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Kaewunruen, Sakdirat; Ngamkhanong, Chayut; Ng, Jipong

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Influence of time-dependent material degradation on life cycle serviceability of interspersed railway tracks due to moving train loads

Sakdirat Kaewunruen

Department of Civil Engineering, School of Engineering, University of Birmingham, 52 Pritchads Road, Edgbaston B15 2TT, UK

s.kaewunruen@bham.ac.uk

Chayut Ngamkhanong

Department of Civil Engineering, School of Engineering, University of Birmingham, 52 Pritchads Road, Edgbaston B15 2TT, UK

cxn649@student.bham.ac.uk

Jipong Ng

Department of Civil Engineering, School of Engineering, University of Birmingham, 52 Pritchads Road, Edgbaston B15 2TT, UK

jxn442@alum.bham.ac.uk

Abstract

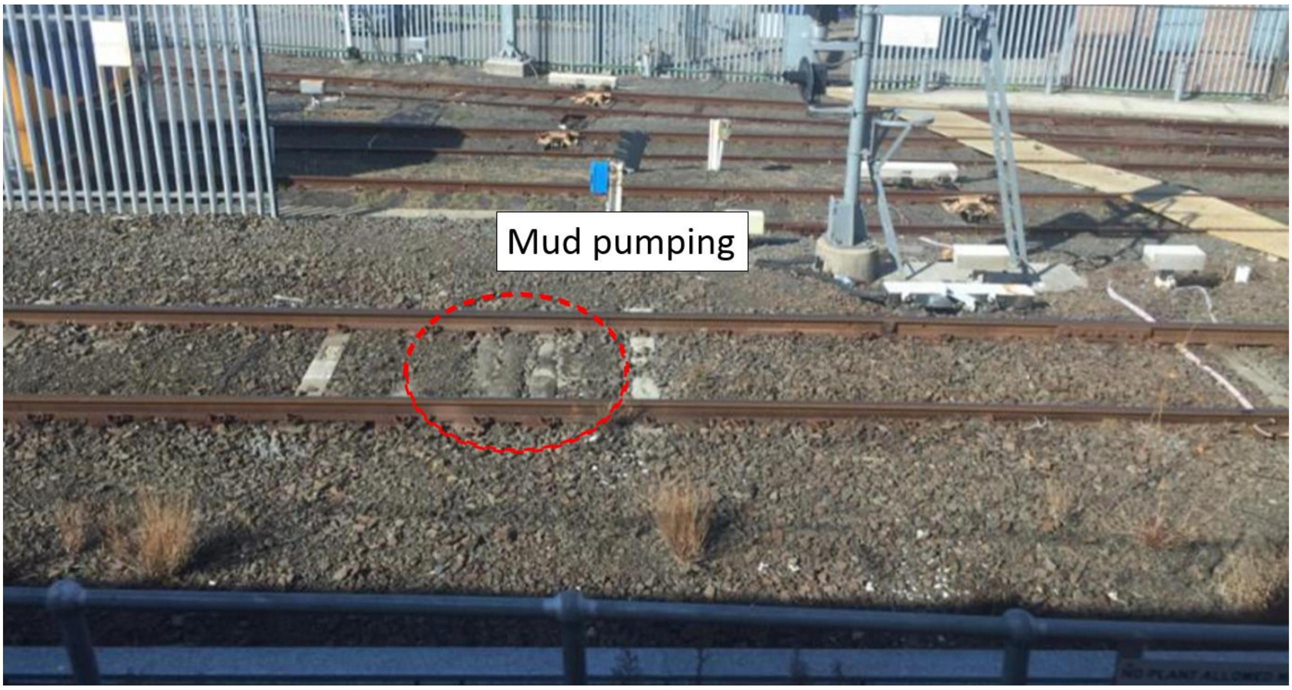
Presently, timber-sleepered tracks are still being adopted in railway networks transporting goods and passengers. However, the deterioration of timber sleepers is evident after years of service due to natural decay; and it is difficult to seek cost-effective hardwood sleepers to replace the aging sleepers. An impermanent "interspersed" approach is an alternative method used to substitute rotten timbers with concrete sleepers. Although the interspersed tracks offer a cost-effective short-term solution for certain track classes, there are some drawbacks to this practice, since the interspersed track has inconsistent stiffness problems, and the different track decay rate can cause uneven settlement and foundation failure, which can lead to significant track deterioration over time. The emphasis of this study is placed on the long-term behaviour of interspersed track components under repeated train loading. Interspersed track models in three-dimensional space have been developed and validated using a finite element method. The effects of deteriorated railway components (timber, rail pads, ballast) are taken into account to examine the dynamic performance of the interspersed tracks under moving train loads. This study will help rail track engineers better understand the time-dependent behaviour of interspersed tracks, enable a truly predictive track maintenance and improve the reliability of infrastructure asset maintenance and life cycle management.

Keywords: Interspersed tracks; timber sleeper; concrete sleeper; dynamic response; nonlinear transient analysis; tensionless support; time-dependent behaviour; material deterioration.

1. Introduction

Railway timber sleepers are still being used as a prevalent type of railway sleepers in the global railway industry [1-2]. The service life expectancy of the timber railway sleepers is generally between 15 to 20 service years, depending on their applications, operation parameters, environmental factors and the level of maintenance quality. However, timber-sleepered tracks degrade over time and therefore extensive preservation works are imperative to maintain and strengthen the performance of the timber tracks [3]. Nowadays, limited availability of reliable and high-quality timbers, and restrictions on deforestation, have inspired the world to explore more alternatives to substitute the aged timber sleepers [4-6]. Therefore, in general, the practice of utilising concrete railway sleepers has been implemented and employed as seen in many countries on their modernised railway lines [7].

The aging timber sleepers in the second or third class railway lines with low operation speed are often replaced by concrete sleepers, as can be found in various countries (e.g. Australia, Japan, United Kingdom, United States, etc.). This temporary to pseudo-permanent solution is called an "interspersed track" [2-5]. The concepts of this solution are to maintain track quality and improve sufficient short term solutions (less than 10 years) that could be agile, cheap, effective, and quick. Although a partial replacement of aged, rotten sleepers is obviously more economical than complete track renewal or a reconstruction, the interspersed track poses some drawbacks. According to open literature and industry knowledge, this practice could consequently undermine the existing ground foundations and also induce inconsistent local stiffness problems on the rail track system [3, 6-9] and different track decay rates [10-16]. It is clear that the long term performance of interspersed tracks can be impaired as seen in Fig. 1. Figure 1 shows the conditions of interspersed railway tracks under low-speed operations (<25 km/h). The tracks have been commissioned between 2006 and 2008 and have served as a link from suburban mainlines to a maintenance depot. As observed from the site visit, it was found that interspersed track was likely to have an uplift behaviour. This could significantly induce the ballast pulverization and densification at the certain location where the mud pumping occurred. Moreover, where the sleeper uplift occurred, this could induce ballast dilation and cause centre bound failure.



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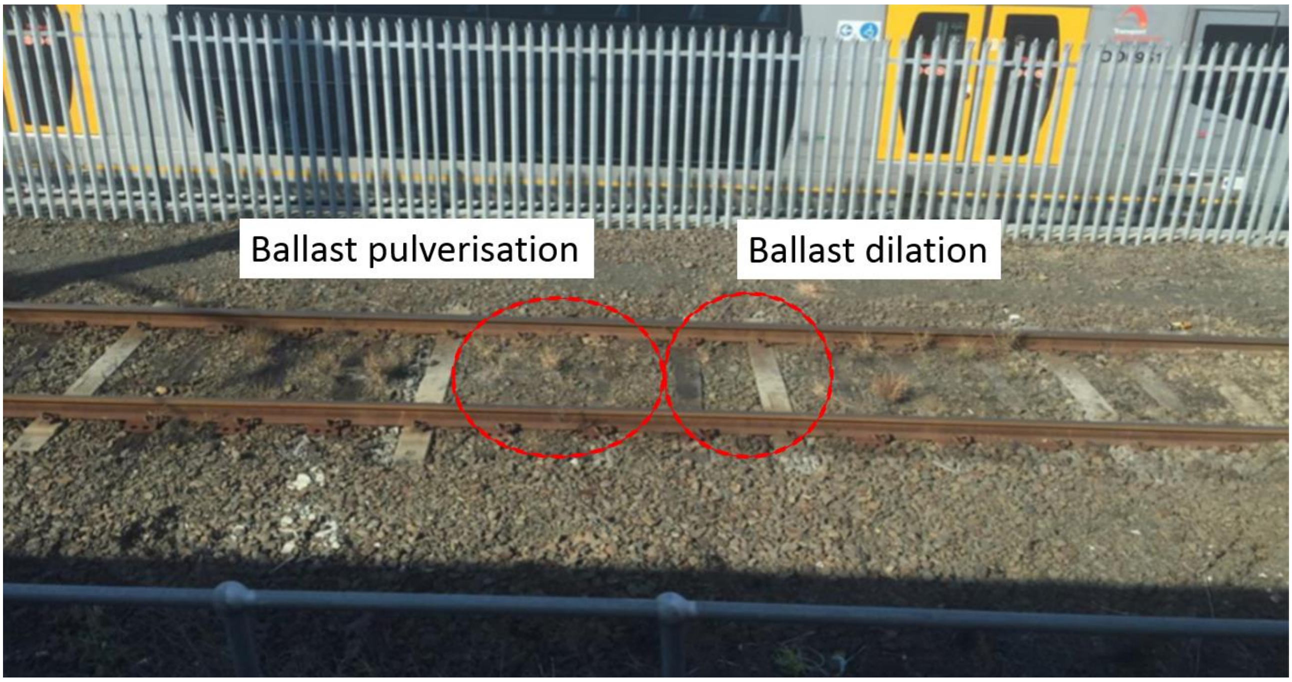

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Fig. 1. Deteriorated interspersed railway track; a) mud pumping b) ballast pulverisation and ballast dilation.

In addition, the aggressive load condition, which may also cause structural cracks in brittle sleepers and densifies and pulverises ballast support, can also affect the overall track degradation. This load is generally referred to as “dynamic impact loading” [17-18]. The dynamic load patterns and magnitudes are dependent on train speed, track geometry, axle load, vehicle type, and wheel/rail defects or irregularities. Moreover, concrete sleeper capacities can be reduced by their modified cross section to fit track clearance [19-20], creep and shrinkage [21-23], and pre-stress losses [24-25]. These are also significant factors that can accelerate track degradation.

Although interspersed tracks have been investigated in open literature [26-28], time-dependent behaviour have not been fully studied and taken into account. This study aims at investigating the dynamic responses of the interspersed railway tracks in three-dimensional space considering the influences of time-dependent degradation of materials. All four types of interspersed railway tracks have been constructed previously using finite element software package, STRAND7 [29]. Validations were carried out earlier against experimental and laboratory data [26-28]. It is noted that this study considers the dynamic responses of interspersed track from year 0 to 20. Material research literature [3, 28] indicates that timber sleepers and rail pads deteriorate fully during the economic service lifetime, whilst the steel rails and concrete sleepers are maintained to a near perfect condition. Based on field investigations, ballast is cleaned or renewed around every 10 years for this class of interspersed track. The outcome of this study will help track engineers undertake truly predictive track maintenance, improve track reliability and inspection regimes.

2. Methodology

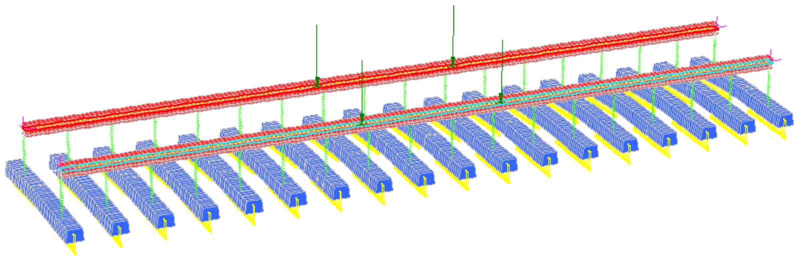
2.1. Finite element modelling

A two-dimensional Timoshenko beam model was previously developed and found to be one of the most suitable options for modeling concrete sleepers [30]. In this study, the finite element models of railway tracks have been validated against the previous numerical and experimental modal parameters [31-32]. Figure 2 shows the finite element models in three-dimensional space for an in situ railway track with different types of sleepers. Using a general-purpose finite element package STRAND7 [29], the numerical model included the beam elements, which take into account shear and flexural deformations [33], for modeling the sleeper and rails. The validated sleeper model has been replicated to construct a track model. The rail pads were simulated using a series of spring-dashpot elements. The stiffness and damping values of high density polyethylene (HDPE) pads were assigned to the spring-dashpot elements. The support condition was simulated using the nonlinear tensionless beam support. This attribute allows the beam to lift over the support while the tensile supporting stiffness is omitted [34]. The tensionless support option can correctly represent the ballast characteristics in real tracks. The simulation iterates until the convergence of contact between sleeper and ballast is reached, prior to calculating dynamic responses and action redistribution. The modelled sleepers are connected to both rails using spring-dashpot elements with hinge nodes at rail seats. Displacement restraints have been applied to the rail ends. It is noted that the effects of length and boundary of track in this study (18 bays or 10.8m) on the computation and the frequencies of interest are negligible [35-37]. Note that the rail ends have been restrained as vertical rollers. The nonlinear transient solver is used to analyse the time history of the nonlinear dynamic responses of railway track subjected to arbitrary dynamic train load. Nonlinear behaviour of the structure due to geometric and material was considered. The nonlinear material models are included, although it is expected to behave within elastic range. The deformed geometric is used to establish the updated equilibrium equation since the equation is linearized at each time step. Note that, for the beam elements which are considered, the element's local reference system is updated and rigid body motion is removed. The following equation (Eq. (1)) is solved by nonlinear transient solver using the Newmark time integration method. It is noted that the equation is originally based on the linear dynamic equilibrium equations. For nonlinear transient dynamic, the expression is modified to include the nonlinearities of geometry and material property.

$$M\ddot{u}(t) + C\dot{u}(t) + Ku(t) = p(t) \tag{1}$$

Where M is global mass matrix, C is global damping matrix, K is global stiffness matrix, $p(t)$ is applied load, $u(t), \dot{u}(t)$ and $\ddot{u}(t)$ are nodal displacement, velocity and acceleration, respectively. The global stiffness matrix is possibly changed due to the geometric nonlinearity considering the effect of second order which can lead to the large node deflection.

In this study, four types of commonly adopted interspersed railway tracks have been adopted, as shown in Fig. 2. They are identified as plain timber railway track ("1 in 1"), "1 in 2", "1 in 3" and the "1 in 4" interspersed railway tracks. By definition, the "1 in 2" entails the establishment of the alternative formation of concrete and timber railway sleepers on the railway tracks, while "1 in 3" is referred to as another type of the interspersed track, where one concrete sleeper is seated alongside every two timber sleepers. Similarly, the "1 in 4" configuration indicates that one concrete sleeper is mixed with every 3 timber sleepers along the railway track. Note that concrete sleeper track is also compared with interspersed tracks in this study.



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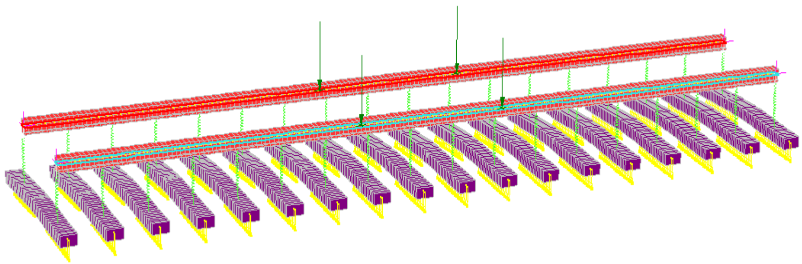

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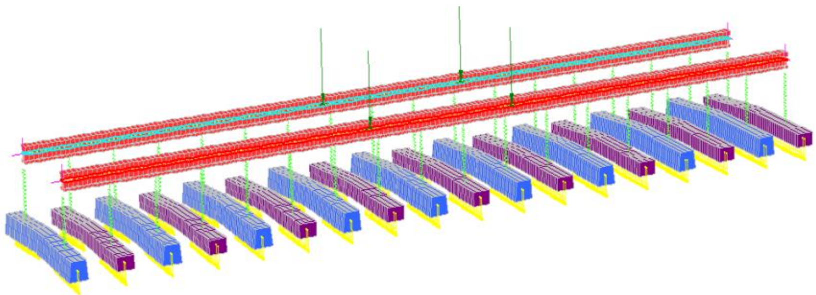

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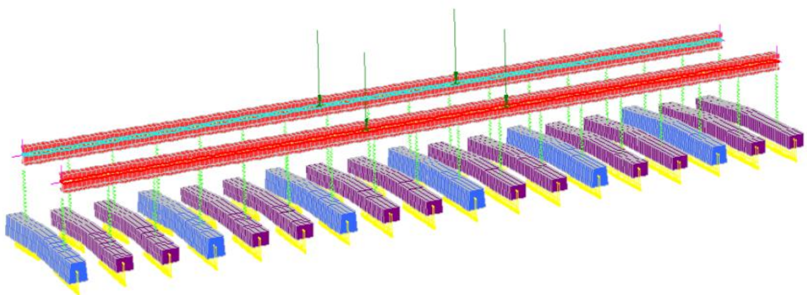

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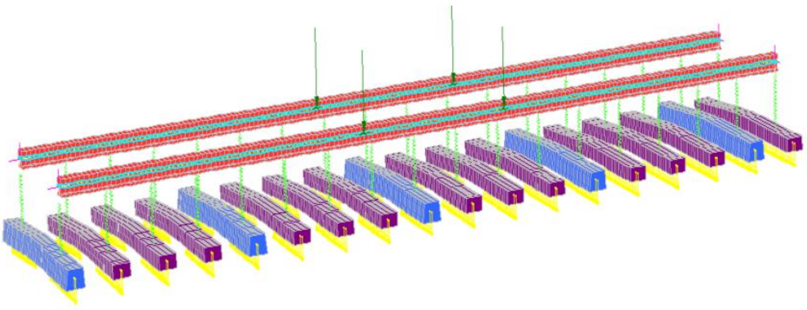


e)

Fig. 2. Railway track models: a) concrete track b) timber track c) “1 in 2” interspersed track d) “1 in 3” interspersed track e) “1 in 4” interspersed track.

2.2. Material properties

In this study, the material properties can be divided into two types based on the material assumptions. As for timber sleepers; rail pads and ballast, the material degradation models, based on time-dependent behavior, are taken into account independently over a 20-year period. Whereas, rail and concrete sleeper properties are assumed to be constant using the properties in Table 1. It should be noted that steel rails are in perfect condition since preventive rail grinding and maintenance are routinely conducted [38-39]. The concept of preventive rail grinding is to maintain the rail when damage is at the lower magnitude and to prevent the impact event generated at wheel-rail interface. Hence, the rails still perform in elastic limit. Concrete sleepers are used to replace the decomposed aged timber sleeper, thus, treated as the new replacement products on interspersed track.

Table 1 Material properties.

Parameters	Characteristic value	Unit
Rail (UIC60)		
Length, l_r	10.8	m
Gauge, g	1.5	m
Modulus, E_r	2e5	MPa
Poisson’s ratio, v_r	0.25	-
Density, d_r	7850	Kg/m^3
Concrete sleeper		
Length, l_s	2.5	m
Spacing, s	0.6	m
Modulus, E_s	3.75e4	MPa
Shear modulus, G_s	1.09e4	MPa
Density, d_r	2740	Kg/m^3

In term of timber sleepers, it should be noted that these sleepers typically deteriorate over time. The mass reduction of timber, due to the fungal degradation, is taken as an indicator in order to estimate the elasticity.

The Scots Pine is chosen as a type of timber sleepers. The modulus of elasticity was found to be decreased due to the gradual rise of the timber depreciation rate symbolized by its own quantity devaluation. It was observed that nearly half of the material stiffness is depreciated when the quantity of the Scots Pine is reduced by 40% and 20% from the decomposition reaction of “white rot fungus” and “brown-rot fungus” respectively [40]. Hence, elastic modulus of timber can be degraded over the time for “white rot fungus” according to Eq. (2).

$$Y=10324-124.2x \tag{2}$$

Where y is the elastic modulus (MPa) of the Scots Pine after fungal aggression,

x is the reduction of mass content (%) in the Scots Pine timber by white-rot fungus

It is assumed that, for year 0, the timber sleepers are completely new and in perfect condition so that the elastic modulus of timber sleeper is 10324 MPa which is in the acceptable range of elastic modulus of timber sleeper confirmed experiment [41-42]. It should be noted that timber sleeper has a service life between 15-20 years. Note that mass reduction content rate is assumed to be 20% every 5 years. Hence, at years 15-20 corresponding to the service of timber sleeper, the percentage of mass loss reduces the modulus of elasticity by about 70% while the bending and compression are significantly decreased comparted to modulus of elasticity [40]. Timber elasticity reduction over time is shown in Fig. 3.

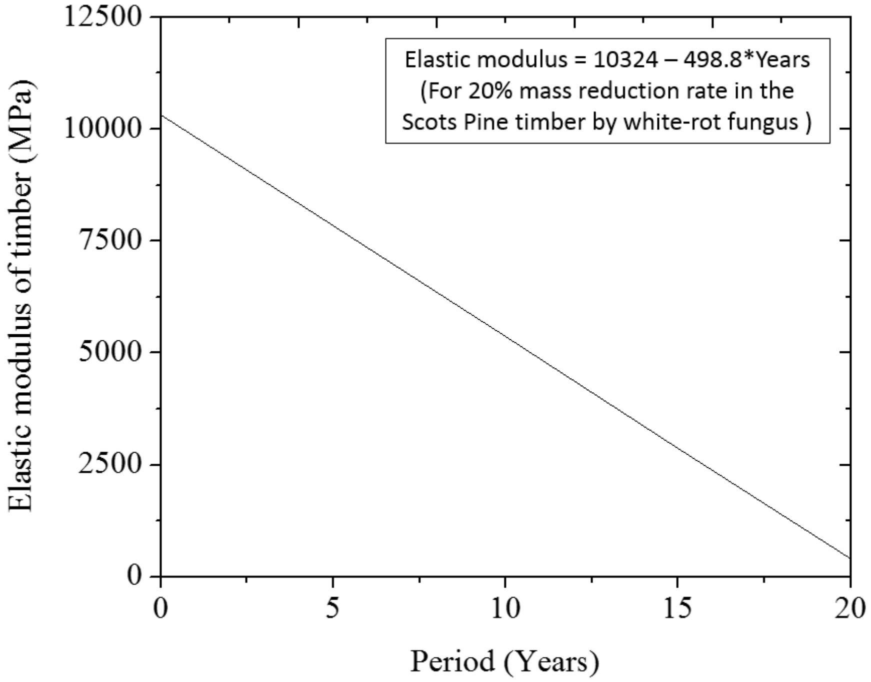


Fig. 3. Elastic modulus of timber sleepers.

According to previous studies, it is evident that deterioration rate of rail pads has significant influence on the dynamic properties that affect the dynamic responses of railway tracks [43-44]. The experimental techniques using instrumented hammer coupled with modal analysis have been developed in order to extract the dynamic characteristics of rail pad [45-46]. It is mentioned in the literature that the stiffness of HPDE (High Density Polyethylene) rail pads is in the range between 800-2500 MN/m [47]. In this study, the material degradation rate of an aged rail pad have been extracted from previous studies at different years in service [47-50]. It is assumed that the stiffness of new rail pads is 800MN/m and the deterioration rate is about 1.5% per year. The stiffness of HDPE rail pads used in this study is shown in Fig. 4. The comparison of deterioration rate is also presented as the slope of the stiffness over time. It is found that the deterioration rate of different types of railpad is between 1.5-2% per year according to previous experiments [45, 50]

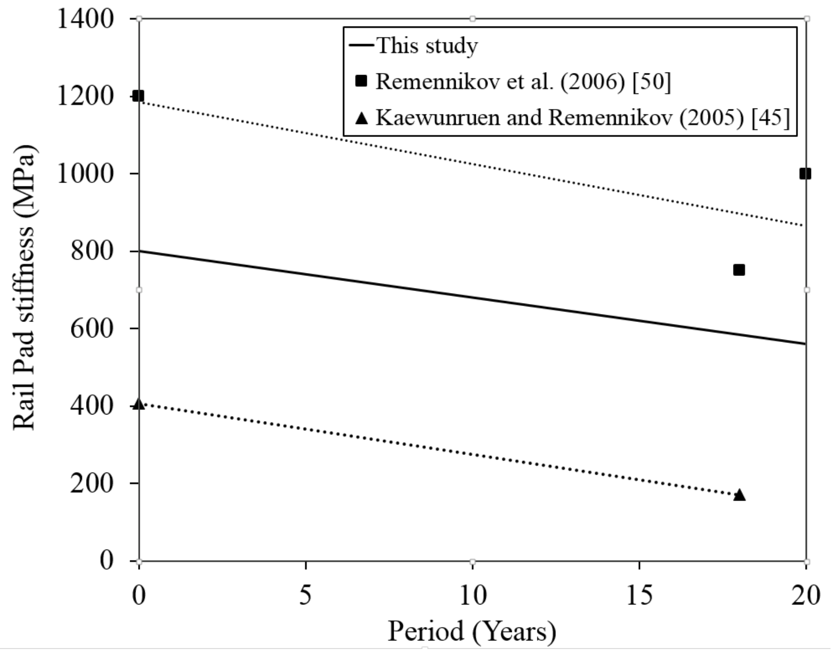


Fig. 4. Rail pad stiffness [48].

As for ballast, stone blowing, appropriate tamping, cleaning or reconditioning activities are conducted when the void contaminant index (VCI), or the amount of fine particles in the ballast layers, have reached over and above 40% [38, 51-52]. Generally, tamping, cleaning and reconditioning activities are executed between two to ten years of railway track service [53]. Stone blowing is one of the maintenance processes that can improve the quality of track (settlement, stiffness, ballast pressure etc.). It is noted that stone blowing can progressively increase the ballast stiffness [54]. Ballast tamping is an initial activity to restore track geometry and re-compact ballast [55]. However, during the improper tamping process, ballast particles can be damaged and broken due to the vibration [56-57]. Ballast cleaning is an activity undertaken when ballast is fouled to certain extent, but the flankiness of ballast remains functional [58]. Ballast reconditioning is an activity undertaken when the ballast layer is fully renewed due to significant deterioration and rounding [59]. Note that ballast and track stiffness can be either increased or decreased after ballast relevelling and reconditioning depending on the condition [60]. All ballast maintenance work requires track resurfacing activities (including stone blowing, tamping, regulating, and stabilization) to restore the track geometry and cross-track profile back to the design alignment [61]. In this study, the reconditioning period is assumed to improve track stiffness and be taken every 10 years and this is applied to every type of interspersed railway tracks in order to upgrade ballast condition. Thus, ballast reconditioning activities are taken at years 5 and 10. Ballast stiffness over time is shown in Fig. 5.

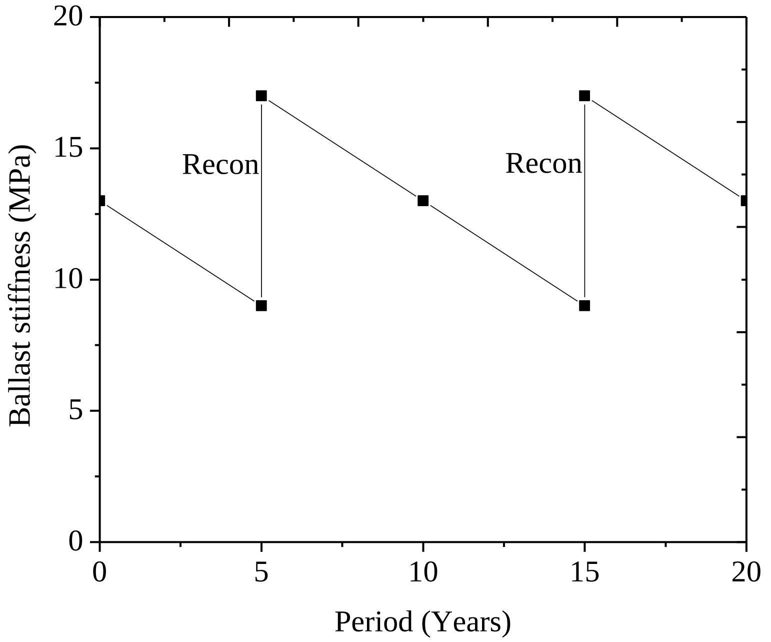


Fig. 5. Ballast stiffness.

2.3. Analysis positions

In this study, rail and sleeper displacements are monitored. Maximum rail displacements at both rail seat and mid span are analyzed. Rail uplifts are also captured at both frontal and rear positions of the sleeper. As for sleepers, the maximum displacement and uplift of timber and concrete sleepers of timber and interspersed track are presented. The overall analysis positions are shown in Fig 6. It should be noted that all of the data captured are from timber and concrete sleepers at bays 9 and 10, which are located at the middle of the track section (18 Bays). The dynamic response of timber track and interspersed track from years 0 to 20 under a train speed of 60 km/h are presented. Note that the applied speed is a common median speed for suburban rail network (i.e. on average from 40-50 km/hr in London, 50-55 km/hr in Tokyo, to 55-60 km/h in Sydney).

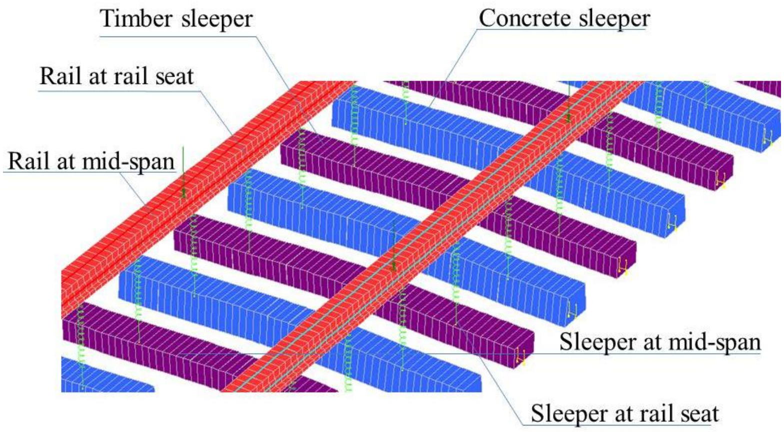
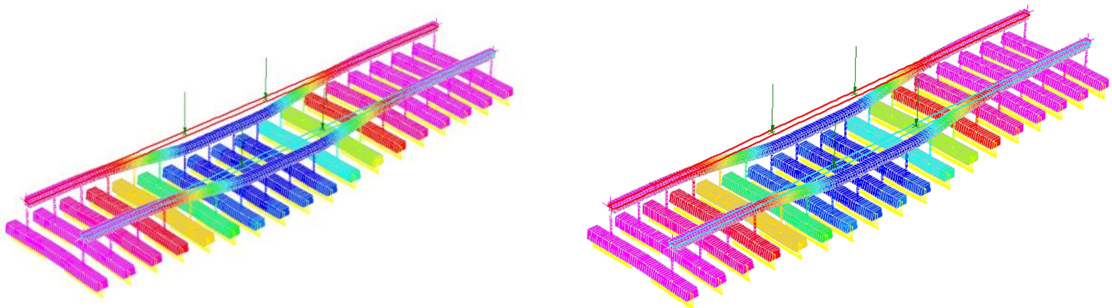


Fig. 6. Analysis positions of interspersed track.

3. Results and Discussion

3.1. Deflected shape of interspersed tracks

The deflected shapes of plain concrete, plain timber and interspersed tracks under the train speed of 60 km/h are presented in Fig. 7. It should be noted that displacement scale of 50 is applied. The deflected shapes, as shown in Fig. 7, illustrate that the railway tracks are excited in the dynamic flexural modes, which are commonly found. It is noted that the sleepers are normally damaged by localised flexural modes. The deflected shapes of each type have almost the same shapes from year 0 to 15. While, at year 20, the timber sleepers in all tracks seem to have higher displacements than concrete sleepers at rail seat and timbers are lifted up at mid span during the train passage. From the Fig. 7, it is clear that concrete sleepers are able to maintain its geometrical shape under train loading.



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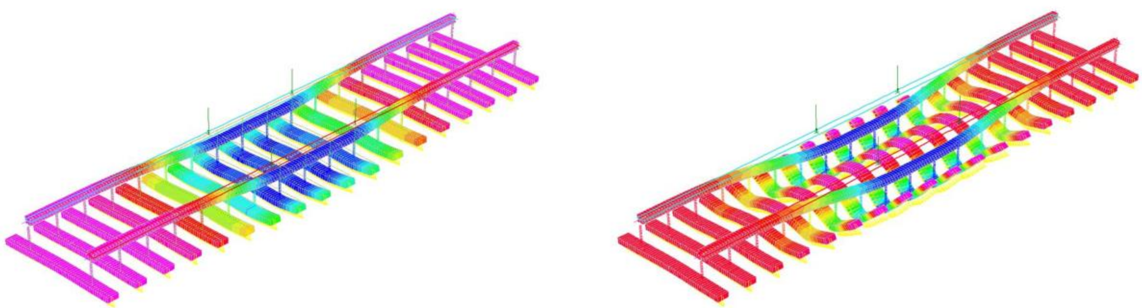

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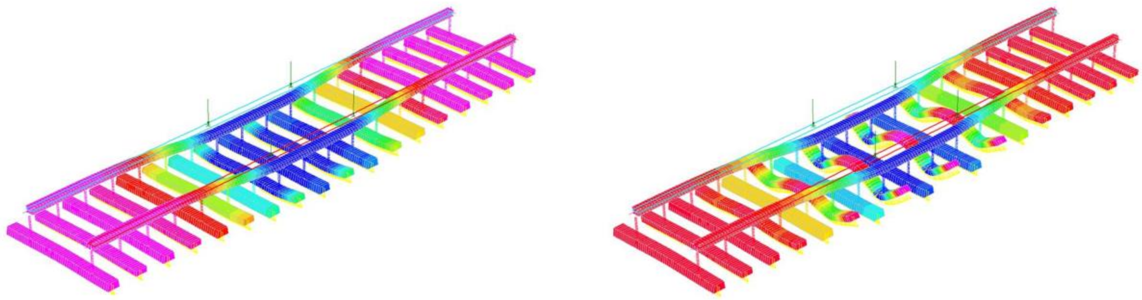

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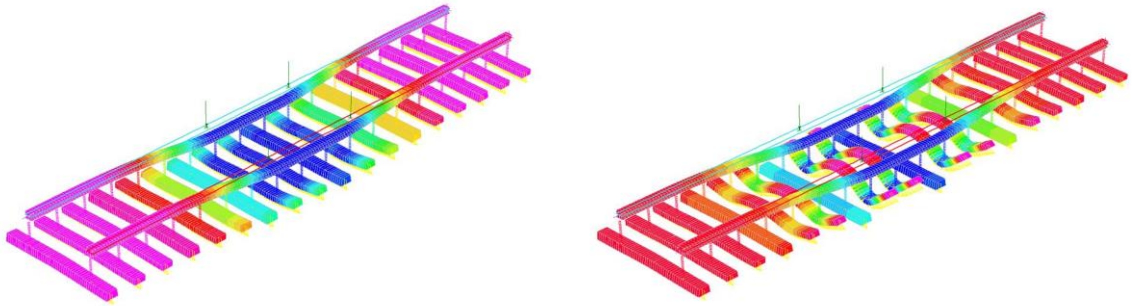

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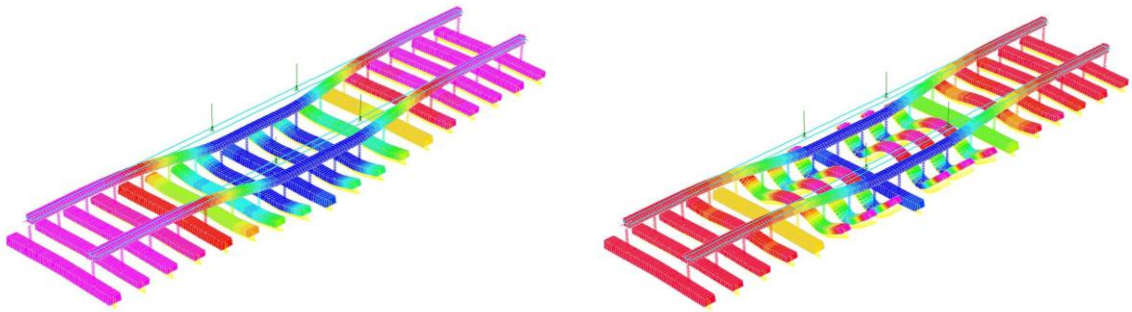


e)

Fig. 7. Deflected shapes at years 0-15 (left) and year 20 (right) of a) concrete track b) timber track c) “1 in 2” d) “1 in 3” e) “1 in 4” interspersed tracks.

3.2. Rail displacement

The effects of train velocity on the maximum responses of rails can be seen in Figure 8. Train speeds from 10 to 120 km/h have been investigated as shown in Figs. 8 and 9. It is clear that the train speed has a slight effect on maximum displacement on all tracks. At year 0, the interspersed track does not reflect the drawback on maximum rail displacement. However, at year 20, the maximum rail displacement of timber track is much greater than interspersed and concrete tracks. It is noted that “1 in 4” track has the highest rail displacement at both positions, followed by “1 in 3” and “1 in 2”, respectively. Moreover, maximum rail displacement responses of the rail are smallest in concrete sleepered tracks in all cases. In addition, it should be noted that uplift behaviour is normally observed in railway track, which can lead to higher track deterioration. Interestingly, train speed significantly affects the maximum uplift behaviour at both rail seat and mid-span. It is also interesting to note that lower interspersion ratios have higher uplift effect. Hence, the more timber is replaced by concrete, the more possibility of uplift movement. It should also be noted that uplift movements of rail lead to the upward displacements of the underlying sleepers.

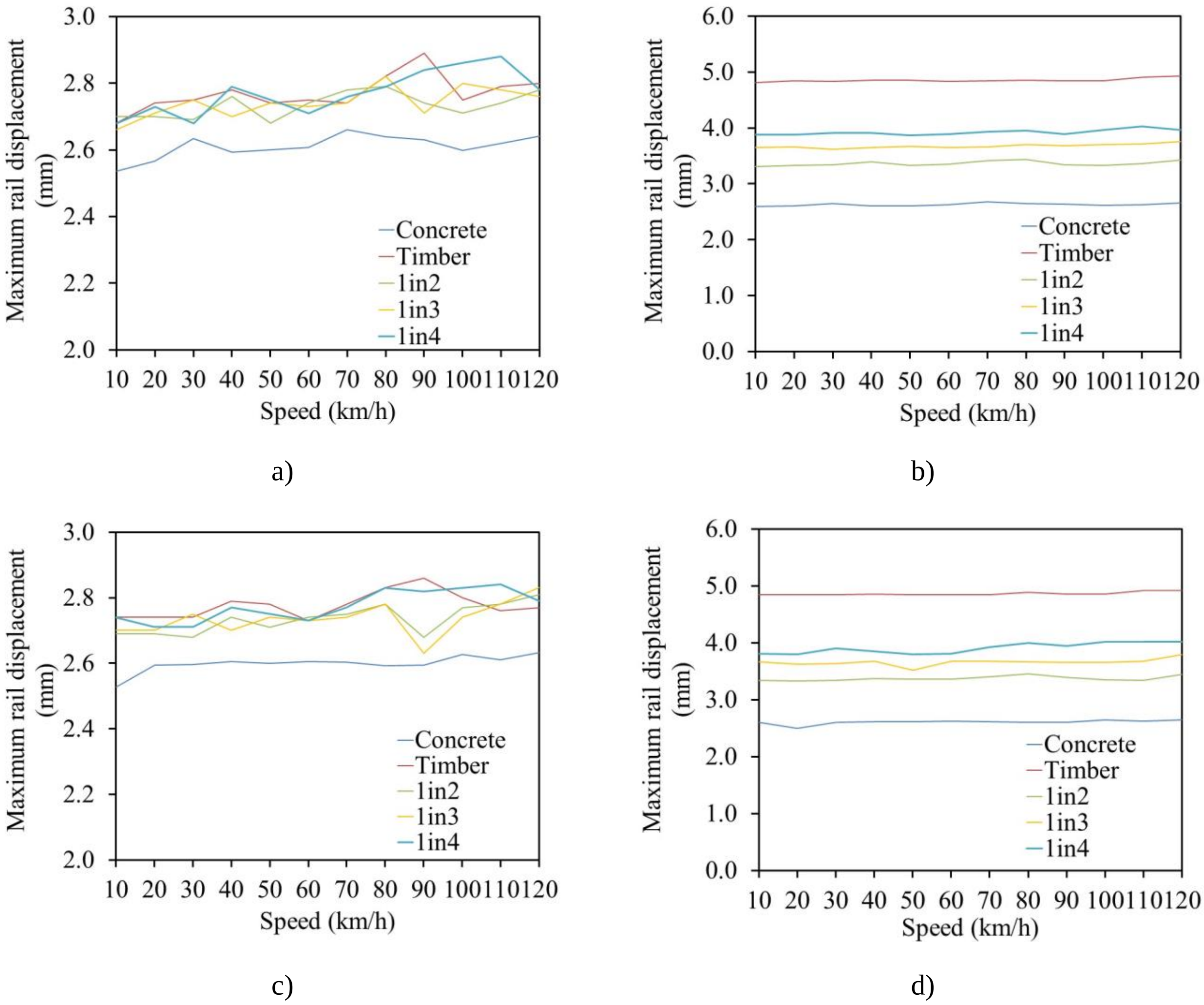
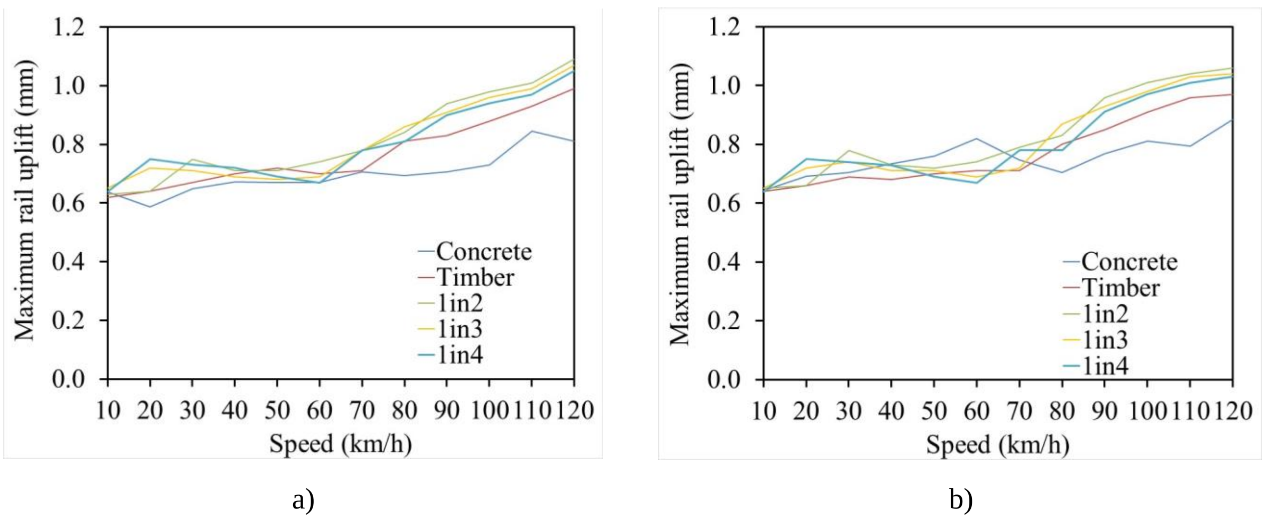
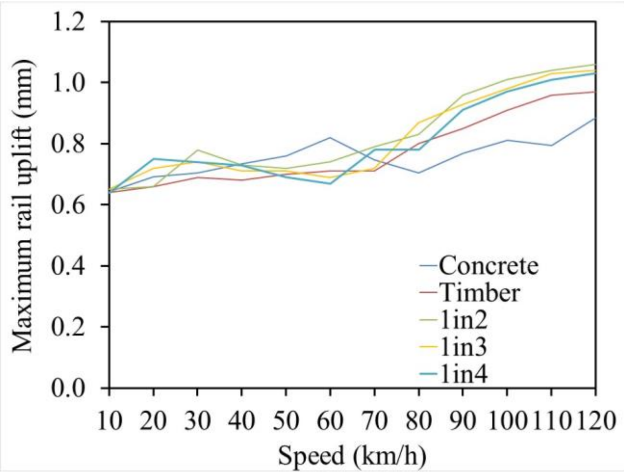


Fig. 8. Maximum rail displacement at rail seat: a) year 0 b) year 20; at mid-span: c) year 0 d) year 20.





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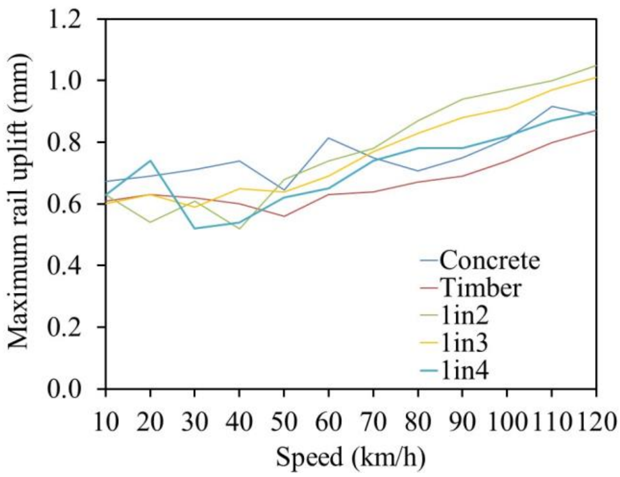

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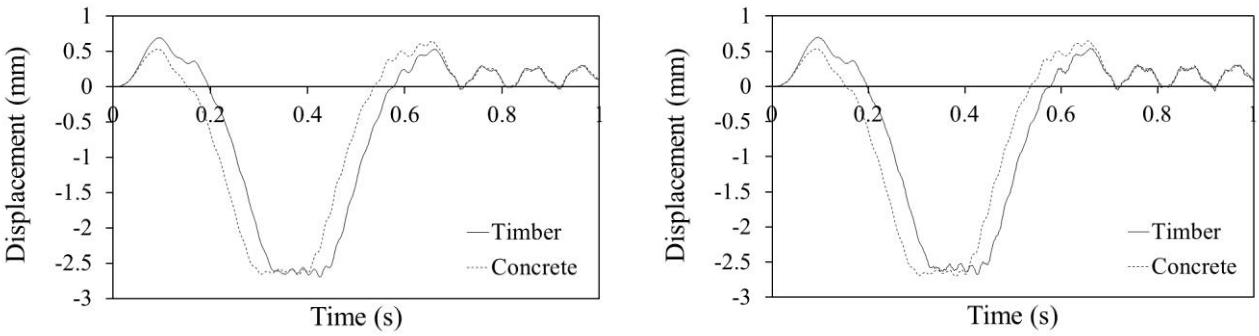
Fig. 9. Maximum rail uplift at rail seat: a) year 0 b) year 20; at mid-span: c) year 0 d) year 20.

3.3. Sleeper displacement

The time dependent responses of timber and interspersed tracks are presented. The analysis positions are the concrete sleeper and adjacent timber sleeper at mid track. The train speed of 60 km/h, which is a common median speed for suburban rail network, is taken into account. The sleeper displacements of new and aging interspersed tracks in time domain are presented in Figs. 10 and 11. It is clear that interspersed track can induce uplift movement on both timber and concrete sleepers. Interestingly, at year 20, for timber sleeper in all cases, sleepers tend to have self-vibration when the train passes.



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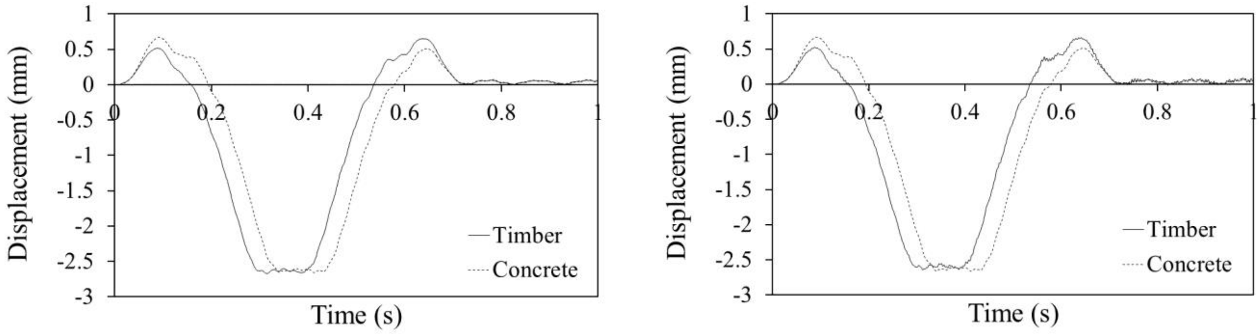

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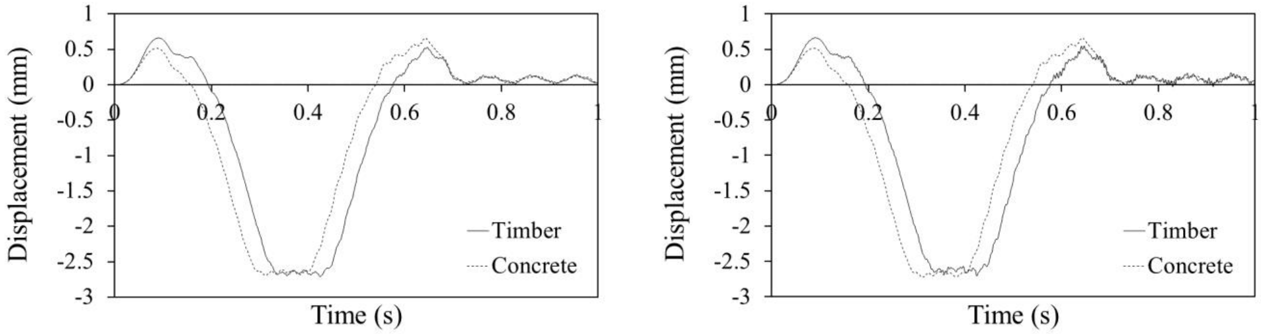

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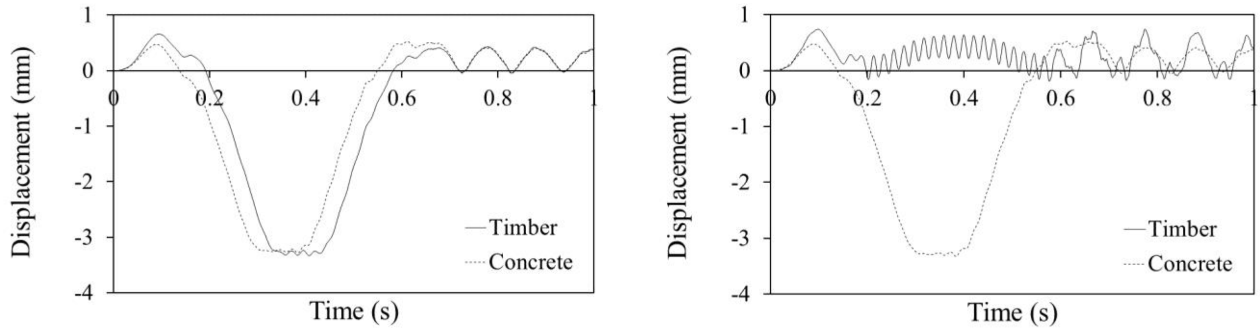
Fig. 10. Sleeper displacement at rail seat (left) and mid-span (right) of a) “1 in 2” b) “1 in 3” c) “1 in 4” interspersed track at year 0.



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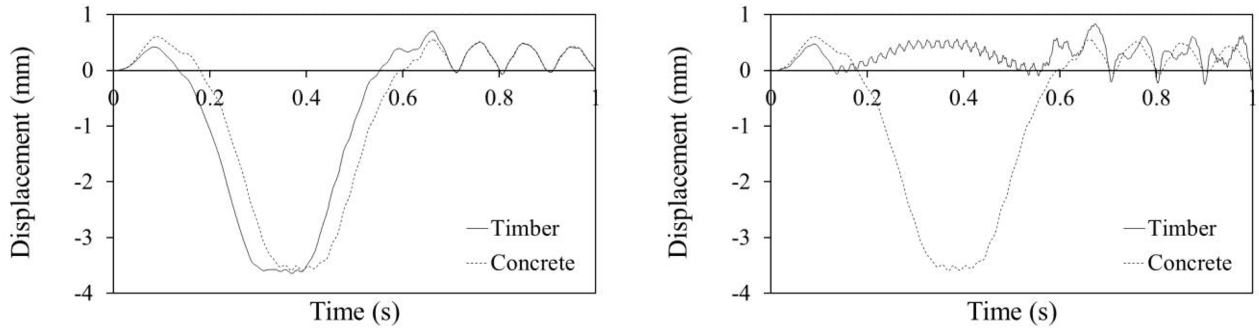

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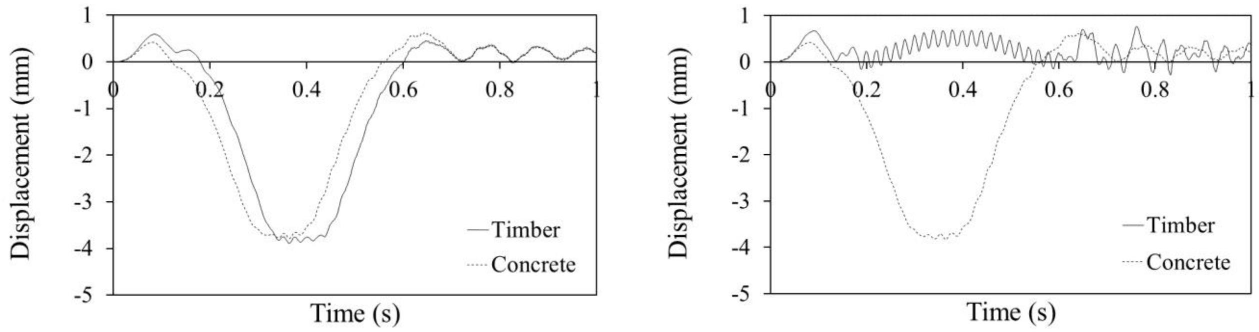

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Fig. 11. Sleeper displacement at rail seat (left) and mid-span (right) of a) “1 in 2” b) “1 in 3” c) “1 in 4” interspersed track at year 20.

Maximum sleeper displacement and uplift of timber and interspersed tracks with respect to train speed are demonstrated in Figs 12 and 13. Train speeds from 10 to 120 km/h have been investigated. The responses of both timber and concrete sleepers in interspersed tracks are presented and compared. It should be noted that the dot line means the concrete sleepers and the straight line means the timber sleeper in interspersed track. The responses are measured in the same track but different sleeper types.

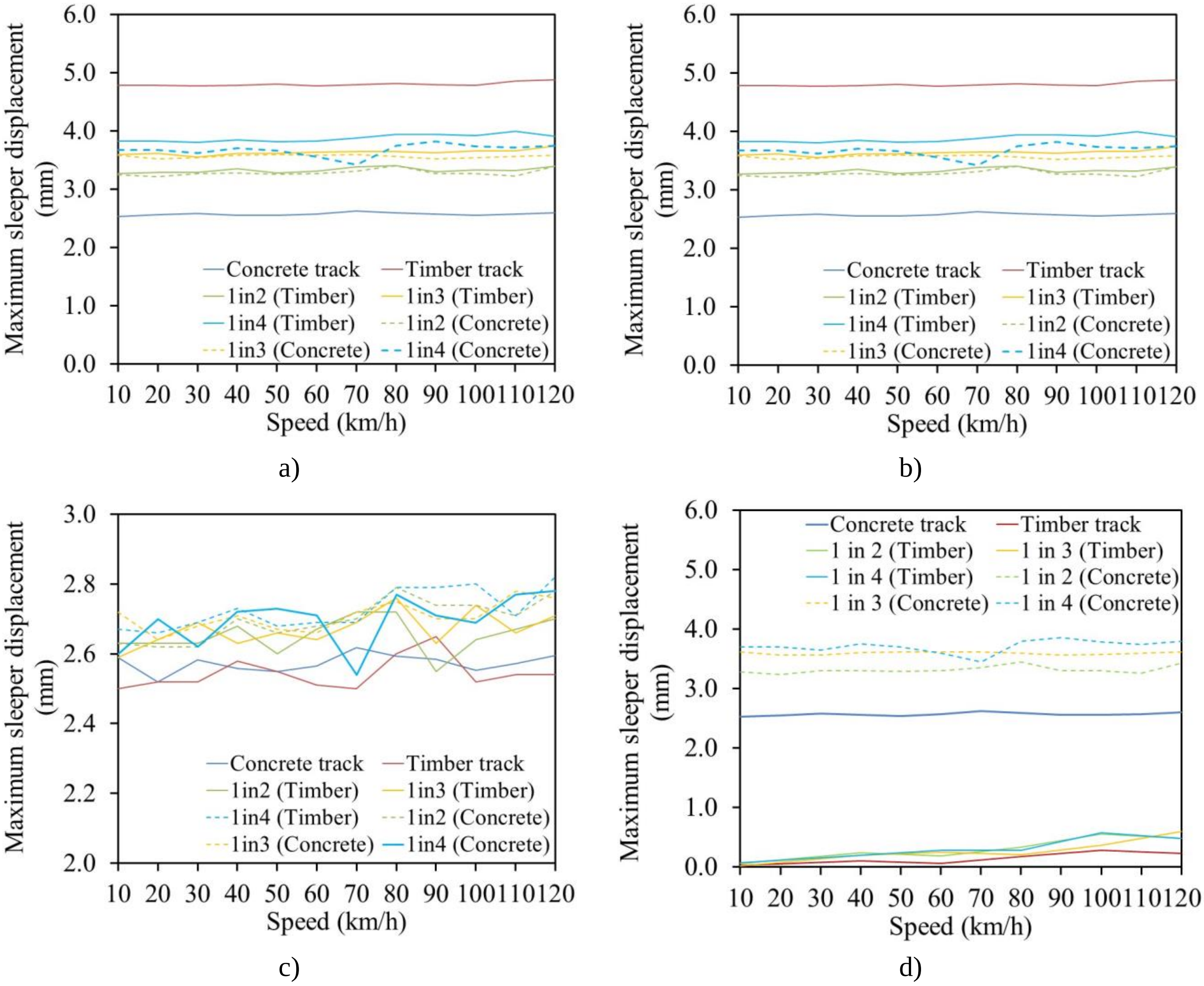


Fig. 12. Maximum sleeper displacement at rail seat: a) year 0 b) year 20; at mid-span: c) year 0 d) year 20.

Interestingly, for timber sleepers in all cases, the sleepers tend to lift up at mid span region so that the maximum displacements are very small due to the free vibrations after train passing. This behaviour is only observed at timber sleepers, while normal displacement and uplift behaviour was found for concrete sleepers. Timber sleepers within each of the interspersed tracks considered are believed to oscillate greatly, and these trends generally increase with increasing train speed. It is interesting to note that train speed significantly affect uplift movement rather than downward displacement. Hence, higher train speed is shown to be one of the influential factors that impairs the performance of the interspersed railway tracks over years.

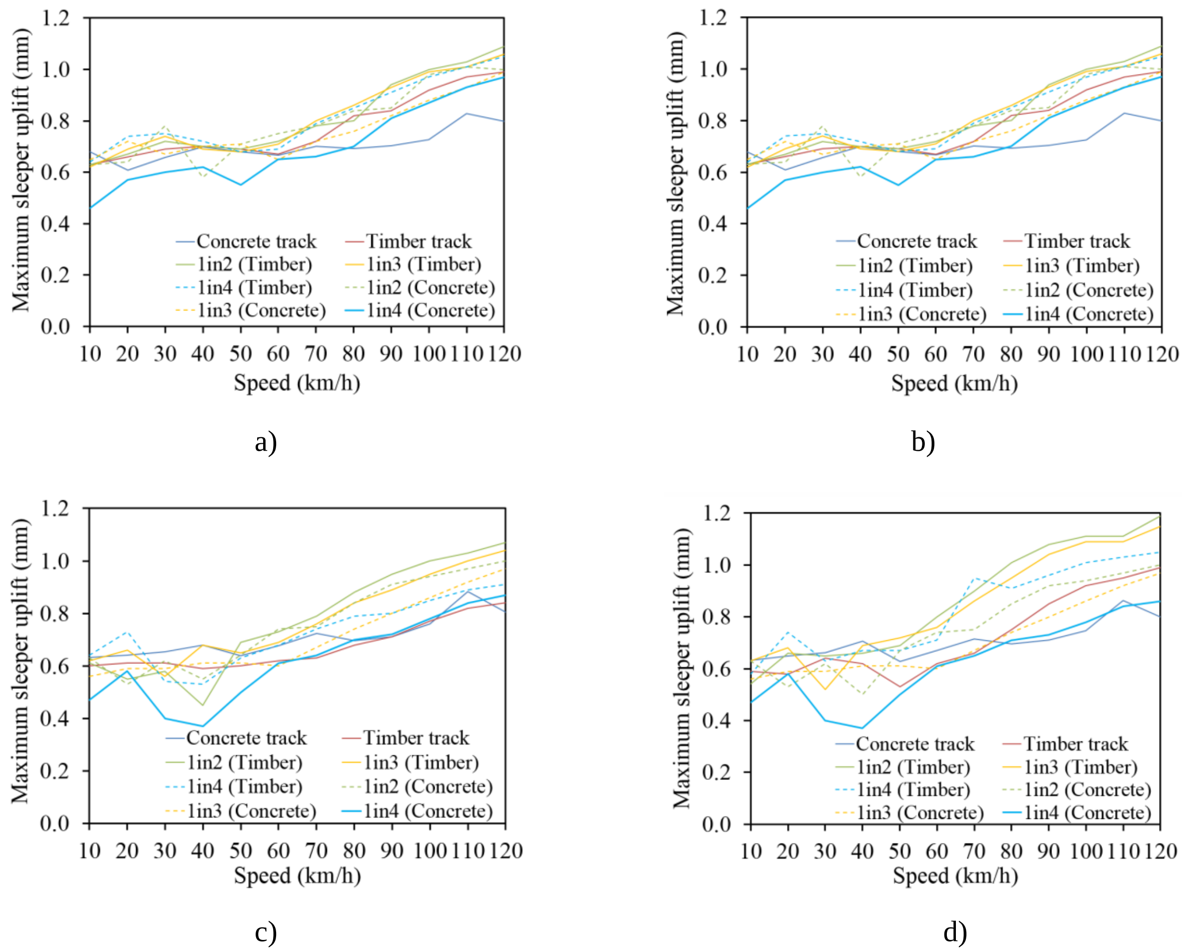
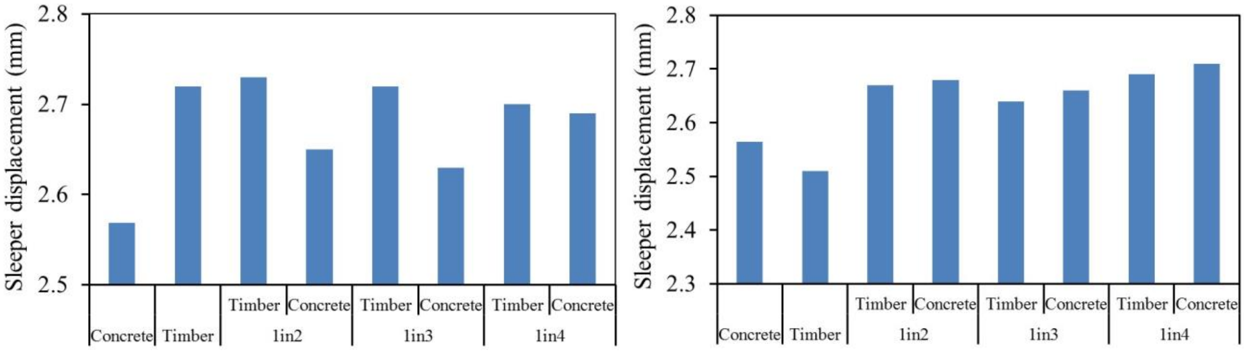
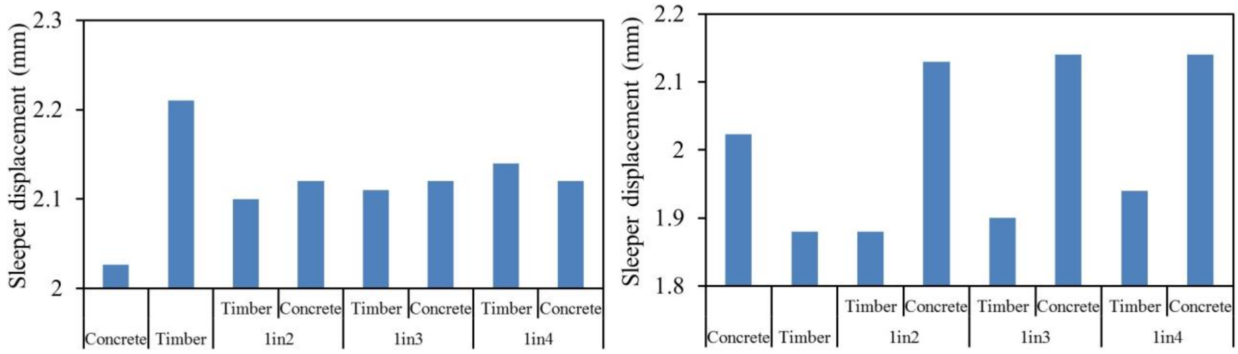


Fig. 13. Maximum sleeper uplift at rail seat: a) year 0 b) year 20; at mid-span: c) year 0 d) year 20.

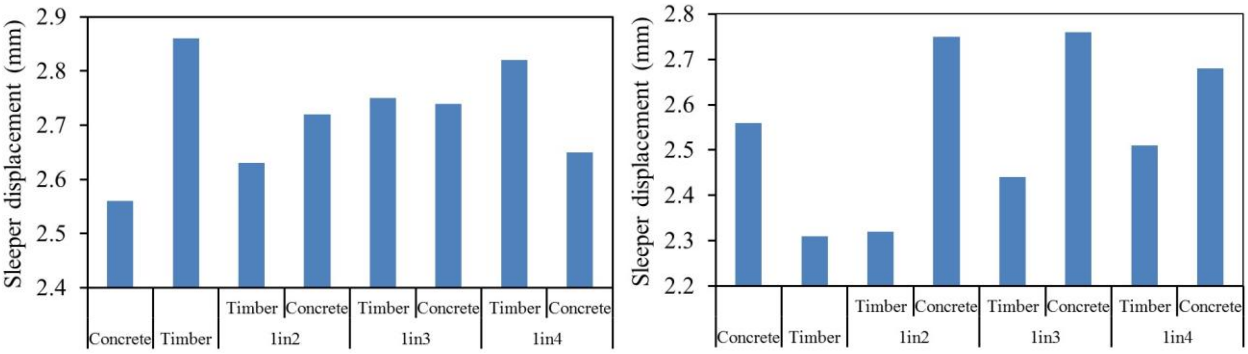
The maximum displacements of concrete and timber sleepers in concrete, timber and interspersed tracks over time are presented in Figs. 14 and 15. At year 0, sleeper displacement in all types of track are similar about the rail seat, while interspersed tracks have a slightly higher displacement at mid span. It is clear the pure concrete sleepered track has the lowest displacement at rail seat whereas, at mid span, concrete sleepers in both pure concrete and interspersed tracks tend to have larger displacement than timber sleepers. However, from years 5 to 20, at rail seat, timber sleepers in plain track have much higher displacement than both timber and concrete sleepers in interspersed tracks. On the other hand, at the mid-span, concrete sleepers in interspersed track have greater displacement than timber sleepers. Between year 0 and 15, however, the highest sleeper displacements are observed at year 10 because ballast reconditioning activities, which can help provide better support conditions, have taken place at years 5 and 15. It is interesting to note that at year 20, very aggressive displacements are observed at concrete sleepers in all interspersed tracks, while the timber sleeper displacement is very low due to the uplift effects on timber sleepers at mid-span. It should be noted that the timber displacements observed at mid-span are due to the free vibration effects. About 5 mm and 3-4 mm displacements are observed for timber and interspersed tracks, respectively.


Sleeper displacement (mm)
2.5
2.6
2.7
2.8
Timber
Concrete
Concrete
Timber
1in2
1in3
1in4
Sleeper displacement (mm)
2.3
2.4
2.5
2.6
2.7
2.8

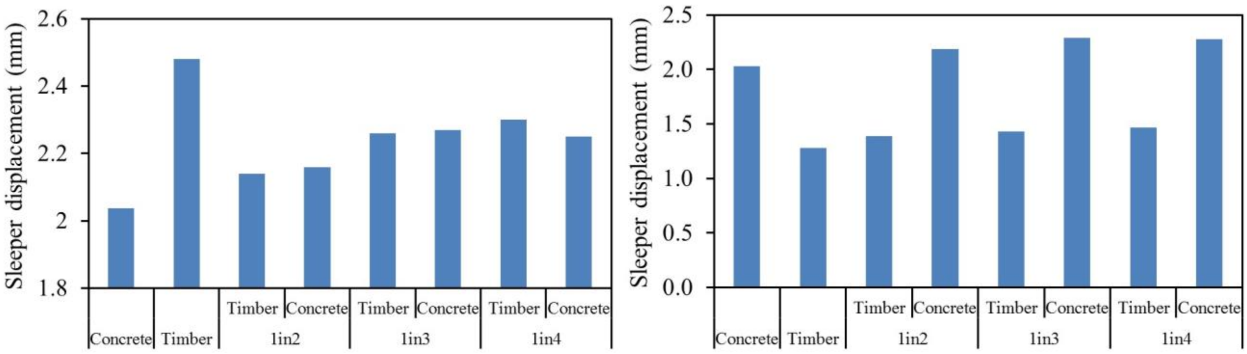
a)


Sleeper displacement (mm)
2
2.1
2.2
2.3
Timber
Concrete
Concrete
Timber
1in2
1in3
1in4
Sleeper displacement (mm)
1.8
1.9
2
2.1
2.2

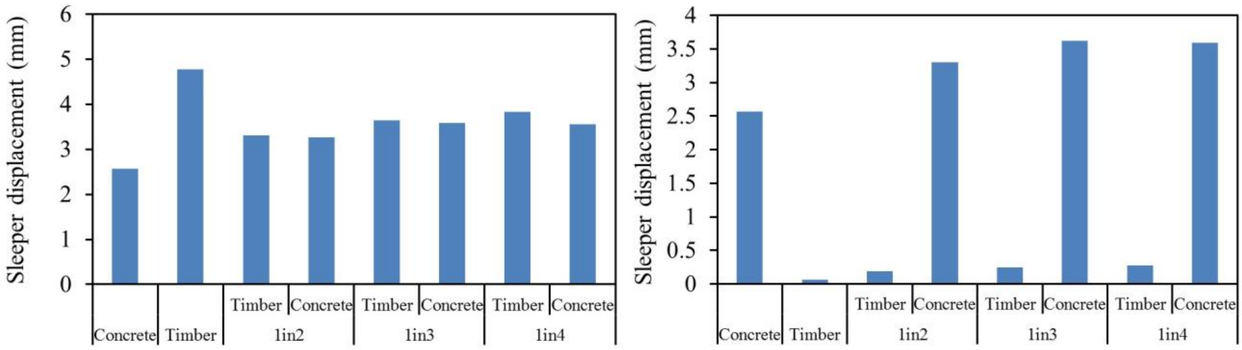
b)


Sleeper displacement (mm)
2.4
2.5
2.6
2.7
2.8
2.9
Timber
Concrete
Concrete
Timber
1in2
1in3
1in4
Sleeper displacement (mm)
2.2
2.3
2.4
2.5
2.6
2.7
2.8

c)


Sleeper displacement (mm)
1.8
2
2.2
2.4
2.6
Timber
Concrete
Concrete
Timber
1in2
1in3
1in4
Sleeper displacement (mm)
0.0
0.5
1.0
1.5
2.0
2.5

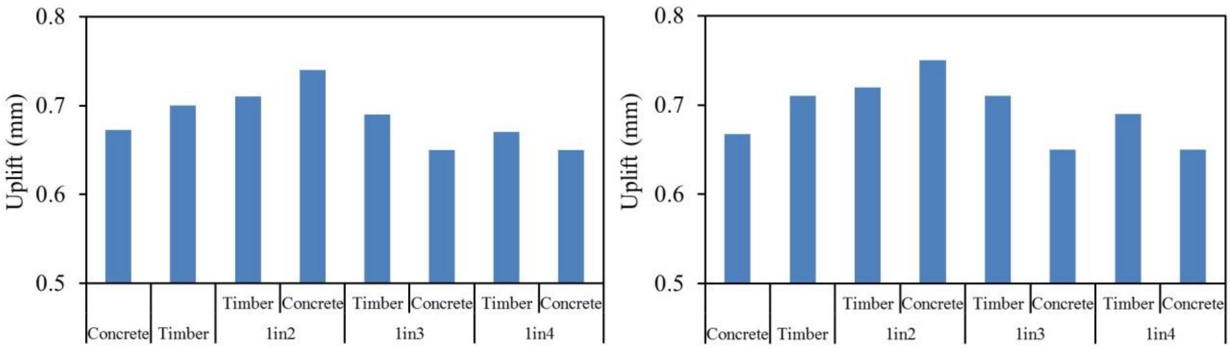
d)



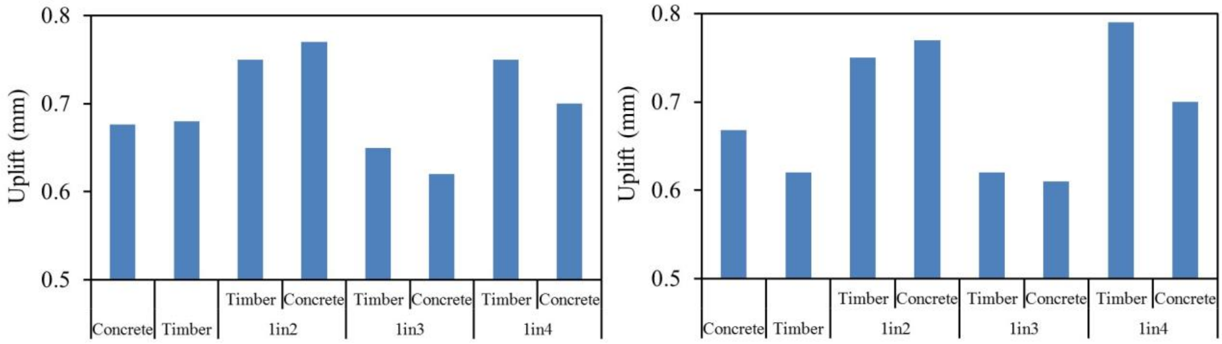
e)

Fig. 14. Sleeper dynamic displacement at rail seat (left) and mid-span (right) at a) year 0 b) year 5 c) year 10 d) year 15 e) year 20.

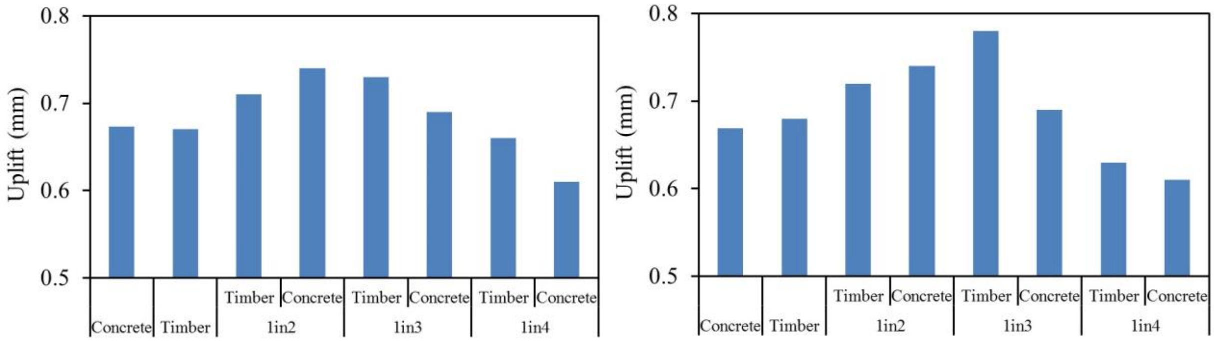
Fig. 15 presents the uplift displacement of concrete, timber and interspersed tracks at both rail seat and mid span at different years in service. Similarly, the interspersed track can experience higher uplift movement than plain concrete and timber tracks. This is due to the uplift movement of the rail as can be seen in previous section. It can be concluded that sleeper uplift movement relates to rail uplift behaviour when the train runs past a specific location. In general, it is noted that “1 in 2” interspersed track tends to have higher uplift displacement than “1 in 3” and “1 in 4” from years 0 to 20. Overall, at years 10 and 20, the uplift behaviour of interspersed track is much greater than that at other periods. It is very clear that interspersed track induces uplift due to the negative or hogging bending moment. Hence, ballast reconditioning can help provide significantly better support condition in order to tackle uplift behaviour. This is a serious issue in interspersed track as this effect could accelerate long-term railway track deterioration. It can be concluded that an increase of ballast stiffness by reconstruction should be carried out over the service life to reduce sleeper displacement and uplift movement. Thus, the replacement of ageing timber sleepers by concrete sleepers should be very careful.



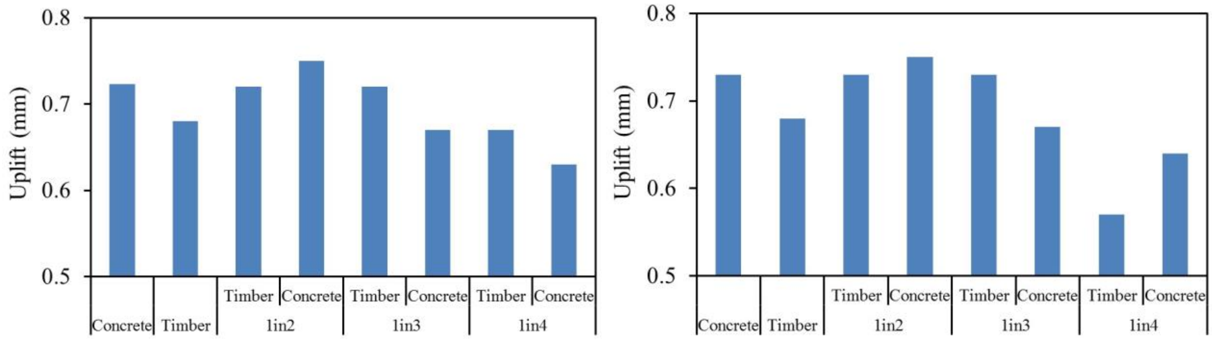
a)



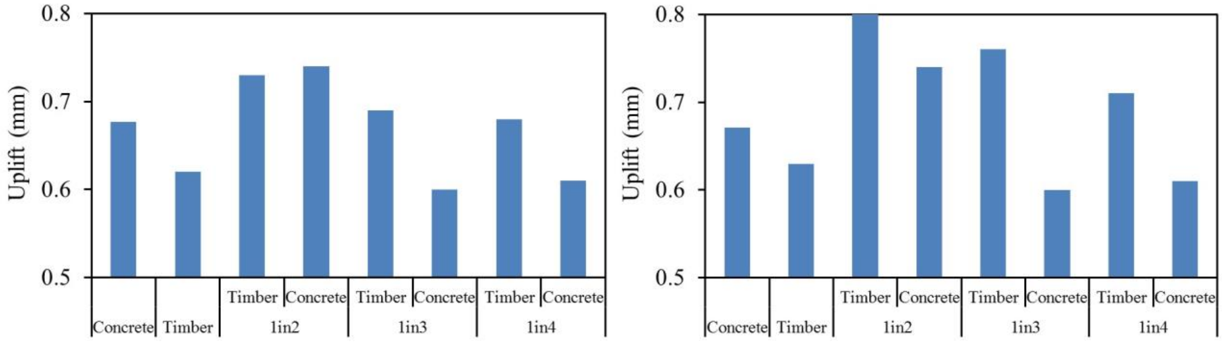
b)



c)



d)



e)

Fig. 15. Sleeper uplift at rail seat (left) and mid-span (right) at a) year 0 b) year 5 c) year 10 d) year 15 e) year 20.

4. Conclusions

This study presents the nonlinear finite element modelling of plain timber and interspersed tracks. Material degradation factors of timber sleepers, rail pads, and ballast are taken into account from new track to aging tracks. From the numerical results, spot replacement of sleepers or interspersed tracks can deteriorate relatively faster than open-face tracks resulting in amplified vertical vibrations and uplift displacements of railway sleepers. The sagging and hogging behavior of sleeper component could then be exacerbated by the dynamic response of interspersed tracks. Train speed also plays a minor role on downward displacement, but play a significant role on uplift movement of interspersed track. In fact, the relative uplift response of sleepers cause faster track deteriorations due to mud pumping, ballast pulverization and ballast dilation. According to obtained results, aging interspersed tracks are severely lifted up especially at year 20. Note that interspersed “1 in 2” track has a worst performance as the maximum uplift occurred. It is interesting to note that the uplift behaviour at mid span can significantly accelerate the center-bound problem as the negative bending moment occurs which lead to the structural crack on top of the sleeper. It is suggested that ballast reconditioning should be undertaken to restore track geometry and re-compact ballast as the aggressive dynamic responses are observed at year 20 while reconditioning, stone blowing and appropriate tamping have just been done 5 years ago. This is due to the fact that the deterioration rate of timber also induces higher displacement. It can be concluded that the replacement of timber sleepers by concrete sleepers induce track stiffness inconsistency which tends to increase deterioration rate of railway track. The insight into this practice will help track engineers undertake truly predictive track maintenance, enhance smarter track inspection regimes, and improve reliability of infrastructure assets in uncertain settings. Moreover, this will help track engineers make a better decisions regarding spot replacement of aging timber sleepers in order to minimize the long-term deterioration.

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