Effects of under sleeper pads on dynamic responses of railway prestressed concrete sleepers subjected to high intensity impact loads

Ngamkhanong, Chayut; Kaewunruen, Sakdirat

DOI:
10.1016/j.engstruct.2020.110604

Document Version
Peer reviewed version

Citation for published version (Harvard):
Ngamkhanong, C & Kaewunruen, S 2020, 'Effects of under sleeper pads on dynamic responses of railway prestressed concrete sleepers subjected to high intensity impact loads', *Engineering Structures*, vol. 214, 110604. https://doi.org/10.1016/j.engstruct.2020.110604

Effects of Under Sleeper Pads on Dynamic Responses of Railway Prestressed Concrete Sleepers Subjected to High Intensity Impact Loads

Chayut Ngamkhanong[1,2], Sakdirat Kaewunruen[1,2]

[1]Department of Civil Engineering, School of Engineering, University of Birmingham, Birmingham B152TT, United Kingdom

[2]Birmingham Centre for Railway Research and Education, School of Engineering, University of Birmingham, Birmingham B152TT, United Kingdom

Abstract

Subjected to operational uncertainties, the investment in railway infrastructure is growing to improve track resilience, to mitigate long-term consequences, prolong the track service life, and reduce unplanned maintenance costs and carbon footprint. Under sleeper pads (USPs) have been widely used in many countries as a resilient component placed underneath the concrete sleepers. However, it is well-known that, with any imperfection of either wheel or rail, railway tracks usually are subjected to impact loading conditions. Accordingly, the application of USPs to mitigate the detrimental impact load consequences on track structure is unprecedentedly highlighted in this paper. Despite the common uses of USPs in various countries in Europe, the dynamic behaviour of the USPs under high-intensity impact loading has not been fully investigated. Note that this study focuses not only on serviceability condition but also an extreme condition which can occur when there are coupled effects of short and long wavelength defects (e.g. dipped rail joint coupled with track settlement). This paper thus presents a 3D finite element model of prestressed concrete sleepers with USPs, using LS-Dyna. This study has confirmed field measurement data that the sleepers with USPs tend to have lesser flexures, contact force and impact energy. However, this study also firstly reveals that the vibration of sleeper with USPs could be amplified by the large amplitude impact force, which can be induced especially when excited by a high-speed train travelling over short-pitch rail defects, rail joints, coupled defects or crossings. It is also interesting to note that a very stiff pad with a bedding modulus of 1 N/mm^3 can be alternatively used as USP as recommended by the results obtained. Based on both numerical and field measurement data, it is implied that the applications of USPs should be very carefully considered since the USPs could trade off the desired benefits by aggravating dynamic behaviour of sleepers with USPs. The new insights will help track engineers to make decision on the design and usage of USP

Keywords: Under sleeper pad; resilient material; dynamic response; impact loading; prestressed concrete sleeper.

1 Introduction

At present, there are many types of resilient materials used in railway system such as rail pads, under ballast mats (UBM), under sleeper pads (USP) etc. in order to provide and improve track resiliency. USPs, which are commonly made of polyurethane elastomer with a foam structure including encapsulated air voids, are resilient pads installed underneath the sleepers to provide additional track resiliency between the sleepers and ballast. It should be noted that railway sleepers are safety-critical components in railway system [1-4]. The typical ballasted railway track with USP is shown in Fig. 1. USPs are often used in ballasted tracks with concrete sleepers. USPs can also be applied in various operational environments such as conventional main lines, urban or high-speed lines or light rail and metro lines. Nowadays, USPs have been developed and used widely and heavily in central Europe such as in Austria, Czech Republic and Germany. Additionally, several counties have carried out pilot trials such as in Sweden, Australia, and China. USPs can be classified by the bedding modulus (C: N/mm^3) as very soft, soft, medium stiff and stiff USPs [5-11]. It is noted that bedding modulus is calculated from the force or pressure per unit deflection under a uniaxial load. It should be noted that only stiff and medium stiff have been used in practice for heavy rail and light rail, respectively [12]. Different types of USPs can be used at different locations and for different purposes, as described in Table 1.

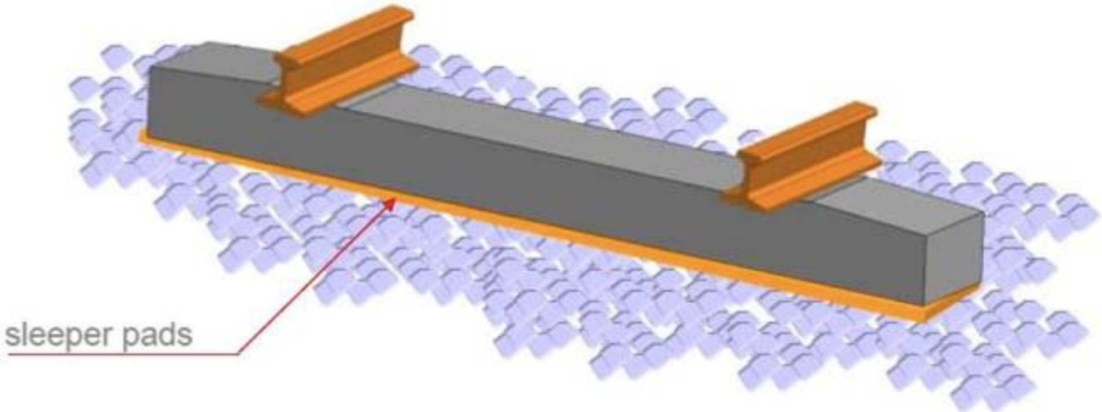


Fig. 1. Typical ballasted railway track and its components with USP [12].

Table 1. USP applications and characterisations [12].

Fields of application of USP	USP			
	Very soft $C_{stat} \le 0.10$	Soft $0.10 < C_{stat} \le 0.15$	Medium stiff $0.15 < C_{stat} \le 0.25$	Stiff $0.25 < C_{stat} \le 0.35$
Improve track quality (reduce ballast breakage and track/turnout pressure)			✓	✓
Transition zones			✓	✓
On existing structures with reduced ballast thickness			✓	✓
Reduction of long-pitch low-rail corrugation in tight curves			✓	✓
Reduction of ground-borne vibration		✓	✓	

The main objectives for using USPs are to moderate track stiffness, to reduce ground-borne vibrations, and to reduce ballast breakage [13-17]. USPs could reduce track stiffness in special areas such as turnout systems (switches and crossings), rail joints, or bridge transitions. The vibration of sleepers could also be isolated by the USPs so that the ballast and formation are uncoupled from the wheel/rail interaction, reducing the ground vibrations affecting surrounding areas and structures. The reduced ballast damage is accomplished by a reduction of contact pressure and thus wears, in the sleeper/ballast interface [18-20]. More uniform load distribution is achieved using USPs, resulting in the reduction of the contact pressure and the smaller variations of support stiffness along the track. It is also noted that USPs can lead to higher railway track economic values and to have substantial wider social benefits [19-25] as USPs can significantly reduce the overall maintenance cost over the long-term period.

An application of USPs was initially trailed back in 1980s on open plain tracks. USPs have been applied in ballasted track as seen in many countries and there were field inspections on the performance of ballasted track with USPs under train operation [26-32]. The outcome showed little improvement at the time whilst the delamination and degradation of the USPs material were the key negative issues found in the field. In recent years, the performance of the USPs has been improved through the outcomes from the test results in central Europe and in Austria, which showed a promising quality and durability of USPs. Despite the benefits of USPs have been presented [30], contradict outcome has been reported by Trafikverkets (Swedish Transport Administration). After several years of field inspections and observations, Trafikverkets reported that there has been no or very little influence of USPs on ballast size reduction and contamination resulting in track quality [34]. This could be a reason why the utilisation of USPs is not significant globally. Moreover, The USPs have different effects on lateral track resistance. It cannot be confirmed whether positive or negative effects will occur at this stage. However, it has been seen that vertical acceleration of sleepers may increase after using USPs especially when the aggressive load is exposed [35]. Hence, it is possible that USPs can lead to excessive sleeper vibration, resulting in ballast dilation or ballast spreading. In general, a railway track often experiences impact loading, which is a shock load applied in short duration [2, 35]. The use of USPs for attenuating impact load and excessive vibration has been studied in the fields at specific locations such as dipped rails/welds, glue insulated joint etc [37-45]. However, the numerical studies into such behaviour have been limited and not fully investigated.

The dynamic responses of railway concrete sleepers with USPs to high-intensity impact loading conditions are presented in this study. It should be noted that the impact load can be induced by Wheel/rail irregularities that greatly exceed the static wheel load. In this study, higher than 1000kN impact load is applied to the system in order to study the performance of USP not only under serviceability but also extreme condition. It should be noted that previous works using finite element modelling on train-track interaction have been studied considering serviceability conditions [46-47]. As for high-intensity impact loading conditions, wheel/rail contact force could be amplified up to 1000 kN when there were coupling effects of dipped rail joint and differential track settlement [48]. It was also noticeable that coupling effects created a higher impact force as the wheel momentarily lost contact longer. It was found that dynamic impact factor can be up to 7 when a settlement depth of 100 mm with 3m settlement length (long wavelength defect) coupled with dipped rail joint of 10 mm in depth (short wavelength defect) [48]. A three-dimensional finite element model has been established that can simulate and predict the dynamic responses of reinforced and prestressed concrete members. A three-dimensional nonlinear finite element model of a full-scale railway prestressed concrete sleeper for static analysis was firstly developed using the general-purpose finite element analysis package, ANSYS [49-52]. The static finite element model has been validated by the static full-scale experiment. The experimental details were based on the Australian Standard [53-54]. The calibrated finite element model has been extended to include ballast support and in situ boundary conditions [55]. The extended model was linked to LS-Dyna for impact analysis. The impact analysis has been validated against the drop impact tests [52, 56]. The initial velocities of drop mass corresponding to actual train load were applied to the rail. These can generate different impact events. This study will focus on the sensitivity of impact loads to the dynamic responses of prestressed concrete sleepers and ballast with USP. The dynamic responses including von Mises stress, maximum displacements and accelerations of concrete sleepers with and without USP are highlighted. Moreover, ballast contact pressure and distribution are investigated. The numerical results are then compared with field measurement data at Austimer (Illawarra Line in NSW Australia). This study will help track engineers to consider using USPs as an insertion element in railway track.

2 Finite Element Modelling

Firstly, the general-purpose finite element analysis package, ANSYS was used to develop and model a three-dimensional finite element model of a full-scale railway prestressed concrete sleeper for static analysis. The dimensions of Austrak broad gauge sleeper are shown in Table 2. Note that the rail gauge length is normally measured between the inner faces of the load-bearing rails. Concrete was modelled using SOLID65 solid elements where each node has three degrees of freedom (translation in x, y and z). The modulus of elasticity of concrete was estimated based on AS3600 [57] using the compressive strengths of 80 MPa (f'_c). As for prestressing wire, LINK8 truss element was considered to withstand the initial strain attributed to prestressing forces, by assuming a perfect bond between these elements and concrete. It should be noted that this truss element cannot resist neither bending moments nor shear forces. Since bond-slip was hardly observed under failure modes [56, 58-60], the perfect bond between pre-stressing wires and concrete was assumed. The 0.2% proof stress is 1,700 MPa and the ultimate stress is 1,930 MPa. The static and dynamic moduli of elasticity of pre-stressing wire are 190,000 MPa. Note that sleeper is fully supported by USP. Moreover, based on Australian standard [54], the use of polymeric materials as an alternative support procedure can represent the real ballast to equally distribute the pressure underneath sleeper. In this study, the ballast is reasonably represented by 6-layer rubber mat which has been proven to be an alternative method to replicate ballast bed. It was clearly shown that the natural frequencies and corresponding mode shapes of track with ballast bed and 6-layer rubber mat were mutually consistent [61].

For USP, the bedding modulus is normally calculated by the relationship between surface pressure (N/mm^2) and deflection (mm). Note that the classification of USP depends on the thickness and elastic modulus. Thus, the elastic modulus of USP is the bedding modulus multiplied by its thickness. In this study, the 10 mm USPs are used for all types so that the elastic modulus of each type is different depending on the bedding modulus.

The properties of materials are shown in Table 3. In this model, support condition is constrained in the vertical direction at the bottom surface of ballast. The contacts between each element are modelled using *CONTACT_AUTOMATIC_SURFACE_TO_SURFACE which is a contact algorithm establishing contact when one surface penetrates on another surface. This contact algorithm provides more accurate results when coarse mesh is defined. As the contact between concrete and prestressing wires is a perfect bond, shared node method is used to constraint this contact. It should be noted that mesh sizes between 20 and 50mm are considered for sleeper depending on the location and these sizes have been proven to be the proper sizes for analysis.

Table 2. Sleeper dimension (Austrack Broad Gauge Sleeper)

		At rail seat (mm)	At mid-span (mm)

Gauge length	Total length	Top width	Bottom width	depth	Top width	Bottom width	Depth
160	2.695	224	250	210	224	250	180

Table 3. Material properties.

Parameter		Characteristic value	Unit
Rail (UIC60)			
Modulus, E_r		2×10^5	MPa
Poisson's ratio, v_r		0.25	-
Density, d_r		7850	kg/m^3
Concrete sleeper			
Modulus, E_s		3.8×10^4	MPa
Poisson's ratio, v_r		0.2	-
Density, d_r		2400	kg/m^3
HDPE rail pad			
Modulus, E_r		1250	MPa
Poisson's ratio, v_r		0.42	-
Density, d_r		8960	kg/m^3
Under sleeper pad			
Thickness		10	mm
Poisson's ratio, v_r		0.45	-
Density, d_r		1100	kg/m^3
Bedding modulus, C	Soft	0.15	N/mm^3
	Medium stiff	0.25	
	Stiff	0.35	
	Very stiff	1.00	
Rubber mat			
Thickness		60	mm
Modulus, E_s		250	MPa
Poisson's ratio, v_r		0.45	-
Density, d_r		1100	kg/m^3

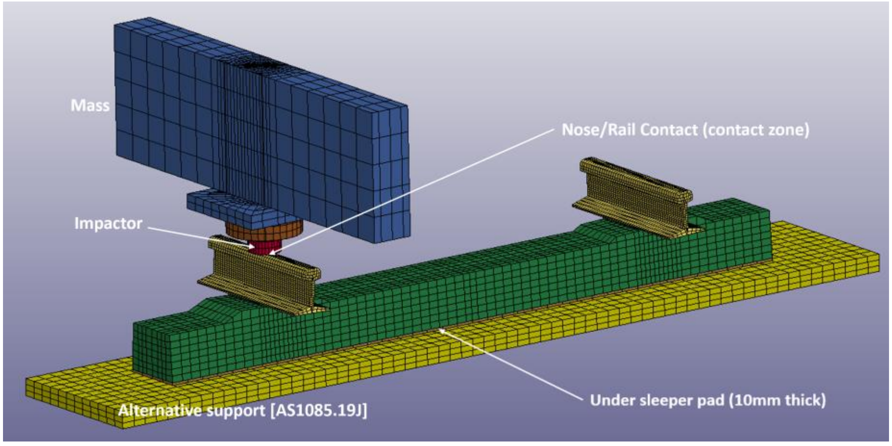
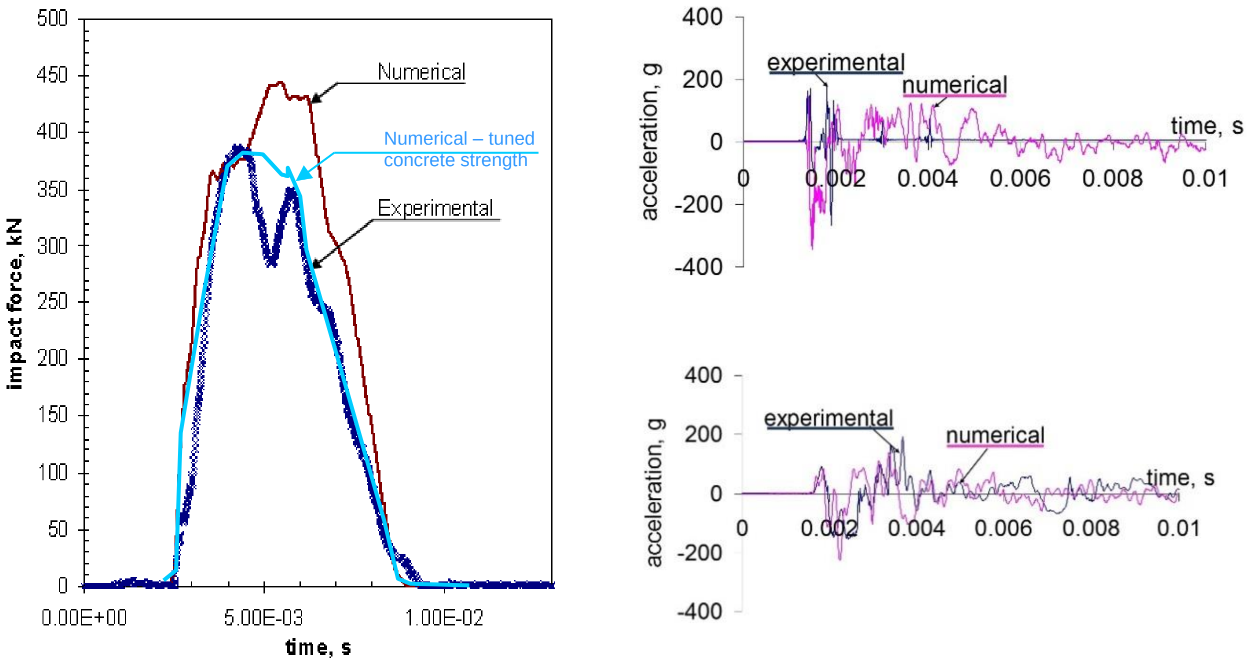


Fig. 2. Finite element model of sleeper with USP.

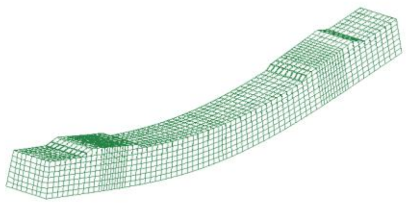
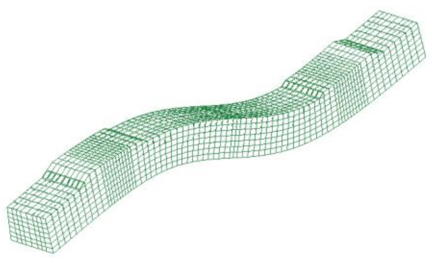
The extended finite element model was calibrated using vibration data [51, 57]. The updated finite element model was then transferred to LS-Dyna [58, 59], as shown in Fig. 2. In this study, the simulation results are achieved by assigning the initial velocity to the drop mass to generate an impact event, similarly to the actual drop tests [52, 56]. Note that the falling velocity is applied to the drop mass instead of applying the gravity acceleration as this is more convenient than changing the weight of drop mass to vary the impact forces. The in-situ conditions of railway concrete sleeper are replicated. It should be noted that, for the verification purpose, the drop height used is 0.1 m. Comparison between numerical and experimental results is shown in Fig. 3. It is seen that the finite element model is fairly sufficient for use in predicting impact responses of the prestressed concrete sleepers. Moreover, the sleeper models have been validated earlier using experimental modal analysis, which is a non-destructive technique to obtain the fundamental mode shapes and corresponding frequencies via frequency response function [62]. The free-free condition is used as boundary condition in both numerical and experimental. The experimental modal analysis using impact hammer excitation technique is used to identify mode shapes and corresponding frequencies over the frequency range between 0 and 1600 Hz. The modal parameters are identified by the Frequency Response Function (FRF) curve which is the acceleration response of the sleeper with respect to the force excitation by impact hammer. The signals are processed using DATS modal analysis software. The results show the excellent agreement with the eigenvalue analysis using finite element analysis with less than 5% difference, as seen in Table 4. The trends of peak acceleration responses are quite close to each other, although there is a certain phase difference. Thus, this study considers 3 cases of falling velocities: 0.74 m/s, 1.94 m/s and 3.14 m/s.

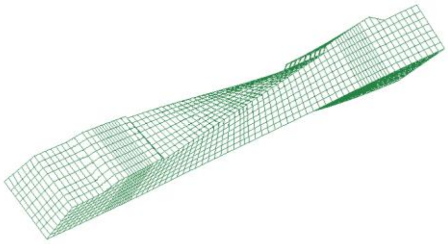
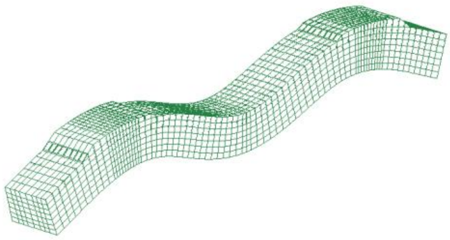


a) b)

Fig. 3. Comparison between numerical and experimental results: a) contact shock load b) acceleration of sleeper at rail seat (top) and mid-span (bottom).

Table 4. Mode shapes and natural frequencies (dynamic strength, $f'_{c,d}$= 90 MPa)

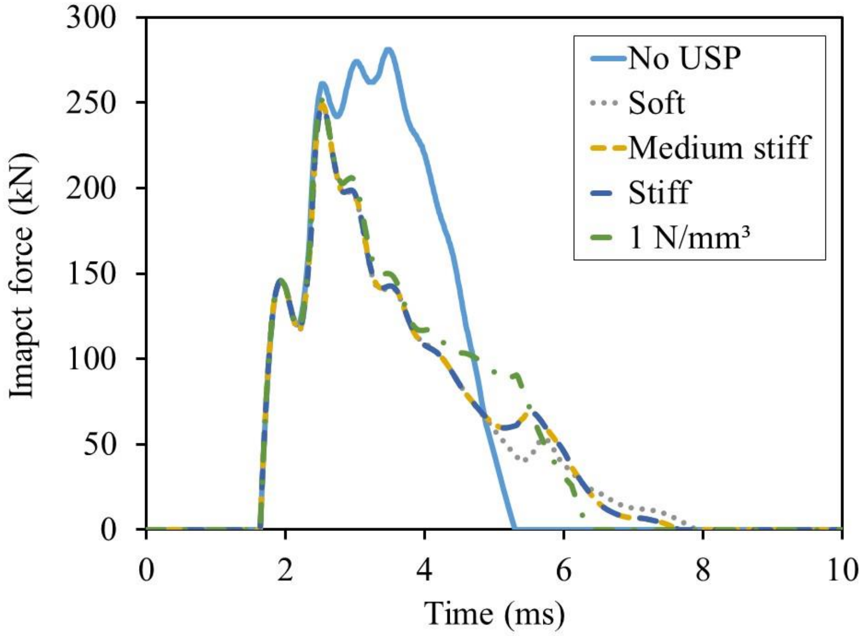
Mode no.	Mode shapes	Natural frequencies (Hz)		Difference (%)
		Experiment	Numerical	
1	 (1st bending)	112.64	107.29	4.75
2	 (2nd bending)	312.50	299.46	4.17

3	 (1st twisting)	436.60	427.45	2.09
4	 (3rd bending)	605.51	581.52	3.74

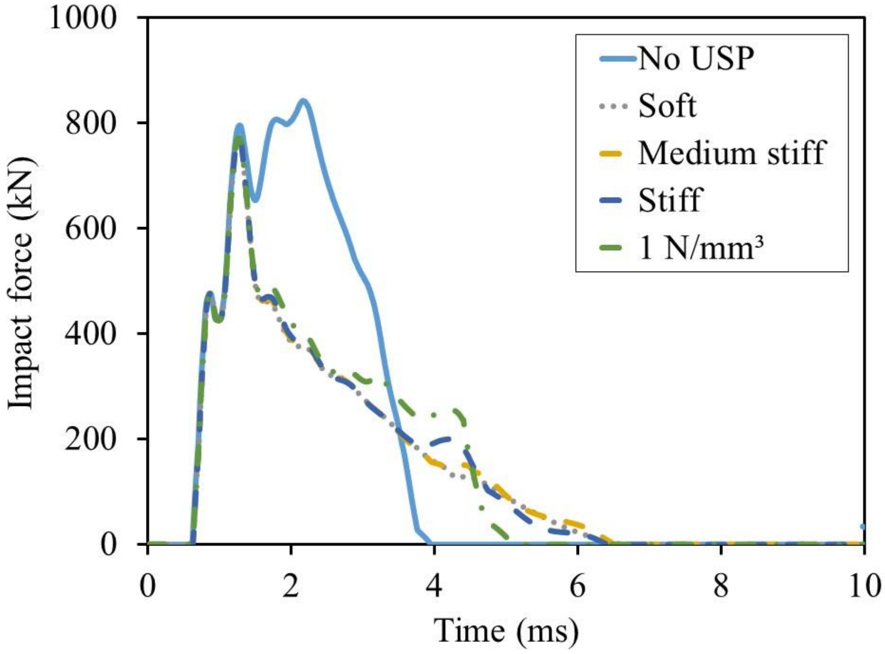
3 Results and discussions

3.1 Impact loads

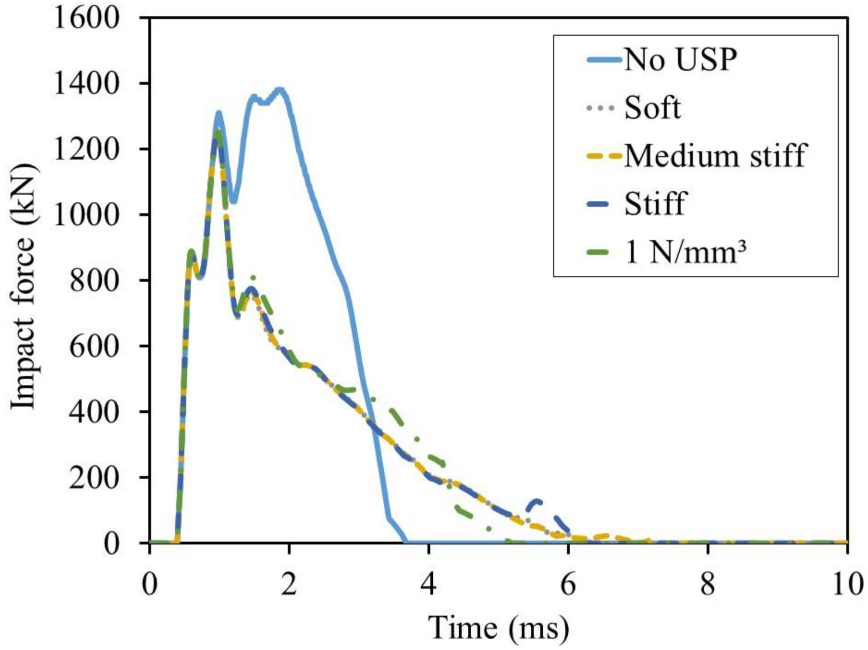
As mentioned, 3 types of USPs: soft, medium stiff, and stiff, are considered. It has been recommended that medium stiff and stiff USPs are useful for prolonging the service life of railway track as seen in many countries. Moreover, a very stiff pad, which has never been used for USP, is taken into account in order to study the possibility to use a very stiff pad for USP. It is noted that the very stiff USP has a bedding modulus of 1 N/mm^3. In this analysis, the initial velocities of 0.74 m/s (A), 1.94 m/s (B), and 3.14 m/s (C) of drop mass are applied. Time histories of impact forces are presented in Fig. 4. It is clearly seen that impact forces reduce significantly by about 10% when using USP. It is interesting that pulse duration increases when USP is used because the support is softer. Thus, the support plays a role in impact response since the impact magnitude decreases as well as track stiffness, whilst, pulse duration is inversely proportional to the stiffness [63]. It should be noted that the pulse durations are in the range of 3-4 ms. The impulse, which is the integral of force over time, is then calculated. The impulse represents the average impact force during the collision. The different initial velocities of drop mass generate different impact forces. The impact forces and impulses of applied forces to sleepers with and without USP are presented in Table 5. It should be noted that even pulse durations increase when using USP, the impulse significantly decreases since the area of higher impact force decreases as clearly seen in Fig. 4. It is concluded that impact event of sleeper with stiffer support can stop more quickly than a sleeper with softer support. It is also important to note that, for impact events, strain rate plays a significant role since the strength of material can be increased dramatically resulting in no crack observed in sleeper under single impact event. Strain rate can significantly increase the dynamic strength of sleeper by about 20% higher than static strength [64-65]. It was observed under experiment that crack can be visually seen after applying multiple high-intensity impact loads and thus the linear elastic properties of sleeper are acceptable for single impact load in this study as the sleeper is still in elastic stage [66].



a)



b)



c)

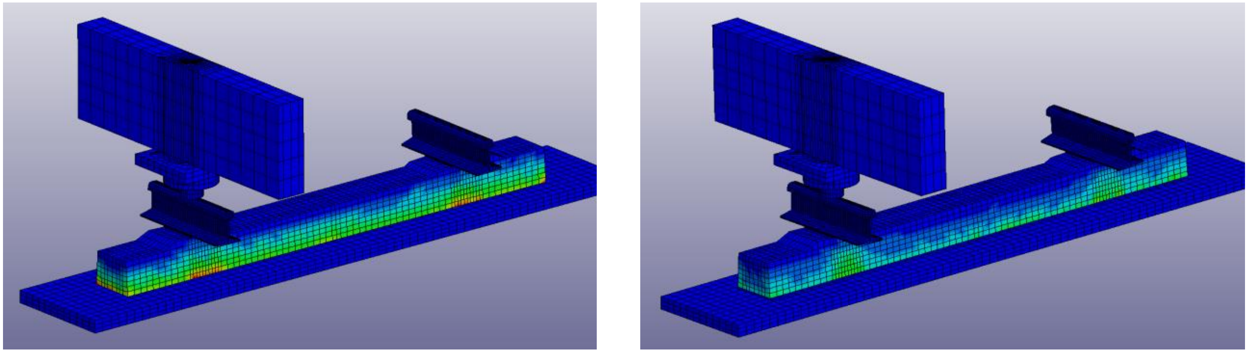
Fig. 4. Impact loads of with initial velocities of drop mass of a) 0.74 m/s (A) b) 1.94 m/s (B) c) 3.14 m/s (C).

Table 5. Contact force and impulse.

Case	Initial velocity (m/s)	Contact force (kN)		Reduction (%)	Impulse (kNs)		Reduction (%)
		Without USP	With USP		Without USP	With USP	
A	0.74	288	249	11.43	647	552	14.68
B	1.94	843	772	8.41	1766	1415	19.88
C	3.14	1380	1252	9.31	2888	2291	20.67

3.2 Sleeper responses

Fig. 5 shows the comparison of von Mises stress contour between sleepers without and with USP under gravity without load. It is seen that the dynamic stress concentration on the soffit of concrete sleeper is less than that with USP especially at rail seat.

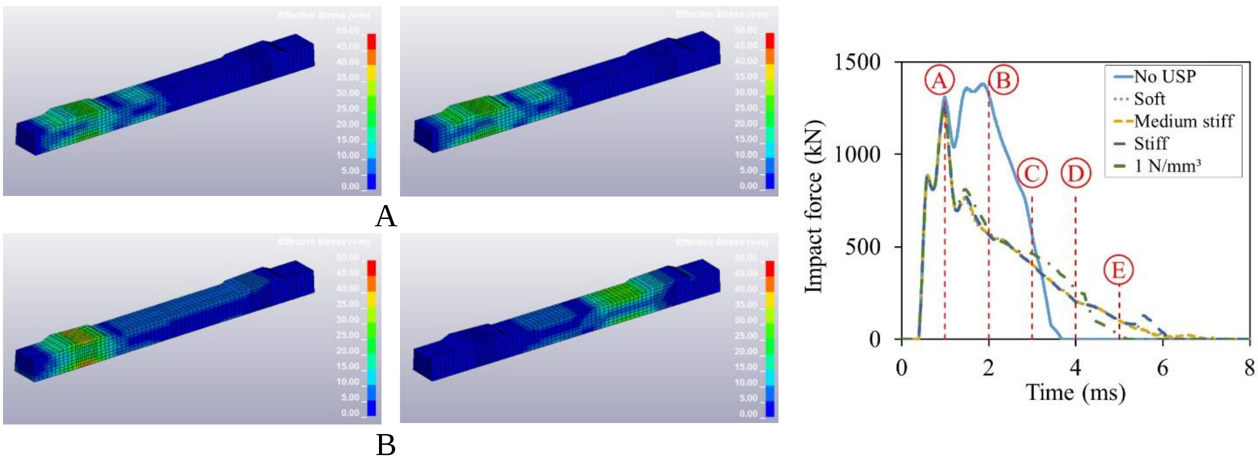


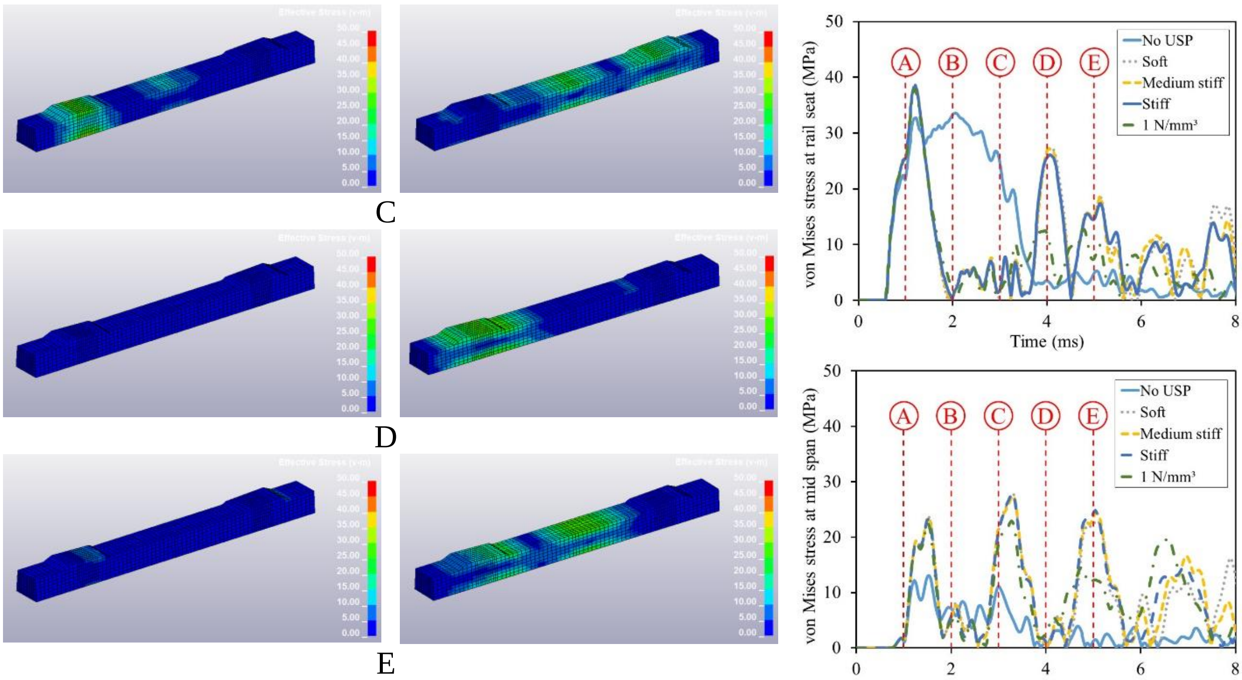
a) b)

Fig. 5. Von Mises stress contour of sleeper a) without USP b) with USP.

However, the maximum von Mises stress occurs at both top and soffit of sleeper at rail seat when applying the load. Although it is clearly seen in Fig. 5 that the von Mises stress at soffit are significantly redistributed and reduced. Nonetheless, the von Mises stress slightly increases especially on top of sleeper using USP when applying the load. It is noted that the point measured, which is the maximum stress occurred, is located on top of sleeper. It is found that stiff USP redistributes the loading area along the sleepers and slightly increases the maximum and overall von Mises stress response, as seen in Fig. 6. Moreover, USPs slightly expand the stress contour and extend the impact duration.

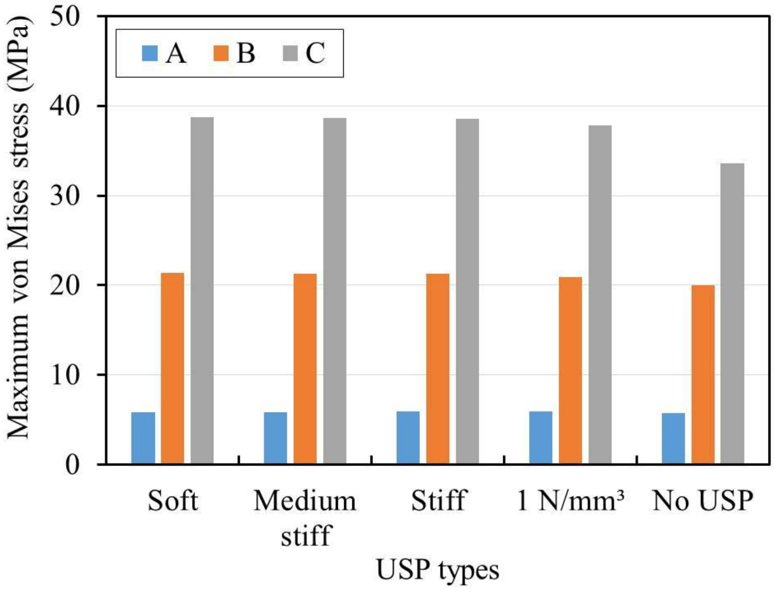
The effects of bedding modulus of USP on the maximum von Mises stress of the concrete sleepers subjected to impact loads at the top of sleeper are presented in Fig. 7. The bedding moduli of USP are generally varied from less than 0.10 N/mm^3 (very soft) to 0.35 N/mm^3 (stiff), depending on the type of usage. In this analysis, the bedding moduli of 0.15 N/mm^3, 0.25 N/mm^3, 0.35 N/mm^3, and 1 N/mm^3 are considered. Even though it is noticeable that the use of USP can obviously decrease the contact force and impulse, von Mises stresses of sleeper at both rail seat and mid-span slightly increase when using USP. It should be noted that at the von Mises stress can be increased from about 33 MPa to 38 MPa which is about 14%. However, each type of USP does not clearly reflect significant different in von Mises stress responses in both locations. Nevertheless, a very stiff USP (1 N/mm^3) presents a better overall performance on von Mises stress than other USPs.



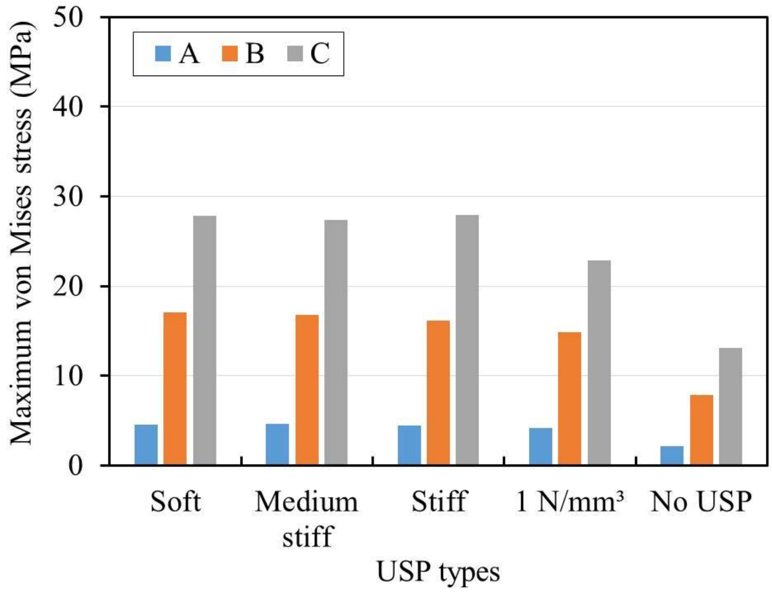


a) Sleeper without USP b) Sleeper with stiff USP

Fig. 6. Stress contour of sleeper with USP under impact load case A at different time a) Sleeper without USP b) Sleeper with stiff USP.



a)



b)

Fig. 7. Maximum von Mises stress at a) rail seat b) mid span.

Fig. 8 shows the sleeper displacement. Although it is noticeable that the use of USP can obviously decrease the contact force and impulse, displacements of sleeper at both rail seat and mid-span can be notably increased as well as von Mises stress when using USP. USPs are likely to have negative effects on sleeper displacement at both rail seat and mid span. This is because the use of USP affects the overall track characteristics by reducing track stiffness and making track softer. Even though USP types do not show the significant change in von Mises stress response, it is noticeable that sleeper with stiff USP has lower displacement rather than that with soft USP. It is also interesting to note that sleeper with USP tend to have worse performance when the higher impact load is applied. As for soft USP, about 4.5-7.5 times higher in sleeper displacement when using USP is observed while about 3-4 times is noted when stiff USP is used. It is also noted that higher impact loads lead to higher sleeper displacement ratio. This concludes that USP has worse performance when higher intensity impact load is applied. However, as for very stiff USP, about 2% displacement enlargement is observed in all load cases. Thus, even though, displacement of sleeper can be increased when USP is used, stiffer USP has better performance in sleeper displacement. It can be also concluded related to pulse duration that shorter impact events may have less severe responses than longer impact events even the maximum impact force is higher.

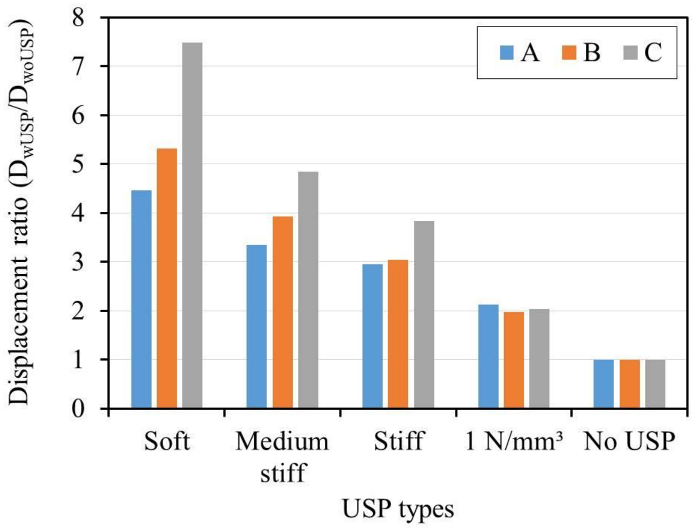
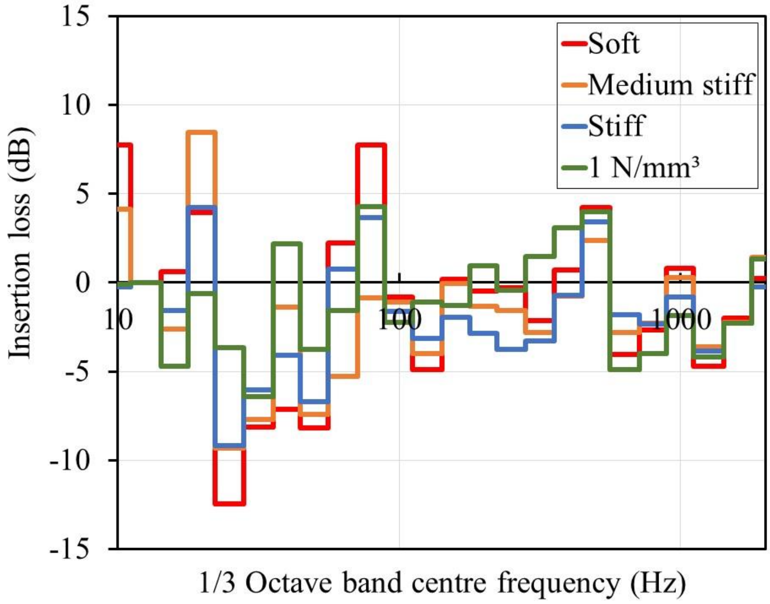
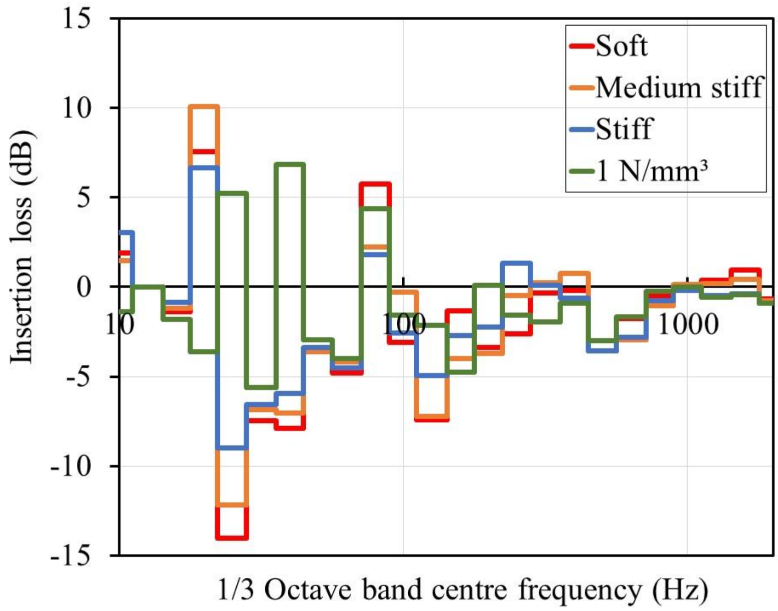


Fig. 8. Sleeper maximum displacement ratio at rail seat

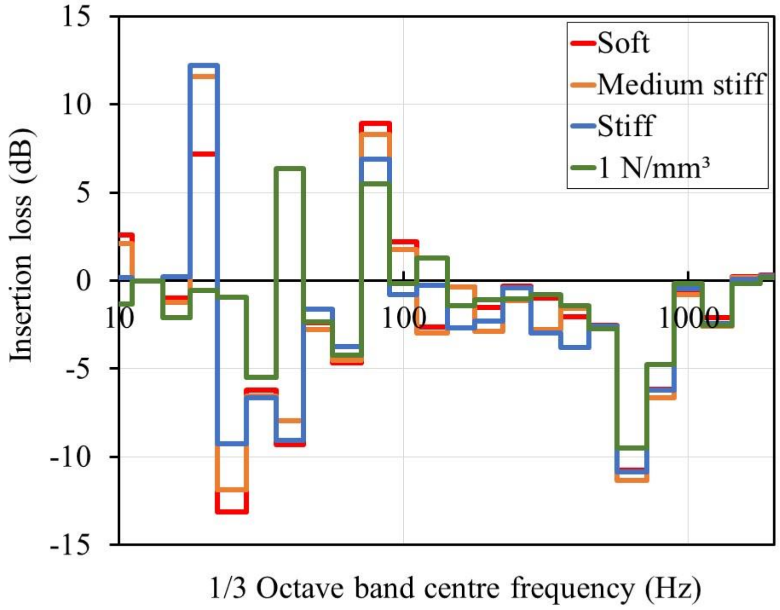
The acceleration vibrations are also presented in term of insertion loss. Fig. 9 demonstrates the insertion loss over one-third octave frequency band in concrete sleepers due to USP. Insertion loss is calculated by the logarithm of acceleration ratio of sleeper without USP with respect to that with USP in term of decibel (dB) (insertion loss = 10log ($A_{w/oUSP}/A_{w/USP}$)). It is clearly seen that USP can increase vibrations of concrete sleepers at certain frequency ranges. Thus, USPs tend to have large effect on acceleration amplitude vibrations of sleepers, especially when excited by a high-frequency impact force. This is because there is a reduction of concrete sleeper stiffness due to the adoption of USP.



a)



b)

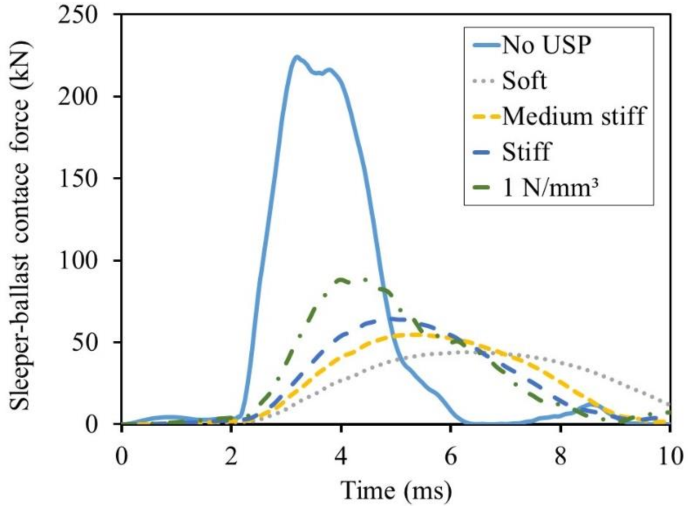


c)

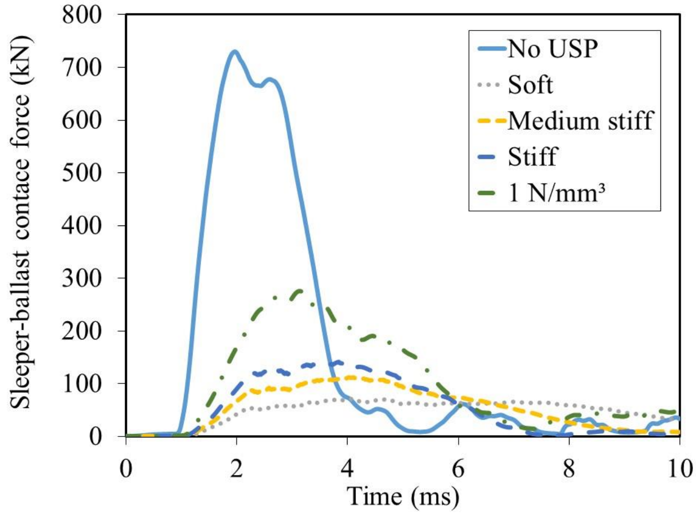
Fig 9. Insertion loss due to USP under load cases a) A b) B c) C

3.3 Ballast responses

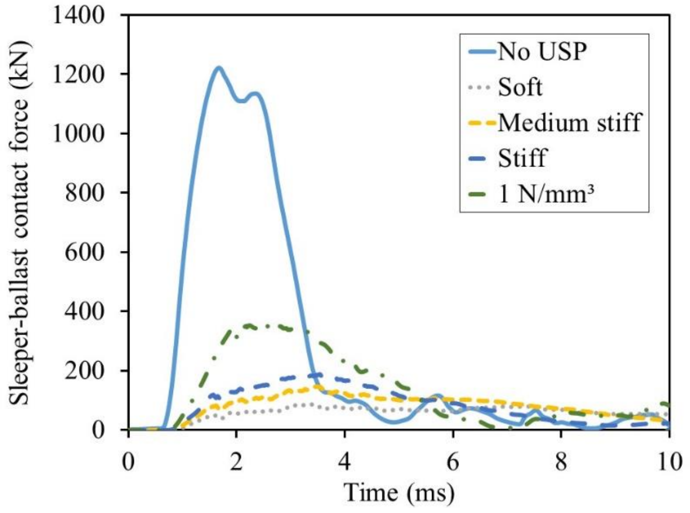
In order to reduce the sleeper-ballast contact pressure, many techniques, such as USP, frame and half frame sleepers, have been developed and adopted to the field. Based on previous studies, USP can increase the contact area between sleeper and ballast, resulting in ballast pressure reduction. However, numerical evidence has not been fully presented especially when railway tracks are subjected to high impact loads. Sleeper-ballast contact forces under the impulse generated by a drop mass are presented in Fig. 10. It is clearly seen that USPs can effectively reduce the contact force between sleeper and ballast in all cases. It is interesting that sleeper-ballast contact force can be reduced by about 70-95% by using normal USP (Fig. 11). It should be noted that the softer pad has a slight positive effect on reducing contact pressure compared to the stiffer pad. Moreover, very stiff pad can reduce sleeper-ballast contact force by about 60-70%. It is noted that very stiff can be possibly used as USP since it has a positive effect on ballast responses while reducing sleeper vibration compared to other USPs. However, this study considers the continuum support instead of discrete element modelling in order to purely understand the effect of USP and its bedding modulus on sleeper-ballast interaction. Thus, this model is acceptable, and all cases are consistent.



a)



b)



c)

Fig. 10. Sleeper-ballast contact force a) case A b) case B c) case C.

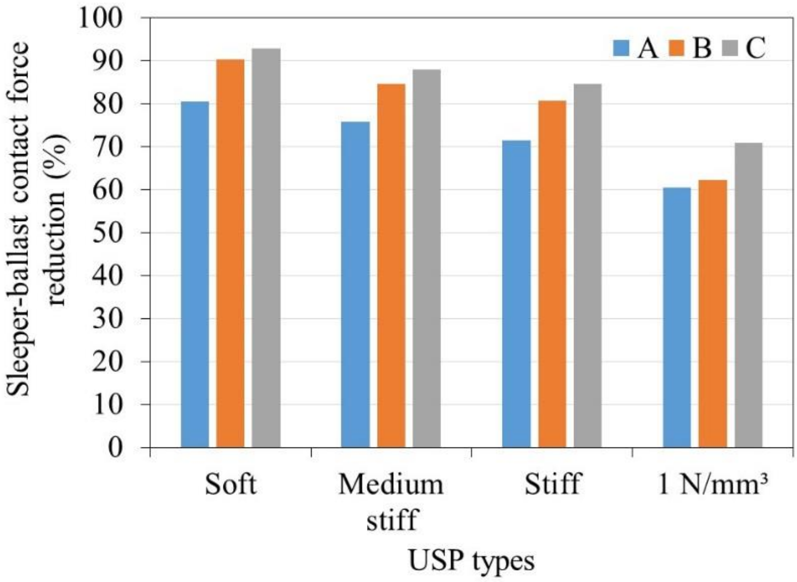
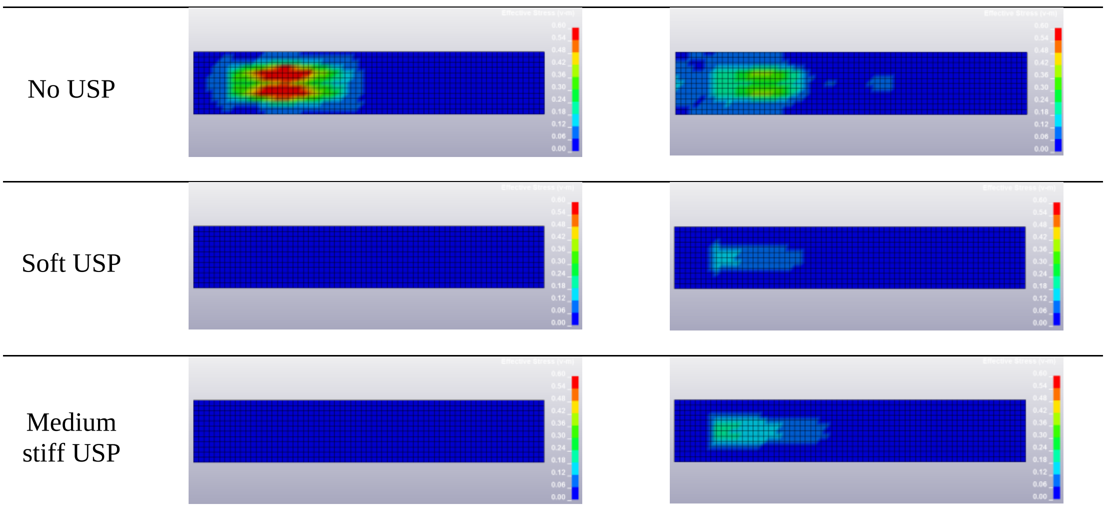


Fig. 11. Sleeper-ballast contact force reduction.

Fig. 12 illustrates the distribution of contact pressure on ballast under impact load. It should be noted that ballast is modelled as a continuum model which is a packed assembly of particles and continuous mass in order to reduce the computational time. Hence, this study assumes that the sleeper surface is fully contacted to ballast. It is clearly seen that USP can significantly reduce the contact pressure, especially at rail seat, although, the contact pressure is distributed over the larger area and prolong the impact event. This illustrates that USP can redistribute the impact load actions better along the contact between concrete sleeper and ballast. In addition, it is interesting to note that, at rail seat, soft USP has more benefit in sleeper-ballast contact stress reduction rather than other USPs as clearly seen in Fig. 12. As for very stiff pad, even though the stress occurred after 4 ms of impact event is changeless from sleeper without USP, the overall ballast stress can be significantly reduced especially the first half of impact event. However, this phenomenon cannot be observed in sleeper as all types of USP lead to similar phenomena and significantly gain vibration and displacement of sleeper.



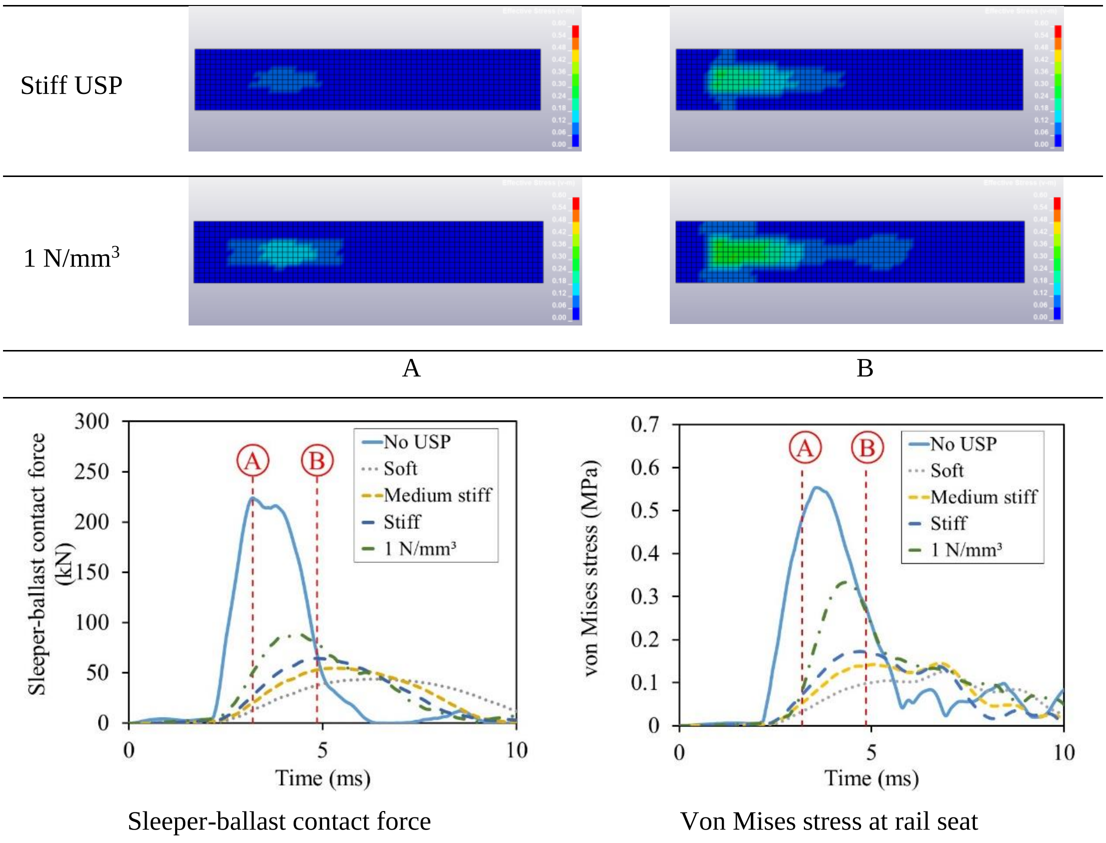


Fig. 12. Contact pressure distribution on ballast under impact load.

3.4 Field measurement data

The vibration measurements of sleepers with USPs have been carried out in the field at Austimer (Illawarra Line in NSW Australia) [67]. The trial ballasted track inspected consists of UIC60 rail, heavy-duty concrete sleeper (e-Clip) and HDPE rail pads. The 10 mm stiff USPs were installed underneath sleepers at ordinary track and glued insulated joints (GIJs), as shown in Fig. 13, in order to examine the dynamic performance of the USPs and confirm the numerical results. The vibrations of freight and passenger trains with speed between 40 and 100 km/h, respectively, running pass by were measured. The data obtained from this case was then compared to the sleeper data without USPs on ordinary railway track (ORD). Apart from ordinary track, the accelerometers were installed at the rails (at GIJ and rail web) and sleepers (DR: down rail seat, MID: mid span and UP: up rail seat) of railway tracks with and without USPs. The schematic location of the sensors can be seen in Fig 14. In this study, three cases are presented previously and about 130-200 kN-impact loads corresponding to the travelling speed of 40-100 km/h of freight and passenger trains over GIJ from field measurement are correlated to the finite element modelling under load case A. It should be noted that, for load cases B and C in the numerical study, the events of those cases are difficult to visually observe in the field as those cases are the coupled effects of short wavelength and long wavelength effects. Thus, only the percentage ratio, which is the relative value can be represented. Rail seat data is used to compare with numerical results as the finite element modelling at mid span cannot provide a realistic track behaviour due to the unbalanced loads and the modelling is based on the experimental condition. The six types of train and speed (Freight train: 40 km/h, 65 km/h; Passenger shuttle: 75 km/h, 80 km/h, 90 km/h; Passenger intercity: 100km/h) travelling over railway track with USPs are taken into account. The comparison between numerical results and field measurement data is presented in Figs 15-16. It can be seen that there is a correlation between both within the acceptable value. Based on field measurement data, it is seen that the vibration of tracks with USPs is possibly higher than those without USPs. The results represent the percentage ratio of the particular response with USP over its counterpart without USP. It is also seen that the average percentage ratio from field measurement is quite close to numerical results. Note that the percentage ratio is used because the impact events in any cases are different so that they cannot be compared by absolute value. The example of vibration signals of railway tracks at GIJ and ordinary track are shown in Figs. 15-16.

Fig. 13. Sleepers with USPs at glued insulated joints (GIJs) [67].

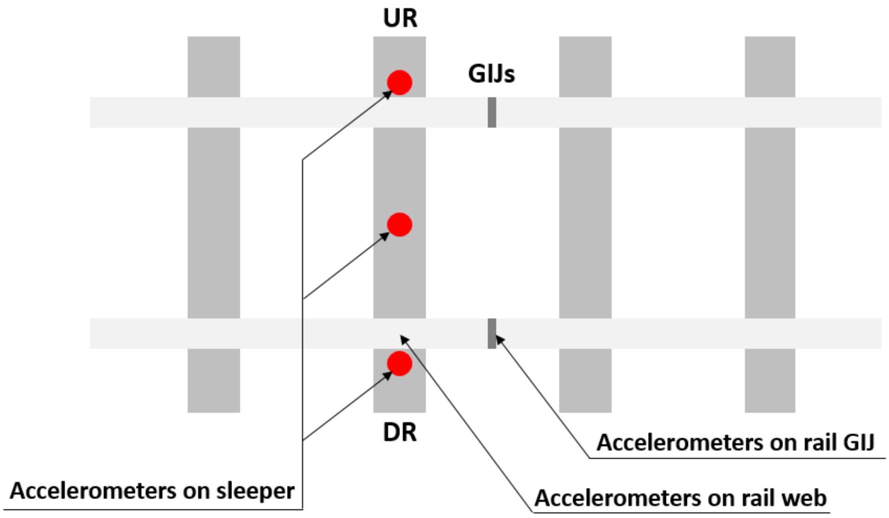


Fig. 14. Schematic location of the sensors in the field.

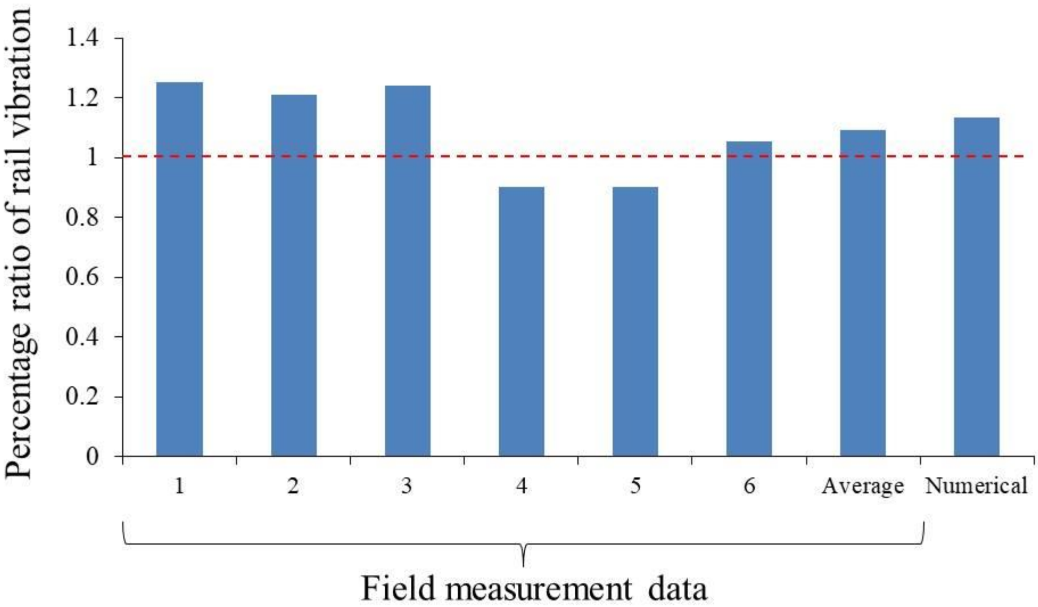


Fig. 15. Percentage ratio of rail vibrations of tracks with and without USPs.

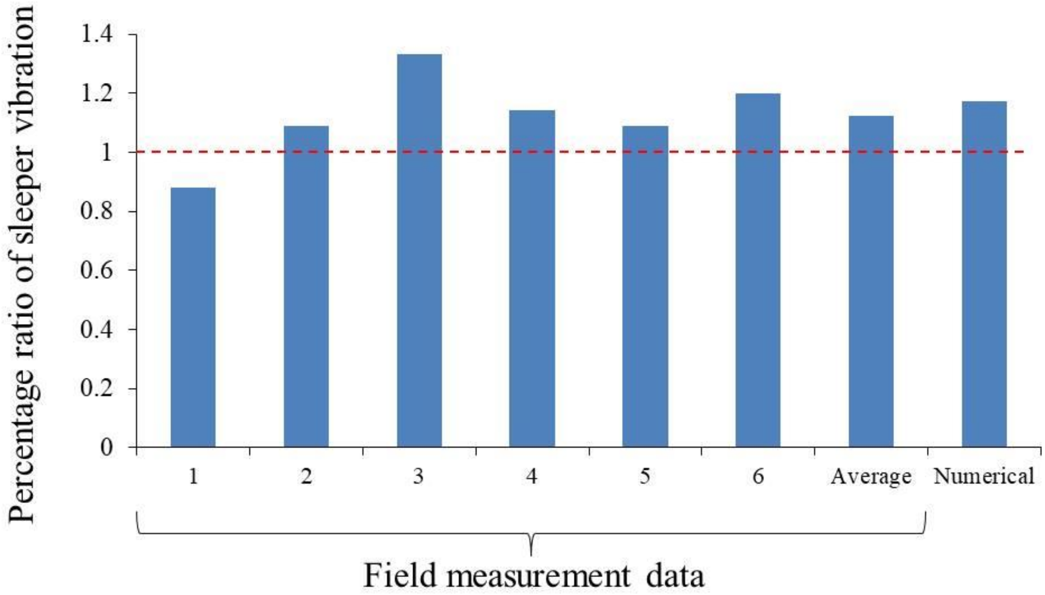


Fig. 16. Percentage ratio of sleeper vibrations of tracks with and without USPs.

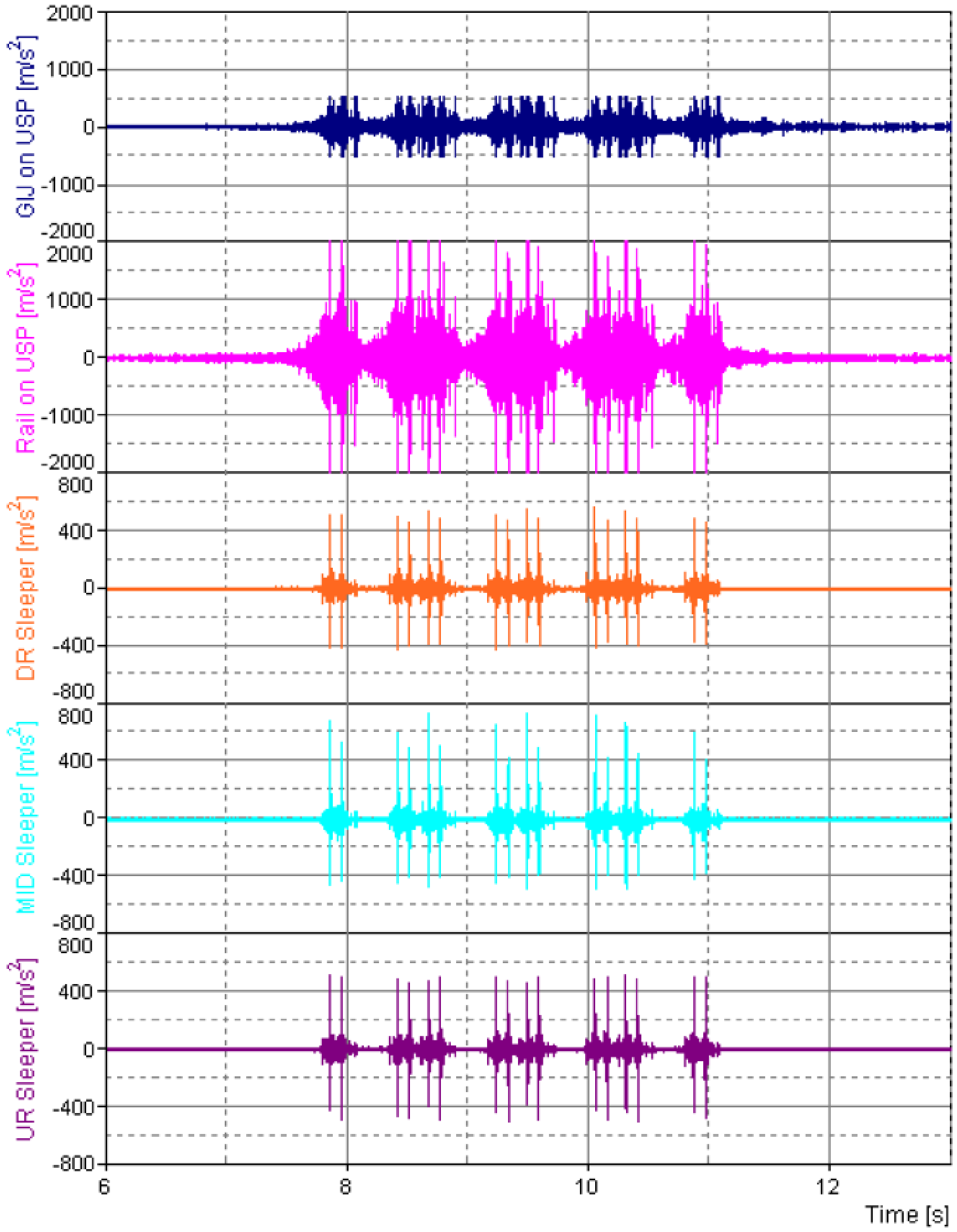


Fig. 17. Rail and sleeper with USPs vibrations at GIJ [67].

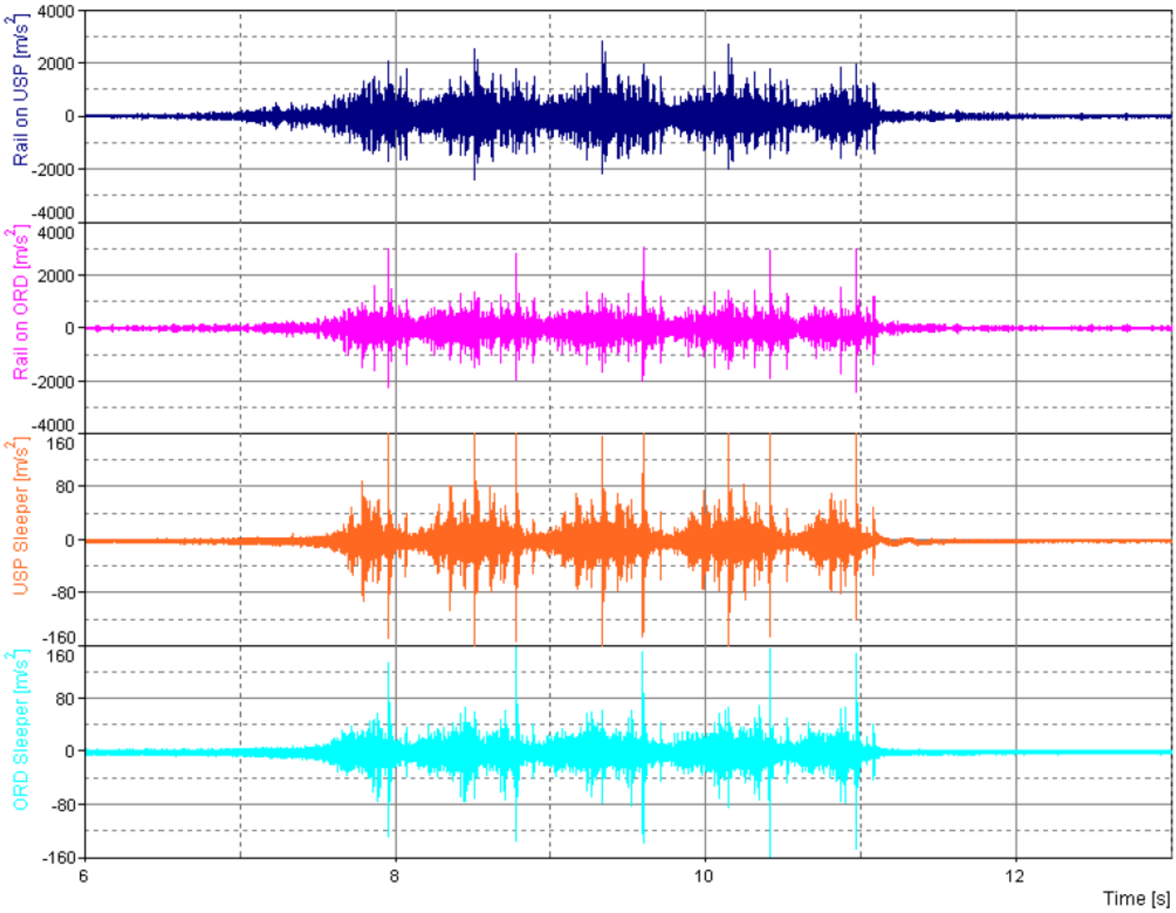


Fig. 18. Rail and sleeper vibrations at ordinary plain track [67].

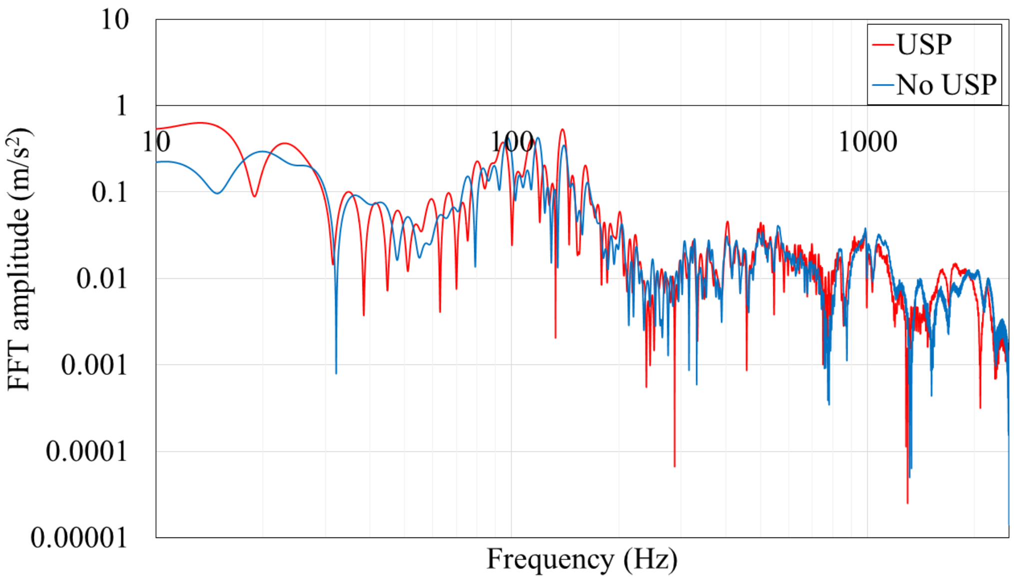


Fig. 19. An example FFT vibrations of sleepers.

From Figs. 17-18, it is clearly seen that railway track with USPs tends to induce higher vibrations than those without USPs at both rail and sleeper. This is also evidenced by the vibration of sleepers in the frequency domain (Fig. 19). However, the vibration of rail on USP sleeper is high, as seen in Fig. 17, because rail surface defect was observed during the visual inspections. It should be noted that this was a result of wheel slip or wheel burn after construction while the condition of GIJ was still good. Note that sleeper vibrations are highly influenced by train speed over a broad range of frequency band while the axle loads affect the vibration amplitude of sleepers at low frequency band. In terms of ballast condition (Fig. 20), ballast breakage and pulverisation surrounding sleepers with USP were not observed by visual inspection. Also, there was no pocket and void of ballast under the sleeper with USPs. These positive inspections are related to the numerical results that previously show that the use of USPs can help reduce the ballast contact pressure. Hence, the reduced ballast damage can be accomplished by a reduction of contact pressure, and thus wears, in the sleeper-ballast interface. The field measurement data can confirm the correctness of numerical results that the utilisation of USPs should be very carefully considered since this can either have positive or negative effects on railway track under impact loading condition.

Fig. 20. Ballast condition [67].

4 Conclusions

The emphasis of this study is placed on the effects of USPs on the dynamic responses of railway concrete sleeper subjected to high-intensity impact loading. Finite element models of sleeper with USP have been conducted and analyzed using LS-DYNA. Three main types of USP: soft, medium stiff, and stiff, are considered in this study. The feasibility of using very stiff pad with bedding modulus of 1 N/mm^3, is also studied in order to be an alternative for USP application. The initial velocities of drop mass are applied to the rail as an impact load. The models have been validated against the experimental results. The velocities applied to the mass corresponds to the drop mass of 600kg with the variations of height. This study is the first to consider the influences of extreme impact condition on railway track, where the coupling effects are taken into account, on sleeper vibrations with and without USP. It is noted that the impact load of about 1000kN which has never been considered in the open literature, is applied to the model. The results show that the USPs can change the overall track stiffness, then significantly reduce wheel-rail contact forces by about 10%. This is because the pulse duration may increase when using USPs which can increase the impulse although the contact forces reduce. Although the studies have found that the sleepers with USPs tend to have lesser flexures, contact forces, this numerical study, and the field measurement data also confirm that a sleeper with USPs could experience a larger displacement and acceleration amplitude vibrations, especially when excited by a high-frequency impact force. However, the benefit of using USP is observed since it can significantly reduce the pressure on ballast resulting in minimal ballast breakage and pulverisation. Interestingly, softer USP provides better results as this can effectively reduce ballast pressure responses compared to stiffer one, although, the USP may have negative effects on sleeper responses under impact loads. This study also introduces the very stiff pad with 1N/mm^3 bedding modulus, which has never been used, as an alternative. Besides, it is interesting to note that very stiff pad with 1N/mm^3 bedding modulus can be effectively used in extreme conditions as USP since this pad has less negative effects on sleeper vibration rather than other USPs while it can slightly reduce the impact force distributed to ballast. The new insight from this study will help track engineers to make a better decision on the design and usage of USPs in any railway network especially at the prone area to high-intensity impact load.

Acknowledgements

The authors would also like to thank British Department for Transport (DfT) for Transport – Technology Research Innovations Grant Scheme, Project No. RCS15/0233; and the BRIDGE Grant (provided by University of Birmingham and the University of Illinois at Urbana Champaign). The author gratefully acknowledges the Japan Society for the Promotion of Science (JSPS) for his JSPS Invitation Research Fellowship (Long-term), Grant No L15701, at Track Dynamics Laboratory, Railway Technical Research Institute and at Concrete Laboratory, the University of Tokyo, Tokyo, Japan. The authors are sincerely grateful to the European Commission for the financial sponsorship of the H2020-RISE Project No. 691135 "RISEN: Rail Infrastructure Systems Engineering Network", which enables a global research network that tackles the grand challenge of railway infrastructure resilience and advanced sensing in extreme environments (www.risen2rail.eu) [68].

References

[1] S. Kaewunruen, A.M. Remennikov, Non-destructive testing (NDT): A tool for dynamic health monitoring of railway track structures, Materials Australia 39(6) (2006).

[2] A.M. Remennikov, S. Kaewunruen, A review on loading conditions for railway track structures due to train and track vertical interaction, Structural Control and Health Monitoring 15 (2008) 207-234.

[3] B. Indraratna, C. Rujikiatkamjorn, W. Salim, Advanced Rail Geotechnology – Ballasted Track, CRC Press, London, UK, 2011.

[4] C. Ngamkhanong, S. Kaewunruen, C. Baniotopoulos, A review on modelling and monitoring of railway ballast, Structural Monitoring and Maintenance 4 (2017) 195-220.

[5] A. Johansson, J.C.O. Nielsen, R. Bolmsvik, A. Karlström, Under sleeper pads – influence on dynamic train-track interaction, Wear 265 (2008) 1479–687.

[6] International Union of Railway, USP Report, Under sleeper pads, Project no. I/05/U/440, Summarising report, 2009.

[7] International Union of Railway, USP recommendations, Under Sleeper Pads, Recommendations for Use, UIC-Leaflet, Draft Document, 2013.

[8] R. Schilder, USP-under sleeper pads, Applications and benefits of elastic elements in ballasted tracks, UIC project no. I/05/U/440, Paris 17, 2006.

[9] J. Jenkins, S. Stephenson, G. Clayton, G. Morland, D.L. Lyon, Incidences des paramètres

caracteristiques de la voie et des vehicules sur les efforts dynamics verticaux qui se développent entre rail et roue, Rail International 3(10) (1974) 682-702.
[10] S. Lakušic, M. Ahac, I. Haladin, Experimental investigation of railway track with under sleeper pad, 10th Slovenian road and transportation congress, Portorozˇ, Slovenija, 2010.
[11] British Standards Institution, BS EN 16730:2016 Railway applications — Track —Concrete sleepers and bearerswith under sleeper pads, BSI Standards Limited 2016, UK
[12] S. Kaewunruen, A. Aikawa, A.M. Remennikov, Vibration attenuation at rail joints through under sleeper pads, Procedia Engineering. 189 (2017) 193-198.
[13] International Union of Railway, UIC Leaflet 917 Guidelines for under sleeper pad, Paris, France, 2015.
[14] T. Dahlberg, Railway track stiffness variations-consequences and countermeasures, Int. J. Civ. Eng. 8 (1) (2010) 1–12.
[15] P. Schneider, R. Bolmsvik, J.C.O. Nielsen, In situ performance of a ballasted railway track with under sleeper pads, J. Rail Rapid Transit 225 (3) (2011) 299-309.
[16] W. Stahl, Improvement of ballasted tracks using sleeper pads – investigations and experiences in Germany, Munich University of Technology, Germany, 2004.
[17] F. Müller-Boruttau, U. Kleinert , Betonschwellen mit elastischer Sohle, ETR. 50 (3) (2001).
[18] B. Indraratna, D. Ionescu, H.D. Christie, STATE-OF-THE-ART LARGE SCALE TESTING OF BALLAST, In Railway Technical Society of Australasia (eds), CORE 2000 Railway Technology for the 21st Century (2000) 24.1-24.13.
[19] J.A Zakeri, R. Abbasi, Field investigation of variation of loading pattern of concrete sleeper due to ballast sandy contamination in sandy desert areas, Journal of Mechanical Science and Technology 26 (12) (2012) 3885-3892.
[20] F. Ferreira, B Indraratna, Deformation and Degradation Response of Railway Ballast under Impact Loading–Effect of Artificial Inclusions, ICRT 2017: Railway Development, Operations, and Maintenance, 2017.
[21] V.L. Marine, M.J.M.M. Steenburgen, I.Y. Sheets, Combating RCF on switch points by tuning elastic track properties, Wear. 271(1) (2009) 158-167.
[22] S. Setsobhonkul, S. Kaewunruen, J.M. Sussman, Lifecycle Assessments of Railway Bridge Transitions Exposed to Extreme Climate Eventsm, Front. Built. Environ. 3 (2017).
[23] C. Ngamkhanong, A.T. Nascimento, S. Kaewunruen, Economics of track resilience, In The 3rd World Multidisciplinary Civil Engineering - Architecture - Urban Planning Symposium, IOP Conference Series: Material Science and Engineering, 2018.
[24] A. Ortega, S. Blainey, J. Preston, Installation of under sleeper pads on ballasted railway tracks: An economic analysis of their potential implementation, Proc IMechE, Part F: J Rail and Rapid Transit, 2017.
[25] M.H. Bin Osman, S. Kaewunruen, Uncertainty Propagation Assessment in Railway-Track Degradation Model Using Bayes Linear Theory, Journal of Transportation Engineering, Part A: Systems 144 (7) (2018).
[26] S. Kaewunruen, C. Ngamkhanong, A.M. Renemmikov, Dynamic Responses of Railway Prestressed Concrete Sleepers with Under Sleeper Pads to High Intensity Impact Loads, In The 3rd World Multidisciplinary Civil Engineering - Architecture - Urban Planning Symposium, IOP Conference Series: Material Science and Engineering, 2018.
[27] S. Kaewunruen, J.M. Sussman, H.H. Einstein, Strategic framework to achieve carbon-efficient construction and maintenance of railway infrastructure systems, Frontiers in Environmental Sciences 3 (6) (2015).
[28] S. Nimbalkar, B. Indraratna, S.K. Dash, D. Christie, Improved performance of railway ballast under impact loads using shock mats, ASCE Journal of Geotechnical & Geoenvironmental Engineering 138 (3) (2012) 281-294.
[29] S. Kaewunruen, A.M. Remennikov, Under sleeper pads: field investigation of their role in

detrimental impact mitigation, Proceedings of the 13th International Railway Engineering Conference, Edinburgh, UK, 2015.

[30] P. Schneider, R. Bolmsvik, J.C.O. Nielsen, In-situ performance of a ballasted railway track with under sleeper pads, Journal of Rail and Rapid Transit 225 (3) (2011) 299-309.

[31] M.V. Tuler, S. Kaewunruen, Life cycle analysis of mitigation methodologies for railway rolling noise and groundbourne vibration, Journal of Environmental Management 191 (2017) 75-82.

[32] R. Tavares de Freitas, S. Kaewunruen, Life cycle cost evaluation of noise and vibration control methods at urban railway turnouts, Environments 3 (4) (2016) 34.

[33] R. Schilder, USP (under sleeper pads) – a contribution to save money in track maintenance, in AusRAIL PLUS (Sydney: AusRAIL PLUS), 2013.

[34] B. Larsen, Under Sleeper Pads on the Ofoten Line, Proceedings of the 19th Nordic Seminar on Railway Technology, Luleå, Sweden, 2016.

[35] C. Jayasuriya, B. Indraratna, S. Nimbalkar, Analysis of the Performance of Under Sleeper Pads- A Critical Review, International Conference on Geotechnical Engineering (ICGE), Colombo, Sri Lanka, 2015.

[36] C. Ngamkhanong, S. Kaewunruen, B.J.A. Costa, State-of-the-Art Review of Railway Track Resilience Monitoring, Infrastructures 3 (2018).

[37] A. Paixão, J.N. Varandas, E. Fortunato, R. Calçada, Numerical simulations to improve the use of under sleeper pads at transition zones to railway bridges, Engineering Structures 164 (2018) 169-182.

[38] H. Li, G.R. McDowell, Discrete element modelling of under sleeper pads using a box test, Granular Matter 20 (2) (2018) 2-26.

[39] L. Le Pen, G. Watson, A. Hudson, W. Powrie, Behaviour of under sleeper pads at switches and crossings–Field measurements, Proceedings of the Institution of Mechanical Engineers, Part F: Journal of Rail and Rapid Transit 232 (4) (2018) 1049-1063.

[40] S. Kaewunruen, Discussion of "Mitigation of Ground Vibration Generated by High-Speed Trains on Saturated Poroelastic Ground with Under-Sleeper Pads", ASCE Journal of Transportation Engineering 141 (1) (2015).

[41] J. Mottahed, J.A. Zakeri, S. Mohammadzadeh, Field and numerical investigation of the effect of under-sleeper pads on the dynamic behavior of railway bridges, Proc IMechE, Part F: J Rail and Rapid Transit, in press, 2017.

[42] J.A. Zakeri, M. Esmaeili, H. Heydari-Noghabi, A field investigation into the effect of under sleeper pads on the reduction of railway-induced ground-borne vibrations, Proc IMechE, Part F: J Rail and Rapid Transit 230 (2016) 999–1005.

[43] S. Kaewunruen, T. Ishida, A.M. Remennikov, Dynamic Performance of Concrete Turnout Bearers and Sleepers in Railway Switches and Crossings, Advances in Civil Engineering Materials, (2018) doi.org/10.1520/ACEM20170103. ISSN 2379-1357.

[44] S. Kaewunruen, C. Ngamkhanong, M. Papaelis, C. Roberts, Wet/dry influence on behaviors of closed-cell polymeric cross-linked foams under static, dynamic and impact loads, Construction & Building Materials 187 (2018) 1092-1102.

[45] Z. Yang, A. Boogaard, Z. Wei, J. Liu, R. Dollevoet, Z. Li, Numerical study of wheel-rail impact contact solutions at an insulated rail joint, International Journal of Mechanical Sciences, 138-139 (2018) 310–322.

[46] C.A. Ribeiro, A. Paixão, E. Fortunato, R. Calçada, Under sleeper pads in transition zones at railway underpasses: numerical modelling and experimental validation**.** Structure and Infrastructure Engineering 11(11) (2015) 1432-1449.

[47] A. Paixão, C.A. Ribeiro, N. Pinto, E. Fortunato, R. Calçada, On the use of under sleeper pads in transition zones at railway underpasses: experimental field testing, Structural and infrastructure engineering, 11(2) (2015) 112-128

[48] S. Kaewunruen and C. Chiengson, Railway track inspection and maintenance priorities due to dynamic coupling effects of dipped rails and differential track settlements, Engineering Failure Analysis, 93 (2018) 157-171.
[49] S. Kaewunruen, A.M. Remennikov, Effect of a large asymmetrical wheel burden on flexural response and failure of railway concrete sleepers in track systems, Engineering Failure Analysis 15 (8) (2008) 1065-1075.
[50] S. Kaewunruen, A.M. Remennikov, Experimental simulation of the railway ballast by resilient materials and its verification by modal testing, Experimental Techniques 32 (4) (2008) 29-35.
[51] S. Kaewunruen, A.M. Remennikov, Nonlinear finite element modeling of railway prestressed concrete sleeper, Proceedings of the 10th East Asia-Pacific Conference on Structural Engineering and Construction, EASEC 4 (2006) 323-328.
[52] S. Kaewunruen, and A.M. Remennikov, Experimental and numerical studies of railway prestressed concrete sleepers under static and impact loads, Civil Computing 3 (2007) 25-28.
[53] Standards Australia, “Railway track material - Part 14: Prestressed concrete sleepers” Australian Standard: AS1085.14-2003, 2003a. 11.
[54] Standards Australia, “Railway track material - Part 19: Resilient fastening assemblies” Australian Standard: AS1085.19-2003, 2003b.
[55] British Standards Institution (BSI), European Standard Railway applications. Track. Concrete sleepers and bearers, London UK, 2016.
[56] S. Kaewunruen, A.M. Remennikov, Low-velocity impact analysis of prestressed concrete sleepers. Concrete Institute of Australia’s 23rd Biennial Conference 07, October 18-20, Adelaide, Australia, 2007.
[57] Standards Australia. Design of concrete structures. Australian Standard: AS3600-2001; 2001.
[58] S. Kaewunruen, A.M. Remennikov, Impact responses of prestressing tendons in railway concrete sleepers in high speed rail environments. Proceedings of the 5th Computational Methods in Structural Dynamics and Earthquake Engineering, May 25-27, Crete Island, Greece, 2015.
[59] S. Kaewunruen, A.M. Remennikov, S. Minoura, Dynamic responses of railway ultra-high-strength concrete sleepers under extreme impact loading. Proceedings of the 6th Computational Methods in Structural Dynamics and Earthquake Engineering, June 15-17, Rhodes Island, Greece, 2017.
[60] R. You, K. Goto, C. Ngamkhanong, S. Kaewunruen, Nonlinear finite element analysis for structural capacity of railway prestressed concrete sleepers with rail seat abrasion, Engineering Failure Analysis 95 (2019) 47-65.
[61] S. Kaewunruen, Experimental and numerical studies for evaluating dynamic behaviour of prestressed concrete sleepers subject to severe impact loading, PhD thesis, School of Civil, Mining & Environmental Engineering, University of Wollongong, 2007.
[62] A. M. Remennikov, S. Kaewunruen, Experimental Investigation on Dynamic Railway Sleeper/Ballast Interaction. Experimental Mechanics 46 (2006) 57–66.
[63] Z. Cai, Modelling of rail track dynamics and wheel/rail interaction, PhD Thesis, Department of Civil Engineering, Queen’s University, Ontario, Canada, 1992.
[64] C. Ngamkhanong, D. Li, S. Kaewunruen, A.M. Remennikov, Dynamic Capacity Reduction of Railway Prestressed Concrete Sleepers Due to Surface Abrasions Considering the Effects of Strain Rate and Prestressing Losses, International Journal of Structural Stability and Dynamics 19 (1) (2018) 1940001.
[65] H. Wakui, H. Okuda, A study on limit-state design for prestressed concrete sleepers, Concrete Library of JSCE 33 (1999) 1-25.

[66] S. Kaewunruen, A.M. Remennikov, Progressive failure of prestressed concrete sleepers under multiple high-intensity impact loads, Engineering Structures, 31 (10) (2009) 2460-2473.
[67] S. Kaewunruen, In-situ performance of under-sleeper pads (USPs) at glued insulated joints (GIJs), Technical Report TR.208, RailCorp, Technical Services, Sydney Australia, 75p, 2012.
[68] S. Kaewunruen, M.J. Sussman, M Akira, Grand Challenges in Transportation and Transit Systems. Frontiers in Built Environment 2 (2016).