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Low-velocity impact analysis of railway prestressed concrete sleepers

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Synopsis: Railway prestressed concrete sleepers are required to resist repetitive impact stress waves from dynamic interactions between the rail vehicle and track infrastructure in services. The magnitude of the shock load relies on various factors such as axle load, types of wheel/rail imperfections, speeds of vehicle, track stiffness, etc. This paper demonstrates the application and development of finite element modelling to predict the dynamic responses of prestressed concrete sleepers, particularly under a variety of controlled low-velocity, drop-weight impact loads. The numerical model of prestressed concrete sleeper has been developed using a finite element package, LS-Dyna. It has been verified by the experiment carried out using the high capacity drop-weight impact machine at the University of Wollongong. In the validation experiment, the accelerometers were installed along the top surface of the tested sleeper. The low-velocity impact loading was generated by the drop weight impact machine with the varied drop heights from 100 to 500 mm. The drop mass used in these experiments was 5.81 kN. The results, which are the acceleration responses captured by the device in the loading range of 300 to 600 kN, are discussed herein. The experimental results provide very good correlation with numerical simulations. In addition, the numerical studies on the influential parameters of railway track environment are highlighted.

Keywords: shock and impact, dynamic response, prestressed concrete, railway sleepers, experiments, simulations, and finite elements.

Introduction

In railway track structures, railway sleeper plays a major role in distributing train axle loads from the rails to the underlying ballast supporting system. Typical ballasted railway track and its components are presented in Figure 1 (1). It has been chronically believed based on the industry practice that railway concrete sleepers possess reserved strength that are untapped. Accordingly, it is crucial to evaluate the spectrum and amplitudes of forces applied to the railway track, in order to understand more clearly the behaviors in which track components respond to those forces, and to identify the processes whereby concrete sleepers in particular carry those force actions. Recent findings show that the nature of the majority of loading conditions on track structures is of dynamic impact (2). Those loads are normally of short duration but of very high magnitude. They are ascribed to the wheel/rail interactions associated with irregularities, i.e. wheel burns, wheel flats, corrugations, non-uniform track modulus, and any other out-of-round wheel defects. Structural performance monitoring is an effective way to establish better understanding into the impact behaviors of prestressed concrete sleepers.

In addition, cracks in concrete sleepers have been visually observed by many railway organizations. As described in the review (3), 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. 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. Existing structural design concept for prestressed concrete sleepers in Australia 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. However, it is inevitable to avoid those criteria in any consideration of rail track designs since even the standard quality ride of rail vehicles still involves with the low-velocity impact forces. In order to devise a new limit states design concept whereas the extreme loading conditions can be taken into account, 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 (4). A major research task at the University of Wollongong is to evaluate the dynamic responses of concrete sleepers under static and impact loads. There have been only a few studies related to the modelling of prestressed concrete sleepers. Most of them predicted the rail seat flexural behaviour of the concrete sleepers (5-6). Also, since high-capacity impact tests require significant amount of resources and are time consuming, a suitable way to develop an understanding of the impact behaviour is to use the numerical impact simulations.

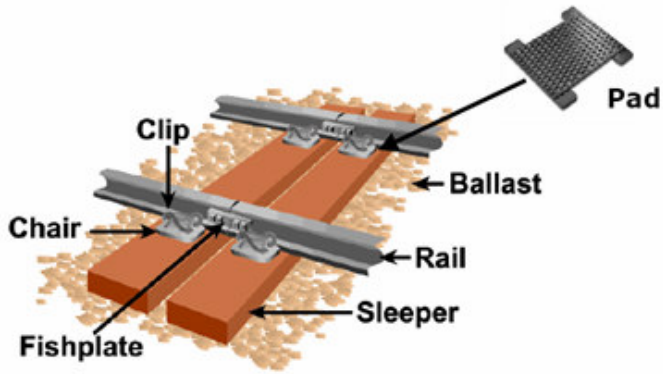


Figure 1 Typical ballasted railway track and its components (1)

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 for static analysis was developed using the general purpose finite element analysis package, ANSYS10 (7). 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. In the current practice, the railway concrete sleeper is designed to resist prestressing force fully throughout the whole cross section as the force/moment redistribution can be seen in Figure 2. This makes the smeared crack analogy 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 (7). The experimental details were based on the associated Australian Standards (8, 9).

The calibrated finite element model has been 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. This paper points out the impact analysis of prestressed concrete sleepers only in elastic range whereas the drop heights are limited to impart the low-velocity shocks, which are equivalent to the peak dynamic forces ranging from 200-1,700 kN. The further study on nonlinear range will be presented in the future. The highlights in this paper focus on the influence of track components, particularly the ballast support and rail pads, on the elastic impact behavior of the railway prestressed concrete sleepers.

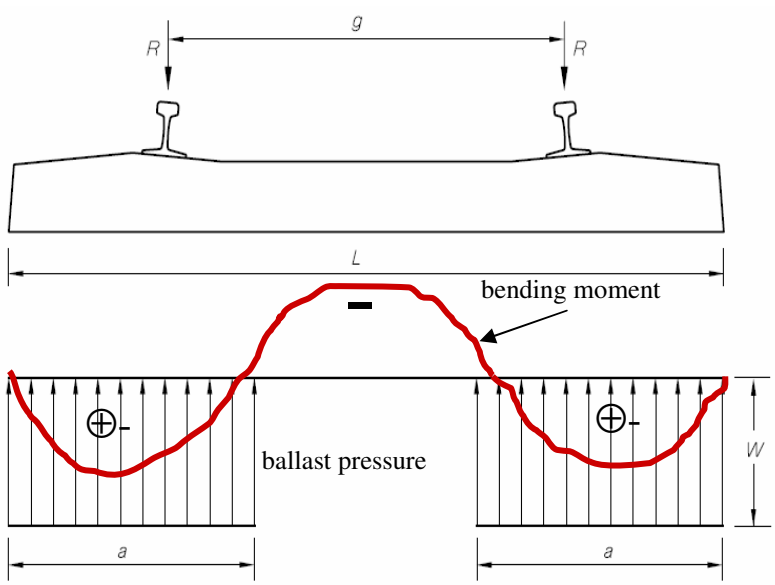


Figure 2 Moment distribution for standard gauge sleepers (8)

Finite Element Modelling

In this study, the concrete part of the sleeper was modelled using a three-dimensional solid element, which has the material model to predict the failure of brittle materials (7). This element is defined with eight nodes – each with three degrees of freedom: translations in nodal x, y, and z directions. To simulate the behaviour of prestressing wires, a truss element, were used to withstand the initial strain attributed to prestressing forces, by assuming perfect bond between these elements and concrete. 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 (E_c) can be found based on AS3600 (11) using the compressive strength of 88 MPa.

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 static and dynamic elasticity of moduli of prestressing wire are 190,000 MPa.

The multi-linear isotropic dynamic stress-strain curve for the concrete and prestressing wires can be calculated based on the consideration of the effect of strain rate. Based on the assumption of perfect bond between prestressing wires and concrete, the dynamic material properties of concrete and prestressing wires can be determined as follows (12).

Concrete:

$$\sigma = f'_{c,dyn}\left[2\frac{\varepsilon}{\varepsilon_{c0,dyn}} - \left(\frac{\varepsilon}{\varepsilon_{c0,dyn}}\right)^2\right] \tag{1}$$

$$\frac{f'_{c,dyn}}{f'_{c,st}} = 1.49 + 0.268\log_{10}\dot{\varepsilon} + 0.035\left[\log_{10}\dot{\varepsilon}\right]^2 \tag{2}$$

$$\frac{\varepsilon_{c0,dyn}}{\varepsilon_{c0,st}} = 1.24 + 0.053\log_{10}\dot{\varepsilon} \tag{3}$$

where σ is the dynamic stress, $f'_{c,dyn}$ is the dynamic compressive strength, $f'_{c,st}$ is the static compressive strength of concrete, ε is the dynamic strain, $\varepsilon_{c0,st}$ is the static ultimate strain, and $\dot{\varepsilon}$ is the strain rate in concrete fibre.

Prestressing wires:

$$\frac{f_{y,dyn}}{f_{y,st}} = 10^{0.38\log_{10}\dot{\varepsilon}^{-0.258}} + 0.993 \tag{4}$$

where $f_{y,dyn}$ is the dynamic upper yield point stress, $f'_{c,st}$ is the static upper yield point stress of prestressing wires (about 0.84 times proof stress), and $\dot{\varepsilon}$ is the strain rate in tendon.

A three-dimensional model of a typical railway prestressed concrete sleeper was developed initially in ANSYS (7) as illustrated in Figure 3. The dedicated solid bricks represent the concrete and the embedded three-dimensional spar elements 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). For impact simulations, a FE model was extended to include rails, rail pads, ballast bed, and falling mass, as shown is Figure 4. The extended finite element model was calibrated using vibration data (13-16). The updated finite element model was then transferred to LS-Dyna. 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.

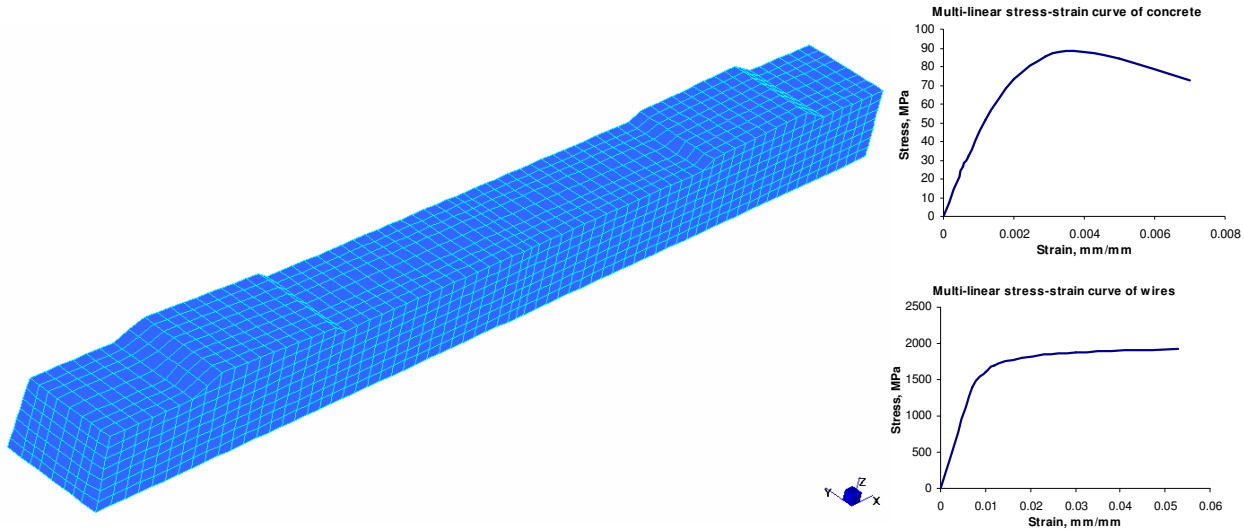


Figure 3 A three-dimensional model of railway sleeper (4)

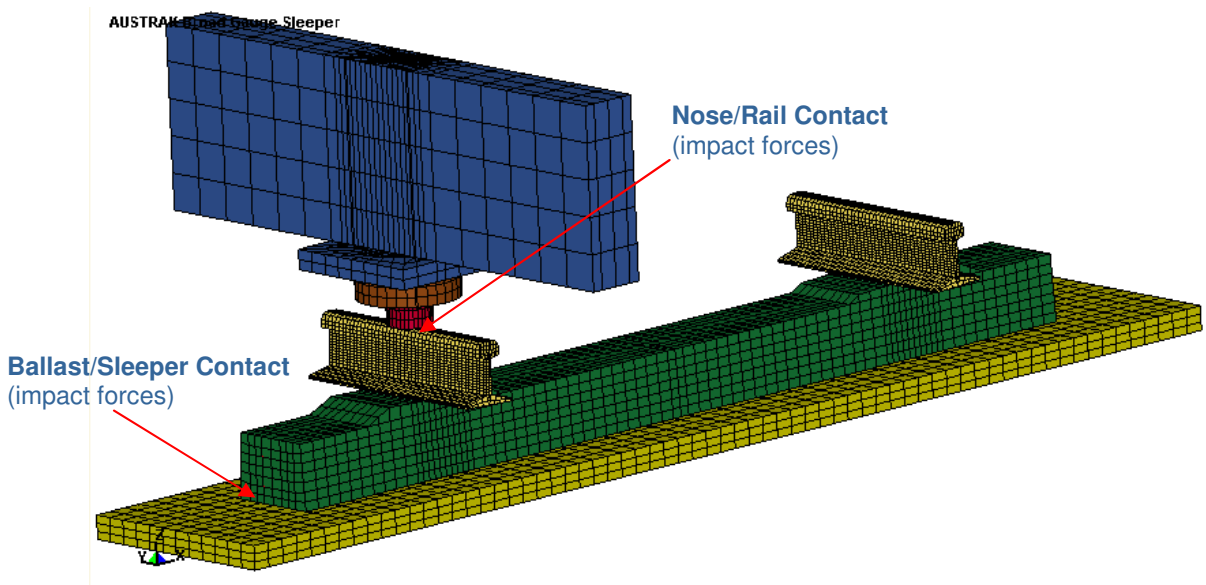


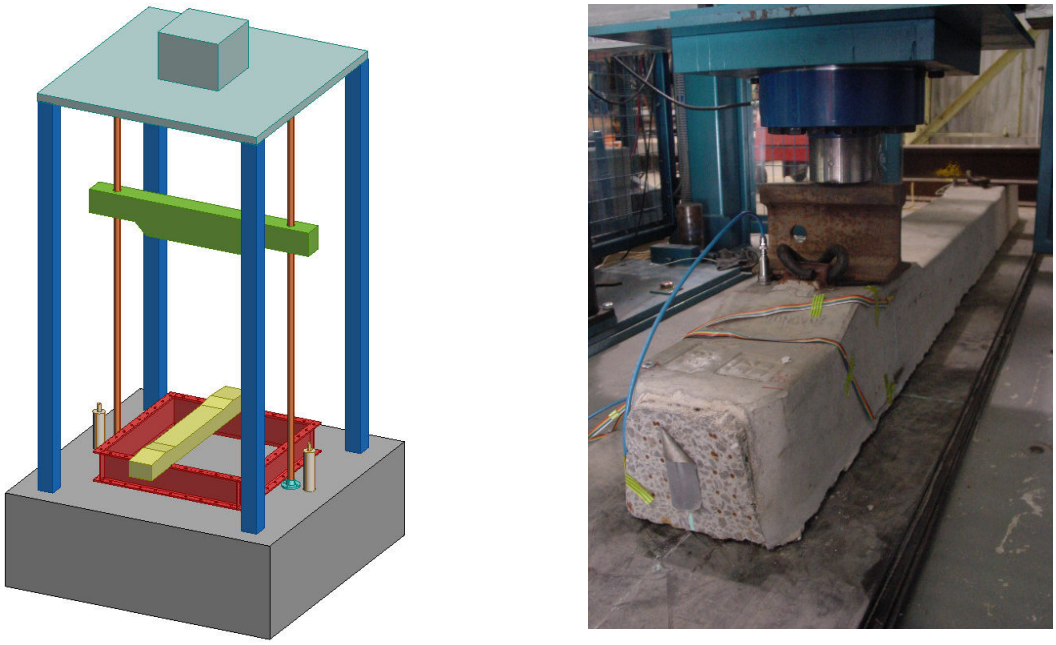
Figure 4 Extended finite element model of railway sleeper (4)

Experiment and Model Validation

The prestressed concrete sleepers used in this study were kindly 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 details of static responses, rotational capacity, post-failure mechanism, and residual load-carrying capacity of the prestressed concrete sleeper can be found in ref: (17).

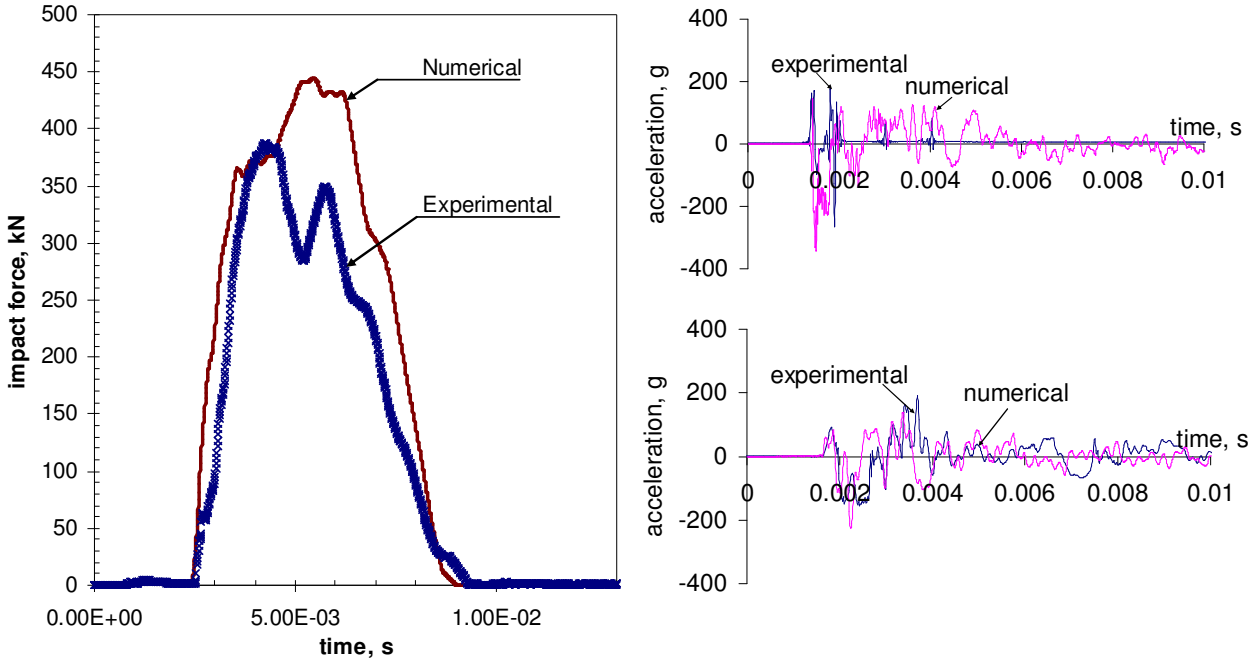
A new high-capacity drop-weight impact testing machine has been developed at the University of Wollongong, as depicted in Figure 5a. The drop mass assembled is 5.81 kN with the varied height from 0 to 6m in total, which provide the maximum capacity of 10m/s drop velocities. Experimental setup and impact tests were arranged in accordance with the Australian Standards, as shown in Figure 5b. The accelerometers have been used to measure the dynamic responses at mid-span and railseat. The contact impact force between impactor and rail was recorded using the dynamic load cell connected to the data acquisition system. For the verification purpose, the drop height used was 0.1m since there was the

measurement limitation for the accelerometers employed. The in-situ conditions of railway concrete sleeper were replicated. Attempts to simulate impact loading actually occurred in tracks were succeeded experimentally and numerically. Comparison between numerical and experimental results can be found in Figure 6. It is found that the finite element model is fairly sufficient for use in predicting impact responses of the prestressed concrete sleepers. The trends of peak acceleration responses are quite close to each other, although there is certain phase difference.



a) sketch of impact machine b) impact test setup

Figure 5 Experimental overview



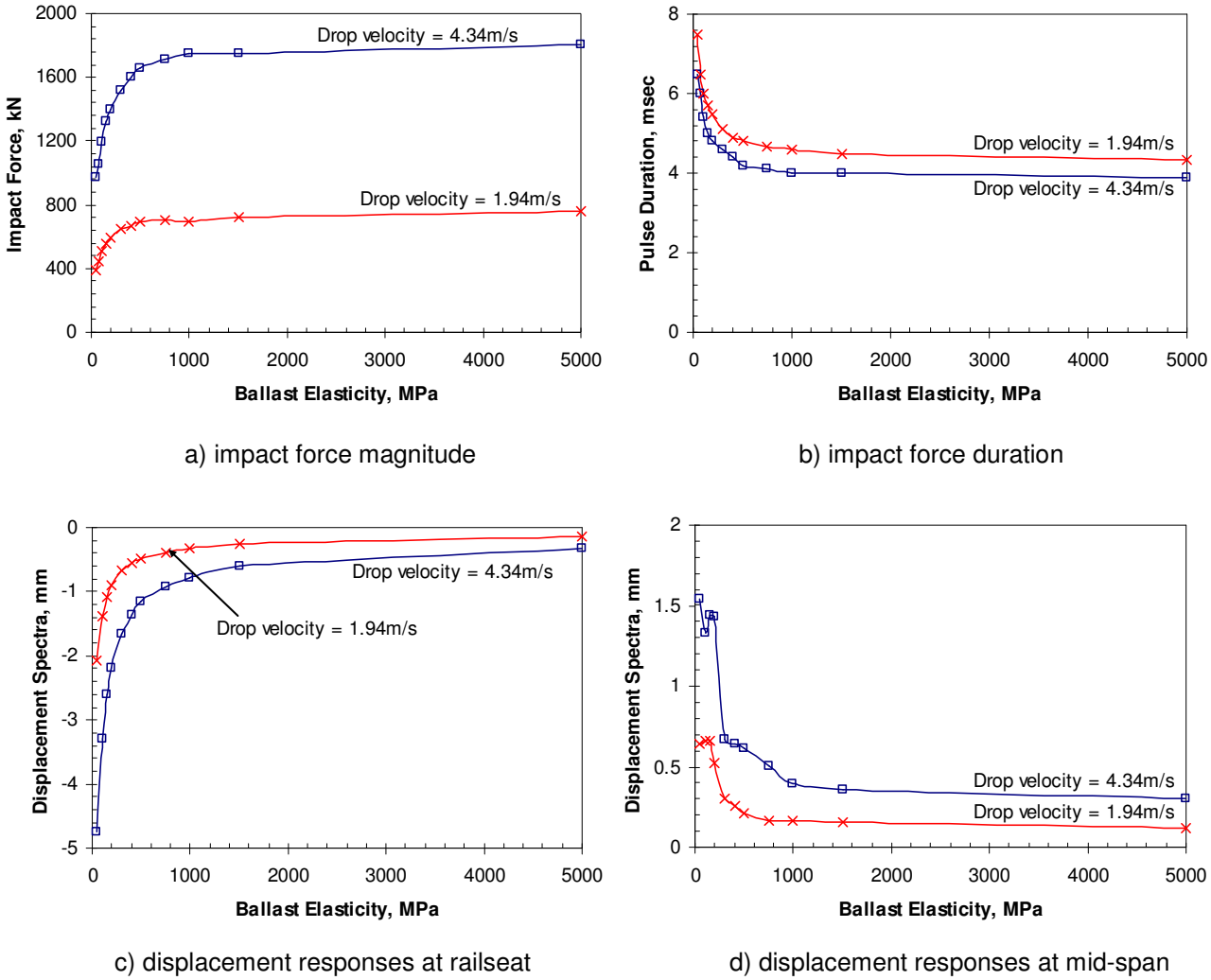
a) contact shock load b) at railseat (top); at mid-span (bottom)

Figure 6 Comparison of numerical and experimental results

Influential track environments

In general, the main track components that require maintenance or renewal apart from the sleeper itself include the ballast bed and rail pads. The ballast bed requires re-packing and tamping every six months or a year depending on the characteristics of gravels used at particular locations. It degrades through the breakage of gravel, resulting in the large settlement of railway tracks (16). Rail pads deteriorate through the age of use. The wearing process can be incurred due to the impact loads or asymmetrical burden on the pads. Once the rail pad deteriorates, its properties also change (18, 19). Based on this understanding, the parametric studies have been conducted and highlighted in this paper.

In the impact analysis, the drop velocity is also varied to evaluate the effect of drop heights on the impact force occurring on railway track structures. On the other hand, this analysis provides the insight into the effect of railway track environments on the contact impact forces due to the identical causes and the responses of concrete sleepers to such loading. For example, a wheel, with 10mm wheel flat on a specific vehicle and running at 80 km/hr, generates different contact impact forces on tracks with different environments. However, this study focuses only on ballast and rail pad parameters as they play key role on the interface impact force characteristics and there responses of prestressed concrete sleepers.



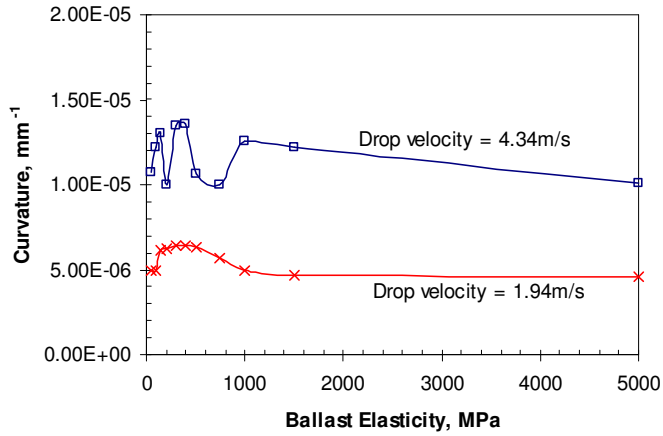
a) impact force magnitude

b) impact force duration

c) displacement responses at railseat

d) displacement responses at mid-span

Figure 7 Influence of ballast elasticity on contact impact forces and dynamic responses

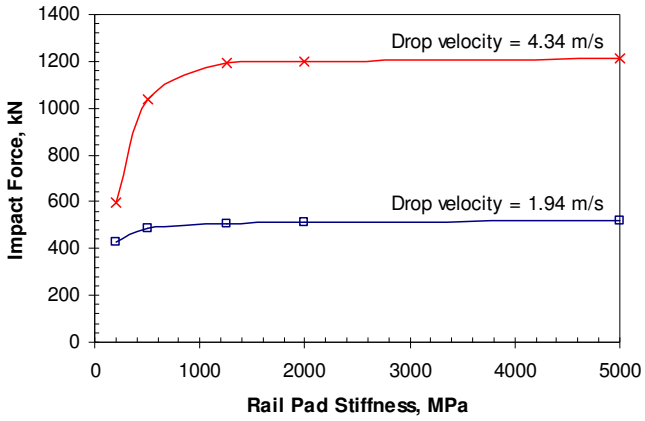


e) bending curvature at railseat

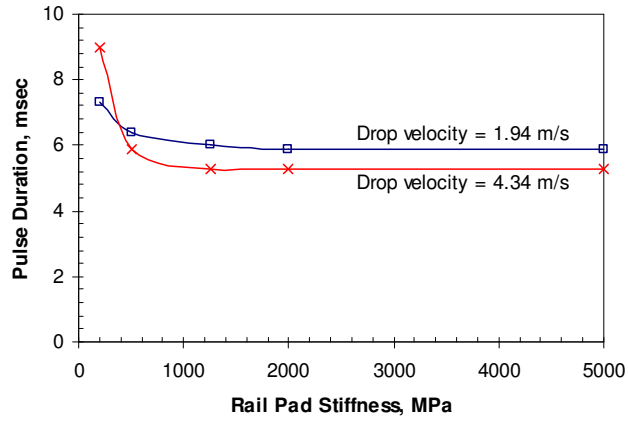
Figure 7 Influence of ballast elasticity on contact impact forces and dynamic responses

Effect of ballast bed

The influence of ballast strength on the contact impact forces and dynamic responses of prestressed concrete sleepers is presented in Figure 7. Clearly, the ballast stiffness in the low range between 50 MPa and 1500 MPa plays substantial role in both the impact force magnitude (Figure 7a) and the corresponding pulse duration (Figure 7b). The contact forces increase dramatically during that low range whilst the effect of ballast elasticity becomes insignificant when the stiffness is large. Analogously, the impact duration, which will affect the resonance responses of railway sleepers, decrease greatly in the low range of ballast stiffness, and vice versa. These behaviours can be detected for either very low velocity impacts at 1.94 m/s (equivalent to the drop height of 0.2m in the test rig) or even at 4.34 m/s (equivalent to the drop height of 1m in the test rig). It can be observed that the impact force magnitude varies from 390 kN to 670 kN and from 970kN to 1,800kN, while the duration changes from 7.5msec to 4.3msec and from 6.5msec to 4.0msec, for drop velocities of 1.94 m/s and 4.34 m/s, respectively. The maximum dynamic displacement responses are plotted against the ballast strength in Figures 7c (at railseat) and 7d (at mid-span). However, it is discovered from Figure 7e that the ballast stiffness has little effect on the impact responses in terms of bending curvatures of the railway concrete sleeper.

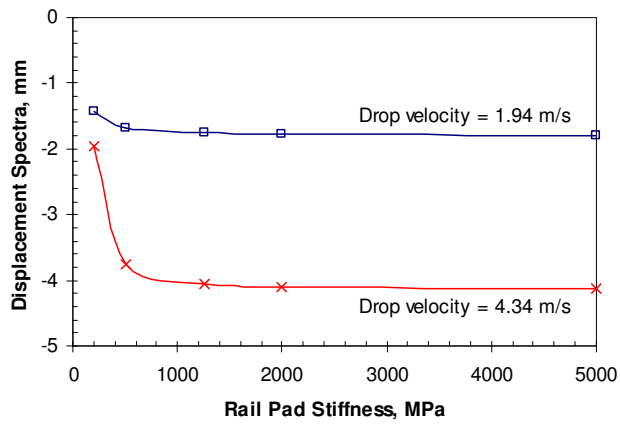


a) impact force magnitude

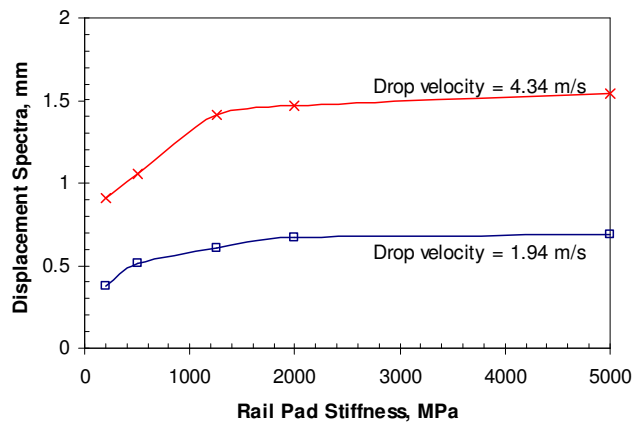


b) impact force duration

Figure 8 Influence of rail pad stiffness on contact impact forces and dynamic responses



c) displacement responses at railseat

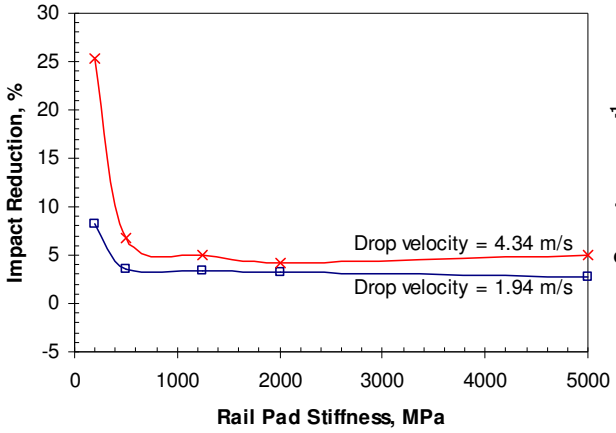


d) displacement responses at mid-span

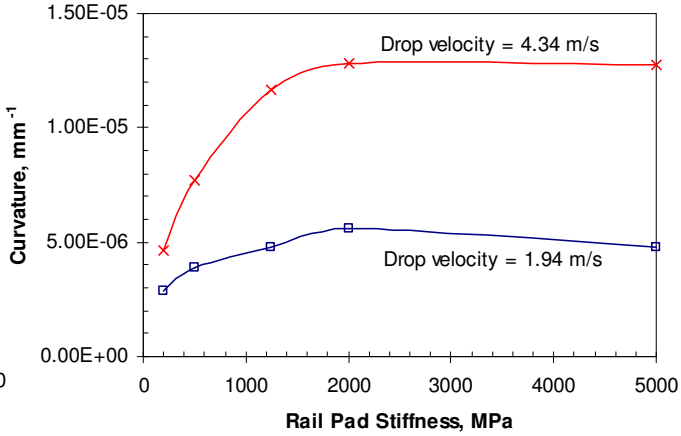
Figure 8 Influence of rail pad stiffness on contact impact forces and dynamic responses

Effect of rail pads

Figures 8a and 8b depict the influence of rail pad stiffness on the contact impact force magnitude and duration, while Figures 8c and 8d show the effect on the displacement response spectra at railseat and mis-pan of the sleeper, respectively. At the stiffness range between 200MPa and about 750MPa, the substantial changes of impact force characteristics (both magnitude and duration) can be observed. However, the greater rail pad parameters are unlikely to affect the impact force magnitude and duration. The impact force magnitude varies from 400kN to 500kN and 600kN to 1,200kN, while the associated duration diminishes from 7.5msec to 6.0msec and from 9.0msec to 5.3msec, for the drop velocities of 1.94m/s and 4.34m/s, respectively. Alternatively, the rail pads tend to reduce the impact force from the rail foot as shown in Figure 9a and help attenuate the flexural responses in the prestressed concrete sleeper as presented in terms of curvature changes in Figure 9b. The impact reduction is calculated from the difference between the contact impact force at rail interface and the load burden that is distributed to rail seat of the sleeper. In contrast, the impact attenuation is considered from the effect of rail pad stiffness on the changes of sleeper curvature. From Figure 9a, it is apparently found that the softer the rail pad, the larger the force reduction. In addition, the soft rail pad considerable attenuate the impact forces, resulting small flexures.



a) impact force reduction



b) bending curvature

Figure 9 Influence of rail pad stiffness on impact responses of the prestressed concrete sleeper

Conclusions

The low-velocity impact analysis has been carried out in this paper. Initially, the three-dimensional finite element model was developed for static analysis. It has then been appended the track components to ensure the in-situ conditions found in actual tracks. A commercial finite element package, LS-Dyna, has been employed for impact analysis and validation against the drop impact tests. The emphasis of this study is placed on the elastic responses whereas the drop heights are limited to impart the low-velocity shocks. The further study on nonlinear behaviors will be presented in the future. This paper firstly point out the influences of track components, particularly the ballast support and rail pads, on the elastic impact behavior of the railway prestressed concrete sleepers.

Clearly, the ballast bed has strong influence over the contact impact force characteristics including magnitude and duration, particularly in the stiffness range lower than 1,500 MPa. On the other hand, the high stiffness of ballast insignificantly affects those characteristics. This finding confirms the preliminary results done earlier that the effect of high ballast stiffness is insignificant (12). It is also found that the ballast bed has slight effect on the impact responses of prestressed concrete sleepers.

In addition, the rail pads tend to play vital role on both the contact impact force characteristics and the responses of prestressed concrete sleepers. The softer rail pads are likely to have more substantial influences on the impact reduction and impact attenuation.

Acknowledgement

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