EVALUATING THE PERFORMANCE OF DIFFERENT SLEEPER SHAPES AND MATERIALS

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KEYWORDS: Sleeper shapes, support conditions, composite, finite difference, finite element

ABSTRACT
Sleepers are conventionally designed in a cuboid shape of similar volume regardless of the material of construction. However, the bending stiffness and load transfer into the track bed is material dependent; and modifying the shape of sleepers by making use of advances in manufacturing ability could improve load transfer characteristics. A parametric study was performed on 6 different shapes of concrete and composite sleepers resting on 4 different types of support to understand which shape works best with each the different support condition. The sleeper shapes and support conditions were modelled using two methods (1) a 2D beam on elastic foundation formulation solved by the finite difference numerical method and (2) a 3D finite element method. Comparison of the results demonstrated that the 2D FDM method was able to reliably predict important characteristics of behaviour – the deflection, pressure and bending moment profiles. The FDM was then used to compare the performance of the different sleeper shapes. The sleeper performance was evaluated for least differential deflection and pressure considering the volume of material used and the lowest range of bending moments present. The overall differential deflection was greater for the composite sleepers than for concrete, but greater improvements were observed for the optimised composite sleeper shapes. The difference between the negative and positive bending moments reduced as the height of the middle section of the sleeper increased and the support in the middle part increases. On average, sleeper with a larger bending stiffness in the middle performed better.

INTRODUCTION
In the early days of railways, timber logs were used as sleepers to support the railway track; these quickly evolved into a rectangular cross sectional shape to provide (relatively) uniform support properties (Ferdous et al., 2018). The cuboidal shape of a timber sleeper makes economic use of the material but may not necessarily provide an optimal shape for stress transfer into the trackbed. Although alternate materials, which are less limited in their potential shape for construction of railway sleepers are available, sleepers formed of different materials have tended to retain their classical cuboid shape. Nowadays, precast concrete sleepers and bearers which provide enhanced durability and ease of production are usually the sleeper material of choice. However, concrete sleepers have potential disadvantages compared with timber sleepers, for example their heavier weight and a hard sleeper to ballast interface. Timber sleepers are lighter and provide a softer sleeper to ballast interface, but are less durable. Recent advances in material engineering, have led to the availability of a variety of composite sleepers which may replicate the advantages of natural timber with the durability of concrete. Composite sleepers may be formed of different polymers sometimes reinforced with glass fibre or steel. FFU (fiber-reinforced foamed urethane) is one of these materials. FFU sleepers have a longer service life and are more resistance to harsh weather than timber. FFU sleepers were first developed in 1978 and have since been used for more than 1,300 km of track length in Japan, China, Taiwan, the USA and Europe (Koller, 2015). FFU sleepers are similar in weight to timber sleepers and their bending stiffness is comparable to hardwood timber sleepers.

This paper explores the potential for new sleeper shapes, formed of composite or concrete materials, to transfer more effectively stresses into the trackbed. Using FEM (Finite element method) and FDM (finite difference method) techniques, the two approaches are compared, and 6 sleeper shapes are assessed for different support conditions representing stages during a maintenance interval. Performance is assessed in terms of deflection, pressure and bending moment along the sleeper length.

NUMERICAL MODELS

Conventional modern railway track is composed of two vignole rails resting on viscoelastic pads and fastened with a pre-clamping force to pre-tensioned steel reinforced concrete sleepers. For computer modelling of railway track performance, simplifications are required. The sleeper spacing and ballast stiffness are usually merged into constant parameters in typical analyses within vehicle track interaction models, e.g. VAMPIRE (DeltaRail, 2015), GEOTRACK (Chang et al., 1980), etc. It is less common to attempt to model fully the interaction between individual sleepers and ballast and here too simplifications are required. In this research the interaction between an individual sleeper and the ballast has been modelled.

Finite difference model (FDM)

A governing differential equation for an infinite beam on an elastic foundation with constant bending stiffness (flexural rigidity or *EI*) and support (beam modulus, *k*), can be evaluated mathematically to find a closed form solution (Timoshenko, 1927). However, a closed form solution in the case where the flexural rigidity (EI) and the support condition (*k*) varies for a beam of finite length (e.g. a sleeper) cannot be found. In this case a governing differential equation with varying *I* and *k* is needed which may then be solved using finite difference techniques. The governing differential equation with variable *I* (hence flexural rigidity *EI*) and variable *k* (beam support modulus) can be shown to be (Eqn 1):

$$\mathbf{I}W'''' + 2W'''\mathbf{I}' + W''\mathbf{I}'' + kW/Edx^4 = 0 \qquad \text{(Eqn 1)}$$

Where:

- I is the second moment of area of the beam,
- W is its displacement,
- x is the position along the beam
- E is the elastic modulus.
- $'$ is the degree of derivative

For a beam (sleeper) of finite length L and loading points at particular locations (railseats), appropriate boundary conditions may be applied and forwards, central and backwards approximations for differentiation used to set up a stiffness matrix. This may then be solved in a finite difference method analysis using an inbuilt linear algebra solver to perform the Gaussian elimination and determine the deflections (Le Pen and Zervos (2018)). Using this implementation in Matlab (Mathworks, 2016) the second moment of area of the sleeper (thus the flexural rigidity) and the elastic support can be varied with x. The deflections may be used to infer the bending moment and pressure on the support using standard beam theory.

Using this approach, a 2D finite difference simulation was set up with two symmetrically placed point loads applied to a beam (Figure 1). The sleeper was discretised into 2500 parts from n = 1 to n = 2501. Each part, rests on its own elastic support of beam modulus, n_K. The point loads are applied at 500mm from each end of the sleeper.

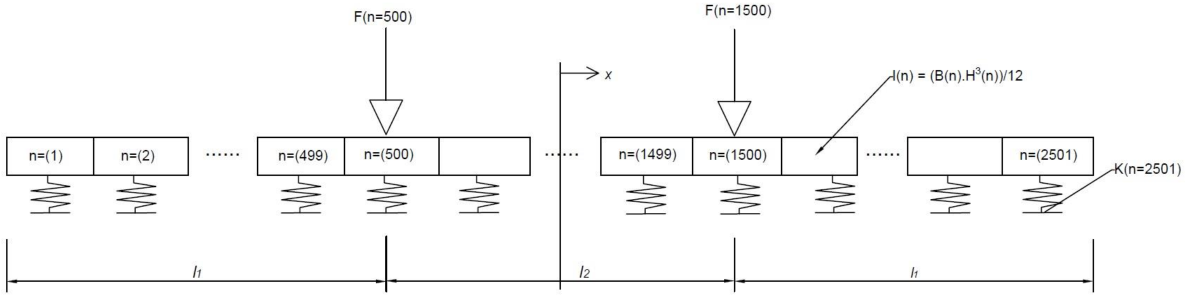


Figure 1: Finite difference model

Finite Element model (FEM)

Figure 2 shows the 3D rectangular solid in finite elements resting on an elastic foundation that was set up to compare with the finite difference method. The sleeper was modelled using general purpose tetrahedral elements, C3D10 with a 2.5 mm mesh.

In Abaqus, a simple way of including the stiffness effects of a support (such as the soil) without modelling the details of the support, is to use Elastic Foundation Elements (Simulia, 2014). Foundation pressures act on springs for ground elements, normal to the element faces on which they are applied.

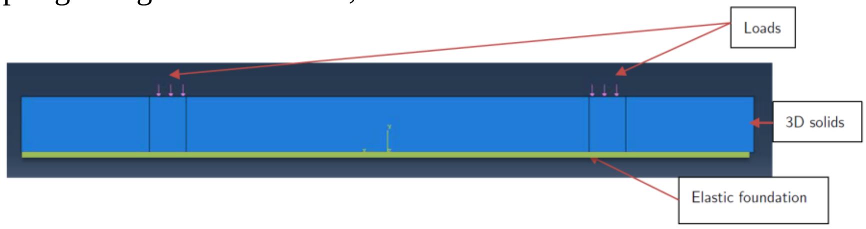


Figure 2: 3D model in Abaqus

PARAMETRIC STUDY

A range of different analyses were conducted on different sleeper geometries, support types and support stiffnesses. The results from both methods were compared.

Materials

Both concrete (Young's Modulus = 30 GPa) and FFU (Young's Modulus = 8 GPa) (Kaewunruen et al., 2017) can be manufactured in (more) complex shapes than timber sleepers. The same values of Young's Modulus was used for both the 2D-FDM and the 3D-FEM.

Support Conditions

Sleepers are required to resist bending moments, which are usually highest at the railseat and at the sleeper centre. Bending moments are sensitive to the pressure distribution between the sleeper and the substructure (ballast). Several potential pressure distributions may be used to represent different stages during a maintenance interval for sleepers on track. During initial installation and later maintenance tamping, the ballast is raised below the railseats, leading to increased initial pressures on the ballast surface at these locations. Over time and with traffic the sleeper settles, and the pressure distribution becomes more uniform. However, because the ballast at either end of the sleeper is less well confined, eventually the sleeper support becomes concentrated in the middle; a condition referred to as centre binding. Simplified load(downward arrows) and reaction(upward arrows) models shown in Figure 3 parts a, b and c are reported by the International Union of Railways, (2004) to cover most of this maintenance cycle. The reaction forces are dependent on the stiffness of the support. It is the intention to carry out maintenance before centre binding can develop. However, in the case that this does not happen, Figure 3(d) indicates a centre bound case developed for this research. These four support conditions have been considered in the parametric study.

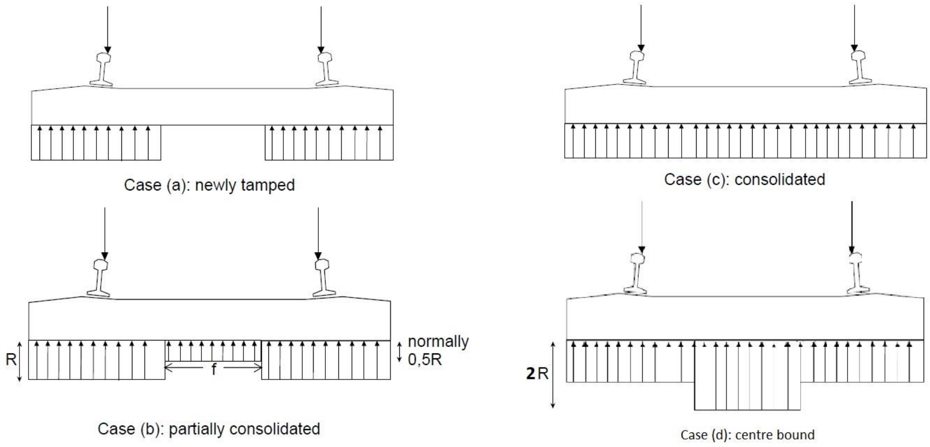


Figure 3: Sleeper reaction cases (Modified from (International Union of Railways, 2004))

Geometry

To evaluate the influence of shape on performance, six different shapes were evaluated as shown in Figure 5. Their second moment of area, I, is shown in Figure 4. These shapes and their justifications are described as follows:

- Shape 1 is a simple cuboid with the rough dimensions of a Monoblock timber or concrete sleeper, representative of a classical shape.
- The height of shape 1 has been increased by 30% in shape 2. This results in a sleeper with greater flexural rigidity.
- In shape 3, the middle portion of the sleeper has been made smaller with respect to shape 1 to give the sleeper a dumbbell shape. This shape is expected to be less prone to centre binding. However only a minimal reduction in flexural rigidity is expected because the height is unchanged.
- In shape 4, the height at the centre has been reduced by half. This leads to a less flexurally stiff sleeper but the contact area in the middle is also larger than in shape 3.
- In shape 5, the middle section volume has been reduced by a factor of almost 4. This middle section is not expected to contribute structurally.
- In shape 6, the height of the middle section has been made bigger to increase the flexural rigidity while retaining a narrower central footprint which may guard against centre binding.

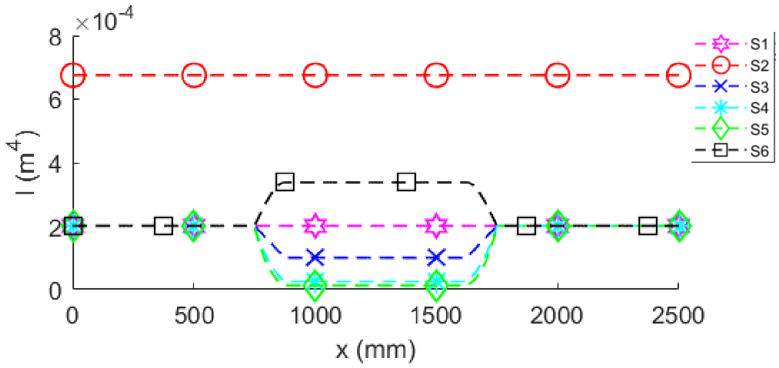
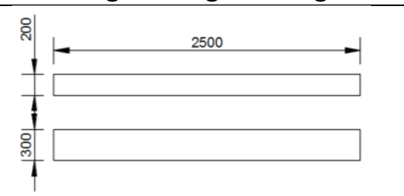
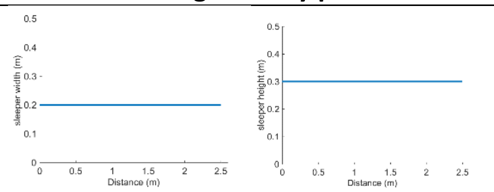
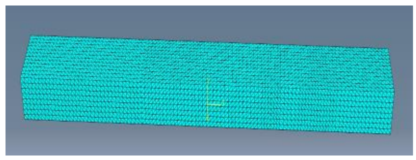
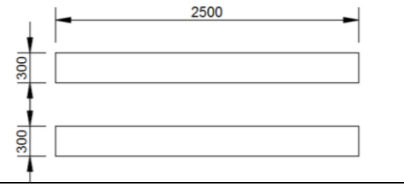
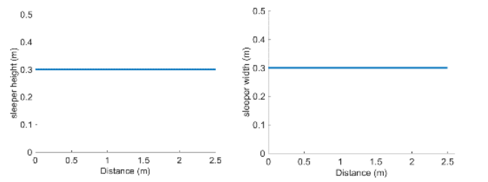
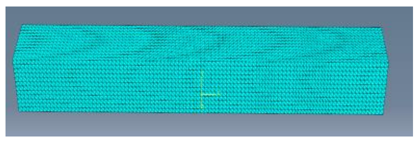
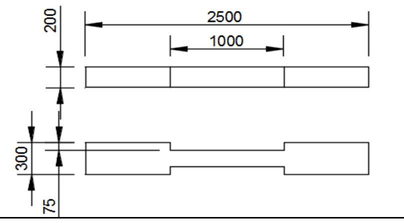
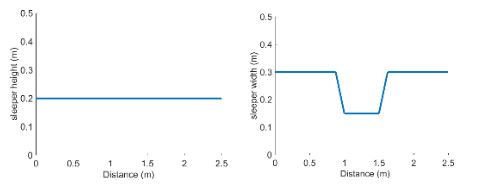
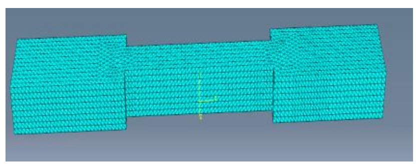


Figure 4: Second moment of area of different shapes

N.	Engineering Drawing	Matlab geometry profile	Abaqus3D
S1			
S2			
S3			

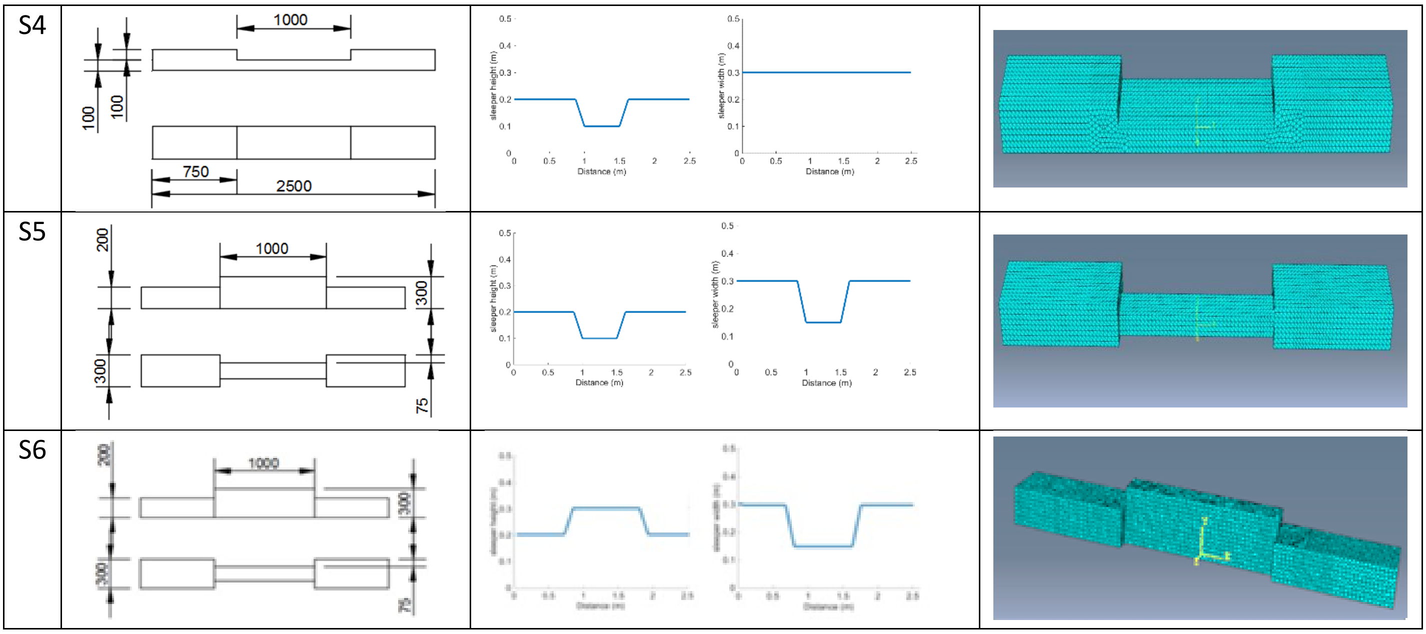


Figure 5: Sleeper shapes

List of simulations

In total, 24 simulations were run (Table 1), combining the four support conditions with the six sleeper shapes. In support cases a and b the foundation modulus and axle load were held constant; in support cases c and d the support modulus is varied with the changed portions determined by using the appropriate factor as shown in Figure 3. The magnitude of the foundation modulus and the railseat loads applied are realistic in terms of the deflections produced on in service track for a sleeper resting on ballast overlying a softer subgrade as a heavy axle load train passes (Le Pen et al., 2014; TSWG, 2016; Le Pen et al., 2018).

Table 1: List of simulations

Case	Support type	Stiffness/ ($N/mm/mm^2$)	Axle Load (kN)	Geometry
V1-V6	Newly Tamped	0.12	80	S1-S6
V7-V12	Partially Consolidated	0.12	80	S1-S6
V13-V18	Consolidated	0.12	80	S1-S6
V19-V24	Center bound	0.12	80	S1-S6

RESULTS AND DISCUSSION

Model Validation (comparison of FDM and FEM results)

Figure 6 shows the simulation results for deflection of shapes S1 and S5 on newly tamped (V1, V5) and consolidated (V13, V16) support. These are chosen for comparison since these shapes and support types are extreme cases. Both methods gave results consistent with each other. Mean values of the deflection are given in brackets after the name of the sleeper type in the legend to Figure 6.

In principle for linear elastic analyses, the FDM and FEM results would be expected to be identical. However, in the FDM implementation, changes in geometry are approximated by varying *I* and must be implemented gradually for the finite difference solution to converge reliably. In FEM the 3D geometries can be specified with sharp changes. It was found that in FDM changes to *I* must be implemented over 125 mm of sleeper length (see Figure 4). The use of smaller steps was attempted, but resulted in a loss of accuracy. Because of the gradual change of *I* in FDM, small differences between FEM and FDM results are expected. However, it can be seen from Figure 6 that both methods produce very similar results. In the remainder of this paper, only the FDM results are shown.

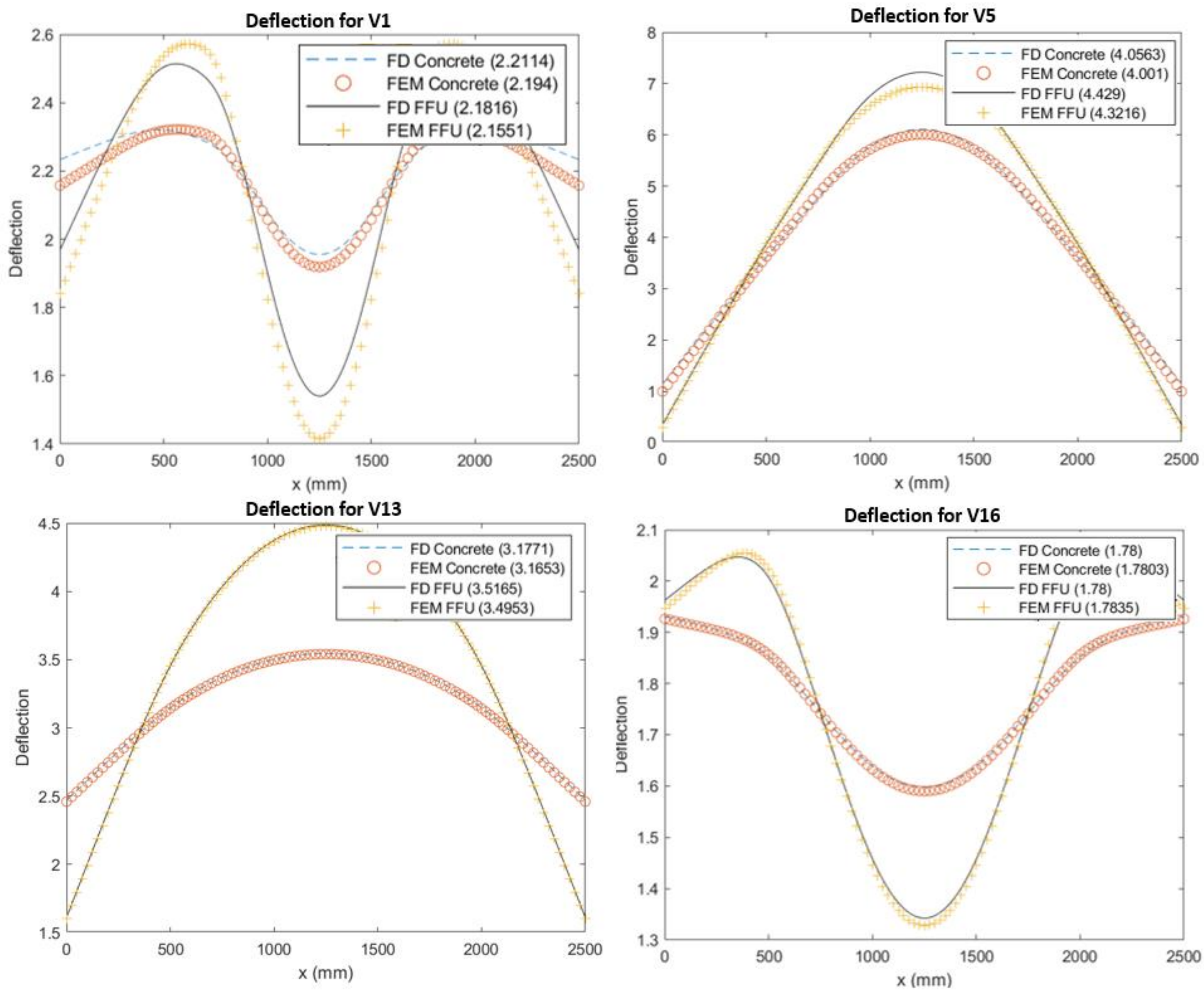
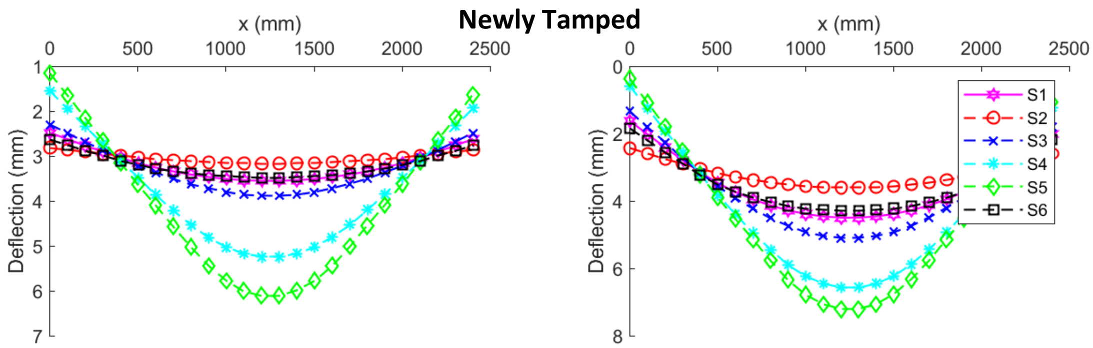


Figure 6: Comparison of FEM and FD results

<u>Comparison of sleeper shapes and support cases</u>

Deflections

The deflections of the different shapes on the different support types are shown in Figure 7 and Figure 8.



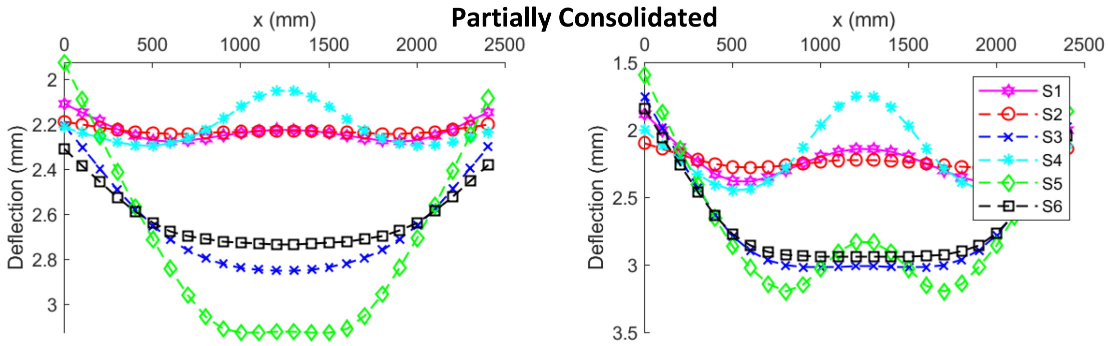


Figure 7: Deflection for V1-V12 for (a) left Concrete Sleeper (b) right FFU sleeper

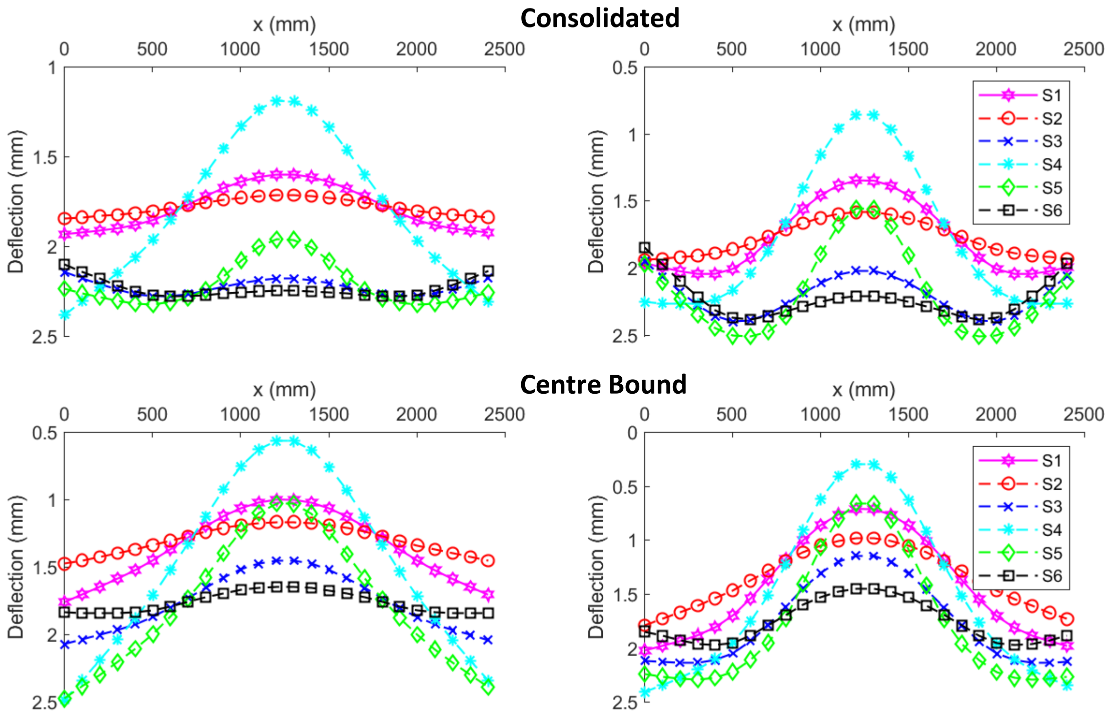


Figure 8: Deflection for V13-V24 for (a) left Concrete Sleeper (b) right FFU sleeper

Figure 7 and Figure 8 show that the deflected profiles of the lower stiffness FFU sleeper shapes have greater undulations than the stiffer concrete sleepers.

Shape 2 is stiffer than all the other shapes as a result of its increased height. The second moment of area of sleeper shape 2 is very high compared to the others, hence both the deflection and the differential deflection are significantly less in all support cases.

Shape 4 has a reduced-height middle portion. In most support cases this means that the maximum deflection and the pressure are larger at the sleeper ends and the differential deflection is increased. The sleeper has lost much stiffness from material removal and bends more in the middle compared with other shapes. However, despite these drawbacks, shape 4 does perform relatively well for the initial support condition with greater support below the railseats as do duoblock sleepers.

Under all the different support conditions, shape 5 performed very poorly when compared to the rest. In terms of the metrics and conditions considered, this confirms that the bending stiffness of the middle part comparatively plays a significant role.

Shape 3 and shape 6 provided better performance under consolidated and centre bound support conditions. These sleepers tend to bend in a ‘U’ shape rather than the typical ‘W’ shape.

The pressures follow the same patterns as the deflections for these shapes. Among all the shapes, S3 and S6 (neglecting S2 on the basis that it is too large by volume) seem to be the most efficient in material usage because they reduce peak stresses and distribute stress more evenly.

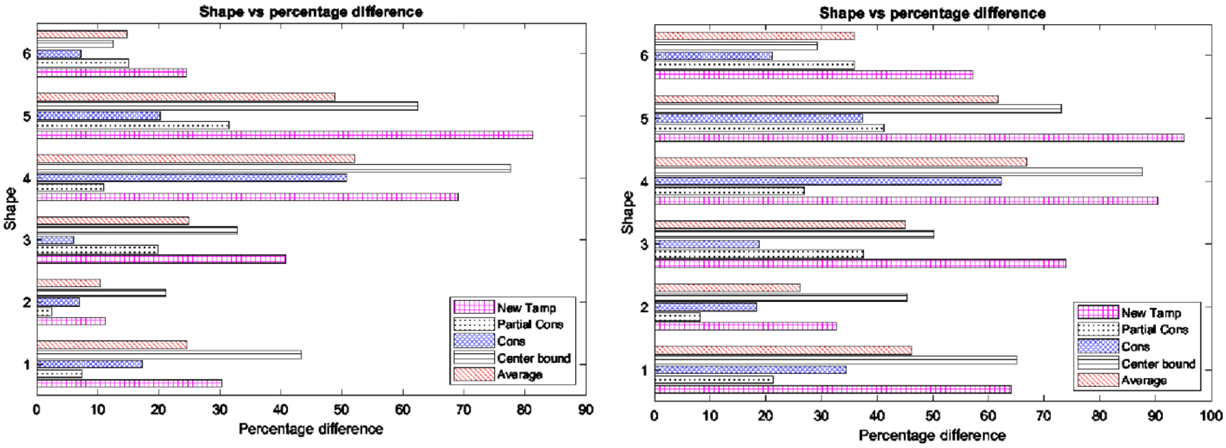


Figure 9: Percentage differential deflection of (a) concrete sleeper (b) FFU sleeper

Figure 9 shows the percentage difference between the maximum and minimum deflections for all the support types that were tested. It this representation, the differential deflection for S3 (which has reduced height in the middle) appears worse than that of S1 in the newly tamped and partially consolidated support types. Shapes S4 and S5 perform quite poorly in certain support conditions. Shape S6 maintains the benefits of its reduced width and greater height in the middle which allow it to reduce its ballast contact area while retaining flexural rigidity. The concrete sleepers have lower percentage differences generally owing to their greater flexural rigidity.

The comparison of the deflection profiles of the six sleeper shapes indicates the importance of finding an optimum thickness and height to obtain the least differential deflection for all the support cases.

Pressure

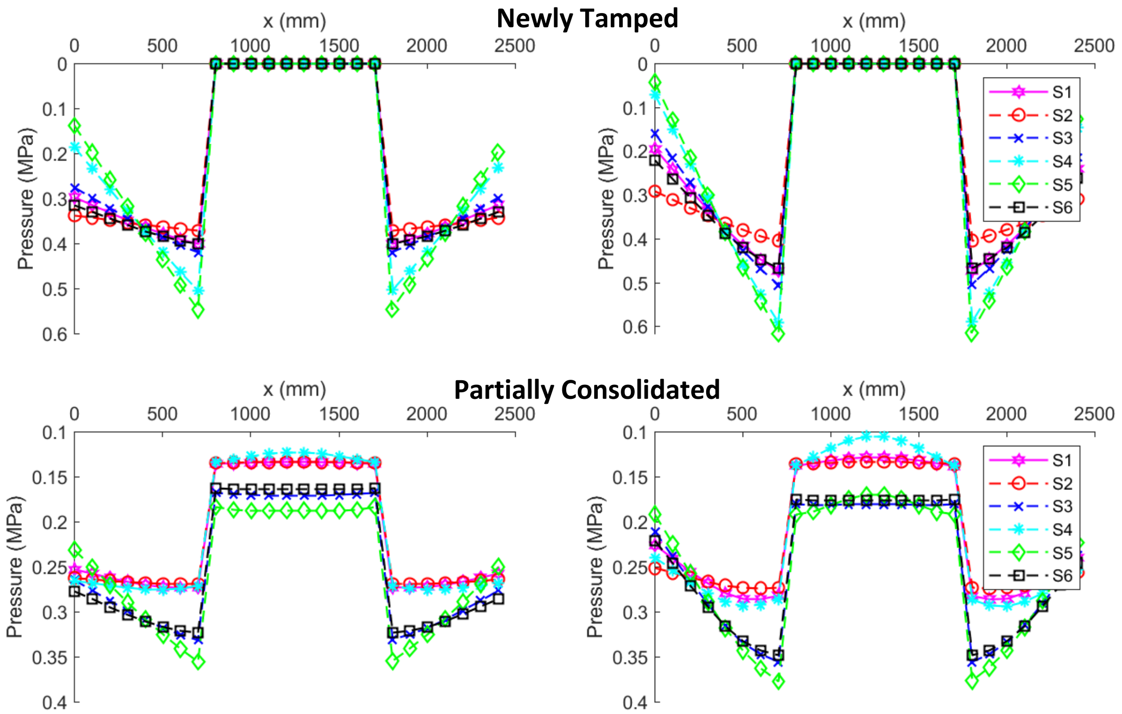


Figure 10: Pressure for V1-V12 for (a) left Concrete Sleeper (b) right FFU sleeper

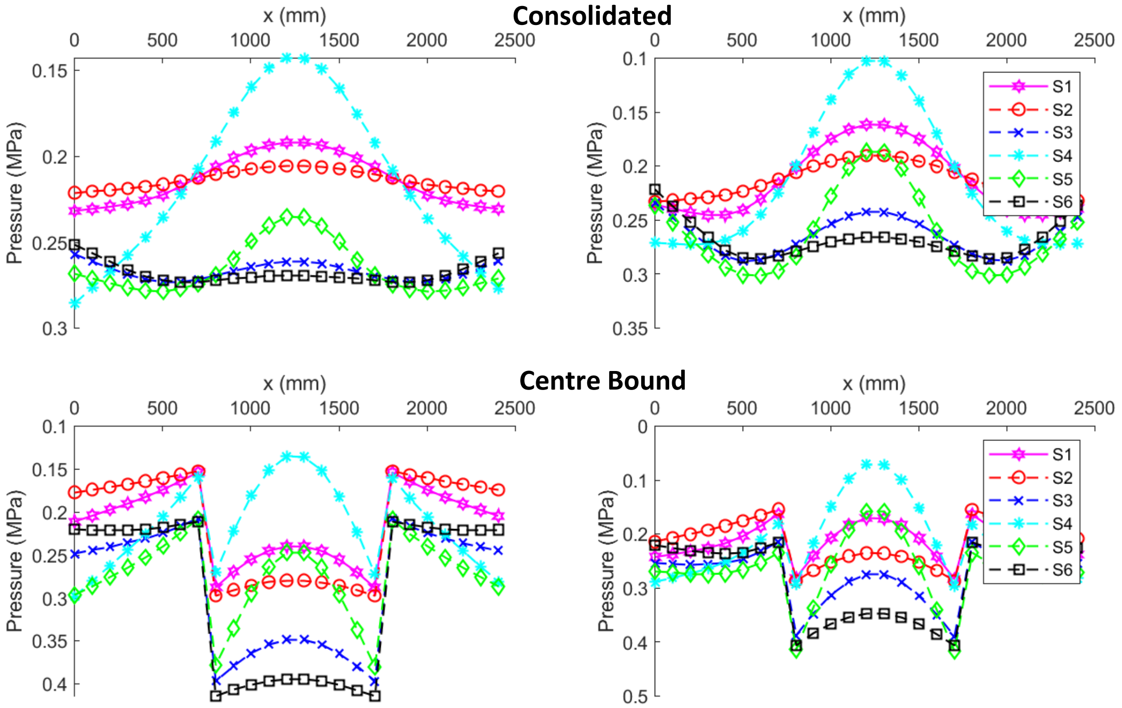
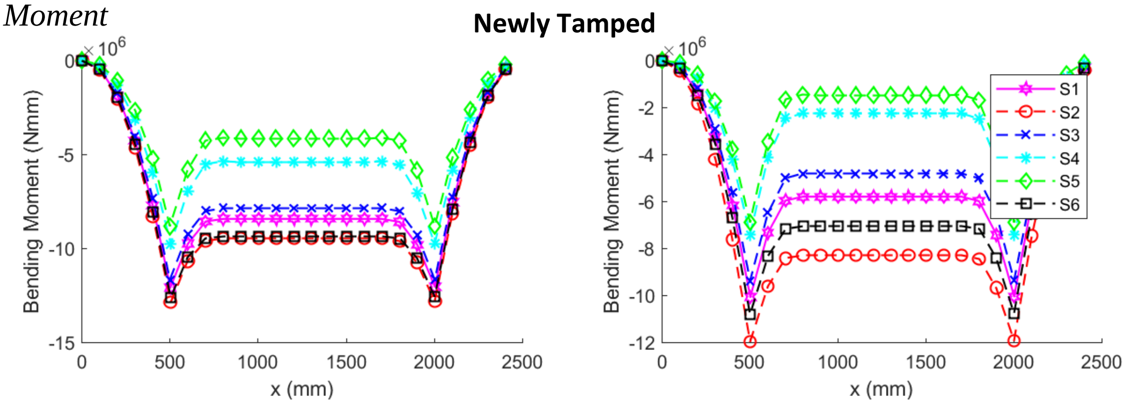


Figure 11: Pressure for V13-V24 for (a) left Concrete Sleeper (b) right FFU sleeper

Figure 10 and Figure 11 show that the pressure distribution is highly influenced by changes in support condition and the changing width of some of the sleeper shapes in the middle (S3, S5 and S6). High values may reflect that the sleeper width has narrowed and because of this the influence of high pressure may appear exaggerated (because it does not necessarily correspond to a greater local force when evaluated over a contact area). Also, when the support condition is newly tamped, there is no supporting pressure below the middle part of the sleepers. The change in pressure decreases the support consolidates and becomes centre bound. The difference in pressure is also higher in sleepers which has a smaller width in the middle which suggests that their support will become consolidated much faster and may not become centre bound because the different of pressure is less in these shapes.

Bending Moment



Partially Consolidated

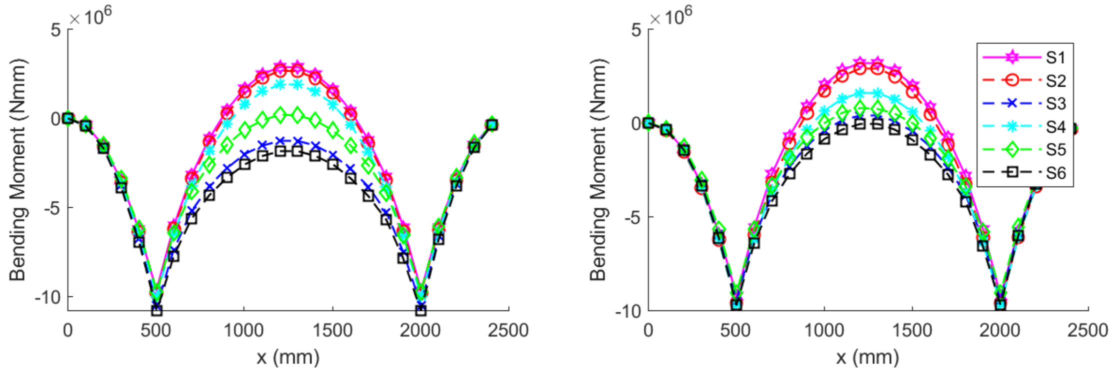


Figure 12: Bending Moment for V1-V12 for (a) left Concrete Sleeper (b) right FFU sleeper

Consolidated

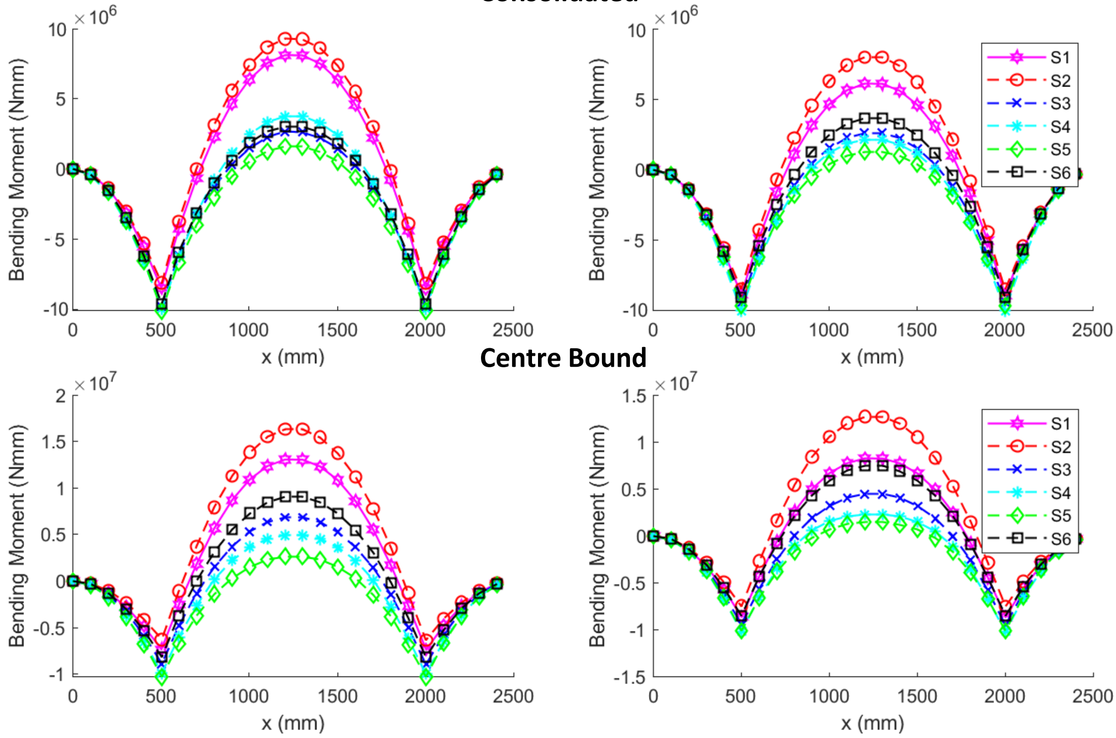


Figure 13: Bending Moment for V13-V24 for (a) left Concrete Sleeper (b) right FFU sleeper

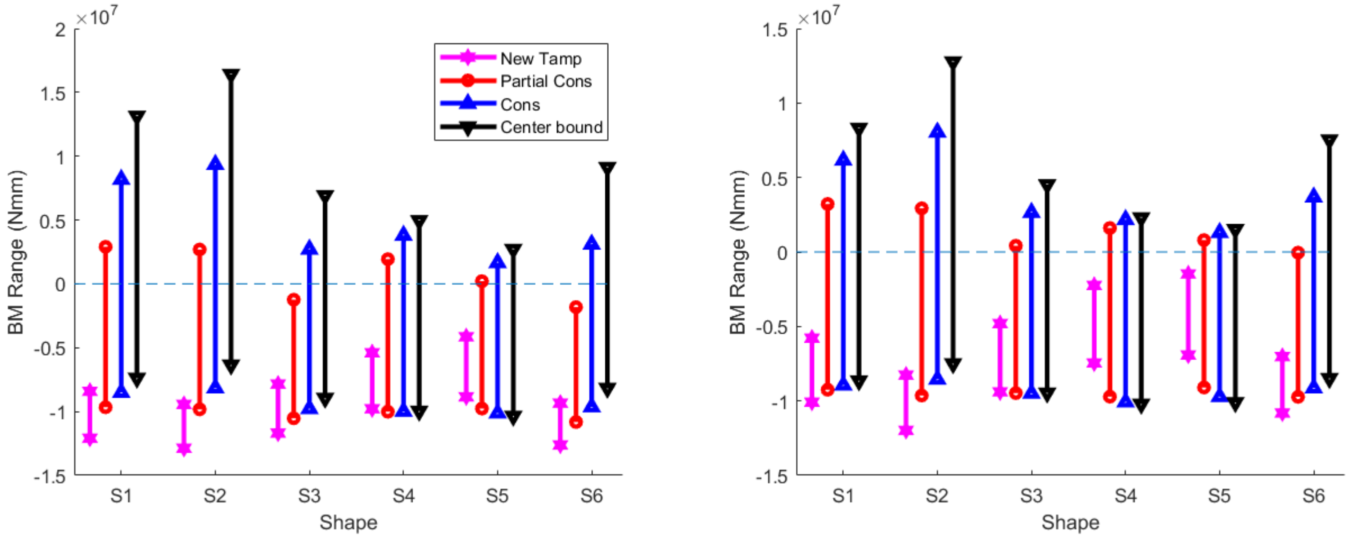


Figure 14: Range of BM of (a) left concrete sleeper (b) FFU sleeper

Figure 14 shows the range between the bending moment at the railseat and the middle part. In a newly tamped support, bending moment is mostly negative with its greatest negative magnitude below the railseats, with little change to the middle part. For the centre bound support case representing the opposite extreme, positive bending moment at the greatest magnitude occurs in the middle of the sleeper. The simulations in this paper have not considered the ultimate bending capacity for the sleeper shapes and materials evaluated. Clearly appropriate reinforcement is required considering all the possible support cases. The stiffer concrete sleepers attract greater bending moments as they work to retain lower differential deflection.

CONCLUSION

A finite difference 2D beam model was setup in Matlab and was validated against a 3D FEM model in Abaqus. A parametric study was carried out on six shapes resting on four different types of support. The study looked at the influence of changing the properties of the sleeper middle to reduce the width and/or reduce/increase the height. It was shown that:

- Greater material flexural rigidity reduces differential deflections.
- A reduced width in the middle part mitigates the effects of a centre bound support but results in greater bending.
- An increased height of the overall sleeper results in lesser differential deflection but the increased volume of material may be uneconomic
- Reducing the sleeper height in the middle results in a sleeper with a greater tendency to bend
- Shape 6 with an increased height in the middle portion retained both the benefits of a maintained bending stiffness and a reduced support
- Sleeper with a reduced width in the middle part may not undergo centre bound condition because the pressure which causes ballast movement to the middle part is minimal.

Shape 6 performed better in terms of differential settlement for both FFU and concrete sleepers for most support types.

ACKNOWLEDGEMENTS

Dr Antonis Zervos for making available the numerical finite difference tool that was later adapted for running these simulations and EPSRC for funding through the programme grant Track to The Future (EP/M025276).

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