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SIMULATING SHOCK LOADS IN RAILWAY TRACK ENVIRONMENTS: EXPERIMENTAL STUDIES

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Abstract

The nature of loading conditions on railway tracks is mostly of regular loading patterns due to passage of wheels of rolling stock. Dynamic forces on a railway track caused by abnormal impacts due to wheel flats, rail dips, etc. are usually highly impulsive with short durations and high frequency contents. There have been a number of investigations on the wheel/rail impacts due to wheel and rail imperfections and track abnormalities. However, the effect of railway track environments including ballast and rail pads has yet been addressed. Intensive studies on the impact resistance of railway concrete sleepers have been conducted at the University of Wollongong, Australia. In order to understand more clearly the manner in which track components respond to those forces, and to clarify the processes whereby concrete sleepers in particular carry those actions, it is vital to ascertain the spectrum and amplitudes of forces applied to tracks. In addition, artificial impacts replicating the generic actual wheel/rail interaction must be identified, prior to investigating the shock responses of the railway concrete sleepers.

This paper presents the experimental studies into the effects on dynamic loading conditions of track environments including the ballast support condition and rail pads. An assembled in-situ concrete sleeper has been constructed and subjected to artificial shock loading using a large capacity drop-weight hammer. The attempts to simulate the repeated impacts due to general wheel flats or engine burns are demonstrated so as to investigate of probabilistic impact failure of the concrete sleepers. The shock loadings under various track environments have been quantitatively monitored and recorded by National Instrument multi-channel PXI-SCXI using LabView8. These impacts could eventually lead to cracking and failure of the sleepers, and hence are important in the context of developing the new reliability-based design approach for the railway prestressed concrete sleepers.

1. INTRODUCTION

Ballasted railway tracks have been built and used intensively throughout Australia. In general, there are two major parts of ballasted railway track, including the super-structure and the sub-structure. The super-structure is made up of steel rails, the fastening systems and railway sleepers (or so-called 'railroad ties' in the US); whilst the ballast, sub-ballast, sub-grade and formation, form the sub-structure. Figure 1 illustrates the ballasted track components. The railway sleepers are an important component of railway track structures. Its main role is to distribute loads from the rail foot to the underlying ballast bed and foundation. There is a widespread notion based on the industry experience that railway concrete sleepers have reserves of strength that are untapped. It is thus important to ascertain the spectrum and amplitudes of forces applied to the railway track, to understand more clearly the manner in which track components respond to those forces, and to clarify the processes whereby concrete sleepers in particular carry those actions. In addition, cracks in concrete sleepers have been visually observed by many railway organizations. As noted in the review [1], the principal cause of cracking is the infrequent but high-magnitude wheel loads produced by a small percentage of "bad" wheels or railhead surface defects. Those loads are of short duration but of very high magnitude. For instance, the typical loading duration produced by wheel flats is about 1-10 ms, while the force magnitude can be over 400 kN per rail seat. Current design philosophy for prestressed concrete sleepers is based on permissible stress principle taking into account only the static and quasi-static loads, which are unrealistic to the actual dynamic loads on tracks. In order to devise a new limit states design concept, the research efforts are required to perform comprehensive studies of the loading conditions, the static behaviour, the dynamic response, and the impact resistance of the prestressed concrete sleepers [2-5]. A major research effort at the University of Wollongong is to evaluate and compare the ultimate capacities of concrete sleepers under static and impact loads.

Railway prestressed concrete sleepers have been utilized in railway industry for over 50 years. Based on the current design approach, the design life span of the concrete sleepers is also considered around 50 years [6]. In reality, the nature of loading conditions on railway track structures is time dependent. It has been found that wheel/rail interactions result in much higher-frequency and much higher-magnitude forces than simple quasi-static loads. These forces are often called as '*dynamic wheel/rail*' or '*impact*' forces. The typical impact loadings due to train and track vertical interaction has been presented in ref [4] with particular reference to the shapes of the typical waveforms of impact loads generally found in railway track structures. According to a recent finding [7], the probabilistic shock loading on the tracks can be predicted, for instance:

$$\frac{1}{T} = 10^{-0.01F+4.1} \tag{1}$$

where F is the force magnitude and T is the return period associated with the impact force.

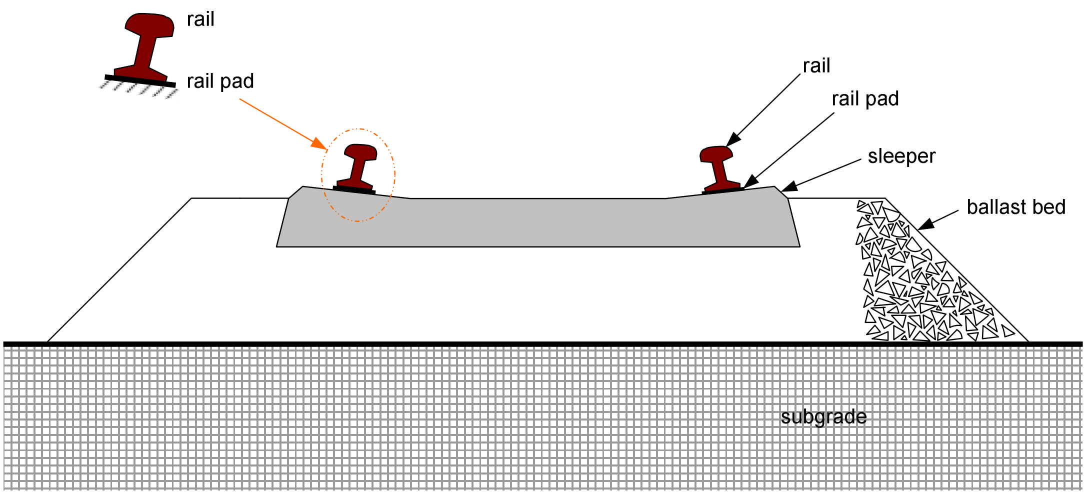


Figure 1 Typical ballasted track structure

Figure 2 High-capacity drop-weight impact machine at the University of Wollongong

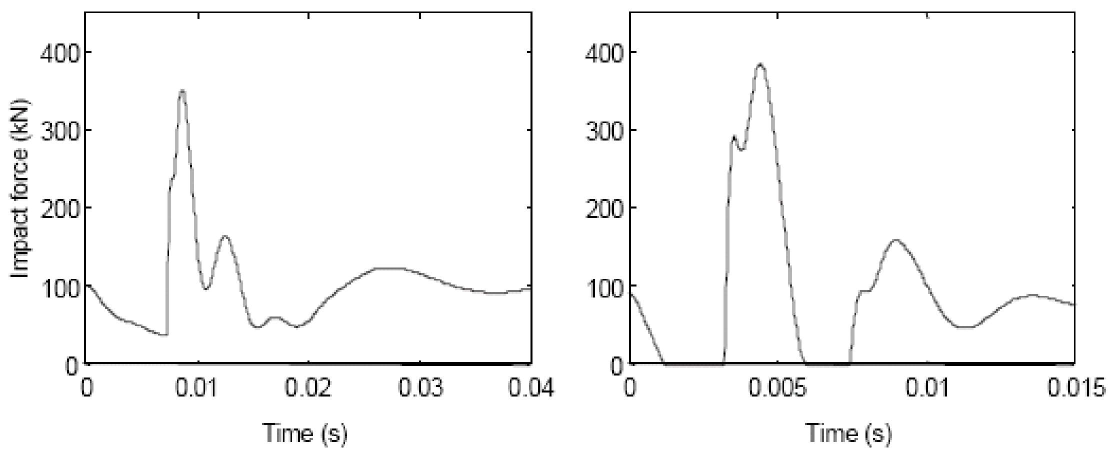
All static, quasi-static, and impact loads are very important in design and analysis of railway track and its components. Generally, dynamic shock loading corresponds to the frequency range from 0 to 2000 Hz due to modern track vehicles. The shape of impact loading varies depending on various possible sources of such loading, e.g. wheel flats, out-of-round wheels, wheel corrugation, short and long wavelength rail corrugation, dipped welds and joints, pitting, and shelling. Wheel/rail irregularities induce high dynamic impact forces along the rails that may greatly exceed the static wheel load. In all cases, the impact forces are significantly dependent on the train speed. These impulses would occur repetitively during the roll. Loss of contact between wheel/rail, so-called "wheel fly", will occur if the irregularity is large enough, or the speed is fast enough. However, the impact force could be simplified as a shock pulse acting after the static wheel load is removed. The typical magnitude of impact loads from the reviewed cases [4] varies roughly between 100 kN and up to 750 kN, depending on the causes and the traveling speed of train. The durations of such loads are quite similar, varying between 1 and 10 ms. However, the representative values of the first peak ($\boldsymbol{P_1}$) of the forces caused by dipped joints should be about 400 kN magnitude with 1 to 5 ms time duration. For the second peak ($\boldsymbol{P_2}$), the average values are about 80 kN magnitude and 5 to 12 ms time duration. Therefore, it should be taken into account that the typical duration of impact wheel forces varies widely between 1 and 12 ms [4,8].

In this investigation, the new high capacity impact machine, as depicted in Figure 2, has been developed to evaluate the possibility to simulate the shock loading conditions. The prestressed concrete sleepers were supplied by an Australian manufacturer, under a collaborative research project of the Australian Cooperative Research Centre for Railway Engineering and Technologies (Rail CRC). The sleepers are arranged under the actual in-situ condition, using the alternative method, in accordance with AS1085.19 [9]. To produce different shock quantity, the drop height and the softening media (to reduce contact stress) are the experimental parameters to be varied.

2. EXPERIMENTAL OVERVIEW

Artificial impacts simulating actual probabilistic loads can be rendered using a free falling mass. This drop-weight technique is one such feasible option as it can be conveniently facilitated and is the economical option. Therefore, the high-capacity drop-weight impact testing machine, which is currently the largest in Australia, has been developed as depicted in Figure 2. To eliminate surrounding noise and ground motion, the concrete sleepers were set up and placed on a strong isolated floor in the laboratory. The thick rubber mat was used to replicate the ballast support. It was found that the test setup represents the concrete sleepers in general soft track systems [8-10]. To apply impact loads, the drop hammer used has the weight of 5.81kN. At the railseat was installed the rail with fastening system to transfer the load to the specimens. The roller was attached to the steel drop mass through runners guiding the descent of the drop weight hammer. The hammer was hoisted mechanically to the required drop heights and released by an electronic quick release system. The core of the test rig is the free-fall hammer that can be dropped from a maximum height of 6m, or equivalent to the maximum drop velocity of 10 m/s. The impact load was monitored and recorded by the dynamic load cell connected to the computer.

Efficiency of drop weight hammer has been obtained through the calibration tests done using high speed camera. It is found that due to friction of guiding runner the hammer's experimental velocity averagely reduces to 98% of theoretical velocity. Experimental setup and impact tests were arranged in accordance with the Australian Standards. The in-situ conditions of railway concrete sleeper were replicated as shown in Figure 2. Simulations of impact loading that actually occurred in a track were succeeded experimentally and numerically [10-12]. For instance, typical shock loadings due to a wheel flat are depicted in Figure 3 [13]. In this example, the magnitude is roughly varied from 350-400kN over a duration of about 3-5 ms. This study presents the experimental techniques to achieve such shock loading quantities using a drop-weight impact hammer. In addition to vary the drop heights, the techniques include changing of track environments (effects of rail pads and ballast support) as well as alleviating of contact stresses (by inserting a variety of softening media at the contact zone between the impactor and the rail head). Table 1 shows the experimental programs to investigate the effects on the impact load characteristics of drop height, track environment, and contact stress. The drop heights were varied between 0.1m and 0.8m. The rail pad used in the test setup is the HDPE type. Two different support conditions represent the real 'hard' and 'soft' tracks in practice. Figure 4 shows the experimental setup.



a) at train speed 30 km/hr　　b) at train speed 80 km/hr

Figure 3 Dynamic forces due to 2 mm rounded wheel flat [13]

Table 1 Experimental programs

No	Drop height (m)	Use of rail pad [Y: yes; N: no]	Support condition	Use of softening media
1	0.2, 0.4, 0.6, 0.8	Y	Soft	direct contact 1mm neoprene 2mm neoprene 3mm neoprene
2/3	0.2, 0.4	Y/N	Soft	direct contact 1mm neoprene 2mm neoprene 3mm neoprene
4/5	0.2, 0.4	Y/N	Hard	direct contact 1mm neoprene 2mm neoprene 3mm neoprene

Figure 4 Experimental setup

3. RESULTS AND DISCUSSIONS

In the first case, the full installation of in-situ sleeper has been carried out to replicate the real condition on the track. The dynamic stiffness of the new HDPE pad (High density polyethylene 7.5mm thick) is about 1,200 MN/m [14]. The conveyor belt in mining industry is found suitable for use as the alternative support [8,15]. The impact forces measured from the dynamic load cell from direct contact between rail and impactor are presented in Figure 5. Very small bending crack was firstly detected at the drop height of 600mm but the small shear cracks were also found after few blows at the drop height of 800mm. However, no major failure can be observed. From the test undertaken it is evident that the sleeper exhibits a significant amount of reserved strength. Figure 5 shows that the higher drop heights provide the larger magnitude of impact loading, but slightly reduce the shock duration. The magnitude of the shock loading associated with the flexure of the sleeper varies from 380 to 1,150 kN while the duration remains in a small range between 4 and 6 ms. It should be noted that the first peaks are related to the contact stresses at the contact zone between the impactor and the railhead. The actual flexural responses of the sleeper are most likely due to the second peaks.

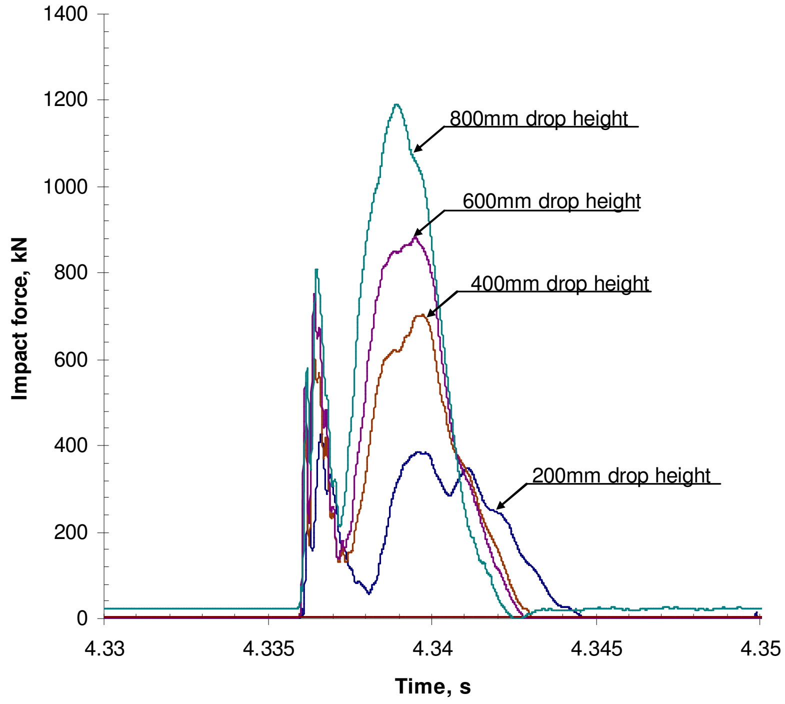


Figure 7 Impact forces at different drop heights

Table 2 Impact load characteristics in the soft track with rail pad

Softening media	**Drop height**			
	0.2m.		0.4m	
	Impact characteristics		**Impact characteristics**	
	Magnitude, kN	Duration, ms	Magnitude, kN	Duration, ms
Direct contact	426	7	700	7
1mm Neoprene	362	9	611	8
3mm Neoprene	327	9	466	9
5mm Neoprene	300	11	419	10

Table 3 Impact load characteristics in the soft track without rail pad

Softening media	**Drop height**			
	0.2m.		0.4m	
	Impact characteristics		**Impact characteristics**	
	Magnitude, kN	Duration, ms	Magnitude, kN	Duration, ms
Direct contact	564	6.5	904	5
1mm Neoprene	322	2	858	5.5
3mm Neoprene	436	8	530	8
5mm Neoprene	359	9	493	8.5

Table 4 Impact load characteristics in the hard track with rail pad

Softening media	**Drop height**			
	0.2m.		0.4m	
	Impact characteristics		**Impact characteristics**	
	Magnitude, kN	Duration, ms	Magnitude, kN	Duration, ms
Direct contact	441	8	761	6.5
1mm Neoprene	429	8.5	622	8
3mm Neoprene	386	9	563	8.5
5mm Neoprene	313	11	365	10

Table 5 Impact load characteristics in the hard track without rail pad

Softening media	**Drop height**			
	0.2m.		0.4m	
	Impact characteristics		**Impact characteristics**	
	Magnitude, kN	Duration, ms	Magnitude, kN	Duration, ms
Direct contact	675	5.5	1036	4
1mm Neoprene	503	6.5	905	5.5
3mm Neoprene	485	8	800	7
5mm Neoprene	400	9	475	9

Tables 2-5 present the impact load characteristics under various conditions. It is found that the impact force magnitude increases up to 20 to 25 % when using the rail pad in the soft track, while it ascends as much as 45 to 50% in the hard track. On the other hand, the duration gently reduces either when the support condition is stiffer or when the rail pad is very stiff (or when no use of rail pad). It appears when considering the similar experimental setups that the shock quantities (including magnitude and duration) tend to be more susceptible to the rail pad effect in the hard track than those in the soft track. The support condition seems to dominate the impact responses as well as the corresponding behaviour of the concrete sleepers. Remarkably, the rail pad plays a role on the man-made shock loading quantities, as it tends to attenuate the impact stresses (reducing the magnitude of force) and filter the impulse frequencies (extending the time duration of impact). This is because the in-situ sleepers on the soft track possess the global track modulus less than the hard track. Also, it is well known that the contact force quantity largely depends on the contact stiffness [16]. The magnitude of impacts was found to increase as the contact stiffness, whilst the pulse duration is inversely proportional to the contact stiffness. Then, it is clearly found that the rail pad provides the resilient support as a spring to the rail [16], thus weakening the contact stiffness.

The influence on artificial shock quantities of the softening media to reduce the contact stress between the impactor and the railhead is established from the above experiments. Regardless of the effects of the use of rail pad or the support conditions, the softening media significantly affects the shock loading quantities. It is discovered that the thicker the softening media, the lesser the impact magnitude but the larger the pulse duration. The effect of the softening media is constantly similar (about 25-30% decrease) at all conditions, whether in the soft or the hard track, or whether with or without the use of rail pad.

4. CONCLUDING REMARKS

Wheel or rail abnormalities were found to cause the large impact load during the dynamic interaction between the wheel and rail. The impact load characteristics are typically of high magnitude but short duration. In general, the force magnitude varies between 300 and 400 kN, with the pulse duration from 1 to 10 ms. This magnitude of impact corresponds roughly the fifty-year return period, which is about only once in the design life span of concrete sleepers. The research conducted at the University of Wollongong, Australia, aims to understand more clearly the manner in which track components respond to those forces, and to clarify the processes whereby the concrete sleepers in particular carry those actions. It is therefore very important to ascertain the statistics related to the spectrum and amplitudes of forces applied to tracks, as well as to develop a methodology to replicate the impacts.

This paper presents the effects on dynamic loading conditions of track environments including the ballast support condition and rail pads. The techniques of free falling mass and contact stress alleviation have been demonstrated through the extensive experimental programs. With particular reference to the track environment, the rail pad plays a more significant role on the artificial shock quantities than the support conditions. The uses of rail pad clearly demonstrate the preclusion of excessive dynamic stress from the rail to the railway sleepers. However, the support condition is most likely to involve with the global track modulus and the sleeper's inertia, which is directly proportional to the impulse magnitude and vice versa. In spite of the sound effects of track environment, the softening media dominantly diminish the contact stress and shock loading magnitude but enlarge the impact duration.

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REFERENCES

[1] Murray, M. and Cai, Z., "Literature review on the design of railway prestressed concrete sleeper' *RSTA Research Report*, Australia, 1998.

[2] Gustavson, R., "Static and dynamic finite element analyses of concrete sleepers", *Licentiate of Engineering Thesis*, Department of Structural Engineering, Chalmers University of Technology, Sweden, 2000.

[3] Kaewunruen, S. and Remennikov, A.M., "Field trials for dynamic characteristics of railway tracks using impact excitation technique", *NDT&E International*, in press, 2007.

[4] Remennikov AM and Kaewunruen S, "A review on loading conditions for railway track structures due to wheel and rail vertical interactions". *Progress in Structural Engineering and Materials*, invited, (2006).

[5] Kaewunruen, S. and Remennikov, A.M., "Rotational capacity of railway prestressed concrete sleeper under static hogging moment", *Proceedings of the tenth East Asia-Pacific Conference on Structural Engineering & Construction (EASEC-10)*, Bangkok, Thailand, August 3-5, 2006.

[6] Standards Australia, "Railway track material - Part 14: Prestressed concrete sleepers" *Australian Standard: AS1085.14-2003*, 2003.

[7] Leong, J. "Development of a limit state design methodology for railway track", *Master of Engineering Thesis*, Queensland University of Technology, 2007.

[8] Esveld C, *Modern Railway Track*, The Netherlands MRT Press, 2001.

[9] Standards Australia, "Railway track material - Part 19: Railway fastening system" *Australian Standard: AS1085.19-2001*, 2001.

[10] Kaewunruen, S and Remennikov, AM, "Experimental and numerical studies of railway prestressed concrete sleepers under static and impact loads". *Civil Computing*, April, in press, (2007).

[11] Kaewunruen, S and Remennikov, AM, "Low-velocity impact analysis of railway prestressed concrete sleepers". *23rd Biannual Conference of Concrete Institute of Australia –Concrete07*, October 18-20, Adelaide, Australia , accepted, (2007).

[12] Kaewunruen, S and Remennikov, AM, "Investigation on static and dynamic performance of railway prestressed concrete sleepers". *SEM Annual Conference and Exposition on Experimental Mechanics*, June 3-6, Springfield, MA, USA, accepted, (2007).

[13] Wu, T.X., & Thompson, D.J. A hybrid model for wheel/track dynamic interaction and noise generation due to wheel flats. *ISVR Technical Memorandum No. #859*, Institute of Sound and Vibration Research, University of Southampton, UK, 2001.

[14] Remennikov, A., Kaewunruen, S. "Determination of dynamic properties of rail pads using instrumented hammer impact technique". *Acoustics Australia* 33(2): 63-67, (2005).

[15] Kaewunruen, S., Remennikov, A.M. "Railway ballast replication using modal data". *Experimental Techniques*, accepted, (2007).

[16] Cai, Z. "Modelling of rail track dynamics and wheel/rail interaction". *Ph.D. Thesis*, Department of Civil Engineering, Queen's University, Ontario, Canada, 1992.

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