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Mechanics and Novel Designs of Polymeric Railway Sleepers in Track Structure

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Abstract

Polymer sleepers can combine a stiffness behaviour comparable to timber sleepers with the consistency and lifespan of concrete sleepers, but their specific characteristics and potential advantages should be considered: material viscoelasticity, bending stiffness range, and freedom of shape.
Due to viscoelasticity, laboratory tests on polymer sleepers should be performed dynamically, at strain rates applicable to in-track conditions. Cyclic loading should be performed intermittently, introducing pauses between cycling to reduce heating, creep effects and to give track representative results.
In analyses, polymer (and timber) sleepers should be considered a beam on an elastic foundation, because of their limited bending stiffness. To accommodate analytical calculations, a simplified calculation method was derived, using a sleeper flexibility factor to account for sleeper bending effects on track deflections.
As a result of repeated train loads, a gap arises between the rail seat location and ballast, and the sleeper shapes according to this gap (i.e. beds-in) on every train passage, causing equalization of the contact stresses over the sleeper length and ballast. Optimisation show that balancing the sleeper (prevention of centre-bound) can reduce resilient rail seat displacements by up to 40% without increasing material usage but only utilizing moulding processes allowing the freedom of sleeper shape.

Keywords: railway, track, railway superstructure, polymeric sleeper, plastic tie, viscoelasticity, track stiffness, sleeper optimization.

1 Introduction

Today, the world's railway networks have around three billion sleepers in use, mostly from timber or concrete, with an annual demand for 60-150 million new sleepers [1]. Timber sleepers combine a medium bending stiffness with a low compression stiffness and a soft sleeper-ballast interface. These properties reduce sleeper loads and impact forces, but they show large variations [2]. Consequently, sleeper loads and settlements can vary in the track. Timber sleepers have a relatively short life expectancy, unless they are preserved with creosote, which causes environmental concerns. Creosote is banned in an increasing number of countries. Hardwood is less vulnerable to decay, but the use of large quantities can promote deforestation.

Concrete sleepers have a high bending and compression stiffness and surface hardness, which results in relatively high bending moments, rail seat loads and ballast stresses [3]. Concrete sleepers are susceptible to fracture from impact and offer little damping of vibrations, which makes them less suitable at some locations in track.

Polymer sleepers have the potential to combine the best characteristics of both traditional sleeper materials – the lower rigidity and surface hardness of timber along with the consistency and lifespan of concrete. Possible application areas for polymer sleepers include:

- Areas with height or weight restrictions.
- Situations with poor drainage, such as track embedded in roadway pavement, due to its resistance against water and moisture.
- Areas with limited accessibility for maintenance, such as tunnels and bridges, due to their longevity without the need for maintenance.
- Areas with noise or ground vibration issues, due to the polymers damping characteristics.
- Areas suffering from ballast fouling, where polymers can compensate for ballast rigidity.
- Areas where spot replacement of timber sleepers is required, due to the compatible characteristics with that of timber.
- Sleepers that need to be drilled/plated in track (Switches & Crossings), which is possible with standard wood working tools.

Polymer sleepers should not be regarded as a direct substitute for timber or concrete sleepers, but their characteristics and potential advantages should be considered, the most prominent of which are:

1. The viscoelastic behaviour of polymers.
2. A sleeper bending stiffness range that may differ from traditional sleepers, depending on the sleeper composition.
3. The possibilities by the shape freedom in the polymer moulding process.

This paper summarises the effects of these factors on sleeper performance as investigated by Aran van Belkom during PhD research at the University of Southampton. More details on the methods used can be found in [4].

2 VISCOELASTIC BEHAVIOUR OF POLYMERS

Most polymers exhibit mechanical properties that are time- and temperature-dependent. This viscoelastic behaviour (combining viscous and elastic behaviour) induces effects such as creep, strain rate-dependent behaviour and viscous damping. When a polymer is loaded with a constant load, the strain will increase over time, at a declining rate (creep). When the stress is taken away, the viscous part will initially remain, fading away over time (Figure 1a) [5].

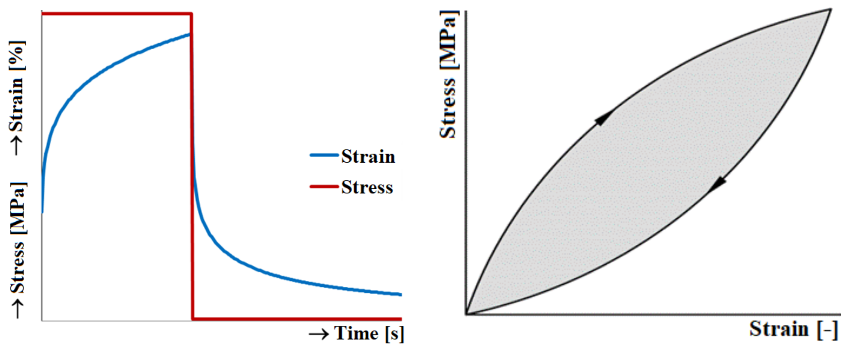

Figure 1: Stress-strain relation in polymers (left) and hysteresis when loading and unloading polymers (right) [6].

Polymers will exhibit a higher Young's modulus and strength when loaded at a higher speed. Laboratory test methods for assessing polymer sleeper behaviour therefore need to incorporate load durations and strain rates that are comparable with actual track loading. Only then will testing provide reliable indicators of actual polymer sleeper performance in track. When loading a polymer, the stress-strain relationship is non-linear (Figure 1b). Heat is dissipated by the material due to hysteresis through the viscous damping. This material damping helps by reducing impact loads. Comparative impact testing shows a 25% reduction of impact loads on a polymer sleeper compared to concrete [7].

Laboratory sleeper testing is normally based on loading tests with millions of load cycles representing passing trains during the sleeper's lifespan. In such laboratory tests the loading cycles are applied continuously without pauses to condense the test time. Submitting polymer sleepers to continuous cyclic load tests can lead to heating up of the sleeper body, due to the hysteretic damping, which is an artefact of the laboratory loading procedure and is not representative for the situation in track.

When heating up of the polymer during testing is experienced, a solution often chosen is to reduce the load frequency. But polymeric sleepers have a lower stiffness when loaded slower [8]. Testing at a reduced frequency therefore gives an unrealistic deformation behaviour. Additionally, the creep due to the constant part of the cyclic loading gives an additional strain that is not representative for the in-track situation. A better solution is to apply intermittent loading, introducing pauses between numbers of load cycles (Figure 2) which reduces the heat dissipation of the polymer in the same way that reducing the load frequency does, but without the negative side effects.

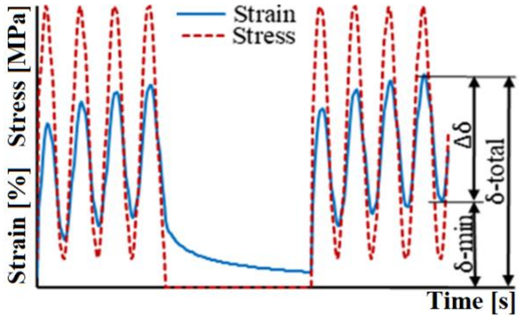

Figure 2: Stress-strain relation of polymers under intermittent cyclic loading.

A series of tests with polymer sleepers was performed to show the effect of intermittent testing and justify its advantages [9]. From the performed tests, two examples are shown in Figure 3. For the deflections (left-hand vertical axis) two values are given: the black lines give the minimum deflections (δ-min), as explained in Figure 2. The red lines ($\Delta\delta$) give the difference between the minimum and maximum deflection. The total deflections are not specified in the graph, they are the sum of δ-min and $\Delta\delta$. This division was made to provide a clear distinction between the continuous nature of δ-min, versus the short duration of $\Delta\delta$.

Figure 3a shows a comparison between a continuous test and an intermittent test, both at 5 Hz. Due to the heating up during the continuous test and consequent deflections that exceeded the machine's capacity, this test was prematurely stopped. To establish that not only the temperature affects the test results, Figure 3b shows a test at a reduced frequency of 1.4 Hz, to minimise heating up. The δ-min values in the graph still show a large difference, due to the creep of the continuous part of the loading. This additional deflection may contribute to premature material failure but is test-induced and is not representative for track.

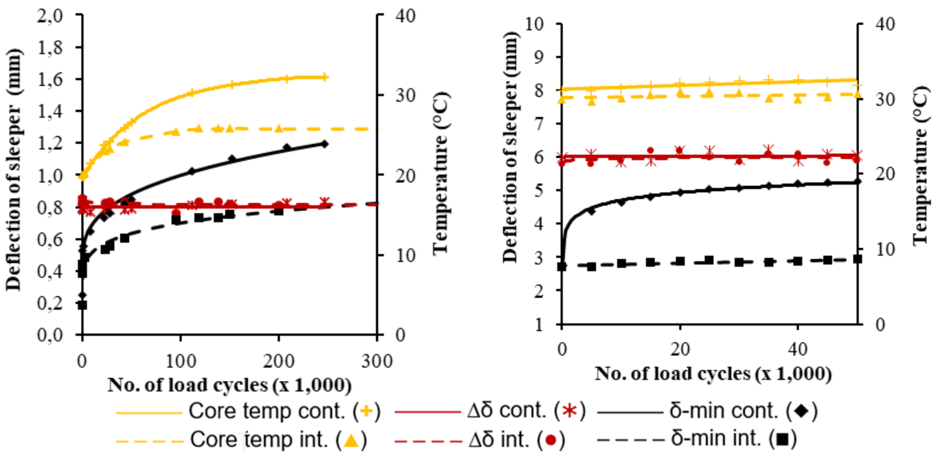

Figure 3: Bending tests according ISO 12856-2: a) Test at 5 Hz, performed at CTU in Prague, sleeper type Lankhorst 202, 3-point bending test at 600 mm span, load 100 kN, intermittent regime: 30s. of loading, 60 s. of unloading; b) Test at 1.4 Hz, performed at TU Munich, sleeper type Lankhorst 201, 4-point bending at 500-500-500 mm, load 45 kN, intermittent regime: 45 s. of loading, 90 s. of unloading.

The tests show that an intermittent test regime is effective and reduces unwanted viscoelastic side-effects such as creep and heating up of the sleeper. The choice of the best loading-unloading regime will always be a trade-off between time to perform the test and validity of the results in track. The longer the pauses, the more the results will resemble the situation in track, but the longer the test will take.

3 SLEEPER BENDING STIFFNESS AND THE EFFECTS ON TRACK

By themselves, polymers have a Young's modulus and thermal expansion which renders them unsuitable as a sole material for a sleeper in relation to their bending stiffness and track gauge stability [10]. Polymer sleepers are therefore combined with other materials, for example with glass fibres or with discrete reinforcement over the length of the sleeper. Depending on the chosen sleeper construction, the resulting sleeper bending stiffness may be out of the stiffness range for traditional sleeper materials (Table 1). Discrete reinforcements allow for a higher achievable bending stiffness, but anisotropy due to the reinforcements can cause shear deflections which should be considered.

Youngs modulus (bending)	[GPa]
Concrete	34 - 38
Timber	6 - 18
Polymer with short fibres	2 - 5
Polymer with discrete reinforcement	5 - 20

Table 1: Young's modulus range estimate for different sleeper materials/compositions [4].

Since current sleeper standards mostly lack proper functional performance requirements [11, 12, 13], track loading calculations should be performed to form the basis in understanding the effects of sleeper bending stiffness (and strength) properties on track performance, starting from the desired track support stiffness.

Figure 4 shows the typical calculated track deflection with a concrete sleeper, a glass fibre reinforced (GFR) polymer sleeper (Young's modulus 3 GPa) and a sleeper that can either be an oak sleeper, or a steel bar reinforced (SBR) polymer sleeper [6]. For a concrete sleeper, the ballast compression is higher than for a timber or polymer sleeper, since the concrete sleeper rigidity reduces the distribution of the wheel load along the track, thus increasing the load on one sleeper. For a concrete sleeper, the compression of the rail pad and the trackbed creates 95-98 % of the total track deflection. For a polymer or a timber sleeper, there is an additional deflection at the rail seat location due to the bending of the sleeper, and also the sleeper compression creates an additional deflection, in combination accounting for 30% of the track deflection. To take this into account, the sleeper should be considered as a deformable body when performing track analyses.

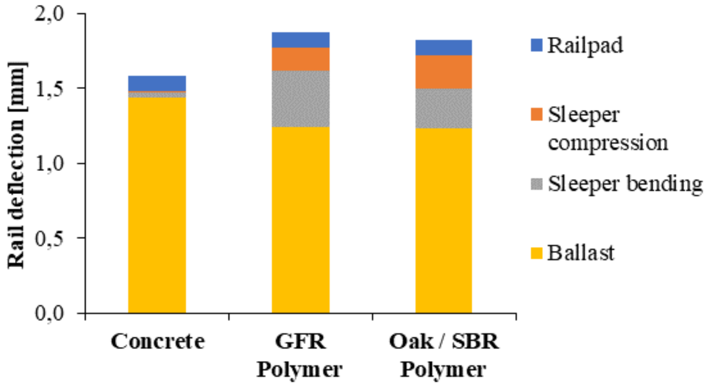

Figure 4: Break-down of rail deflections on different sleeper types, where "Ballast" gives the mean ballast compression under the sleeper, and "Sleeper bending" the additional deflection at the rail seat due to bending.

A railway track is often analysed as a beam on an elastic foundation (BOEF). To incorporate a sleeper as a deformable body in this analysis, also the sleeper should be considered a BOEF (support case A in Figure 5). The ballast is then modelled as a uniform Winkler support, i.e. acting as a set of individual elastic springs. However, tamping lifts the ballast around the rail seats and a more realistic model for freshly tamped ballast would concentrate the elastic support in these zones (support case B in Figure 5). Such an analysis with two BOEF-layers (rail and sleeper) can be performed with finite element analyses but is analytically complex. Analytical calculations can be simplified by introducing a flexibility factor for sleepers on a Winkler support f_W.

For a rigid sleeper, the relationship between the load exerted on the rail seat (P) and the deflection at the rail seat (δ_R) can be calculated [14, 15] by Equation (1).

$$\delta_R = \frac{P}{CwB} \tag{1}$$

In which C is the bedding modulus of the ballast, w the sleeper bottom width, and B is either the length supported by ballast for a sleeper end for load case B (Figure 5), or half of the sleeper length for load case A. For a sleeper which cannot be considered rigid, the Equation (1) can be altered to Equation (2).

$$\delta_R = \frac{Pf_W}{CwB} \tag{2}$$

For Equation (2), it was investigated that the added sleeper flexibility factor f_W can be calculated with Equation (3):

$$\boldsymbol{f_W = \sqrt[4]{1 + \frac{Cw}{64EI}B^4}} \tag{3}$$

In which EI is the bending stiffness of the sleeper. The implications of this flexibility factor f_W are interesting. It represents the contribution of the sleeper bending to the rail deflection. When f_W equals one, the sleeper is infinitely stiff (a factor f_W

lower than one is not possible). An f_W-value of two means that the rail deflection is doubled compared to a rigid sleeper. The range of possible values of f_W can be found in Table 2. More information on this calculation method can be found in [16]. The use of this f_W-value gives insight in what can be achieved with sleeper bending stiffness. If the bedding modulus of the ballast is low, it is not possible to correct that with the sleeper stiffness if f_W is already almost one. A solution then has to be found in the bedding modulus of the ballast, not in the sleeper stiffness.

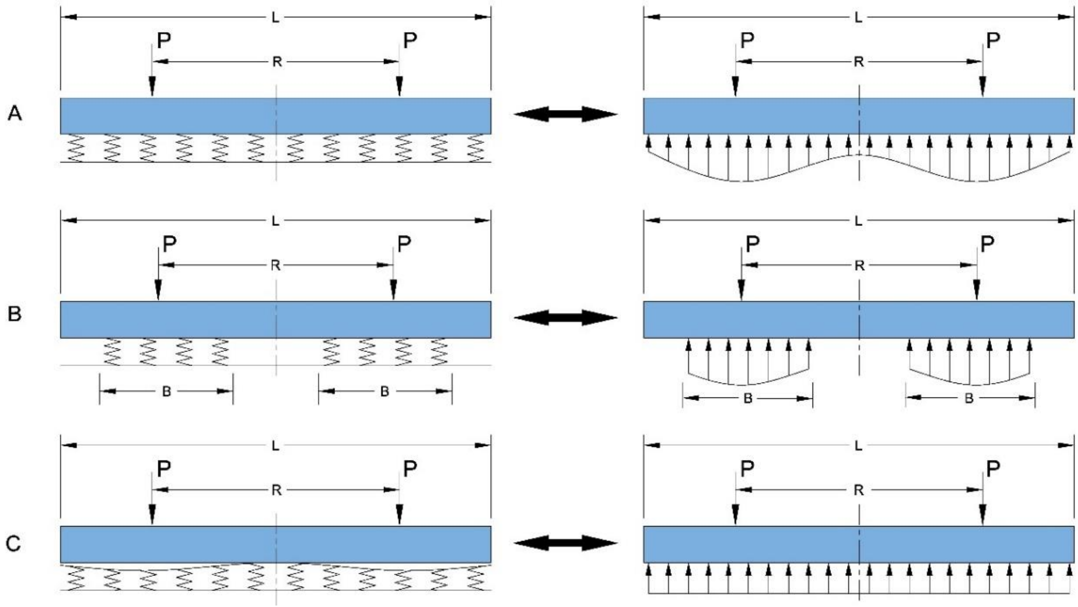

Figure 5: Considered sleeper support conditions: Load case A: Uniform elastic Winkler foundation; Load case B: Newly tamped track on a Winkler foundation; Load case C: Bedded-in sleeper with uniform stress distribution under the sleeper. The support conditions in the left-hand figure can be translated into the reaction load distributions in the right-hand figures.

Sleeper				Ballast	Interaction	
Material		Dimensions: width×height [mm]	Bending modulus E [GPa]	Ballast bedding modulus C [N/mm^3]	Sleeper supported length B [mm]	f_W [-]
Concrete	Stiff	300×250	38	0.04	700	1.0
	Flexible	250×200	38	0.25	1500	1.2
Timber	Stiff	275×160	20	0.04	700	1.0
	Flexible	250×150	6	0.25	1500	1.9
Polymer	Stiff	275×160	20	0.04	700	1.0
	Flexible	250×150	1	0.25	1500	2.9

Table 1: Considered ultimate values and consequent flexibility factor (f_W) for the stiffest sleeper/most flexible ballast combinations and vice versa for different sleeper materials.

For validation of calculated f_W-values, complementary to finite element analyses, laboratory tests were performed on different sleeper types, using rubber supports to simulate the ballast response (Figure 6a). The advantage of rubber over a ballast box is that the rubber response is defined. Ballast can settle, introducing a second, undefined variable, making interpretation of results difficult. Results of this test shows that the f_W factor properly aligns with sleeper bending behaviour in practice (Figure 6b). The graph shows the normalised sleeper deflection, meaning that the value for a rigid sleeper is set to one. The graph therefore gives a direct reading of the measured sleeper flexibility factor f_W.

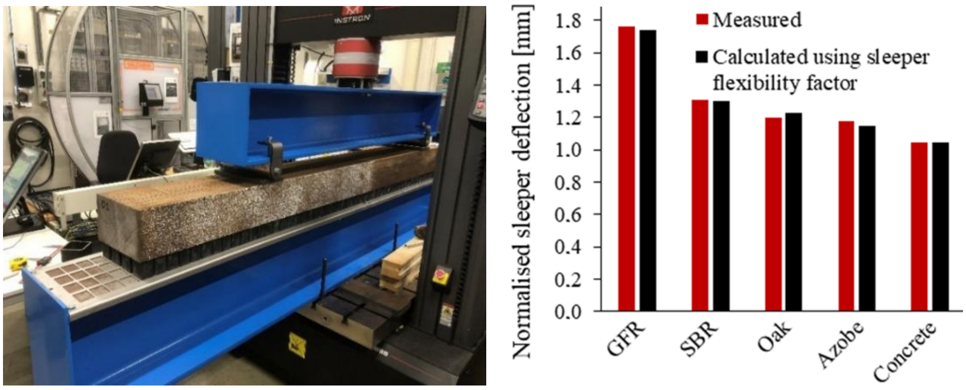

Figure 6: Sleeper deformation: a) Testing of a sleeper on a rubber support; b) comparison of test results with calculations (GFR = Glass fibre reinforced polymer sleeper, SBR = Steel bar reinforced polymer sleeper) [4].

With trains passing the sleeper, the ballast below the rail seat, which experiences a higher stress, will undergo more settlement compared to ballast below the rest of the sleeper. This will result in a redistribution of the ballast stresses along the sleeper, until a condition is reached, designated as “bedded-in” (support case C in Figure 5), where ballast stresses under the loaded sleeper are equalised along the sleeper length. This support condition is an ideal and in reality would be affected by local differences in ballast bearing capacity and subgrade conditions along the sleeper length.

The calculation for a bedded-in sleeper with uniform supports is straightforward when only the final situation (and not its evolution) and only the differential settlement along the sleeper length is considered (and not the total settlement). The dashed line indicated δ_0 in Figure 7 shows the deflection for a sleeper starting initially in contact with a continuous, uniform Winkler support. The δ_0-line shows that the ballast compression is greater at the rail seat than in the sleeper centre. The eventual elastic deflection distribution for a bedded-in sleeper under load is shown by the solid line, labelled δ_1. The ballast compression at the sleeper centre is now greater than in the initial case, due to the equalisation of the stress distribution along the sleeper length. The dotted line, labelled *gap*, represents the gap under the sleeper in the unloaded situation for the bedded-in sleeper. Since the ballast compression is uniform along the sleeper length, the distance between the lines *gap* and δ_1 is constant along the sleeper length. In Figure 7, the gap is assumed to be zero at the sleeper centre, which makes this sleeper a centre bound sleeper (will be discussed later).

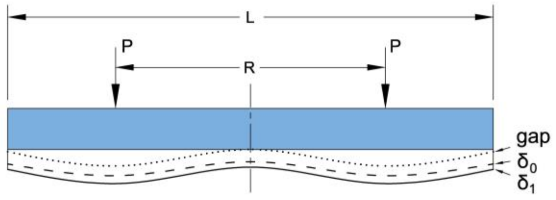

Figure 7: Schematic elastic ballast displacements for bedded-in sleepers, with a gap under the rail seat.

The gap at the rail seat is equal to the difference between the deflection at the centre and at the rail seat for the loaded, bedded-in sleeper. The total rail deflection during train passage can be calculated by adding the ballast compression for a rigid sleeper on a continuous ballast bed (Equation 1) to this gap (disregarding rail pad compression). For a sleeper with constant cross-sectional properties, the rail deflection δ_R can be calculated using standard deflection formulae (neglecting shear deformations) in Equation (4).

$$\delta_R = \frac{2P}{CwL} + \frac{PR^2}{L}\left(\frac{12L\mathrm{R} - 6L^2 - \mathrm{R}^2}{192EI}\right) \tag{4}$$

In which *EI* is again the bending stiffness of the sleeper. Figure 8 shows the deflection and bending moment along the length of a loaded sleeper for support case B and C for a rectangular concrete, oak and polymer sleeper (Young's modulus 5 GPa) in a standard gauge track, calculated using the parameters given in Table 3.

Characteristic and symbol		**Unit**	**All sleepers**		
Bedding modulus	*C*	[N/mm^3]	0.1		
Centre-to-centre distance rails	*R*	mm]	1,520		
Rail seat load	*P*	[kN]	40		
Sleeper bottom surface area		[m^2]	0.65		
Rail mass on each sleeper end		[kg]	32.4		
Sleeper depth	*h*	[mm]	150		
Sleeper length	*L*	[m]	2.6		
Unsupported centre length (load case B)		[m]	0.44		
			Concrete	**Oak**	**Polymer**
Young's modulus	*E*	[GPa]	37	12	5
Shear modulus	*G*	[% of E]	42	8	36
Sleeper mass		[kg]	200	100	100

Table 3: Properties for deflection curve calculation in Figure 8.

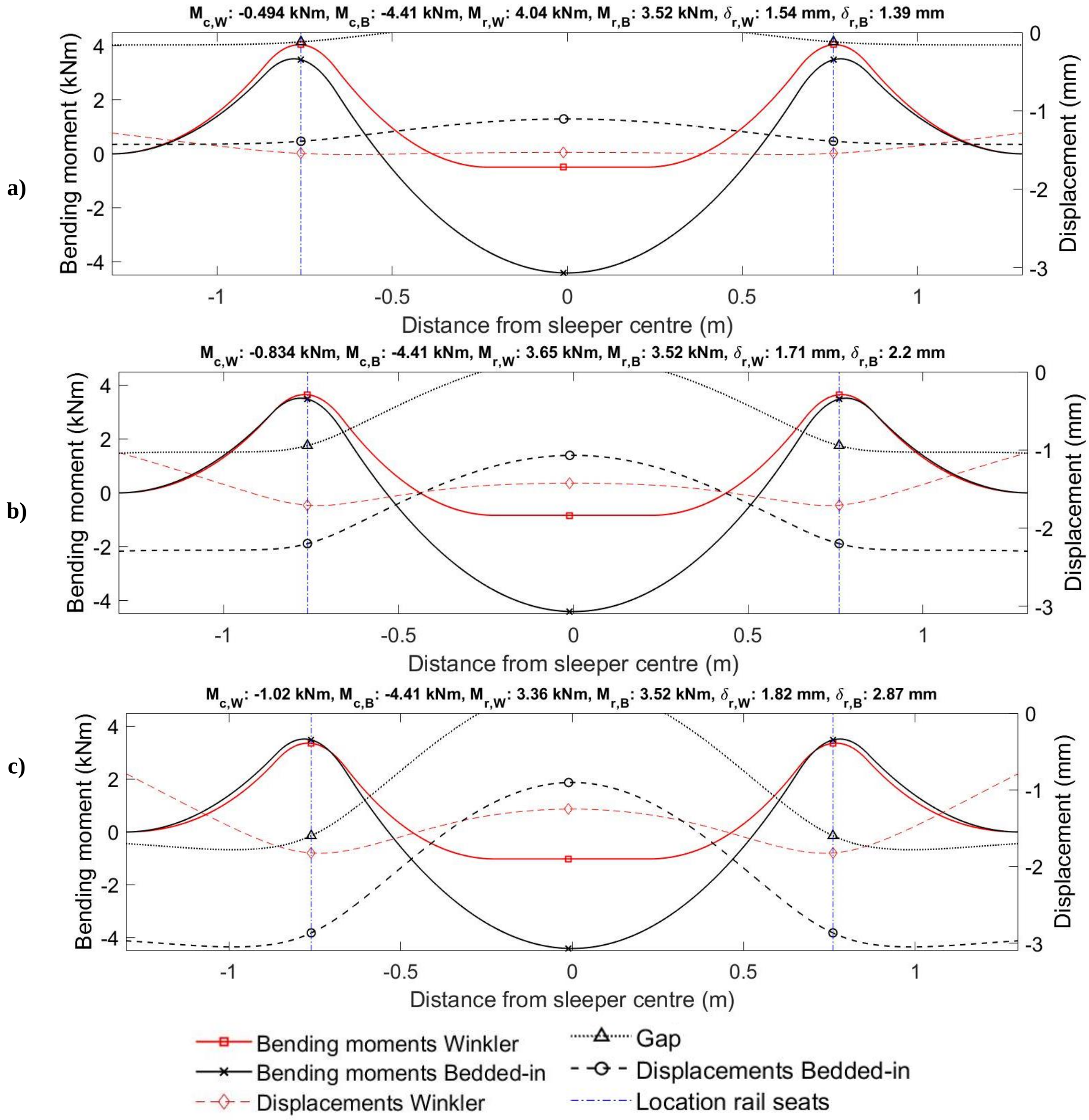

Figure 8: Deflection curves for sleepers with properties according to Table 3 for load case B and C for: a) Concrete sleeper; b) Oak sleeper; c) A chosen polymer sleeper. Subscript W = Winkler foundation, B = bedded-in, c = centre sleeper, r = rail seat.

Figure 8 shows that, once bedded-in (load case C), all sleepers of this length (2.6 m) become centre-bound in a standard gauge track, meaning that the unloaded sleeper rests on the ballast only in the sleeper centre. This is consistent with findings in Abadi et al [17] and Ferro et al [18]. Also, the resilient displacement at the rail seat becomes larger and the bending moments in the sleeper centre increase during bedding-in. This occurs for all sleeper materials, but it is more pronounced for sleepers of lower bending stiffness. For polymer sleepers that have a relatively low bending stiffness, the effects of bedding-in must therefore be considered.

To validate the results of above calculations, 175 model tests in a ballast-box were performed (scale 1:10) over a 2-year period for a range of sleeper materials and geometries (details in [4]). The sleeper response was monitored during 200,000 load cycles for each sleeper, at 7 locations along the sleeper length. The rate of bedding-in during all tests was monitored and is shown in Figure 8 (only the first 10,000 cycles are shown).

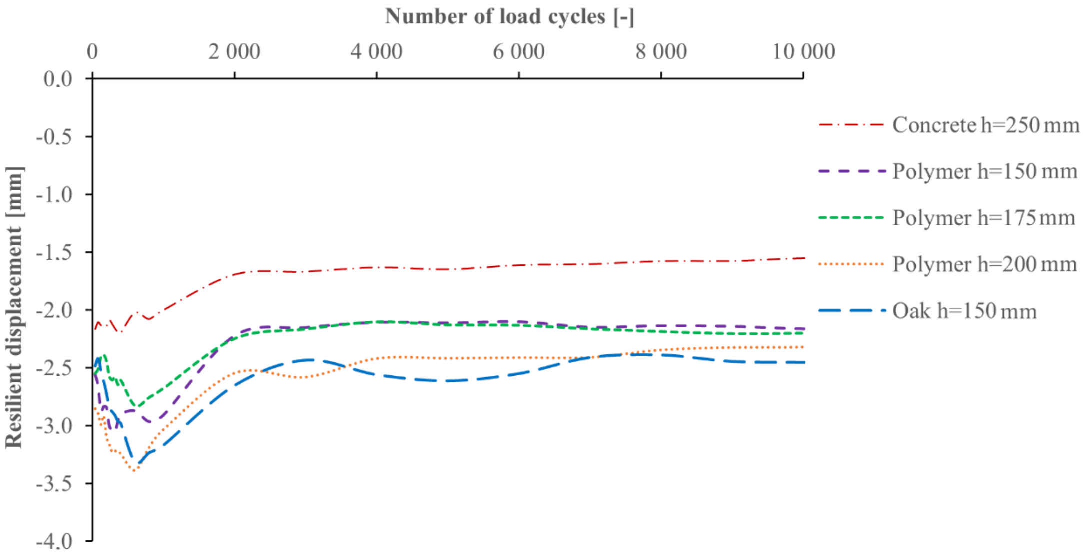

Figure 9: Rail seat resilient displacement development (dimensions for full-scale).

Figure 9 shows that the resilient displacements gradually decrease during the tests due to ballast compaction, but at the start, the displacements first become larger, due to gap formation. The increase of the resilient displacement is more pronounced for flexible sleeper models, and the trough in the graphs shows that most of the gap forms during the first 1,000 load cycles. It is only after the trough that effect of ballast stiffening counters that of the gap formation and the sleeper resilient displacements start to reduce.

Monitoring the rates of change of the vertical positions of the rail seat and the sleeper centre under loaded conditions showed that after 100,000 load cycles, the sleeper models could be considered to be fully bedded-in. This number of cycles did not show to be noticeably influenced by sleeper bending stiffness, ballast height or sleeper material.

To prove the existence of gap formation below the sleeper, epoxy resin was poured into the ballast, following a test on a rectangular polymer sleeper, and the sleeper and ballast were cut along the sleeper length (Figure 10). The gap height was found to correspond approximately to that calculated for the bedded-in support condition.

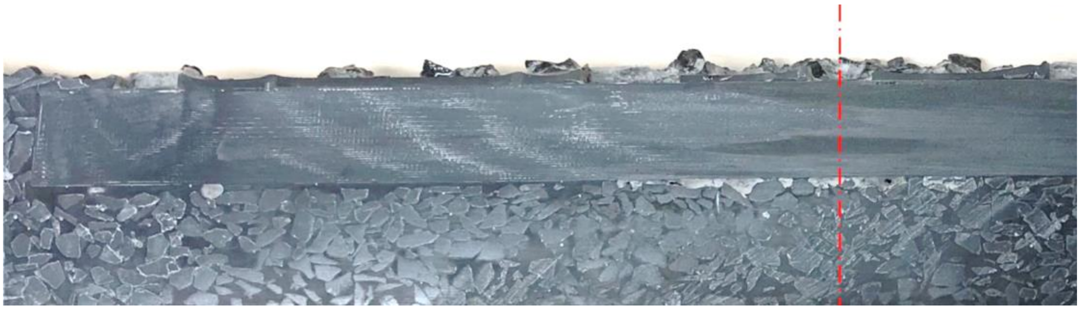

Figure 10: Sleeper and ballast longitudinal section (left part of the sleeper, the red line is the centre line of the sleeper). Black: gap (filled with epoxy), grey: ballast particles (ignore the white air voids, where epoxy came out during cutting). 3D-printed polymer sleeper model 1:10 (15 × 25 × 260 mm, Young's modulus 2.8 GPa.

To provide a full-scale comparison, resilient rail seat displacements were measured for a polymer sleeper in-situ, 8 months after installation, by which time the sleeper had been loaded by approximately 200,000 axles (Figure 13). Measurements were performed on a polymer sleeper (Young's modulus of 5 GPa) by means of digital image correlation (DIC).

The measurements again aligned with the bedded-in calculations, disregarding some damping effects that were not incorporated in the calculation. The conventional calculation on a uniform Winkler support is not representative in this situation, especially for sleepers with a lower bending stiffness.

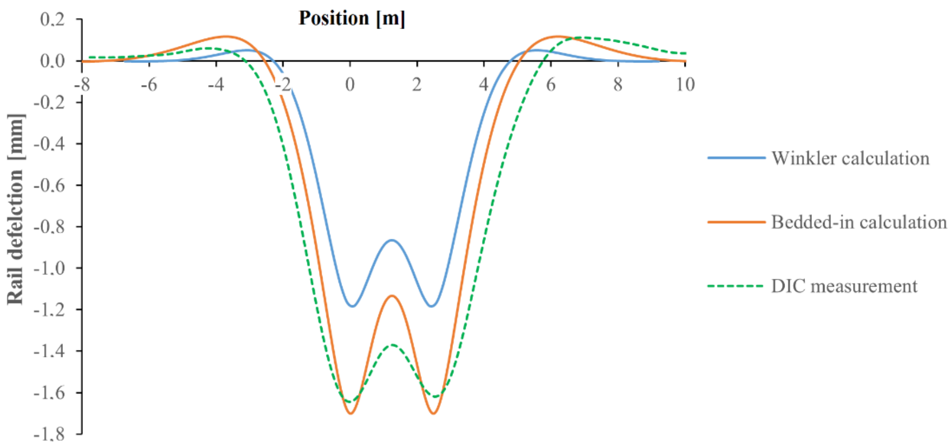

Figure 11: Comparison of calculations with in-situ measurements on a double-axle bogie, 160 kN axle load [4].

3 FREEDOM OF SHAPE OF POLYMERS

As mentioned, most current sleepers become centre-bound once bedded-in. The sleeper length can be increased to create a balanced sleeper (meaning that it is neither centre-bound nor end-bound), which minimises the resilient displacement at the rail seat.

Polymer sleeper moulding processes enable shape possibilities that extend beyond the possibilities of concrete or timber sleepers. Rather than elongating the sleeper, a polymer sleeper can be balanced by changing its shape such that the cross-section varies along its length as shown in the top view in Figure 14a. The depth of the sleeper is kept constant in this analysis. Figure 14b shows that for this geometry, the resilient rail seat displacement for the bedded-in condition is reduced by almost 40% compared with a rectangular sleeper using the same amount of material. Reducing the cross section of the sleeper centre may seem counterintuitive in terms of strength, but the bending moments in the centre of the sleeper in Figure 14 are reduced by 60% compared with those in Figure 10c.

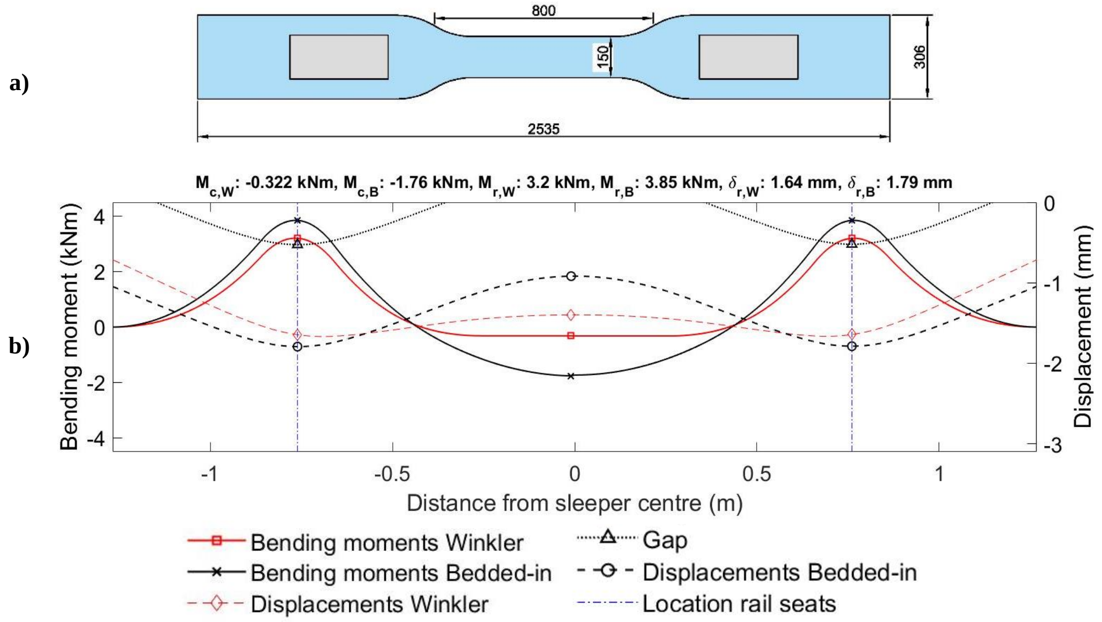

Figure 12: a) Top view of balanced sleeper; b): Deflection curves for balanced polymer sleeper with properties given in Table 3 and geometry given in Figure 12a.

The calculations from Figure 14 were validated in the scaled ballast-box tests. For this purpose, polymer sleepers with optimised bottom surface areas were 3D-printed (example in Figure 13). The resilient displacements of these sleeper models after 200,000 load cycles were in close agreement with the bedded-in calculations.

Figure 13: 3D-printed sleeper model (1:10) with optimised bottom geometry.

4 Conclusions and Contributions

Polymer sleepers have the potential to provide an alternative to timber or concrete sleepers. They can combine a stiffness behaviour comparable to that of timber sleepers with the consistency and lifespan of concrete sleepers.

In track analyses, polymer sleepers should be considered a BOEF, as is done with the rail. To simplify analytical calculations, a sleeper flexibility factor was introduced, which represents a multiplication factor to the rail seat displacement associated with a rigid sleeper.

The viscoelasticity of polymer sleepers should be given ample consideration when designing laboratory tests for sleeper assessment. Tests should be performed dynamically, at strain rates applicable to track. Repeated load tests can be performed intermittently to reduce heating up and creep effects, which are artefacts of the test regime.

As a result of repeated train loads, a gap will arise between sleeper and ballast at the rail seat location, caused by localised ballast compaction and movement, and the sleeper will become shaped to this gap (bed-in) on every train passage. This bedding-in process seems to occur within the first 100,000 load cycles and is especially noticeable within the first 1,000 load cycles. The bedding-in process ends when contact stresses between sleeper and ballast are equalised over the sleeper length, after which only the overall sleeper settlement continues. The lower the sleeper bending stiffness, the larger the gap will become and the faster the formation progresses.

The resilient displacements in the bedded-in situation are more progressive with decreasing sleeper bending stiffness than is the case on a Winkler foundation. The sleeper bending stiffness is therefore an important parameter, but sleeper balancing of the sleeper (preventing it from becoming centre-bound or end-bound) creates additional possibilities to reduce resilient displacements. Current rectangular sleepers are usually too short to be balanced. Polymer sleepers can be produced in a variety of shapes, which gives the possibility to balance sleepers without extending their length. These shape optimisations can reduce resilient displacements by up to 40% for a bedded-in sleeper compared to a rectangular sleeper, without increasing material usage.

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