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IMPACT DAMAGE CLASSIFICATION OF RAILWAY PRESTRESSED CONCRETE SLEEPERS

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SUMMARY

Commonly, railway tracks suffer with the extreme loading conditions, which are attributed 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, as well as they are of low-possibility occurrence during the design life of the prestressed concrete sleepers. In spite of the most common use of the prestressed concrete sleepers in railway tracks, their impact responses and behaviours are not deeply appreciated nor taken into the design consideration. Up until recently, a new limit states design approach, whereas the dynamic effects are included, has been adopted in European countries, and has been proposed for the revision of Australian Standard AS1085.14.

This paper presents the experimental investigations aimed at understanding the progressive collapse of prestressed concrete sleepers in railway track structures under incremental impact loading, in order to form the state of the art of the impact damage classification for prestressed concrete sleepers. Series of repeated impact tests for the in-situ prestressed concrete sleepers were carried out, ranging from a low drop height to the ultimate drop height where the ultimate failure occurred. The cumulative impact damage and crack propagation are highlighted in this paper. The effects of track environment including soft and hard tracks are also presented. By using the concept of damage accumulation, the relationships between cumulative damage of concrete sleepers and given impulse enable the predictions of residual life of the concrete sleepers under severe impact loads. It is noticed that the hard track condition rapidly exacerbates cracking in the concrete sleepers. Based on the progressive impact testing results, the damage classification of prestressed concrete sleepers has been proposed. This proposed damage index can be correlated to either increased axle load or faster train speed using an advanced dynamic analysis of railway track package.

INTRODUCTION

Transportation structures significantly contribute to the social and economic growth of any country around the world. Commonly, it is well known that railway system is the best and safest transportation option for either passenger or freight nowadays. Among the modern types of railway tracks, sleepers or ties are often used in both ballasted and ballastless railway tracks for rural, suburban, or inner city rail networks. The financial viability of the ballasted track relies on its cost-effectiveness in construction, maintenance, and renewal. Esveld [1] claimed that ballasted railway track has many superior advantages; for example, the construction costs are comparatively low, the maintenance and repair of track and its components are convenient, it has high damping characteristics and very good drainage properties, and noise and ground-borne vibrations can be controlled. Current knowledge has led to the over-conservative, empirical method in analysis and design of concrete sleepers. At present, the understanding and knowledge of behaviour of railway tracks in realistic conditions are insufficient, and also very often, those analyses and designs of track structures are not carried out by professional civil engineers. These have led to material wastes due to conservative and poor judgement. Also, the practice results in the unrealistic representation and interpretation in the context of test methods. Generally, the railway tracks are subjected to a variety of dynamic loads, and understanding the dynamic track behaviour is imperative in order to evaluate the structural safety, service life, and true capacity of the railway track components.

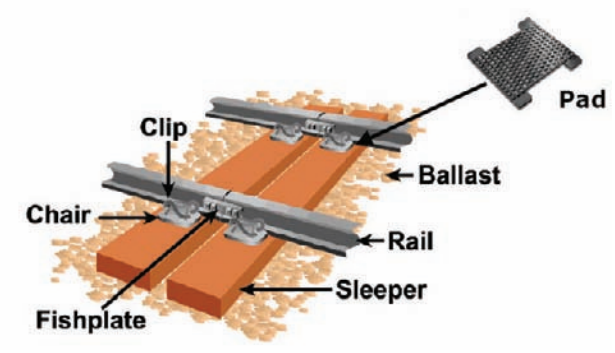


Figure 1 : Typical ballasted rail tracks

The typical ballasted track system can be illustrated in Figure 1. Although railway prestressed concrete sleepers have been developed and utilized in railway industry for over 50 years, the current design approach in Australia and US has been based on permissible stress design whereas the structural behaviours or deformations are kept within the elastic range [2, 3]. The design load calculation for structural design is taken from static or quasi-static loads, by taking into account a dynamic impact factor multiplying with the wheel load. The railseat load calculation is obtained from the simple load distribution. The design bending moments are considered from static load cases and the simplification of elastic-foundation-supported beam theory. It should be noted that the design life span of the concrete sleepers is also considered to be around 50 years [2]. Recent research attention has been focussed on vertical static and dynamic forces on railway tracks when trains are operated at different speeds and different static axle loads. This information will be an important data for the re-evaluation of the limit states capacity of existing tracks, which were designed using the permissible stress concept.

Interactions between the wheel of rolling stocks and the rail often generate interfacial impact forces to railway tracks. The 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 dynamic impact loads are of very high magnitude but short duration, and are caused by either wheel or rail abnormalities such as flat wheels, dipped rails, etc. The typical impact loadings due to train and track vertical interaction has been presented in Remennikov and Kaewunruen [4] with particular reference to the shapes of the typical waveforms of impact loads generally found in railway track structures. Figure 2 depicts the typical impact loads due to a wheel flat [5]. Although the possibility of the large impact loading to cause an extreme failure to an in-situ concrete sleeper could be very low about once or twice in the design life cycle, the cracking damage of track components especially for the concrete sleepers is often observed [6-8].

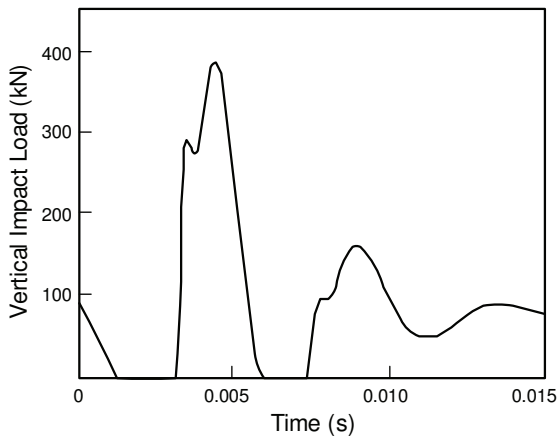


Figure 2 : Typical impact due to a wheel flat [5]

Figure 3 : UoW Impact Testing Machine

The railway sleeper is a major component of railway tracks. Its role is to distribute the load from the rails to the underlying ballast bed. However, the force content is filtered and attenuated by the softtening medium, rail pad installed between sleeper and rail [4]. Up to current knowledge, the behaviour of the in-situ prestressed concrete sleepers under the impact loading has not yet been thoroughly comprehended. In order to evaluate the progressive damage of railway concrete sleepers to impact loads, a high-capacity drop-weight impact testing machine was thus constructed at the University of Wollongong. It is currently the largest one of its kind in Australia with the maximum drop height of 6m, as illustrated in Figure 3 [9]. This paper briefly demonstrates the experimental overview but rather describes the

damage classification in details. The impact tests were carried out using the prestressed concrete sleepers manufactured in Australia. This study enables and enhances the methodology to maintenance practice for the prestressed concrete sleepers on the basis of limit states design concept [10].

TEST SPECIMENS

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 typical full-scale prestressed concrete sleepers, which are often used in broad gauge tracks, were selected for these tests. The dimensions and shape of the prestressed concrete sleeper are shown in Table 1. The high strength concrete material was used to cast the prestressed concrete sleepers, with design compressive strength at 28 days of 55 MPa, and the prestressing steels used were the high strength with rupture strength of 1860 MPa. However, the cored samples, drilled from the sleepers, were taken for a confirmation test, as per the Australian Standard AS1012.14 [11]. It was found that the average compressive strength at the test age of about two years was 80 MPa. It is believed that the high strength prestressing wires are of high quality and the strength will not change during time.

Table 1. Dimensions of the test sleepers

Gauge length (m)	Total length (m)	At railseat (m)		At centre (m)	
		width	depth	width	depth
1.60	2.50	0.20	0.23	0.21	0.18

EXPERIMENTAL TESTING

Severe impacts simulating actual probabilistic loads can be rendered using a free falling mass. The high-capacity drop-weight impact testing machine, which is currently the largest in Australia, has been developed as depicted in Figure 3. 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 [12-16]. 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 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, which is found about 98%. Experimental setup and impact tests were arranged in accordance with the Australian Standards as shown in Figure 4. The drop heights were increased step by step until sleeper cracks can be observed. The impact load histories, crack patterns and widths are recorded. The drop height is then slightly increased until the sleeper fails to hold the rail gauge. The impulse response against normalised crack length can be plotted. Table 2 summarises the experimental programs to investigate the progressive collapses of the prestressed concrete sleepers. The drop heights were varied between 0.1m and 1.5m. The track supports used in the test setup include the hard (deep ballast layer in the substructure) and soft type (shallow ballast layer in the substructure).

Table 2. Testing program

Support condition	Drop Height Used (m)
Soft track	0.1-1.5 (every 0.1 m)
Hard track	0.1-1.0 (every 0.1 m)

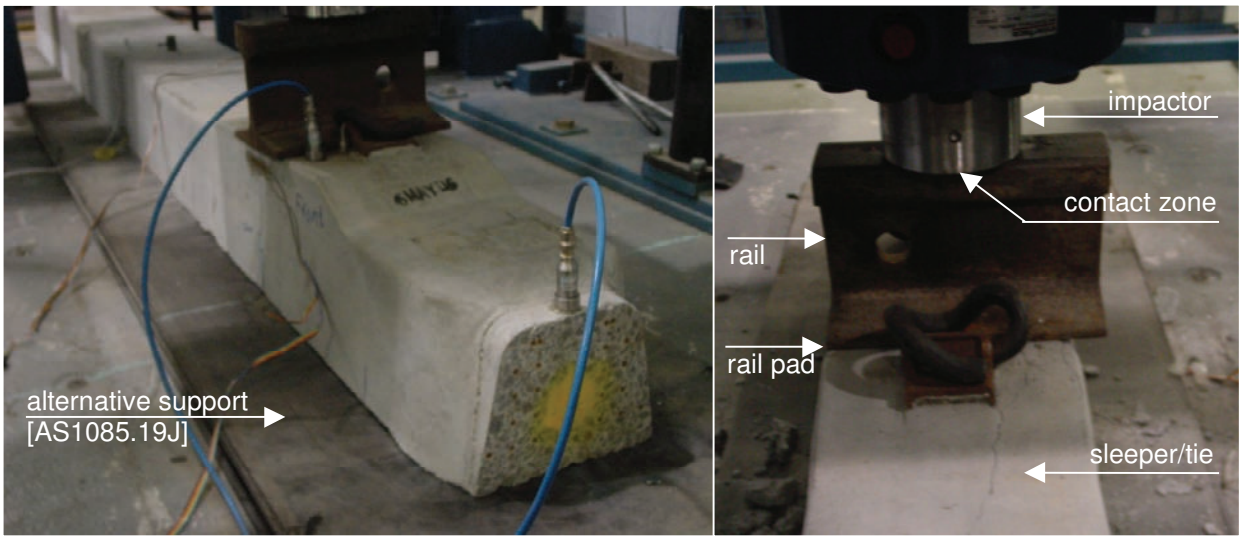


Figure 4 : Experimental setup [17]

IMPACT DAMAGE INDEX

An indicator to estimate the life expectancy of structures subjected to repeated loading is the cumulative damage. The damage accumulation mechanism can be evaluated from the critical crack length in relation to the depth of structural member [18]. The assessment method has been successfully developed for the fatigue life assessment of railway bridges. However, the fatigue damage theory is based on the fatigue stress and not suitable for railway concrete sleepers subjected to periodic impacts. As a result, the impact damage accumulation characteristics of the concrete sleepers are developed as a guide tool for the residual life prediction of the concrete sleepers. The hypotheses of the damage accumulation and fracture mechanics are adopted for this study [18].

The relationships between the damage index and the cumulative load impulse are shown in Figure 5. The damage index D is the ratio between the maximum bending crack length c_{max} and the total depth of the sleeper d or $D = c_{\max}/d$. This ratio provides a means for damage quantification and classification for the prestressed concrete sleepers subjected to impact loading. The load impulse I is the area under the impact load history diagram, which can be simulated as a half sinusoidal function. The cumulative load impulse is the summation of impulses at each stage during the experiments. In addition, if W represents the net impact energy absorbed at failure, then

$$\frac{w_1}{W} + \frac{w_2}{W} + \frac{w_3}{W} + \ldots \frac{w_n}{W} = 1 \qquad (1)$$

where w_1 is the impact energy input of the 1st load impulse and w_n is the impact energy input of the nth load impulse. The cumulative impulse ratio I_R can be formulated using the theory of linear cumulative damage [19], where it is assumed that

$$\frac{w_1}{W} = \frac{I_1}{I_f} \qquad (2)$$

The relation between I_1 and I_f, which are the impulse due to the 1st load impulse and the total load impulse to failure, respectively, read

$$\frac{I_1}{I_f} + \frac{I_2}{I_f} + \frac{I_3}{I_f} + \ldots \frac{I_n}{I_f} = 1 \qquad (3)$$

then, the cumulative impulse ratio I_R can be written as follows:

$$I_R = \sum_i \frac{I_i}{I_f} \qquad (4)$$

where i is the number of impact loads which impart the impulse level greater than the cracking impact load threshold.

Based on the observations, it is found that the concrete sleepers in the hard tracks tend to fail under lower cumulative load impulse compared with those in the soft track environments. The slopes of the curve imply the damage rate of the concrete sleepers. It was found that cracking rate of concrete sleepers in the hard tracks is faster than those in the soft tracks. Surprisingly, the ultimate crack lengths of the concrete sleepers in

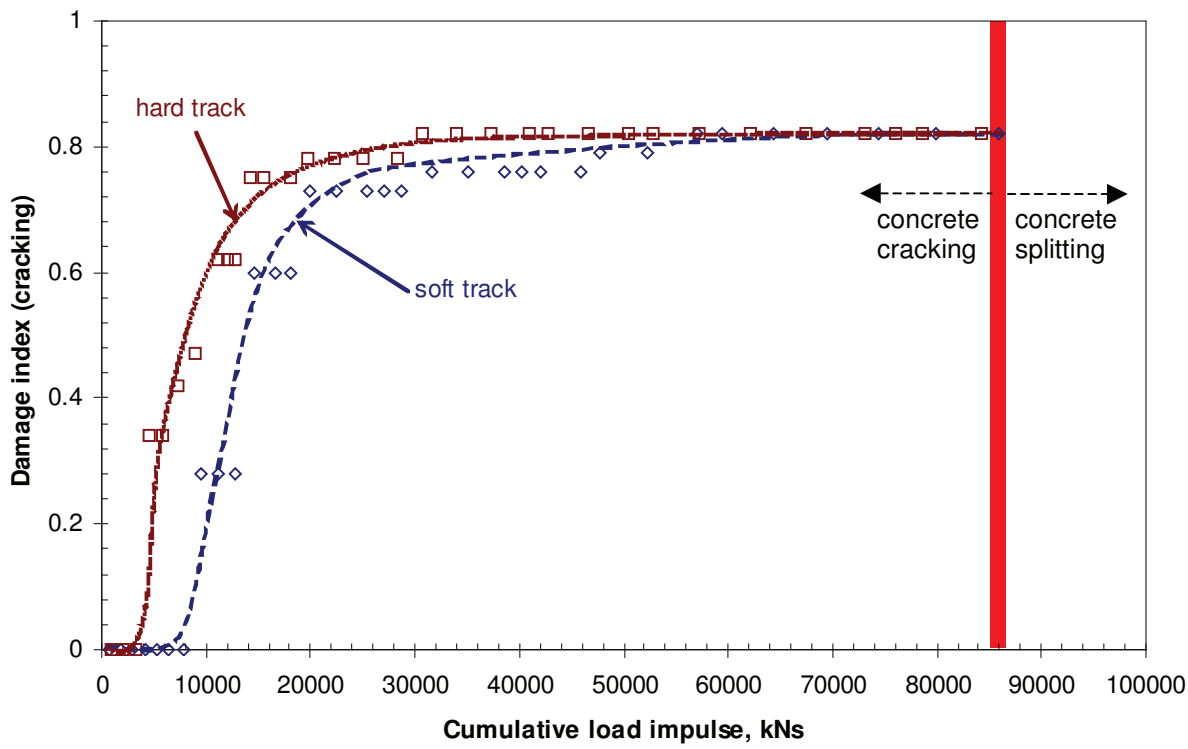


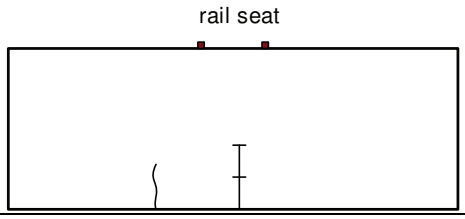
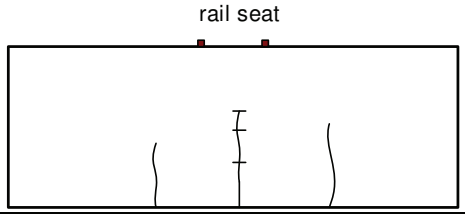
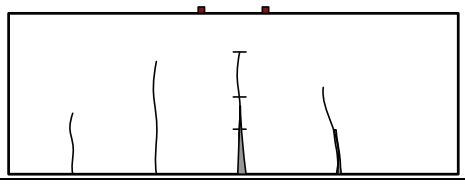
Figure 5 : Cracking damage index of railway concrete sleepers in different track environments

hard and soft tracks were found very close or about 85 percent of sleeper depth at rail seat. Figure 5 also points out that if the cumulative load impulse reaches the ultimate load impulse to failure, the mode of failure will change from concrete cracking to concrete splitting as described above. Based on this concept, the residual life prediction of the concrete sleepers can be carried out with the use of impact load data and their probability of occurrence obtained from a force detection system located in the particular railway tracks.

IMPACT DAMAGE CLASSIFICATION

Based on the progressive impact tests of the concrete sleepers, damage classification of concrete sleepers under loading conditions can be presented in Table 3 [18-21]. The damage classification refers to the assessment of concrete sleepers in track systems, and is associated with cumulative impulse ratio I_R and damage index D, based on cumulative crack length in the concept of fracture mechanics. The classification enables a new track maintenance scheme using limit states design concept.

Table 7.9 Damage classification of prestressed concrete sleepers

Damage Level	Description	Damage index, D	Cumulative impulse ratio, I_R
1. Light damage (reusable)	Few small cracks incur in the concrete sleeper. The cracks grow quickly but significant crack widths can not be observed. The maximum crack length measured from soffit is not significant and do not affect the resistance of the sleeper. 	0-0.50	0-0.20
2. Medium damage (reusable in light tracks)	Cracks incur in the concrete sleeper. The cracks grow consistently and the crack widths can be observed of about 1 to 2 mm. The maximum crack length measured from soffit is remarkable but tends not to weaken the capacity of the sleeper. 	0.50-0.75	0.20-0.65
3. Severe damage (non-reusable)	Major cracks can be detected in the concrete sleeper. Although the cracks grow consistently, the crack widths are significant. The concrete spalling and dust can be noticed. The crack length measured from soffit grows largely and tends to significantly weaken the capacity of sleeper. 	0.75-1.0	0.65-1.0

CONCLUSION

The cracks in railway concrete sleepers have been often observed due to the impact load, even though the possibility of occurrence for this large magnitude load is very low and it could be once or twice in their design life span of fifty to a thousand years. Current design method for prestressed concrete sleepers does not consider the ultimate behaviour under such impact loads. The widespread notion about the reserved strength of a concrete sleeper has raised the concern to develop its new ultimate limit states design concept. As a result, a high-capacity drop weight impact testing machine was constructed at the University of Wollongong, in order to evaluate the progressive damage behaviours of railway prestressed concrete sleepers under extreme impact loading.

By using the concept of damage accumulation, the relationships between cumulative damage of concrete sleepers and given impulse enable the predictions of residual life of the concrete sleepers under severe impact loads. It is noticed that the hard track condition rapidly exacerbates cracking in the concrete sleepers. The crack increment distribution of the hard track concrete sleepers was found in a relatively narrow range of impulse compared with the soft track concrete sleeper. However, uniform and small progress of cracks can be detected under more severe impact loading conditions. Based on the progressive impact testing, the damage classification of prestressed concrete sleepers has been proposed.

ACKNOWLEDGMENTS

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