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# A numerical study to evaluate dynamic responses of voided concrete railway sleepers to impact loading

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## ABSTRACT

The prestressed concrete railway sleepers (or railroad ties), which are installed in railway track systems as the crosstie beam support, are designed to carry and transfer the wheel loads from the rails to the ground. It is well known that railway tracks are subject to impact loading conditions, which are attributable to the train operations with either wheel or rail abnormalities such as flat wheels, dipped rails, etc. These loads are of very high magnitude but short duration. In many cases, it has been reported from the fields that concrete sleepers are lacking of support due to mud pumping or excessive but localised track settlement, so-called 'voided sleepers'. This paper presents a numerical study to evaluate dynamic responses of the voided concrete sleepers to impact loading. A simplified finite element model of concrete sleepers was developed and validated against experimental data. The model has then been used to evaluate the effect of voids on the dynamic responses of concrete sleeper to a typical impact loading. The outcome of this study will help engineers to determine the life of assets and to investigate the failure mode of concrete sleepers and associated track components in actual ballasted tracks. It also gives better insight into the dynamic behaviour of voided concrete railway sleepers.

## INTRODUCTION

There are two broad types of modern railway tracks: commonly, ballasted and ballastless tracks. Both types of tracks have several structural components to withstand loading from trains. This investigation focuses on the ballasted track as illustrated in Figure 1 (Remennikov and Kaewunruen, 2005), commonly built for passenger and freight trains in Australia. In general, train/track interactions induce dynamic loading spectra acting at the interface between wheels and rails. An imperfection of either wheel or rail (e.g. wheel flats, rail squats, rail corrugation, dipped welds or turnout crossings) can easily cause transient or impact loading to a railway track. The impact load magnitude could be as high as six times of a static wheel load and the duration of impulse could be as short as one millisecond (Remennikov and Kaewunruen, 2008). The emphasis of the previous research work has been placed on the dynamic behaviour of wheels and rails. It is found that the research into concrete sleepers is inadequate. The insight into such effect on concrete railway sleepers has not been comprehensively established.

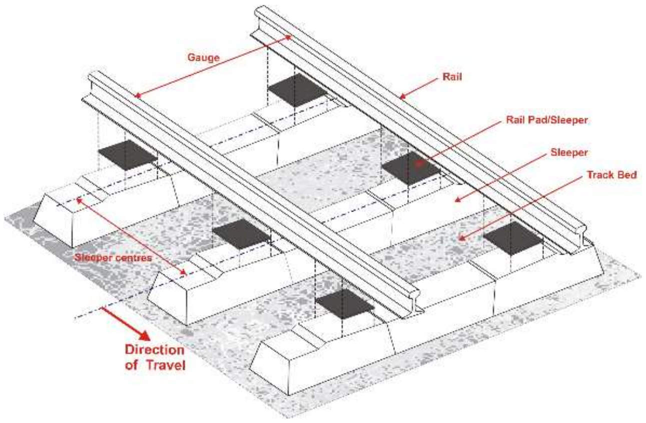
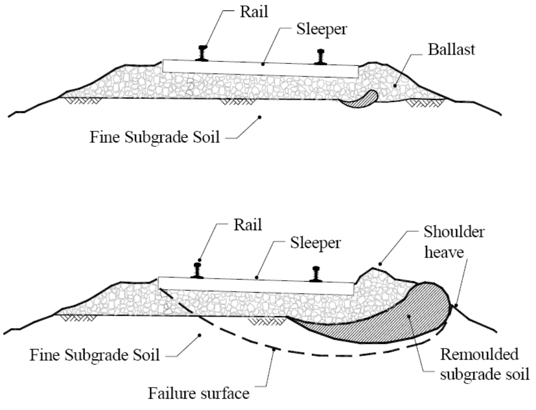


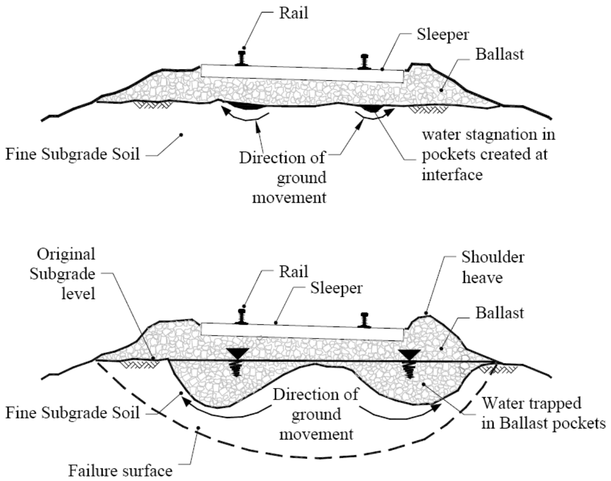
**Figure 1**. Ballasted rail track

Under cyclic heavy train loads, the ballast deteriorates progressively. With the poor drainage of tracks, the design capacity of the formation can be reduced quickly when the water seepages through the layers of subballast and compacted soils. The softened formation would be overstressed by the heavy loads and then yields a plastic, permanent deformation underneath the railway tracks as demonstrated in Figure 2 (Radampola, 2006). The overstressed soil would deform flexibly and may even crack the capping layer (or subballast). This action creates track pumping problem when the mud surges up onto the track surface; and it will form voids and pockets between sleepers and ballast (Kaewunruen and Remennikov, 2007a). It should be noted that the voids and pokets can easily be observed when the formation has failed, while undetectable voids could still happen in a 'good-looking' track. The problem can be examined using a track inspection vehicle that could measure rail top deflections (e.g. 'AK Car' in Australia or 'Dr Yellow' in Tokaido Shinkansen). The localised track depression or settlement would be excessive in this case. Again, such poor condition of track will later be exacerbated by the impact loading due to wheel/rail irregularities. Figure 3 shows an example of the track damage due to impact loading derived from a rail surface defect, called 'squat'. It has been found that there are voids and pockets between some sleepers and ballast. During the passages of trains, although the track is suppressed, the voids and pockets still remain and the sleepers vibrate aggressively and causes wear to the sleepers themselves and to surrounding ballast gravels. Because the track pumps up and down, the abrasion of the sleepers' soffits can be seen after the excavation. The major bottom abrasion has been noticed at the rail seat area mostly and some at the centre of sleepers.

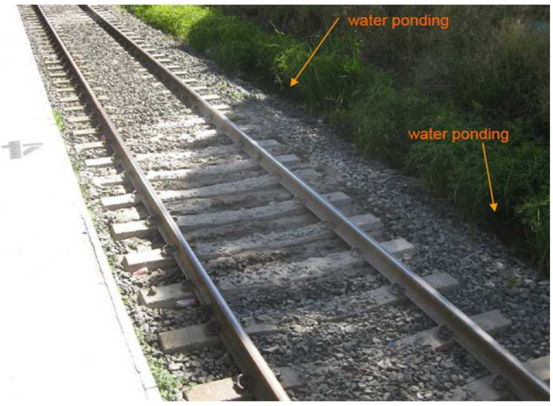
There are some of the past studies related to this matter. Grassie and Cox (1985) studied the dynamic response of tracks with fully and partially supported sleepers. It was found that the dynamic strains of voided sleepers are greater than those of well-supported sleepers, especially at the resonant frequency of about 740 Hz. Plenge and Lammering (2003) found that the partially supported sleepers substantially increase the receptance at sleeper end ranging from 0 to 150 Hz, while it is much less affected at frequencies over 150 Hz. The loss-of-contact sleeper (at centre span) had been included in a track model for the dynamic analysis (Kumaran et al., 2003). The results suggested the increment of dynamic moment magnification at the railseat but a reduction in the bending moment at the mid span of railway sleepers. The limitation of research into this matter makes it difficult to predict the degradation of sleepers and surrounding track components (Kaewunruen & Remennikov, 2008; 2010).



a) shear failure



b) plastic deformation failure



c) classic mud pumping due to poor drainage

**Figure 2**. Track pumping phenomina

This paper provides a better understanding into the dynamic responses of concrete sleepers to impact loading. Using numerical simulations, the parametric studies have been carried out. The insight will help rail operators and maintainers evalute the failure modes and the consequences if the voided sleepers are excited by impact loading. The paper will also discuss the future research to investigate the effect of wheel/rail and track conditions on the contact pressure at the interface between sleepers and ballast.

This study was part of a collaborative research carried out at University of Wollongong, Australia and at Railway Technical Research Institute, Japan.

a) deteriorated track (large localised settlement)

b) pulverised ballast and sleepers (wear)

c) fouled/crushed ballast, abrasion of sleeper soffit and over-stressed formation (after excavation)

**Figure 3**. Track damages due to impact loading

## FINITE ELEMENT FORMULATION AND MODELING OF IN-SITU CONCRETE RAILWAY SLEEPERS

### Modeling and its validation

It has been established that the two-dimensional Timoshenko beam model is a suitable option for modeling concrete sleepers (Neilsen, 1991; Cai, 1992; Grassie, 1995). In this investigation, the finite element model of a concrete sleeper has been previously developed and calibrated against the numerical and experimental modal parameters (Kaewunruen & Remennikov, 2006; Sato et al., 2007). Figure 4 shows the two-dimensional finite element model for an in-situ railway concrete sleeper. Using a general-purpose finite element package STRAND7 (G+D Computing, 2001), the numerical model included the beam elements, which take into account shear and flexural deformations, for modeling the concrete sleeper. The trapezoidal cross-section was assigned to the sleeper elements. The rails and rail pads at railseats were simulated using a series of spring. In this study, the sleeper behaviour is stressed so that very small stiffness values were assigned to these springs. The support condition was simulated using the tensionless beam support feature in Strand7. This attribute allows the beam to lift over the support while the tensile supporting stiffness is omitted. The tensionless support option can correctly represent the ballast characteristics in real tracks (G+D Computing, 2001). Table 1 shows the geometrical and material properties of the finite element model. These data have been validated and the verification results against experimental data have been presented elsewhere (Kaewunruen & Remennikov, 2006; 2007a; 2007b).

**Table 1**. Engineering properties of the standard sleeper used in the modeling

| Parameter lists | | |
|---|---|---|
| Flexural rigidity | $EI_c = 4.60$, $EI_r = 6.41$ | MN/m$^2$ |
| Shear rigidity | $\kappa GA_c = 502$, $\kappa GA_r = 628$ | MN |
| Ballast stiffness | $k_b = 13$ | MN/m$^2$ |
| Rail pad stiffness | $k_p = 17$ | MN/m |
| Sleeper density | $\rho_s = 2{,}750$ | kg/m$^3$ |
| Sleeper length | $L = 2.5$ | m |
| Rail centre distance | $g = 1.503$ | m |

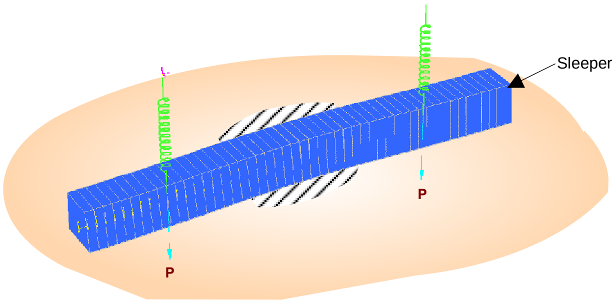


**Figure 4**. Finite element model of an in-situ concrete sleeper

### Highlight in the FE model

To our knowledge, the nonlinear response analysis of railway concrete sleepers in a track system due to the variation of ballast support conditions has not yet addressed by the researchers. Especially when the uplift behaviour due to ballast tensionless support in hogging region of sleepers is considered, a finite element analysis is required to supersede the simple manual calculation. The numerical simulations are conducted using the nonlinear solver in STRAND7, in order to study the effect of ballast stiffness and asymmetrical support conditions on the flexural response of the railway concrete sleeper in a track system. Although there are many types of void formation underneath the sleepers, in this paper only the asymmetrically partial support as shown in Figure 5 will be presented. When $w_R$ approaches nil, the sleeper will be partially hang over by rail bending stiffness. This study will evaluate the effect of partial ballast support on the dynamic responses of railway sleepers to impact loading.

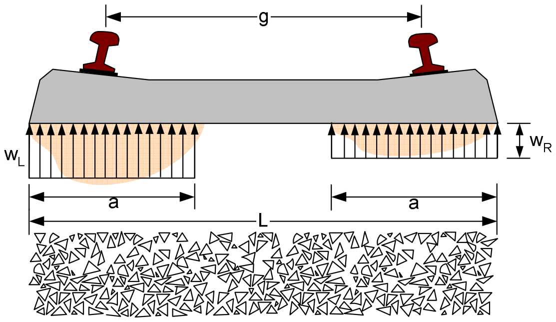


**Figure 5**. Asymmetrical ballast stiffness distribution

### Impact load model

A typical impact force due to a wheel flat is shown in Figure 6 (Remennikov and Kaewunruen, 2008). The actual impact loading can be estimated by using three different transient waveforms: rectangular, triangular, and sinusoidal impulses. Figure 7 shows the waveform estimations of transient loadings used in the dynamic analyses. The emphasis of this study is placed on the parametric effects of various transient waveforms due to different estimation concepts. The common quality of the pulse is the maximum magnitude of 100kN and the duration of 5 msec. These figures are given as a sample guideline for the average parameters of the wheel burden.

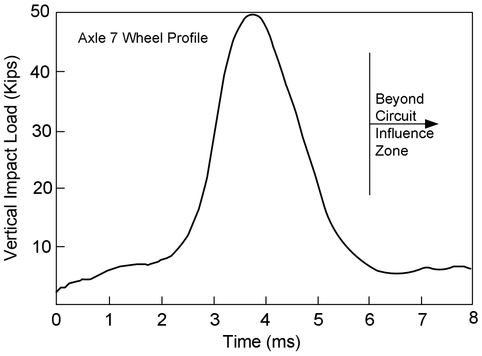


**Figure 6**. A typical impact due to a wheel/rail out-of-round defect (1 kip = 4.448 kN)

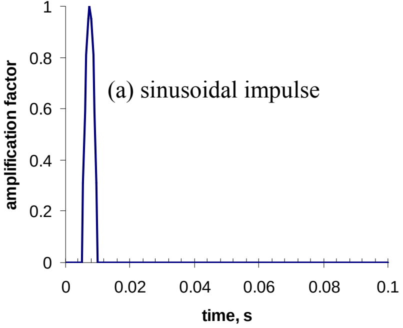


**Figure 7**. Estimations of transient loading

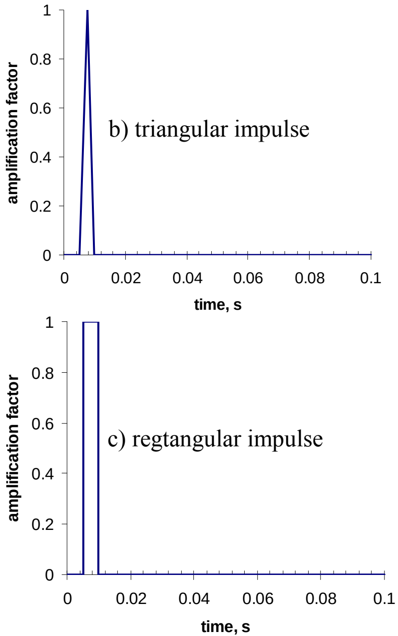


**Figure 7**. Estimations of transient loading

## STATIC RESPONSES OF IN-SITU RAILWAY SLEEPERS

Figure 8 shows the bending moment diagram along the sleeper when subjected to the equal wheel loads of 100kN at both railseats, in comparison with the standard design moments. Based on standard formulas in accordance with AS1085.14 (Standards Australia, 2003; Kaewunruen and Remennikov, 2009a), the design maximum positive bending moment at the rail seat $M_{R+}$ = 12.50 kNm, while the centre negative design bending moment $M_{C-}$= 6.95 kNm. It is typical that the positive and negative moments are associated with the railseat and mid-span sections, respectively. It shows that the standard design moments provide the conservative results (Remennikov et al., 2011). The standard design moment at mid span is about half between the other two cases.

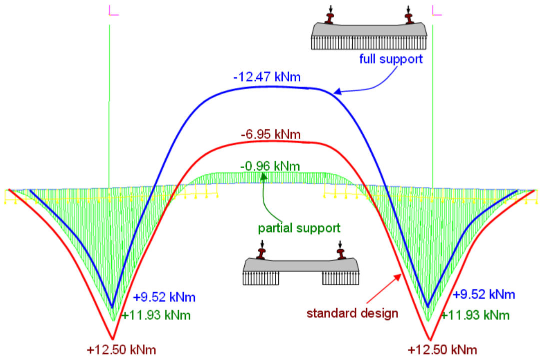


**Figure 8.** Flexural response of an in-situ railway sleeper (Kaewunruen and Remennikov, 2009)

## IMPACT RESPONSES OF FULLY SUPPORTED CONCRETE RAILWAY SLEEPERS

### General

As one of the major problems in the real tracks, it is the difficulty to determine whether the support condition would be partial or full and whether the sleeper would bend enough so that the ballast can provide the compression stiffness. In light of this issue, the full ballast support condition is considered first for the parametric study, so as to evaluate the discrepancy between the dynamic flexural responses of the railway concrete sleepers laid on full and partial support conditions. This case study considers the full support along the whole length of sleeper and determines the effect of waveform shapes on the dynamic responses of sleeper.

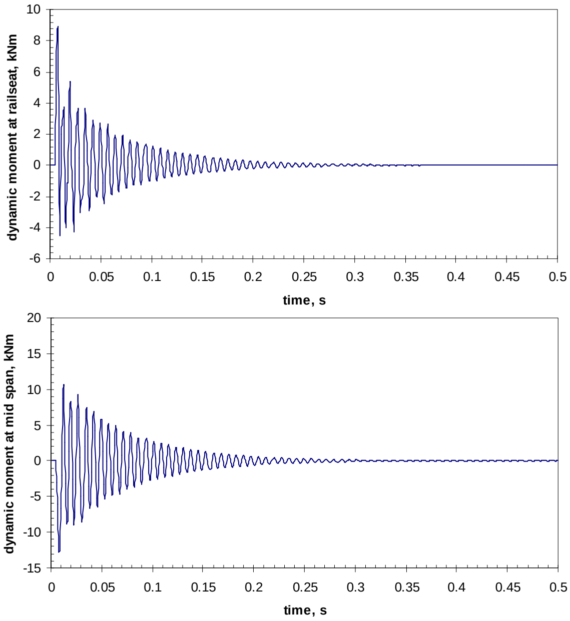


**Figure 9**. Transient responses of fully supported railway concrete sleeper to triangular pulse in time domain

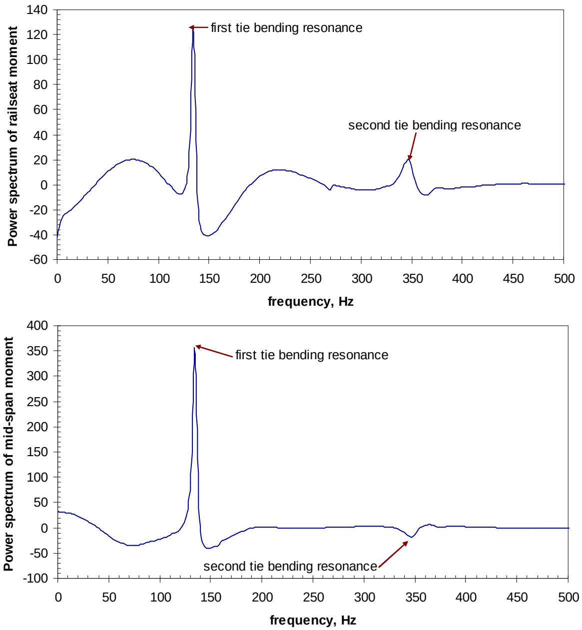


**Figure 10**. Transient responses of fully supported railway concrete sleeper to triangular pulse in frequency domain

### Dynamic responses to triangular impulse

Figure 9 depicts the dynamic bending responses of the fully supported railway concrete sleeper subjected to the triangular pulse while the corresponding power spectra of the dynamic bending moments is illustrated in Figure 10. It is found that the maximum positive and negative dynamic bending moments at rail seats are increased about 0.5 percent and 5 percent, respectively, based on those of partially supported railway concrete sleeper. In contrast, although the negative dynamic bending moment at mid span is very similar to that of the partially supported sleeper, the positive one decreases significantly about 2 times from that of the partially supported sleeper. Figure 10 shows the little influence of support conditions on the modal phase angle of the dynamic bending moments.

## Dynamic responses to sinusoidal impulse

Figure 11 shows that the support conditions have insignificant effect on the dynamic bending moments at rail seats under the sinusoidal transient loading. On the other hand, the support conditions play a role on those at mid span. While the negative dynamic bending moment at mid span increases about 15 percent, the positive dynamic bending moment diminishes over a half. However, it seems that the dynamic phase angles are not affected by the support conditions as shown in Figure 12.

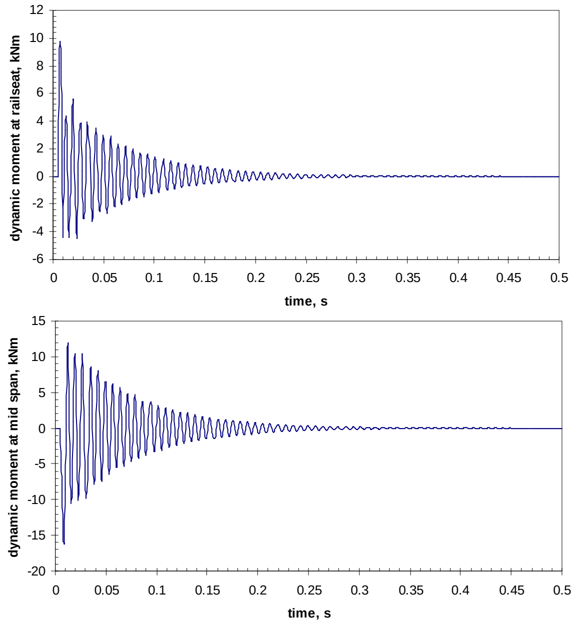


**Figure 11**. Transient responses of fully supported railway concrete sleeper to sinusoidal pulse in time domain

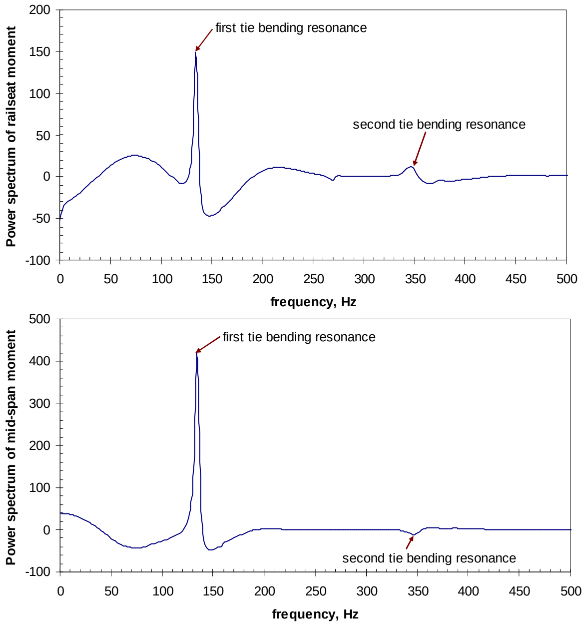


**Figure 12**. Transient responses of fully supported railway concrete sleeper to sinusoidal pulse in frequency domain

## Dynamic responses to rectangular impulse

Figure 13 presents that the full support condition has very little influence on both positive and negative dynamic bending moments at rail seats, subjected to the rectangular impulse. It is however found that the positive dynamic bending moment at mid span reduces over 40 percent, while the negative dynamic bending moment increases about 20 percent due to the effect of the full support condition. It is shown in Fig. 14 that there is no change in dynamic phase differences of the dynamic flexural responses at either rail seats or mid span.

*Remark:* the parametric study indicates that the dynamic bending moment resultants are affected considerably by the different transient waveforms. Choice of impact force modelling should be choosen as close to the actual force as possible: in this case, sinusoidal waveform.

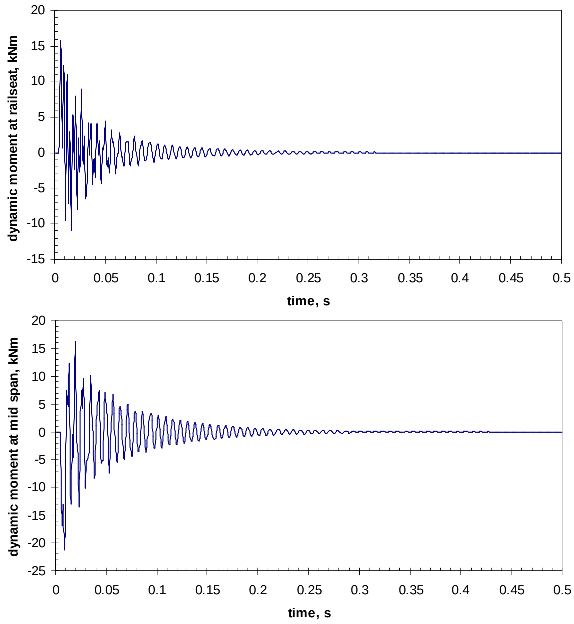


**Figure 13**. Transient responses of fully supported railway concrete sleeper to rectangular pulse in time domain

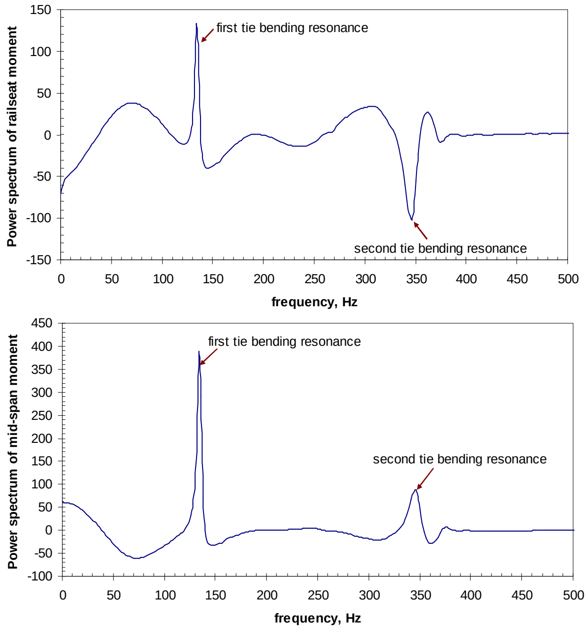


**Figure 14**. Transient responses of fully supported railway concrete sleeper to rectangular pulse in frequency domain

## IMPACT RESPONSES OF VOIDED CONCRETE RAILWAY SLEEPERS

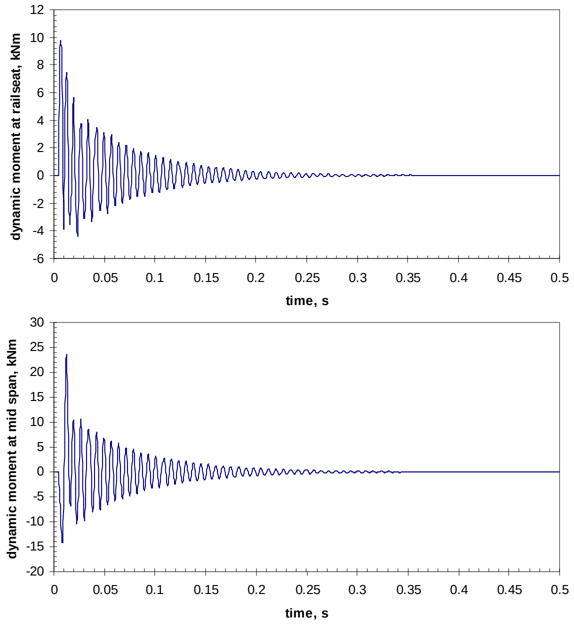


**Figure 15**. Transient responses of evenly supported railway concrete sleeper to sinusoidal pulse in time domain

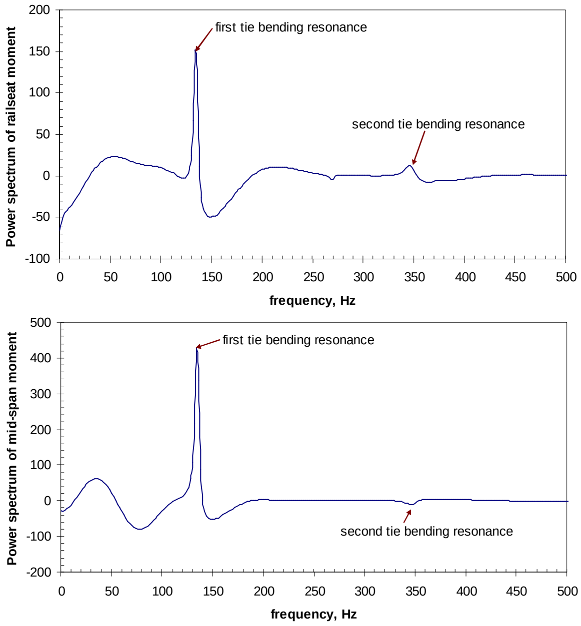


**Figure 16**. Transient responses of evenly supported railway concrete sleeper to sinusoidal pulse in frequency domain

### Symmetrical support condition

Figure 15 depicts the dynamic flexural response of the railway concrete sleeper subjected to the sinusoidal pulse. Overall, the maximum positive dynamic bending at rail seats is about 77 percent of the standard design bending moment, and about 81 percent of the quasi-static response. The ratio between the maximum negative dynamic bending at rail seats and the maximum positive dynamic bending is about 0.45. The maximum negative dynamic bending at mid span, is about 2 times of the standard design bending moment, and about 14 times of the static flexural response. The ratio between the maximum negative and positive dynamic bending moments at mid span is about 0.60. The power spectra of the dynamic bending moments under the sinusoidal transient loading can be seen in Figure 16. It appears that there is a modal phase difference in the dynamic bending responses at mid span.

### Asymmetrical support condition

To evaluate the effect of aysmmetical support at different frequency spectra, the impact load duration (or pulse length, t) is varied with respect to the period of the lowest mode of vibration of model concrete sleeper, $T_1$ (Kaewunruen & Remennikov, 2009b).

Figure 17 presents the dynamic bending moments at the left-hand-side rail seat of voided sleepers (Note: void is always kept on the right hand side). It is found that when the frequency of impact loading is higher than the lowest bending mode of sleeper (or the duration is shorter than $T_1$), the positive dynamic moments tend to remarkably increase with the excitation frequency. This may cause the sleepers to crack and to have shorter service life. However, the void condition does not affect the positive flexural moments at the left-hand-side rail seat of concrete sleepers. On the other hand, the void condition plays a key role in increasing the negative bending moments at the left-hand-side rail seat of concrete sleepers, as shown in Figure 17 (bottom). If the sleeper losses the support at the other end (right-hand-side rail seat), it is likely that a structural crack may occur (Kaewunruen & Remenikov, 2009b; 2010).

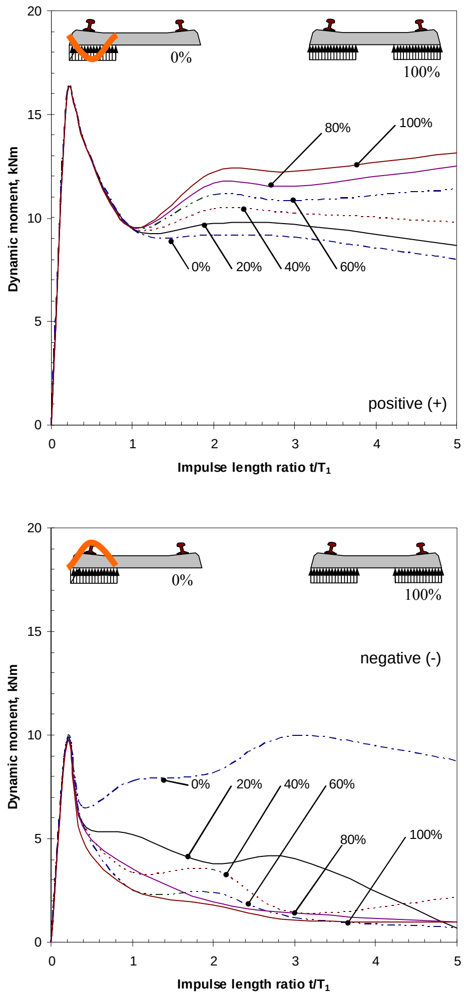


**Figure 17**. Dynamic bending moments at the left-hand-side rail seat of voided sleepers to impact loading

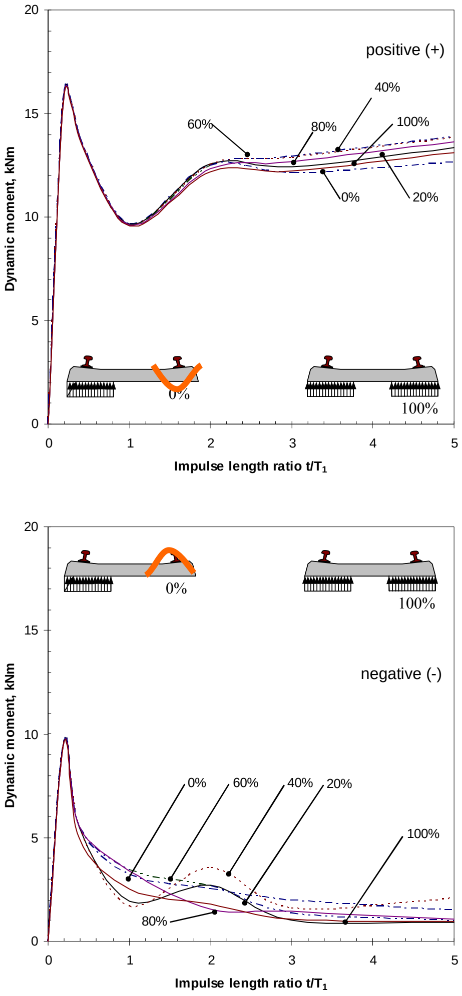


**Figure 18**. Dynamic bending moments at the right-hand-side rail seat of voided sleepers to impact loading

Figure 18 demonstrates the dynamic bending moments at the right-hand-side rail seat of voided sleepers (Top: positive moment; Bottom: negative moment). It indicates that the ballast void has little effect on the positive bending moments but it highly influences the negative bending moments, especially when the excitation frequency is relatively lower than the lowest bending mode of sleeper. In this case, the peak positive bending moments seem to be suppressed at $t/T_1 = 1$, whilst the negative responses fluctuate and are dependent to the excitation frequency.

The dynamic bending moments at the mid-span of the voided sleepers are shown in Figure 19 (Top: positive moment; Bottom: negative moment). It is evident that the positive bending moments at the mid-span are significantly influenced by the ballast support condition. The ballast void in such case could redistribute the impact force onto the negative flexural deformation. When the ballast support is lost at a rail seat, the negative bending moment tend to significantly increase over a wide range of frequency and this may cause wear to crib ballast (Kaewunruen & Remennikov, 2009a) and may radiate low-frequency noise (Thompson, 2010). In contrast, the loss of ballast support tends to suppress the dynamic positive moments at the mid-span. This is because the support condition generally redistributes the load and bends the sleeper up so-called ‘hogging moment’. In addition, it is apparent that the dynamic moments at mid-span of voided sleepers are dependent to the excitation frequency.

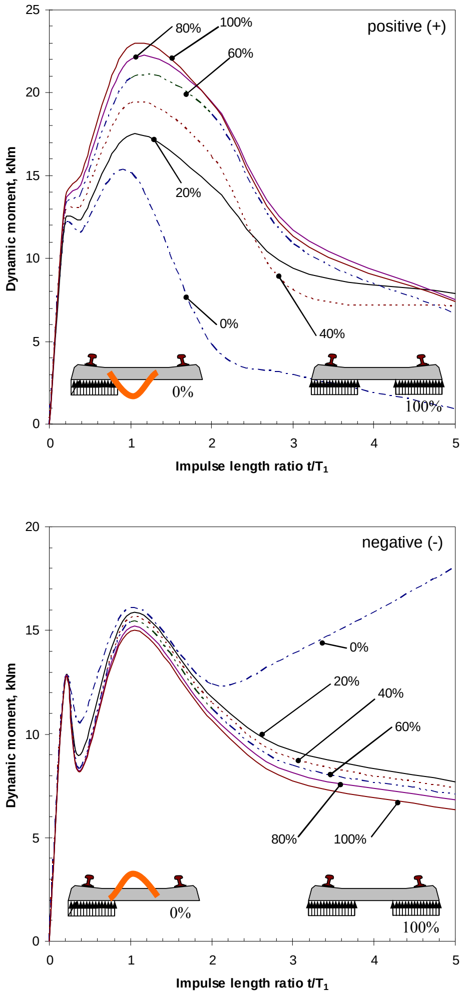


**Figure 19**. Dynamic bending moments at the mid-span of voided sleepers to impact loading

## CONCLUSIONS

This paper numerically investigates the parametric effect of different types of transient loading waveforms on the dynamic flexural responses of the railway concrete sleepers in a track system. It also explores the dynamic influence of full and partial ballast support conditions. An established dynamic finite element model of railway concrete sleepers is utilized in this study. The nonlinear transient solver in STRAND7 was employed to cope with the tensionless support and the nonlinear transient waveforms. The parametric study indicates that the dynamic bending moment resultants are affected considerably by the different transient waveforms. The impact loading excites the railway concrete sleepers and the railway concrete sleeper vibrates aggresively.

To compare between the static and dynamic results, the pulse duration was varied. It is however found that the dynamic bending moment resultants are affected significantly by the rectangular pulse, followed by the triangular and sinusoidal transient waveforms. Using the Fast Furrier Transform (FFT), the critical frequencies as well as the phase difference can be determined through the power spectra. It is noticeable that the dynamic bending moments at mid span act out of phase between the first and the second sleeper-bending resonances. The support condition shows a considerable influence over the dynamic flexural responses either at rail seats or at the mid-span. Apparently, the ballast void tends to reduce the positive dynamic bending moments but to enlarge the negative ones at mid span. It is also noticeable that the dynamic flexural responses of the voided sleepers are dependent to the duration of impact loading or excitation frequency. The dynamic amplification due to impact loading could cause the ballast to wear out and sleeper to crack; and might also increase the low frequency noise.

## FUTURE RESEARCH

Railway Technical Research Institute (RTRI) has developed an instrumented concrete sleeper as illustrated below (Ueakawa et al., 2010). It will be used to determine the transient load distribution characteristics of sleeper onto supporting ballast layer. Other types of voids and pockets have been analysed numerically and will appear elsewhere. The outcome will help track design engineers improve and optimise the shape and dimensional design of concrete sleepers.

**Figure 20**. Instrumented sleepers

## ACKNOWLEDGMENT

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