The effect of modulus of elasticity on the behaviour of railway turnout sleepers

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ABSTRACT: Finite element analysis using a simplified grillage beam model was performed to investigate the effects of the modulus of elasticity of the sleeper, $E_{sleeper}$ and the support modulus, U_s on the behaviour of railway turnout sleepers. This study was conducted with the objective of developing a fibre composite sleeper for replacing timber sleepers. The results indicated that the behaviour of turnout sleeper is significantly affected by the changes in $E_{sleeper}$ and U_s. A high $E_{sleeper}$ and a low U_s generate high bending moments on sleepers with the maximum shear forces almost the same for all the investigated $E_{sleeper}$ and U_s. The turnout sleepers tend to undergo greater settlement into the ballast for lower $E_{sleeper}$ and U_s. The results show that an $E_{sleeper}$ of 4 GPa is optimal for the development of a fibre composite turnout sleeper as analyses showed that the behaviour of sleepers with this elastic modulus on U_s of 20 to 40 MPa are within the specified design codes and standards.

1 INTRODUCTION

Turnout is a part of the railway where track crosses one another at an angle to divert a train from the original track (Pfeil & Broadley 1991). The structure of a turnout is complicated and is one of the weakest parts of the railway track system. Special sleepers laid on a turnout are called turnout sleepers. A turnout consists of individual sleepers with varying lengths and fastening locations (AS 1085-2003). Similarly, turnout sleepers are produced with larger dimensions than the mainline sleepers to cope with the complex loadings due to the crossing of the train. Because of the special nature of turnout sleepers, hardwood timber continues to be the most widely used sleeper material in a railway turnout.

In recent years, hardwood timber for railway sleepers is becoming more expensive, less available and is of inferior quality compared to the timber previously available. This has resulted in most railway industries searching for alternative materials for replacement timber sleepers. A review conducted by Manalo et al. (2010) suggested that fibre composites are viable alternative sleeper materials in railway turnouts where larger and longer timber sleepers are required. As the cost of fibre composites are higher than the conventional materials like timber, concrete and steel, it is important to understand how the turnout sleepers respond to loads caused by a moving train in order to design an optimised sleeper section from this material.

Several researchers have analysed the railway sleepers as a beam on elastic foundation and their results showed a very good agreement between the theoretical and experimental results (Shokreih & Rahmat 2007, Ticoalu 2008). The finite element analyses of these researchers are implemented using single sleeper only. The presence of at least two sets of continuous rails which connects the sleepers makes the inclusion of the entire turnout structure essential in the analysis. For this reason, the behaviour of turnout sleepers should be determined for a group of sleepers instead of a single sleeper, as the contribution of neighbouring sleepers should be taken into account due to the joining effects of the rails.

In this study, a simple and rational structural model which considers the rail, sleeper, ballast, and subgrade in a railway turnout system is developed. The model also considers the effect of the adjacent sleepers on the behaviour of turnout sleepers through the rails secured to the sleepers. Subsequently, the response of sleepers due to wheel load of a train passing a turnout is investigated. The behaviour of sleepers with different moduli of elasticity and the influences of the changes in the support modulus in the performance of turnout sleepers are analysed. The result of this parametric investigation could lead to an optimised section for fibre composite sleepers in a railway turnout.

2 FINITE ELEMENT MODEL OF SLEEPERS

2.1 *Railway turnout geometry*

Standard 1 in 8 left-hand turnout geometry using 47 kg/m rail and a narrow gauge (1067 mm) rail line commonly used in Queensland, Australia is considered. Distance between rail centres is taken as 1137 mm and the spacing of sleepers is 650 mm. Sleeper dimensions were set at 230 mm x 150 mm in consideration of the replacement of deteriorating turnout timber sleepers. The typical range of sleeper support modulus, Us is taken as approximately 10 to 40 MPa (AS 1085.14-2003). A combined vertical design load factor, j of 2.5 is used as recommended by AS1085.14 (2003). Table 1 details the components of the track structure and Figure 1 shows the schematic diagram for a turnout sleeper.

Table 1. Details of the components of the track structure.

Component	Description
Rail section	47 kg/m
Rail gauge (G)	1067 mm
Distance between rail centres (g)	1137 mm
Sleeper spacing	650 mm
Axle load	35 tons
Combined vertical load factor (j)	2.5
Sleeper support modulus	10 – 40 MPa
Allowable ballast pressure	450 kPa
Stiffness of the rails	200 GPa

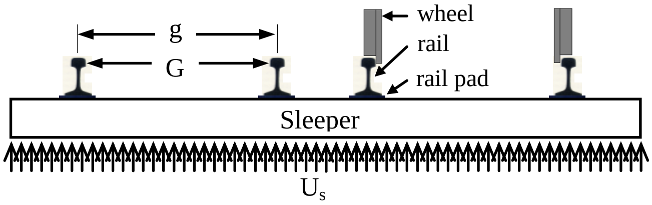

Figure 1. Schematic diagram of a turnout railway sleeper.

2.2 *Grillage beam model of the railway turnout*

A simplified three dimensional grillage model consisting of longitudinal and transverse beam elements has been developed to analyse the behaviour of railway turnout structure. The finite element model considers the rails as long beams continuously supported by equally spaced sleepers. The railway turnout model consists of a total of 57 sleepers including 10 transition sleepers before the switch and after the longest sleeper in the turnout as shown in Figure 2. The transition sleepers are provided to ensure that the wheel load is sufficiently distributed over several sleepers when the train enters and leaves the turnout. The sleepers are laid perpendicular to the through tracks with increasing lengths from the switch until two standard length sleepers could be placed under the through and divergent tracks. The overall length of the modelled track is 25.8 m with sleeper length varying from 2.138 m to 4.27 m.

Strand7 finite element program is used to model the railway turnout system. The rails and the sleepers are modelled as a grillage beam system with the sleepers resting on an elastic foundation (Figure 3). The guard and check rails are omitted to further simplify the modelling procedure. The turnout model is assumed to be in flat terrain and the effect of irregularities on the track and wheels and the dynamic effect are assumed to be represented by the dynamic load factor. The beams are subdivided into reasonable number of elements to achieve a better accuracy of the results but still within reasonable analysis time. A total of 561 Beam2 elements and 454 nodes representing the rails, sleeper plates and sleepers were used in the turnout model. An approximate steel I-section with an almost equivalent moment and torsional inertia was used for the rail. The sleepers are identified by numbering them from 1 to 57 starting from the front of the model as shown in Figure 2.

The centroids of the rail and sleepers are offset with a distance equal to the sum of half their depths. Beam elements were used to connect the rail and the sleepers, which were placed at the level of their respective centroids. These beams are modelled with an axial stiffness equivalent to that of 19 mm steel plate used for timber sleepers. The wheel load was applied directly to both rails. Only the equivalent static wheel load acting on the vertical direction is considered with no lateral and longitudinal loads. The support provided by the ballast and subgrade is modelled as an elastic foundation with a combined effective support modulus using Winkler foundation model.

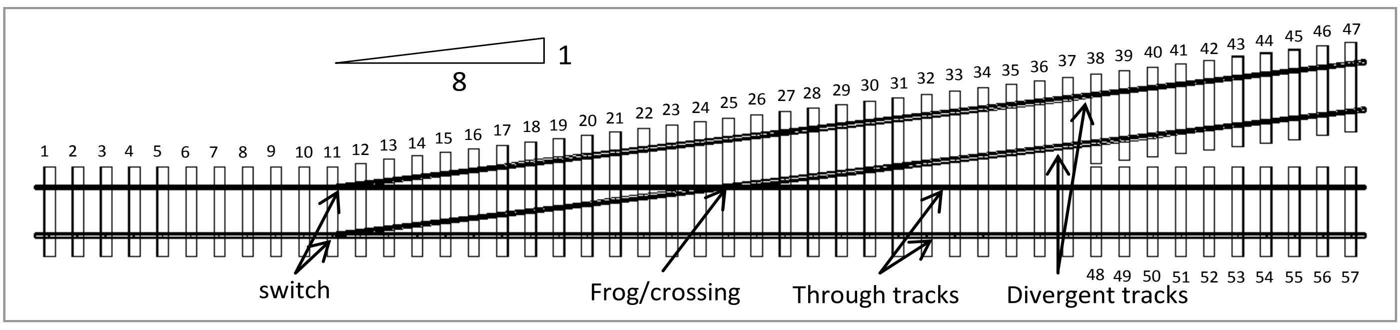

Figure 2. geometry of a 1:8 standard left-hand railway turnout.

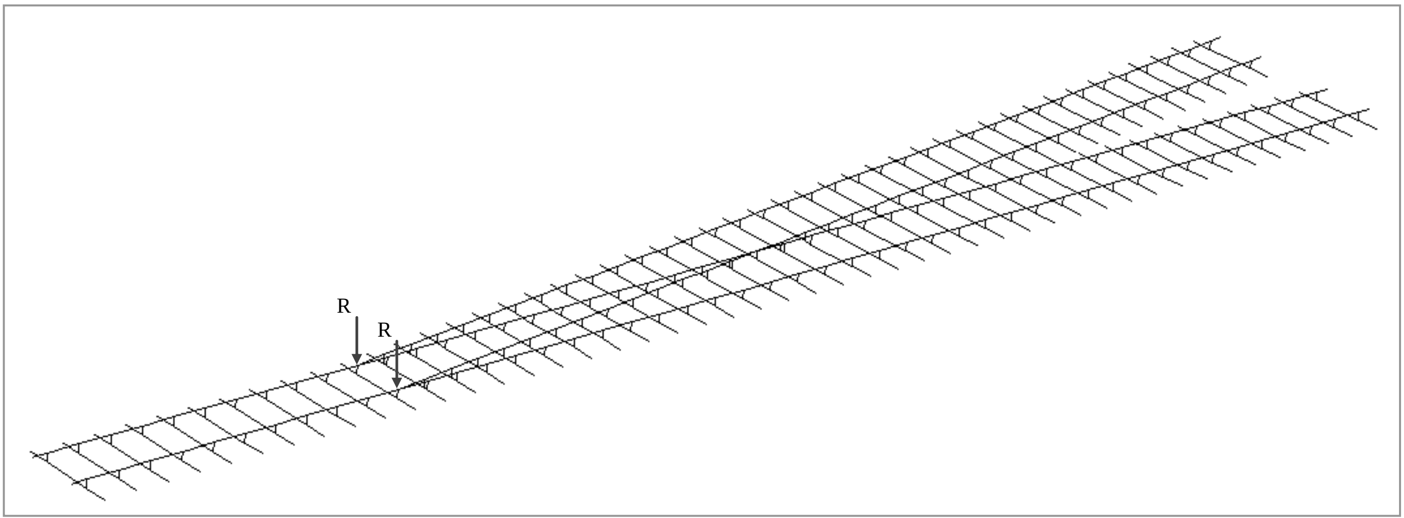

Figure 3. The grillage beam model for railway turnout.

3 PARAMETRIC STUDY

A parametric study was conducted to determine the behaviour of fibre composite sleepers in a railway turnout with varying elastic modulus resting on materials with different sleeper support modulus. Several load cases simulating the passing of the train were investigated to identify the location of the most critical sleeper and to determine the magnitude of the maximum bending moments, shear forces and vertical deflection in the most critical sleepers.

3.1 *Equivalent quasi-static wheel load*

A number of analytical models developed around the world represents the vehicle by a single bogie with two symmetrical wheel masses (Steffens & Murray, 2005). In the AS1085.14 (2003), the magnitude of the equivalent static wheel load Q (in kN) carried by each rail is half of the axle load or vertical load P and is computed as:

$$Q = (P/2) \times 9.81 \quad (1)$$

Rail seat load, R is calculated as a function of design static wheel load, impact factor (j) and axle load distribution factor (DF) which corresponds to sleeper spacing. This gives:

$$R = jQ(DF) \quad (2)$$

Using the design parameters in Table 1 and a distribution factor of 1 (as the axle load is distributed to the sleepers through the continuous rails), this has resulted in an equivalent static wheel load of 430 kN which is used as input to the finite element model. This wheel load was moved along the turnout to investigate the influence of wheel load as it travels through the turnout and determine the location of the most critical sleepers.

3.2 *Support modulus, U_s*

In railway design, it is usually assumed that the ballast, subballast and subgrade are represented by a single element with equivalent ballast/subgrade stiffness (Steffens & Murray 2005). To evaluate the extent of this effect, the behaviour of sleepers in a railway turnout was examined under different values of sleeper support modulus, U_s. As suggested in AS 1085.14 (2003), the value of sleeper support modulus may vary from 10-40 MPa. This elastic foundation is assumed to support the sleepers continuously along its length.

3.3 *Modulus of elasticity of the sleeper, $E_{sleeper}$*

The design of structures using fibre composite materials has been driven by the stiffness requirement rather than strength. Thus, a minimum stiffness that would not affect significantly the behaviour of railway turnout sleepers could result in an optimum design for fibre composite alternatives. A lower range of modulus of elasticity (1-10 GPa) were considered with the objective of developing a fibre composite railway sleeper for replacing timber sleepers. This range of $E_{sleeper}$ is reasonable as most of the currently developed fibre composite sleepers are produced with stiffness of not more than 8 GPa (Aravinthan et al. 2010). Similarly, Ticoalu (2008) suggested a minimum elastic modulus value of around 10 GPa in the development of fibre composite turnout sleepers.

4 RESULTS AND DISCUSSION

The effects of the different sleeper moduli of elasticity and subgrade moduli on the behaviour of turnout railway sleepers are discussed in the succeeding sections. Only the behaviour of sleepers on support modulus of 10 and 40 MPa are presented here to illustrate the effect of different sleeper stiffness on the bending moment, shear forces and vertical deflection of sleepers on a railway turnout.

4.1 *Bending moments in sleeper*

A plot of the maximum positive bending moment on the sleepers due to a set of symmetrical wheel load of a train passing through a railway turnout is shown in Figures 5 and 6. In these figures, the stiffness of sleepers is designated as E while the bending moment is designated as BM.

The results of the FEM model show that the maximum positive moment occurred under the rail seat region where each axle is placed for both the transition and turnout sleepers. The magnitude of the maximum positive bending moment on the sleepers increases with increasing $E_{sleeper}$. The results also show that the positive bending moment increases as the wheel load passes through the switch but decreases after passing through the longest sleeper.

At U_s = 10 MPa, the maximum positive bending moments at the transition sleepers do not vary significantly. When the wheel load enters the switch, there is a significant increase in the magnitude of the positive bending moment in the turnout sleepers with a magnitude between 10.7 kN-m and 24.2 kN-m for the different $E_{sleeper}$. This magnitude of the positive bending moment at the turnout sleepers is 2 to 4 times higher than the transition sleepers.

At U_s = 40 MPa, there is an increase in the difference on the magnitude of maximum positive bending moment at the transition and turnout sleepers with increasing $E_{sleeper}$. In general, the increase in $E_{sleeper}$ from 1 GPa to10 GPa has resulted in almost 200% increase in the maximum bending moment.

The maximum bending moment of the sleepers with $E_{sleeper}$ = 1 GPa is not greatly different from each other for different support modulus while the turnout sleepers with $E_{sleeper}$ = 10 GPa are more sensitive to the changes in the support modulus. This is more evident in sleepers after the train has passed the frog as the length of sleepers in this location is longer. The results indicated that as the sleeper support becomes stiffer there is a slight decrease in the magnitude of the maximum bending moments.

4.2 *Shear forces in sleeper*

Figures 7 and 8 shows the maximum positive shear force in sleepers incurred due to the passing of a train in a turnout. It can be seen from the figures that when U_s = 10 MPa, the magnitude of the maximum positive shear force does not vary significantly for all the investigated $E_{sleeper}$ but a slightly higher shear force was obtained for higher $E_{sleeper}$ when U_s = 40 MPa. The result of the analyses showed that the maximum positive shear force occurs under the rail seat of the transition sleepers.

When the wheel load enters the switch, there is a significant increase in the magnitude of positive shear force on the turnout sleepers. However, there is no significant difference in the magnitude of the maximum shear force for all the investigated $E_{sleeper}$. The highest positive shear force among the turnout sleepers is around 220 kN and occurred when the wheel load is seating on sleepers 12 and 25. This high magnitude of shear force at the switches and frog can be attributed to the effect of a train wheel changing direction at the flangeway opening (of the switch) which causes high shear forces on the sleepers. It is important to note that the highest positive shear force in sleepers 12 and 25 occurs in the region between the through and divergent tracks.

In general, only a slight increase in the maximum shear forces was observed with increasing U_s. This increase is more noticeable in the transition sleepers than the turnout sleepers. This could be due to the presence of two sets of continuous rails which are secured to the turnout sleepers resulting in a stiffer system than the transition sleepers.

4.3 *Vertical deflection of sleepers*

Figures 9 and 10 show the vertical deflection or settlement into the ballast of sleepers with different moduli of elasticity for U_s = 10 MPa and 40 MPa, respectively. The FEM results show that the maximum settlements of the sleepers occurred under the rail seats when the wheel load is directly over the sleepers. The results also show that the sleepers with lower modulus of elasticity will settle more than the sleepers with higher $E_{sleeper}$. As indicated on the figures, there is no major difference in the vertical deflection with $E_{sleeper}$ between 4 GPa and 10 GPa.

The vertical settlement of sleeper decreases as the wheel load enters the switch but increases again after the frog. The lower settlement of sleepers in this location could be due to the presence of a rail between the rail seats which acted as an additional support to lessen the settlement of the sleepers. After the frog, the vertical settlement increased again as the sleepers behaved more like a cantilever beam with the rails on the through tracks acting as supports.

At U_s = 10 MPa, the highest vertical deflection observed on the transition sleepers is between 5.27 and 6.03 mm for all the considered $E_{sleeper}$. As the wheel load enters the switch, the vertical deflection decreases to around 4.0 mm but again increased to almost 6.0 mm after passing the switch. Similar behaviour was observed when U_s = 40 MPa, the vertical deflection was higher in the transition sleepers than the turnout sleepers. However, the maximum vertical deflection of sleepers is below 4.0 mm.

For all the $E_{sleeper}$ reported, sleeper on higher U_s settled the least into the foundation. A more uniform vertical deflection of the sleepers was also observed at higher support modulus which shows that the load is more uniformly spread over sleepers in a railway track. For all $E_{sleeper}$, there is a considerable vertical deflection of sleepers (more than 5 mm) on U_s = 10 GPa but only between 2 to 4 mm for higher U_s.

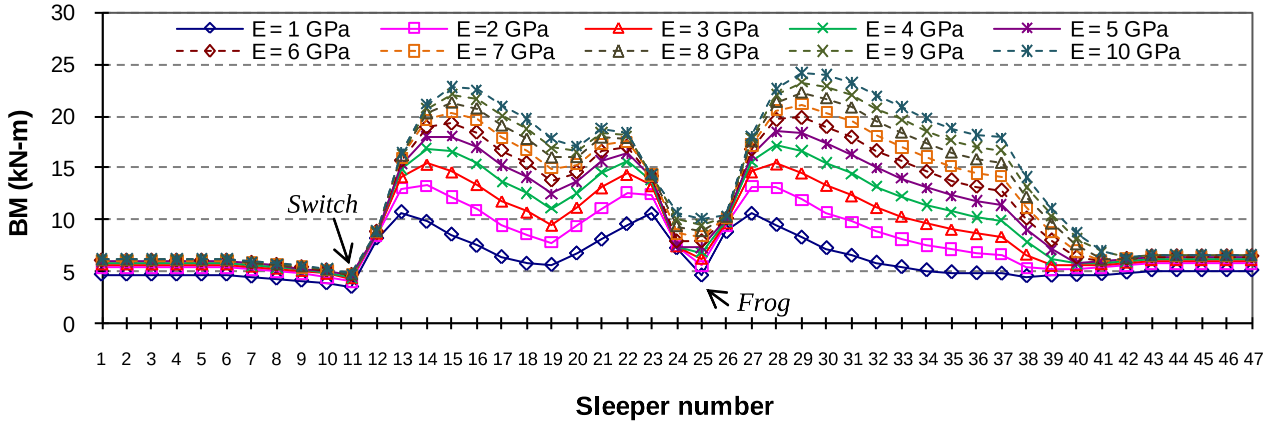

Figure 5. Positive bending moment when Us = 10 MPa.

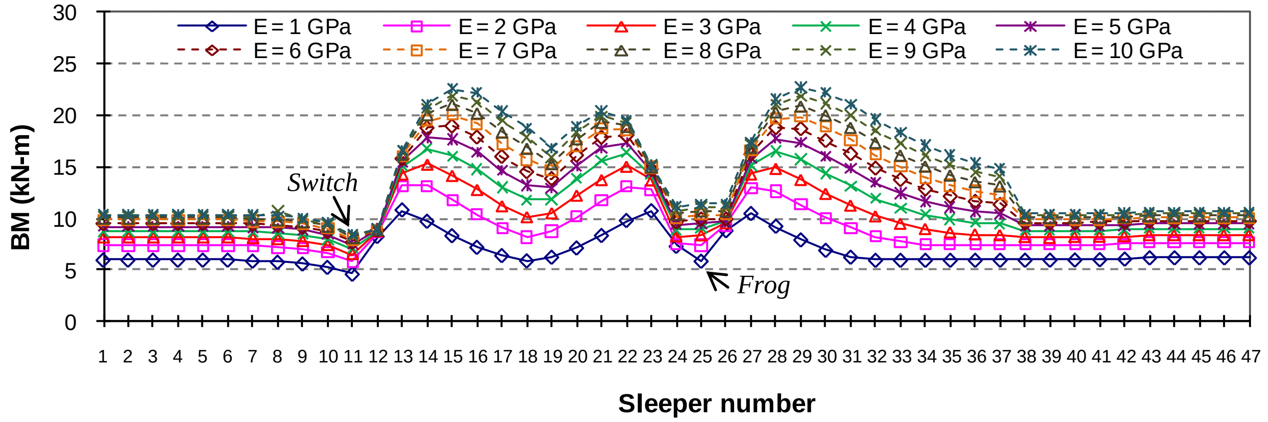

Figure 6. Positive bending moment when Us = 40 MPa.

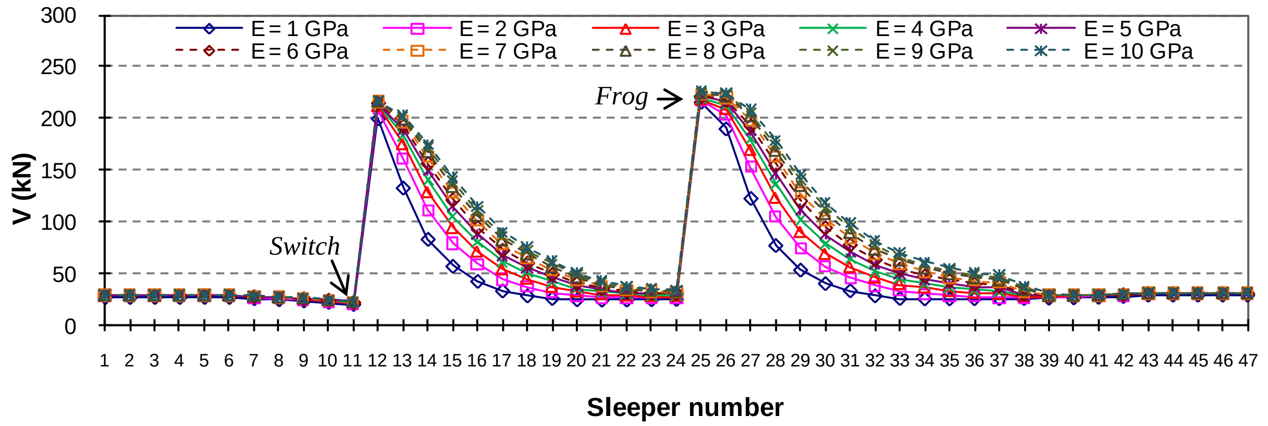

Figure 7. Maximum positive shear force when Us = 10 MPa.

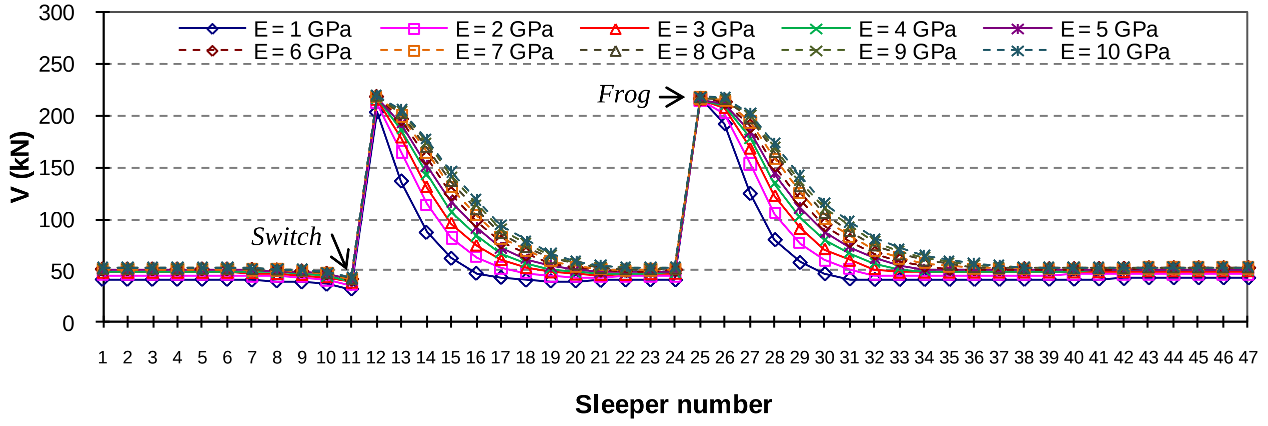

Figure 8. Maximum positive shear force when Us = 40 MPa.

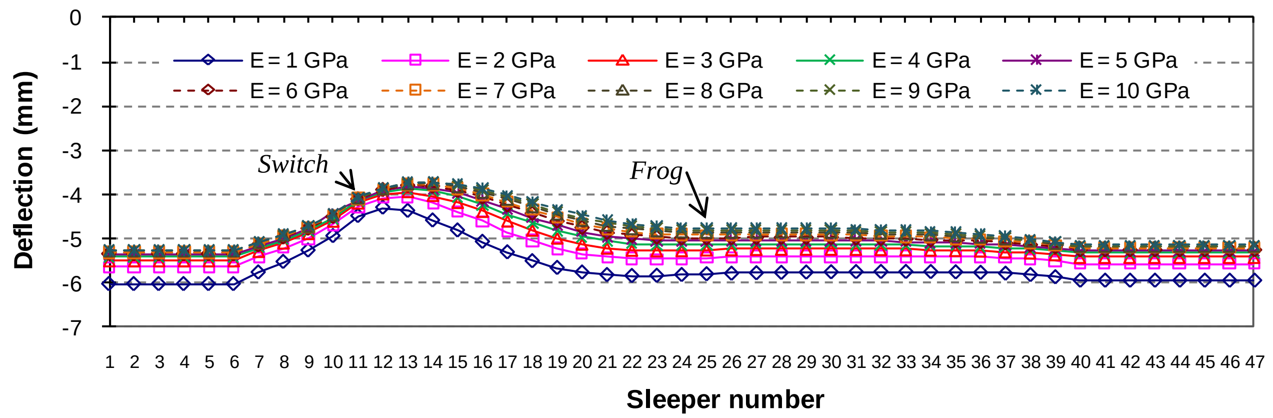

Figure 9. Maximum vertical defelection when Us = 10 MPa.

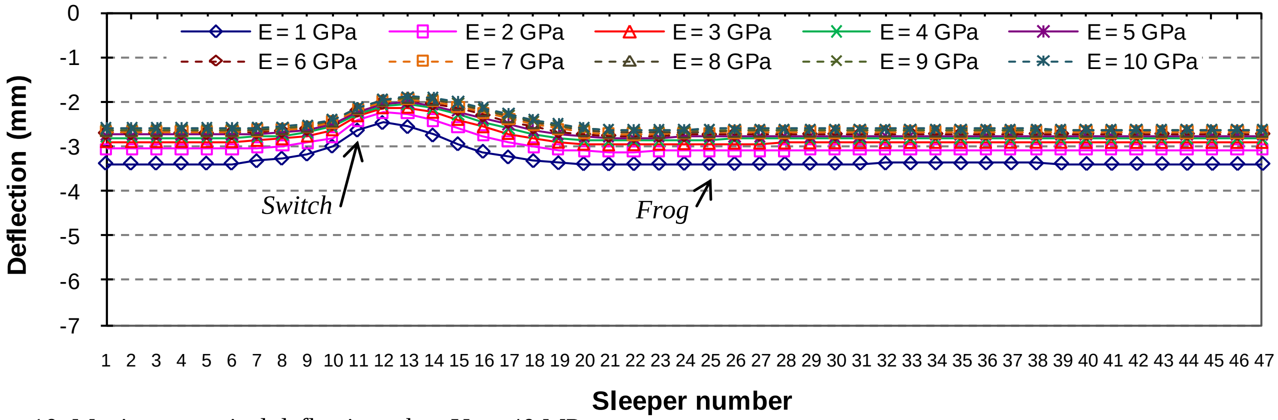

Figure 10. Maximum vertical deflection when Us = 40 MPa.

5 INITIAL EVALUATION FOR THE FIBRE COMPOSITE TURNOUT SLEEPER DESIGN

The results of the FEM analyses provided a basis for an optimum design of fibre composite turnout sleepers. The results suggest that there is no significant difference in the bending moment of sleepers with elastic modulus of 4 to 10 GPa. On the basis of the simulations performed, the fibre composite sleeper alternatives should resist a minimum bending moment of 25 kN-m and a shear force of 220 kN.

Except for U_s = 10 MPa, the calculated vertical deflection in all the combinations used in this study is within the maximum allowable deflection of 5 mm for railway track in Australia. Similarly, the recommend maximum allowable contact pressure between the timber sleeper and the ballast of 450 kPa can only be satisfied using a sleeper with an elastic modulus of at least 4 GPa.

6 CONCLUSION

A simplified grillage beam model was used to investigate the behaviour of sleepers in a railway turnout. In all the scenarios investigated, the highest maximum bending moment and shear forces are produced between the switch and the frog.

The analyses showed that the bending moment in turnout sleeper is less affected by the changes in support modulus but affected significantly by the changes in $E_{sleeper}$. Increasing the U_s from 10 to 40 MPa resulted in only 10% reduction in the bending moment while the increase in $E_{sleeper}$ from 1 to 10 GPa has resulted in a 200% increase. The shear force in sleepers is not sensitive both to the changes of the $E_{sleeper}$ and U_s. Sleeper with lower $E_{sleeper}$ and U_s tend to undergo greater settlement into the ballast.

The results indicated that a fibre composite turnout sleeper can be manufactured with an $E_{sleeper}$ of as low as 4 GPa provided that the support modulus is at least 20 MPa. The sleeper with this elastic modulus satisfies the deflection and sleeper/ballast pressure.

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