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RESISTANCE OF RAILWAY CONCRETE SLEEPERS TO IMPACT LOADING

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Abstract

Railway sleeper is a main part of railway track structures. Its role is to distribute loads from the rail foot to the underlying ballast bed. There is a widespread suspicion 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. Cracks in concrete sleepers have been visually observed by many railway organizations. 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 msec, 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, 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.

This paper presents the results of experimental and numerical studies aimed at predicting the dynamic responses of railway concrete sleepers. Experimental data also convey the exact failure modes for railway prestressed concrete sleepers under static and impact loadings. A high-capacity drop weight impact testing machine was constructed at the University of Wollongong to evaluate the ultimate capacity of prestressed concrete sleepers under impact loads. Energy absorption capacity of the prestressed concrete sleepers was also evaluated to determine the amount of energy required to fail the sleeper under impact load. Static and impact tests were carried out using the Australian-manufactured prestressed concrete sleepers.

Keywords: Impact Loading; Concrete Sleepers; Limit States Design; ANSYS; LS-Dyna

1. Introduction

One of major components of railway infrastructure is railway sleeper. Railway sleeper can be made of steel, timber, plastic, and concrete. The use of concrete material for precast sleepers is very common nowadays. There is a widespread notion based on the industry experience that railway concrete sleepers have reserves of strength that is potential to be exploited. 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. Figure 1 shows an example of concrete sleepers.

Concrete is the brittle material, whereas its tensile strength is not much and sometimes negligible. Bending cracks in concrete sleepers can be occurred and have been visually observed by many railway organizations. 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 [1]. 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 msec, 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. Although the nature of loading on tracks can be of large spikes, the current design concept does not tolerate small cracks. 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 [2-3]. 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. Also, since high-capacity impact tests require significant amount of resources and are time consuming, a convenient means to develop an understanding of the impact behaviour is to use the numerical impact simulations. Nonetheless, there have been only a few studies related to the modelling of prestressed concrete sleepers [4].

Finite element analysis (FEA) provides a tool that can simulate and predict the responses of reinforced and prestressed concrete members. A three-dimensional non-linear finite element model of a railway prestressed concrete sleeper was developed using the general purpose finite element analysis package, ANSYS10 [5]. The concrete section was modelled using SOLID65 solid element where the compressive crushing of concrete and the concrete cracking in tension zone can be accommodated [6-7]. In the current practice, the smeared crack analogy is unsuitable for the replacement of prestressing tendons in the fully prestressed concrete sleeper. The use of a truss element, LINK8, for discrete reinforcement modelling, is then more practicable. An initial strain real-constant feature in ANSYS appropriately substituted the pre-tensioning forces in the tendon elements. However, it was assumed that perfect bonding between concrete and pre-stressing wires. The static full-scale experiment was conducted to validate this FE model. The experimental details were based on the associated Australian Standards [8, 9]. Comparison with experimental load-deflection response is then presented. The calibrated finite element model was extended to include ballast support and in situ boundary conditions. The extended model was linked to LS-Dyna [10] for impact analysis and validation against the drop impact tests.

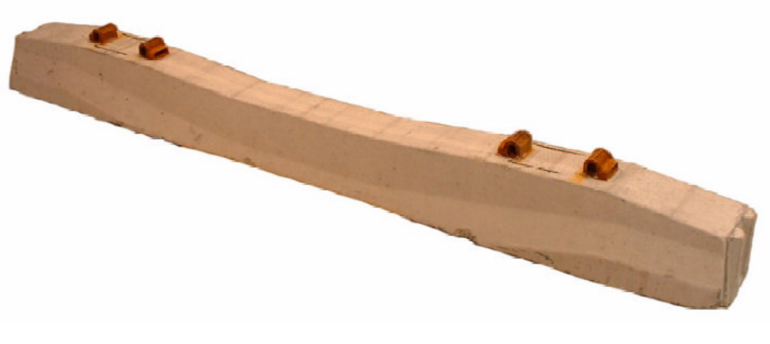


Figure 1: Concrete sleepers

2. Numerical Simulations

2.1 Static Analysis

In this study, ANSYS10 was employed for the non-linear model of a prestressed concrete sleeper. The concrete part of the sleeper was modelled using a three-dimensional solid element, SOLID65, which has the material model to predict the failure of brittle materials. SOLID65 is defined with eight nodes – each with three degrees of freedom: translations in nodal x, y, and z directions. This element is capable of predicting cracking in tension and crushing in compression. Plastic deformation and creep can also be captured. The cracking is determined by the criterion of maximum tensile stress, called *'tension cutoff'*. Concrete crushes when the compressive principal stress (von Mises stress) on the failure surface surpasses the *Willam-Warnke* failure criterion dependent on five material parameters [11]. To simulate the behaviour of prestressing wires, a truss element, LINK8, were used to withstand the initial strain attributed to prestressing forces, by assuming perfect bond between these elements and concrete. LINK8 requires users to input 'real constants' to define reinforcement geometry, material behavior, and prestressing strain. Note that this truss element cannot resist neither bending moments nor shear forces. Non-linear elastic behaviour of concrete can alternatively be defined by the multi-linear stress-strain relationships. The modulus of elasticity of concrete and tensile strength of concrete at 28 days can be found based on AS3600 [12]. The multi-linear isotropic stress-strain curve for the concrete can be computed by [13].

For prestressing wires, the bi-linear elasto-plastic material models can be used as well as the multi-linear isotropic model from the manufacturer's data. The 0.2% proof stress is 1,700 MPa and the ultimate stress is 1,930 MPa. The elasticity of modulus of prestressing wire is 190,000 MPa. Load-deflection behaviour of concrete structures typically includes three stages. The first stage shows the linear behaviour of uncracked elastic section. The next phase allows initiation of concrete cracking and the last stage relies relatively on the yielding of steel reinforcements and the crushing of concrete, see ref: [14] for further analysis details.

A three-dimensional model of a typical railway prestressed concrete sleeper was developed in ANSYS10 as illustrated in Figure 2. The dedicated solid bricks (SOLID65) represent the concrete and the embedded three-dimensional spar elements (LINK8) are used as the prestressing wires. The pre-tensioning was modelled using an initial strain in the tendons corresponding to the prestressing forces at final stage (sustained prestressing force after all losses). More details on material properties and nonlinear results can be found in ref: [14].

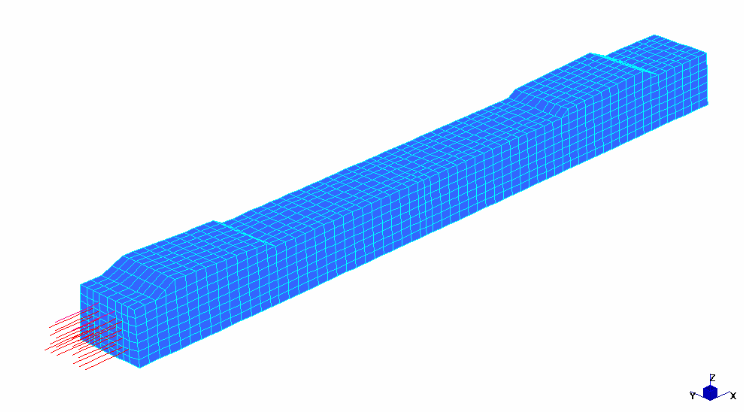


Figure 2: Finite element model of a railway concrete sleeper

2.2 Impact Analysis

For impact simulations, a FE model was extended to include rails, rail pads, ballast bed, and falling mass, as shown is Figure 3 (LS-Dyna model). The extended finite element model was calibrated using vibration data [14]. The updated finite element model was then transferred to LS-Dyna [10]. The simulation results were achieved by assigning the initial velocity to the drop mass to generate an impact event, similarly to the actual drop tests. More results and discussion on the impact analysis can be reached in refs: [14]. The use of impact model is to predict the pre-test contact forces and impact responses of the concrete sleepers. The updated modelling of a brittle material model (MAT72R2) will be appeared elsewhere.

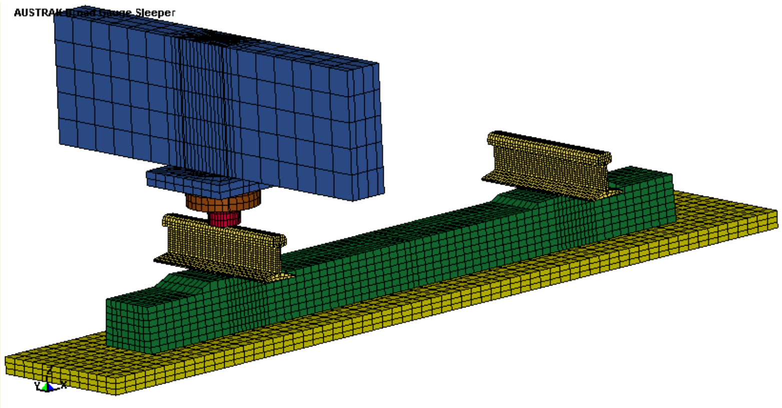


Figure 3: Finite element model of an in-situ railway concrete sleeper

3. Experimental Overview

3.1 Static testing

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). A series of static tests on the concrete sleepers was performed in accordance with the Australian Standards. The negative four-point bending moment test was conducted, see details in ref: [8-9]. The experimental results can also be found in that reference. It should be noted that the initial strain of wires due to prestressing is about 6.70 mm/m, and each prestressing wire has a proof stress of 1860 MPa. According to AS1012.14 [15], the tested average compressive strength of cored concrete is 88.5MPa. These static results were used to evaluate the suitability of the sleeper model implemented in ANSYS as to predict the non-linear responses of the prestressed concrete sleeper to static hogging moment. The details of static responses, rotational capacity, post-failure mechanism, and residual load-carrying capacity of the prestressed concrete sleeper have been presented earlier [14].

3.2 Impact testing

A new high-capacity drop-weight impact testing machine has been developed at the University of Wollongong, as depicted in Figure 4. It is currently the largest one of its kind in Australia. The impact testing facility can accommodate the full-scale structural members, e.g. precast slabs, railway sleepers, steel-concrete composites, and facade. Experimental setup and impact tests were arranged in accordance with the Australian Standards, see details in ref: [8, 9]. The in-situ conditions of railway concrete sleeper were replicated. Attempts to simulate impact loading actually occurred in tracks were succeeded experimentally and numerically. Some impact results will be discussed in the later section, together with numerical simulations.

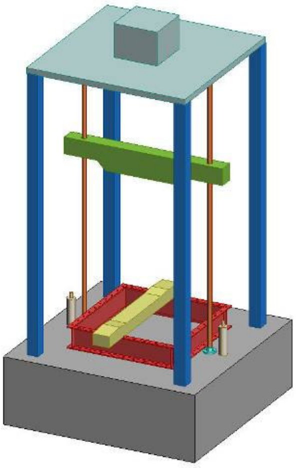
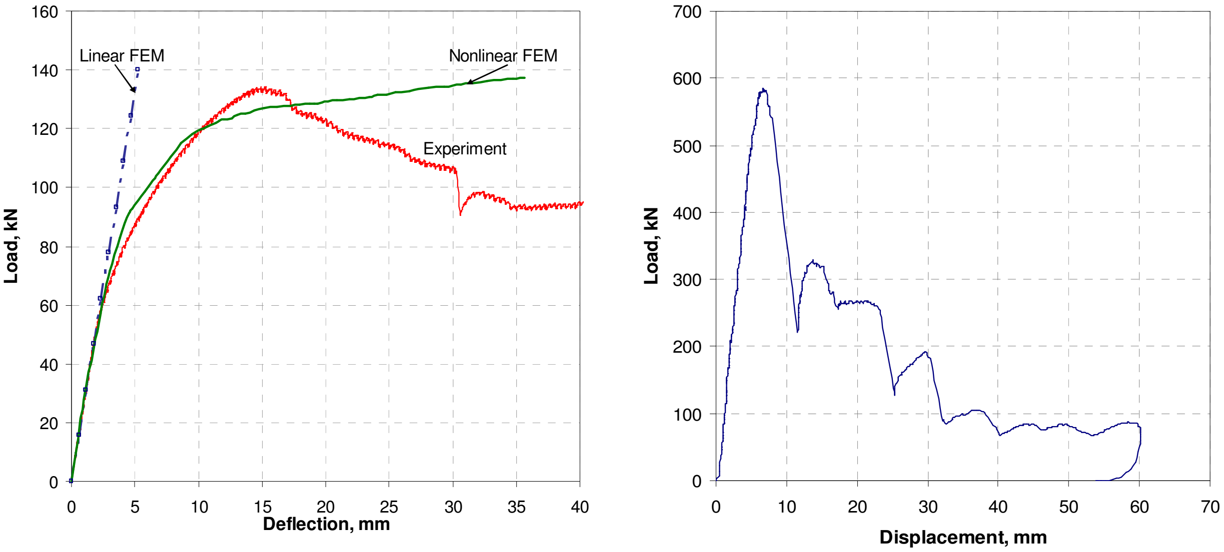


Figure 4: Sketch of impact testing facility at UoW

4. Static behaviour of railway concrete sleepers

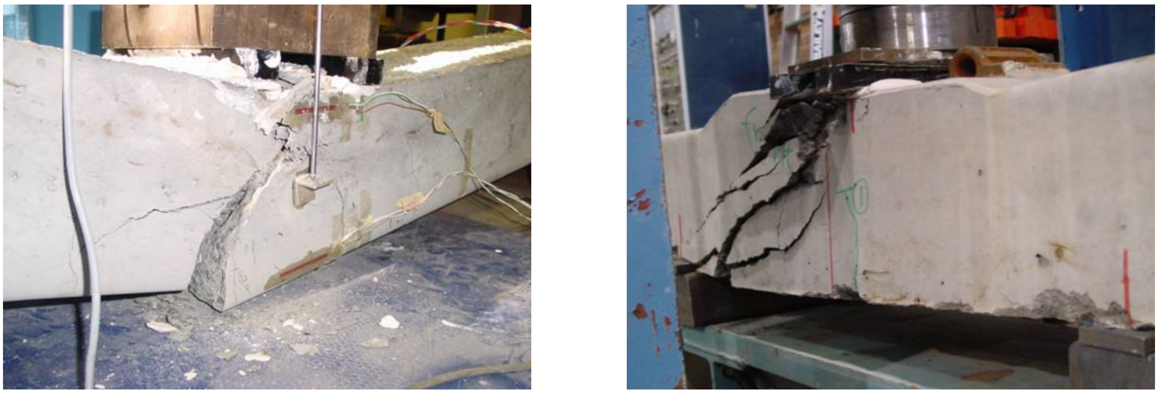
The analytical solutions and experimental results of the concrete sleeper due to static hogging moment are illustrated in Figure 5. Figure 5a presents the hogging behaviour of the concrete sleeper while Figure 5b shows the sagging behaviour of the concrete sleeper. It is found from Figure 5a that the numerical results are very close with the experimental result. To obtain the deflection of 15 mm, the static loads of about 126 and 125 kN are needed, which are, respectively, at 4.5% and 5.3% differences from the experimental results. Bending mode of failure is observed for the hogging behaviour. However, the ductility index is slightly above the unity, or on the other hand, the railway concrete sleeper has relatively low ductility. It can be observed from Figure 5b that the sagging behaviour causes the sudden failure of the concrete sleeper. Complex mode of failure, combining major shear diagonal cracks and some bending cracks can be detected. It should be noted that for both hogging and sagging behaviours, the first cracks are always due to flexures.



a) at mid span

b) at railseat

Figure 5: Static behaviour of railway concrete sleepers (broad gauge)



a) at mid span

b) at railseat

Figure 6: Failures of railway concrete sleepers (broad gauge)

Figure 6 shows the static behaviours of tested railway concrete sleepers at failures. It is clear that the tested concrete sleeper fails in bending under hogging moment as shown in Figure 6a. It is also found that the prestressing wires were snapped during the load increment. Figure 6b illustrates the failure mode of the tested concrete sleeper under sagging moment. Major shear diagonal cracks can be noticed as well as the crushing of concrete at top fibre, describing the shear-bending failure.

5. Impact behaviour of railway concrete sleepers

Figure 7 shows the drop-weight impact experiment and numerical result of the tested railway concrete sleeper. In this case, the falling mass is 600kg and the drop height is 0.2m. The theoretical free falling velocity is 1.98 m/s; however, the drop velocity just before collision used was 1.94 m/s, reckoned from 98% impact testing machine capacity based on high speed camera tests. Based on the drop tests and impact analyses at different drop heights, very good agreements are found between experimental and numerical results. Less than 10% difference of impact peak load magnitude was detected, while the impact durations of about 6 msec were found very similar. Consequently, this calibrated model is sufficient to predict the shock loading and impact responses of prestressed concrete sleepers. These investigations have led to parametric studies and comparisons between drop tests and numerical simulations as illustrated in Figures 7-9.

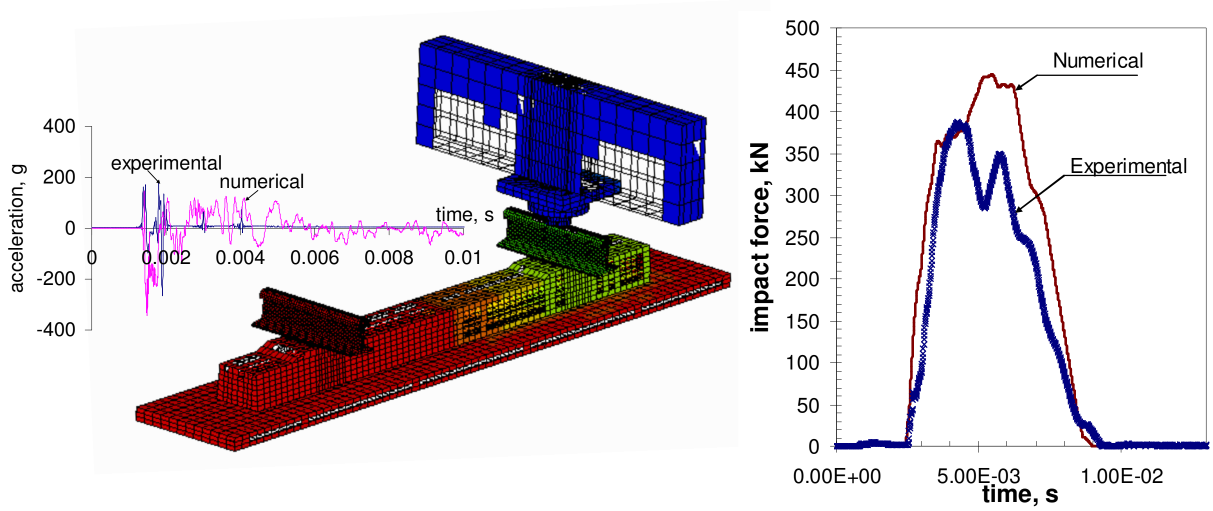


Figure 7: Impact testing and model validation of tested concrete sleepers

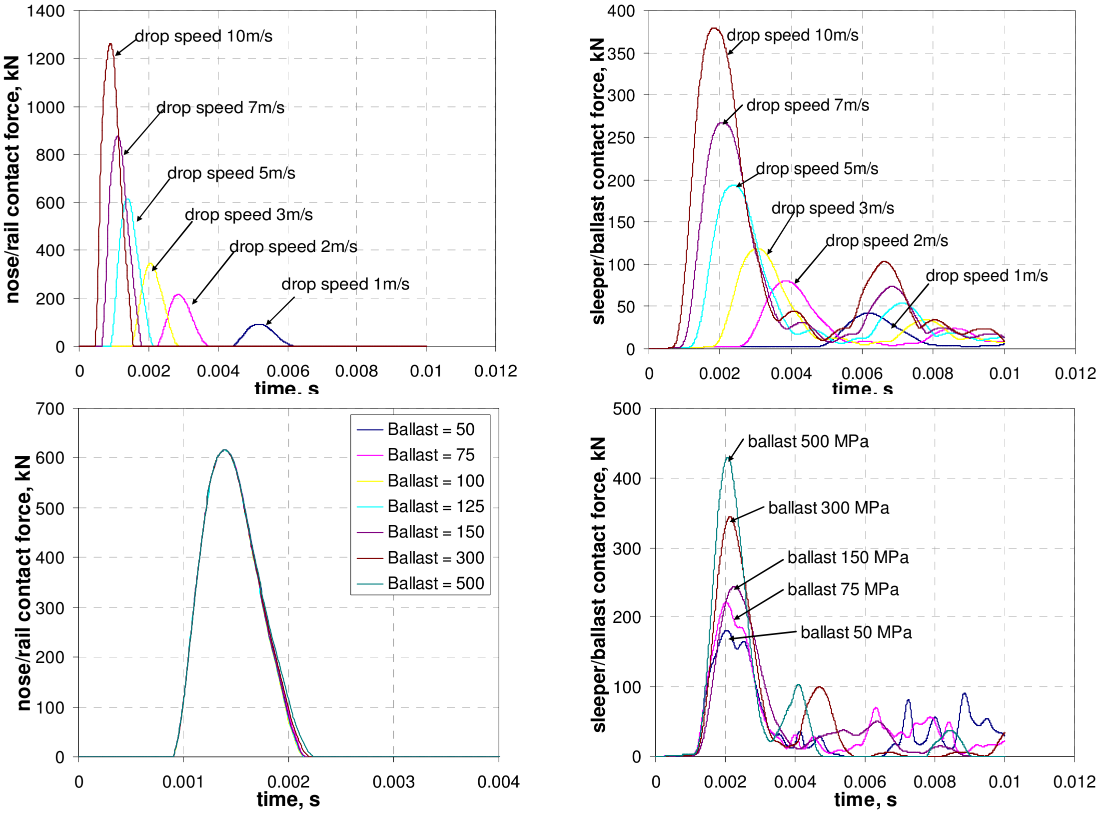


Figure 8: Predictions of contact forces on tested concrete sleepers

The parametric studies to examine the appropriate drop height and the effect of ballast support on the force distributions are depicted in Figure 8. It is found that the drop height, which is directly associated with the drop velocity, plays a vital role on the magnitude of impact load. The ballast support affects exclusively the contact pressures between sleeper and ballast. It is found that the ballast strength does not contribute much to increase the system contact stiffness so that the contact forces are slightly influenced.

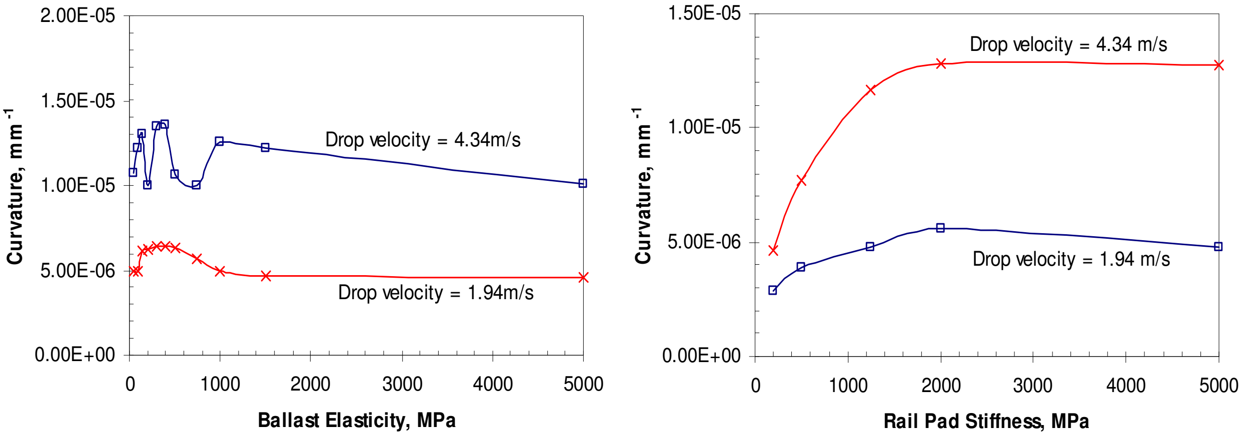


Figure 9: Impact responses predicted for tested concrete sleepers

While it is very difficult to extract all experimental data from the tests, FEA methodology can give accurate simulation of impact responses of tested concrete sleepers as shown in Figure 9. These results showing the influences of ballast and rail pad stiffness have been validated against some low-height drop experiments. The PC sleeper has been subjected to the larger impact step by step until it has been broken. Figure 10 show the impact resistance of the test concrete sleepers in soft track environments. It is found that the ultimate impact failure is found at about 1,600 kN. The failure mode is the combined mode of bending and splitting actions. The splitting fractures are aligned along the prestressing tendons. Based on the probabilistic analysis of dynamic loading, the magnitude of the ultimate impact force is equivalent to that occurred at once in several million years [3].

Figure 10: Impact failure of tested concrete sleeper in soft track environments

6. Conclusion

This paper presents the results of finite element analyses to investigate the static and impact behaviour of prestressed concrete sleeper. Commercial finite element packages, ANSYS10 and LS-Dyna, were employed in static and impact studies respectively. The experimental investigations of railway concrete sleepers under both hogging and sagging moments were carried out, to evaluate its performance under such loading. It was found that only known compressive strength of concrete, measured from exacted cores, and existing formulas are sufficient to model the prestressed concrete sleeper. Apparently, the non-linear material models can well capture the non-linear static behaviour of concrete sleeper. The finite element model was then extended using finite element model updating technique. Linkage between ANSYS and LS-Dyna helps develop the numerical impact modelling. Drop impact tests were carried out to validate the numerical shock simulations. It is found that the extended model can be used to predict impact responses of prestressed concrete sleepers. The model was intensively used to predict the impact responses, to determine appropriate drop height, as well as to evaluate the parametric effects involved in the laboratory tests.

Evaluation of the impact resistance of railway prestressed concrete sleepers designed to the current code AS 1085.14 was conducted as to complement the development of a new limit states design concept. The results of experimental investigations at UoW aimed at determining the ultimate impact resistance of prestressed concrete sleepers required by a limit states design approach. Apparently, the static failure mode is different from the impact failure mode. It is found that the static testing procedure cannot well represent the impact behaviour of in-situ railway concrete sleepers. For static tests, the railway concrete sleepers tend to fail in rather bending or shear. In contrast, the impact resistance of the railway concrete sleepers is most likely of splitting mode due to the lack of bonding between prestressing wires and concrete under dynamic circumstances.

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