172
Plastic	0.319	0.322	0.328	0.333
SC	0.186	0.189	0.19	0.192
Concrete	0.003	0.003	0.003	0.003

Table 5
Differences in the top and bottom deflections of the sleepers.

Sleeper type	Rail seat top deflection (mm)	Rail seat bottom deflection (mm	Difference (mm)
Timber	4.25	4.10	0.15
Plastic	6.17	5.84	0.33
SC	5.13	4.94	0.19
Concrete	3.55	3.55	0.00

However, all the other types of sleepers showed a local compression deflection when the deflections at the top and bottom of the rail seats were compared. The plastic sleeper had a difference of 0.33 mm (5.7 % of the rail seat deflection) in deflection which was the highest of all the other samples. The second highest top-to-bottom difference in deflection was the SC sleeper which had around 0.19 mm (3.8 % of rail seat deflection). The timber sleeper had a slightly less compression of around 0.15 mm (3.6 % of rail seat deflection). The difference in local compressions under the rail seats can be attributed to the compression modulus of the sleepers. This observation shows that the lower the compression modulus, the higher the deflection under the rail seat (i.e. the top-to-bottom deflection difference). For example, the plastic sleeper had almost twice the deflection difference of the SC and timber sleeper because its compression modulus is almost half of the other two types of sleepers.

The percentages of local compression to vertical rail seat deflection for support stiffness of 17 MPa (experimental) varied from 3.6 % for timber sleepers to 5.7 % for plastic sleepers. This low deflection could be because the sleepers were resting on elastic support that already allows vertical deflection as shown in Fig. 9. For example, the FEA analysis indicated that with a support stiffness of 40 MPa this range increases (spans from 8 % for timber to 10 % for plastic sleepers). This result agrees with the findings of Krishnamoorthy et al. (2018) [75] where they indicated stress (or pressure) can be absorbed by elastic layers under the sleeper. This can be confirmed further by the load-displacement graphs of the sleepers under the local compression test (Fig. 3) where sleepers showed almost twice the deflection recorded in Table 5. This was because the sleepers were supported by rigid steel support that would not allow for any vertical settlement, even though, the load applied was smaller than the ballast box test because the steel plate used in the compression test was larger (18 % more contact area than the rail contact area). It was also because in every case the ballast modulus was much lower than the bending modulus of the sleepers and the ballast was unable to completely resist the rail seat vertical displacements of the sleepers. Notwithstanding, a service load of 72 kN per rail seat was applied so decompression might increase at higher levels of loading. It can be said that the contribution of local compression to the total deformation should be considered especially for sleepers with relatively low compressive modulus on a ballast with high support stiffness.

4.5. In-track behaviour of sleepers with different bending and compression moduli

It is expected that the in-track behaviour of alternative sleeper technologies is different from each other due to variations in their material properties. It has been shown that sleeper stiffness characteristics play an important role in the determination of the rail seat load of a track [14]. Changes in the sleeper stiffness also affect the predicted rail seat load as it is related to the rail deflection which is affected by the sleeper material type. This study has shown that the bending modulus has a greater effect on the vertical deflection of sleepers since the maximum contribution of decompression is only at 10 % of the rail seat deflection. A higher rail seat deflection, however, cannot directly imply that the predicted rail seat wheel load is higher. This is because as the rail deflection increases, the track stiffness decreases for a given track configuration which results in the wheel load being carried by a greater number of sleepers. O'Rourke et al. [76] stated that the product of rail deflection (y_{rail}) and track stiffness (k) is constant. According to Clarke [13], the predicted rail seat load calculated according to BOEF theory is:

$$Rail\ Seat\ Load\ (RSL) = S\ k\ y_{rail} \tag{5}$$

where S is the sleeper spacing.

Since an equal RSL of 72 kN was applied to all the sample sleepers and a single sleeper is loaded (i.e. no variation in S), the difference in rail seat deflections recorded (see Table 5) can also be attributed to changes in the overall track stiffness (k). This means that using softer sleepers would reduce track stiffness and vice versa because the product of the two is constant. While the magnitude of track stiffness cannot be evaluated by testing a single sleeper on ballast, the percentage of this change can be evaluated by rearranging Eq. (5) and using the timber sleeper as a benchmark (Table 6). In this calculation, a sleeper spacing of 685 mm is assumed and the rail deflection is equated to the sleeper rail seat deflection. This is justifiable because the purpose is not to calculate the value of (k) but rather the percentage of its change which is independent of the sleeper spacings. As Table 6 shows, the product of $k.y_{rail}$ is constant which agrees with the findings of O'Rourke et al. (1978) [76].

The change from timber sleeper (E_1 = 13.0 GPa) to plastic sleeper (E_1 = 1.0 GPa) reduces track stiffness (k) by almost 30 % (31 % with decompression effect) while k decreased by 17 % (17.2 % with decompression effect) when a synthetic composite sleeper (E_1 = 7.4 GPa) was used. Despite the concrete sleeper having a bending modulus of 38.0 GPa, three times the timber sleepers' bending modulus, the increase in the k is only 15 %. This change in the track stiffness shows that the bending modulus that affects more the value of track stiffness than the local decompression at rail seat. Moreover, the effect is more on the sleepers with stiffness below that of timber sleeper. This can be justified by studying the rail seat deflection of different sleeper stiffness for a given k_s value (17 MPa) according to BOEF theory. As shown in Fig. 10, the rail seat deflection change is more sensitive to sleepers below the MOE of around 13.0 GPa for a given sleeper support stiffness. From these results, it can be concluded that the change in the sleeper stiffness not only

Table 6
Percentage of k change for different sleeper technologies.

Sleeper type	S (mm)	RSL (N)	Recorded y_{rail} (mm)	k (MPa)	% change in k	y_{rail} k (N/mm)
Timber	685	72000	4.10	25.6	Benchmark	105
Plastic	685	72000	5.84	18.0	−29.8	105
SC	685	72000	4.94	21.3	−17.0	105
Concrete	685	72000	3.55	29.6	15.5	105

affect the vertical rail seat and overall deflection of the sleepers but also the track stiffness as shown in Table 6. The change (an increase or decrease) of the track stiffness reflects the sleepers' bending and compressive modulus but the rate of change is not proportional as shown in Table 6. Although the effect of the decompression on track stiffness is minimal (less than 1 %), it was within 10 % of the total rail seat deflection (for stiff support where $k = 40$ MPa) so this effect should be considered in the design of alternative sleepers. Further research in this area however may be needed before the current standards consider the decompression behaviour at the rail seat in the design of railway sleepers. Nonetheless, the findings from this study provided a better understanding of the deflection behaviour of different sleepers (supported by ballast) having distinct mechanical properties, which were demonstrated experimentally and validated by FE analysis.

5. Conclusion

This research evaluated the effect that the bending and compressive modulus had on the behaviour of alternative railway sleeper technologies. Timber, plastic, synthetic composite, and concrete sleepers were statically tested in a ballast box and loaded through two rails to represent a narrow-gauge track configuration. The results of these tests and numerical simulations of sleepers on ballast resulted in the following conclusions:

- Railway sleepers with a low bending modulus such as plastic sleepers have a prominent W-shaped deflected profile along their length when supported by a ballast, whereas stiffer sleepers such as prestressed concrete sleepers have an almost flat profile. Moreover, sleepers with a low modulus of elasticity experience high bending stress in the centre and rail seat and this can lead to material failure if not accounted for at the design stage.
- The compressive modulus has a direct correlation to the level of local compression at the rail seat. Soft sleepers such as plastics (MOE of 1.0 GPa) will have a local deformation of at least 5.7 % of the total rail seat deflection under a service train load (and a support stiffness of 17 MPa) but can go as high as 10 % for stiffer support ($k = 40$ MPa). Local decompression is however negligible to sleepers with high compressive modulus such as prestressed concrete (MOE of 38.0 GPa).
- The bending modulus of sleepers contributes significantly more to the stiffness of a track than decompression. The increase in sleeper bending modulus increases the track stiffness but with the rate of change in track stiffness disproportional to bending modulus. The change in track stiffness is more sensitive to the bending modulus lower than that of the timber sleepers.
- The overall and rail seat deflections are affected by both the changes in the bending and compression moduli, but the bending modulus effect is more prominent.

The findings of this research are limited to the sleeper types tested in the study and considering other sleeper materials beyond the scope of this study is valuable in future research. Although the current design methods account for dynamic load effects through load factors (similar design to static), the true dynamic behaviour should experimentally be evaluated to conclude the effects of the material properties on the dynamic behaviour of a track. Moreover, as the DIC has successfully captured the effect of different sleeper material type on the track modulus, the authors suggest other important studies using the DIC such as quantifying track modulus from various ballast particle size distribution. Despite its limitation, the strategic and systematic method used in this case study can be a guide for future investigations.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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References

[1] C. Esveld, Modern Railway Track, 2nd editon, Delft university of Technology, 2001.
[2] Manalo, T. Aravinthan, W. Karunasena, A. Ticoalu, A review of alternative materials for replacing existing timber sleepers, Compos. Struct. 92 (3) (2010) 603–611.

[3] E.T. Bahtiar, N. Nugroho, M.M. Rahman, Arinana, R. Kartika Sari, W. Wirawan, D. Hermawan, Estimation the remaining service-lifetime of wooden structure of geothermal cooling tower, Case Stud. Constr. Mater. 6 (2017) 91–102.
[4] M. Sasidharan, M. Burrow, G. Ghataora, A whole life cycle approach under uncertainty for economically justifiable ballasted railway track maintenance, Res. Transp. Econ. 80 (2020), 100815.
[5] M. Giunta, S. Bressi, G. D`Angelo, Life cycle cost assessment of bitumen stabilised ballast: a novel maintenance strategy for railway track-bed, Constr. Build. Mater. 172 (2018) 751–759.
[6] S. Senaratne, O. Mirza, T. Dekruif, C. Camille, Life cycle cost analysis of alternative railway track support material: a case study of the Sydney harbour bridge, J. Clean. Prod. (2020), 124258.
[7] S. Kaewunruen, Monitoring in-service performance of fibre-reinforced foamed urethane sleepers/bearers in railway urban turnout systems, Struct. Monit. Maint. 1 (1) (2014) 131–157.
[8] Y. Pang, S.N. Lingamanaik, B.K. Chen, S.F. Yu, Measurement of deformation of the concrete sleepers under different support conditions using non-contact laser speckle imaging sensor, Eng. Struct. 205 (2020), 110054.
[9] M.A. Issa, I. Lotfy, M. Farhat, Temperature Effect on the Performance of Glass Fiber Reinforced High Density Polyethylene Composite Railroad Crossties, 2015.
[10] A. Manalo, T. Aravinthan, W. Karunasena, N. Stevens, Analysis of a typical railway turnout sleeper system using grillage beam analogy, Finite Elem. Anal. Des. 48 (1) (2012) 1376–1391.
[11] M.M. Shokrieh, M. Rahmat, Effects of Young's modulus on response of railway sleeper, Appl. Math. Model. 31 (4) (2007) 700–711.
[12] A. van Belkom, A simplified method for calculating load distribution and rail deflections in track, incorporating the influence of sleeper stiffness, Adv. Struct. Eng. 23 (11) (2020) 2358–2372.
[13] C.W. Clarke, Track loading fundamentals–1 introduction: track and wheel loading, Railw. Gaz. 106 (1957) 45–48.
[14] T. Jeffs, G. Tew, A review of track design procedures: sleepers and ballast, Railw. Australia 2 (1991).
[15] A.D. Kerr, On the determination of the rail support modulus k, Int. J. Solids Struct. 37 (32) (2000) 4335–4351.
[16] S. Kaewunruen, A.M. Remennikov, Sensitivity analysis of free vibration characteristics of an in situ railway concrete sleeper to variations of rail pad parameters, J. Sound Vib. 298 (1-2) (2006) 453–461.
[17] D. Thompson, C. Jones, T. Wu, A. De France, The influence of the non-linear stiffness behaviour of rail pads on the track component of rolling noise, Arch. Proc. Inst. Mech. Eng. Part F J. Rail Rapid Transit 213 (4) (1999) 233–241.
[18] H. Ilias, The influence of railpad stiffness on wheelset/track interaction and corrugation growth, J. Sound Vib. 227 (5) (1999) 935–948.
[19] M. Safari Baghsorkhi, S. Laryea, G. McDowell, N. Thom, An investigation of railway sleeper sections and under sleeper pads using a box test apparatus, Arch. Proc. Inst. Mech. Eng. Part F J. Rail Rapid Transit 230 (7) (2016) 1722–1734.
[20] P. Gräbe, B.F. Mtshotana, M.M. Sebati, E. Thünemann, The effects of under-sleeper pads on sleeper-ballast interaction, J. South Afr. Inst. Civ. Eng. 58 (2) (2016) 35–41.
[21] S. Kaewunruen, A.M. Remennikov, Influence of ballast conditions on flexural responses of railway concrete sleepers, Concrete Australia 35 (4) (2009) 57–62.
[22] T. Abadi, L. Le Pen, A. Zervos, W. Powrie, Measuring the area and number of ballast particle contacts at sleeper/ballast and ballast/subgrade interfaces, Int. J. Railw. Technol. 4 (2) (2015) 45–72.
[23] Standards Australia, AS 1085.14-2012 : Railway Track Material Prestressed Concrete Sleepers, Australia, 2012.
[24] Standard Australia, AS 1085.22: 2019, Railway Track Materials: Alternative Material Sleepers, RISSB, 2020.
[25] International Organization for Standardization, ISO 12856-1: plastics - Plastic railway sleepers for railway applications (railroad ties), Part 1: Mater. Charact. (2014).
[26] AREMA, Chapter 30 - Ties, AREMA, USA, 2014, pp. 1–202.
[27] S. Kaewunruen, C. Ngamkhanong, P. Sengsri, M. Ishida, On hogging bending test specifications of railway composite sleepers and bearers, Front. Built. Environ. 6 (2020), 592014.
[28] M. McHenry, Y. Gao, J.P. Billargeon, Implementing improved composite tie design and testing guidelines, in: Proceedings of the American Railway Engineering and Maintenance-of-Way Association Annual Conference, Chicago, IL, 2018, pp. 206–227.
[29] E. Carrasco, L. Passos, J. Mantilla, Structural behavior evaluation of Brazilian glulam wood sleepers when submitted to static load, Constr. Build. Mater. 26 (1) (2012) 334–343.
[30] S.K. Navaratnarajah, B. Indraratna, N.T. Ngo, Influence of under sleeper pads on ballast behavior under cyclic loading: experimental and numerical studies, J. Geotech. Geoenvironmental Eng. 144 (9) (2018), 04018068.
[31] S. Kaewunruen, T. Tang, Idealisations of dynamic modelling for railway ballast in flood conditions, Appl. Sci. 9 (9) (2019) 1785.
[32] W.L. Lim, Mechanics of Railway Ballast Behaviour, University of Nottingham Nottingham, UK, 2004.
[33] E. Ferro, J. Harkness, L. Le Pen, The influence of sleeper material characteristics on railway track behaviour: concrete vs composite sleeper, Transp. Geotech. (2020), 100348.
[34] FFU Synthetic Sleeper | Railway Technology, 2010 (Accessed 03/06/2019), https://www.renos.fi/.
[35] AGICO Group, Synthetic Sleeper, 2019 (Accessed 15 June 2019), http://www.railway-fasteners.com/.
[36] Evertrak, Evertrak 7000, 2019 (Accessed 10 June 2019), https://www.evertrak.com/.
[37] Sicut Enterprises Ltd, Railway Sleepers, Key Benefits, Sicut Enterprises Ltd, 2019 (Accessed 14 June 2019), http://www.sicut.co.uk/.
[38] TVEMA, Composite Railway Sleepers, 2019 (Accessed 1 May 2019), https://tvema.com/.
[39] Axion, Axion Structural Innovations, ECOTRAX Composite Railroad Ties, 2019 (Accessed 14 June 2019), https://axionsi.com/.
[40] TieTek, Spec Sheet: Composite Railroad Crosstie Technical Data, 2019 (Accessed 14 June 2019), http://www.tietek.net/.
[41] Sunrui, Plastic Composite Sleepers, Luoyang Sunrui Rubber & Plastic Science and Technology Co., Ltd, 2019 (Accessed 15 May 2019), http://www.xssunrui.com/.
[42] Integrico, IntegriTies, 2019 (Accessed 10 June 2019), https://www.integrico.com/integrities.
[43] W. Ferdous, A. Manalo, G. Van Erp, T. Aravinthan, K. Ghabraie, Evaluation of an innovative composite railway sleeper for a narrow-gauge track under static load, J. Compos. Constr. 22 (2) (2018), 04017050.
[44] Queensland Rail, Material Supply Specification TRACK-CT.169, Civil - Sleepers - 115 Mm and 150 Mm Thickness, Queensland, 2018.
[45] J. Nairn, N. Stevens, Rational design method for prestressed concrete sleepers, CORE 2010: rail, Rejuvenation Renaissance (2010) 174.
[46] ASTM D790-17 - Standard Test Methods for Flexural Properties of Unreinforced and Reinforced Plastics and Electrical Insulating Materials, American Society for Testing Materials, Philadelphia, 2017.
[47] European Standard EN 408, Timber structures. Structural timber and glued laminated timber. Determination of some physical and mechanical properties. European Committee for Standardization Brussels, 2003.
[48] B. EN, 408 Timber Structures: Structural Timber and Glued Laminated Timber-Determination of Some Physical and Mechanical Properties, British Standard Institution, London, 2003, pp. 1–33.
[49] M. Verbist, J.M. Branco, L. Nunes, Characterization of the mechanical performance in compression perpendicular to the grain of insect-deteriorated timber, Buildings 10 (1) (2020) 14.
[50] AS 3600 - Concrete Structures, Standards Australia, Sydney, 2018.
[51] S. Kaewunruen, A. Remennikov, Experimental simulation of the railway ballast by resilient materials and its verification by modal testing, Exp. Tech. 32 (4) (2008) 29–35.
[52] T. Abadi, L.L. Pen, A. Zervos, W. Powrie, Effect of sleeper interventions on railway track performance, J. Geotech. Geoenvironmental Eng. 145 (4) (2019), 04019009.
[53] T.C.U. Jideani, P. Grabe, The development of suitable cyclic loading and boundary conditions for ballast box tests, J. South Afr. Inst. Civ. Eng. 61 (4) (2019) 59–72.

[54] AS 2758.7 - Aggregates and Rock for Engineering Purposes, Part7: Railway Ballast, Standards Australia, Sydney, Australia, 2015.
[55] S. Nimbalkar, S.K. Dash, B. Indraratna, Performance of ballasted track under impact loading and applications of recycled rubber inclusion, Geotech. Eng. (2018).
[56] Queensland Rail, Queensland Rail West Moreton System - Review of Proposed Maintenance, Capital & Operations Expenditure, SYSTRA Scott Lister, Brisbane, Australia, 2019.
[57] A.M. Remennikov, S. Kaewunruen, Experimental load rating of aged railway concrete sleepers, Eng. Struct. 76 (2014) 147–162.
[58] Ansys® Workbench Mechanical, Release 1, 2020. https://www.ansys.com/.
[59] E.T. Selig, D. Li, Track modulus: its meaning and factors influencing it, Transp. Res. Rec. (1470) 1994.
[60] R. Aguilar, M. Montesinos, S. Uceda, Mechanical characterization of the structural components of Pre-Columbian earthen monuments: analysis of bricks and mortar from Huaca de la Luna in Perú, Case Stud. Constr. Mater. 6 (2017) 16–28.
[61] P. Sadeghian, B. Fillmore, Strain distribution of basalt FRP-wrapped concrete cylinders, Case Stud. Constr. Mater. 9 (2018), e00171.
[62] J. Sładek, K. Ostrowska, P. Kohut, K. Holak, A. Gąska, T. Uhl, Development of a vision based deflection measurement system and its accuracy assessment, Measurement 46 (3) (2013) 1237–1249.
[63] M. Ghahremannejad, M. Mahdavi, A.E. Saleh, S. Abhaee, A. Abolmaali, Experimental investigation and identification of single and multiple cracks in synthetic fiber concrete beams, Case Stud. Constr. Mater. 9 (2018), e00182.
[64] L. Le Pen, G. Watson, A. Hudson, W. Powrie, Behaviour of under sleeper pads at switches and crossings–Field measurements, Arch. Proc. Inst. Mech. Eng. Part F J. Rail Rapid Transit 232 (4) (2018) 1049–1063.
[65] C. Salih, A. Manalo, W. Ferdous, R. Abousnina, P. Yu, T. Heyer, P. Schubel, Novel bending test method for polymer railway sleeper materials, Polymers 13 (9) (2021) 1359.
[66] X. Liu, V.L. Markine, H. Wang, I.Y. Shevtsov, Experimental tools for railway crossing condition monitoring (crossing condition monitoring tools), Measurement 129 (2018) 424–435.
[67] L. Rui, E. Zappa, A. Collina, Vision-based measurement of crack generation and evolution during static testing of concrete sleepers, Eng. Fract. Mech. 224 (2020), 106715.
[68] iMetrum, Video Gauge - How It Works, 2020 (Accessed 25 March 2020 2020).
[69] iMetrum Limited, Video Gauge User Manual : Version 5.4.4, United Kingdom, 2017.
[70] M. Hetenyi, Beams on Elastic Foundation., 8th Printing, The University of Michigan Press, Ann Arbor, Michigan, 1967.
[71] AS 1085.17: Railway Track Material, Part 17: Steel Sleepers, Australian Standard, 2003, pp. 1–53.
[72] U.S. Department of transportation, Federal Railroad Administration, Performance of plastic composite ties in revenue service, Res. Results (2011) 1–4.
[73] I. Lotfy, M. Farhat, M.A. Issa, M. Al-Obaidi, Flexural behavior of high-density polyethylene railroad crossties, Arch. Proc. Inst. Mech. Eng. Part F J. Rail Rapid Transit 230 (3) (2016) 813–824.
[74] J. Sadeghi, P. Barati, Evaluation of conventional methods in analysis and design of railway track system, Int. J. Civ. Eng. 8 (1) (2010) 44–55.
[75] R.R. Krishnamoorthy, Z. Saleheen, A. Effendy, A. Alisibramulisi, A. Awaludin, the effect of rubber pads on the stress distribution for concrete railway sleepers, in: IOP Conference Series: Materials Science and Engineering, IOP Publishing, 2018, p. 112007.
[76] M. O'Rourke, R. Mair, N. Doyle, Towards the design of rail track for heavy axle loads, in: Heavy Haul Railways Conference 1978, Institution of Engineers, Australia, 1978, p. 388.