3-11-2007

Experimental and Numerical Studies of Railway Prestressed Concrete Sleepers Under Static and Impact Loads

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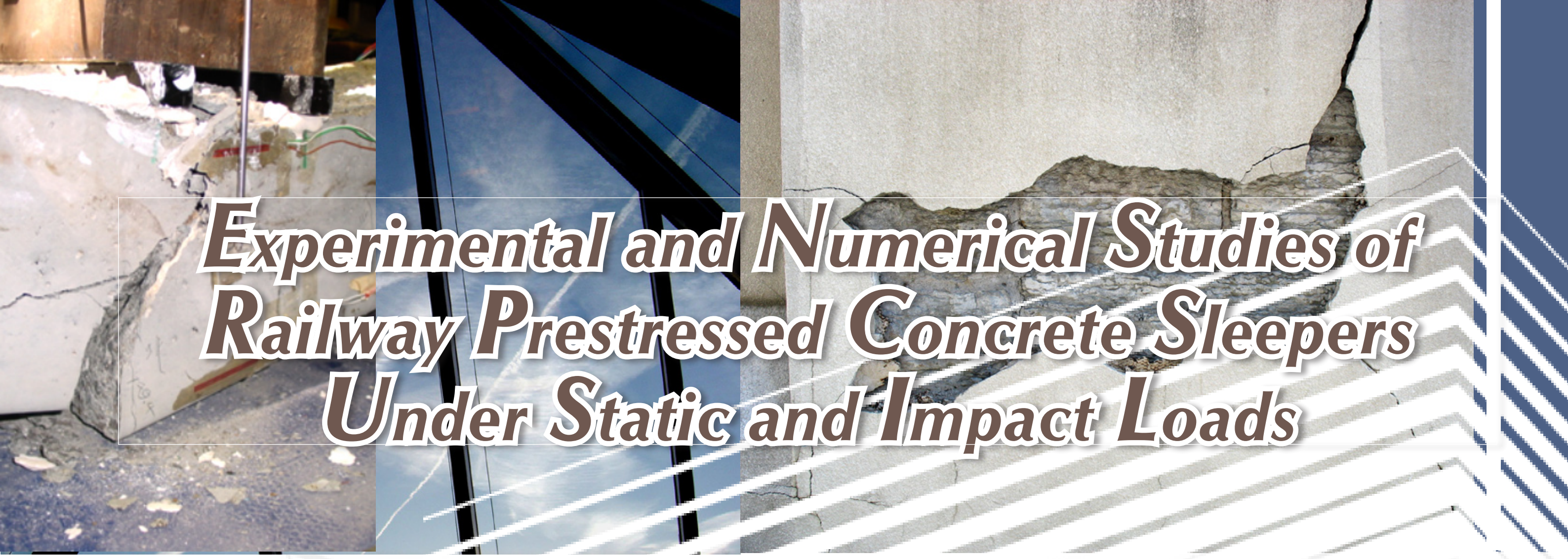
Recommended Citation

Kaewunruen, S. and Remennikov, Alexander: Experimental and Numerical Studies of Railway Prestressed Concrete Sleepers Under Static and Impact Loads 2007.
https://ro.uow.edu.au/engpapers/372



Experimental and Numerical Studies of Railway Prestressed Concrete Sleepers Under Static and Impact Loads

Introduction

Railway sleeper is an important component of railway track structures. Its role is to distribute loads from the rail foot to the underlying ballast bed. 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 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, 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. 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, as shown in Figure 1 [2, 6]. 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.

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 [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 [8-10]. 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 1. The static full-scale experiment was conducted to validate this FE model [5]. The experimental details were based on the associated Australian Standards [10, 11]. 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 [12] for impact analysis and validation against the drop impact tests.

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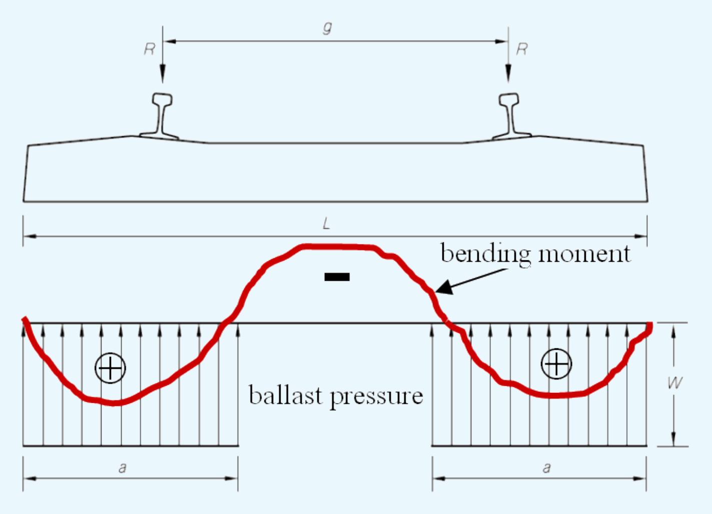

Figure 1: Moment distribution of a standard sleeper [5]

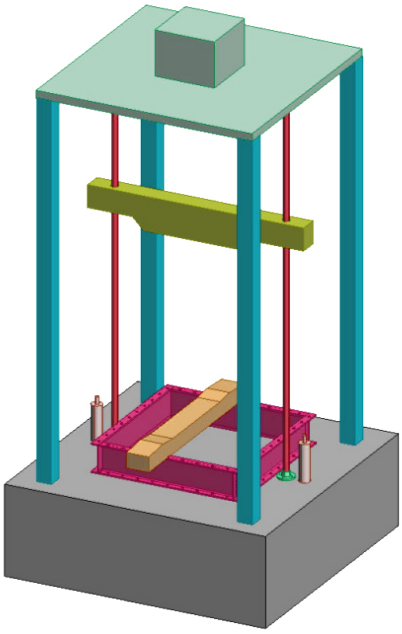

Figure 2: Sketch of high capacity drop weight machine at UoW

Experimental Work

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, see details in ref: [8]. The experimental results can also be found in that reference. The tested average compressive strength of cored concrete is 88.5MPa. This value has been corrected according to AS1012.14 [13]. In addition, sectional analysis of the specimen for ultimate negative moment of middle section was done. The predicted ultimate negative moment is quite close to the experimental result. 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 [8, 14-15].

A new high-capacity drop-weight impact testing machine has been developed at the University of Wollongong, as depicted in Figure 2. Experimental setup and impact tests were arranged in accordance with the Australian Standards; see details in ref: [10, 11]. 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 later, together with numerical simulations; however, the detailed impact tests can be found in ref: [16].

Finite Element Modelings

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. This element is capable of predicting cracking in tension and crushing in compression. 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 [17]. 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. 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) and tensile strength of concrete at 28 days (f'_{ct}) can be found based on AS3600 [18]. The multi-linear isotropic stress-strain curve for the concrete can be computed by [19]. The formulations were presented in ref: [14]. 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. A number of material models have been used in finite element analysis. Four cases of material models have been investigated in this study. 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 3. 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). For impact simulations, a FE model was extended to include rails, rail pads, ballast bed, and falling mass, as shown is Figure 4 (LS-Dyna model). The extended finite element model was calibrated using vibration data [20-21]. The updated finite element model was then transferred to LS-Dyna [12]. 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.

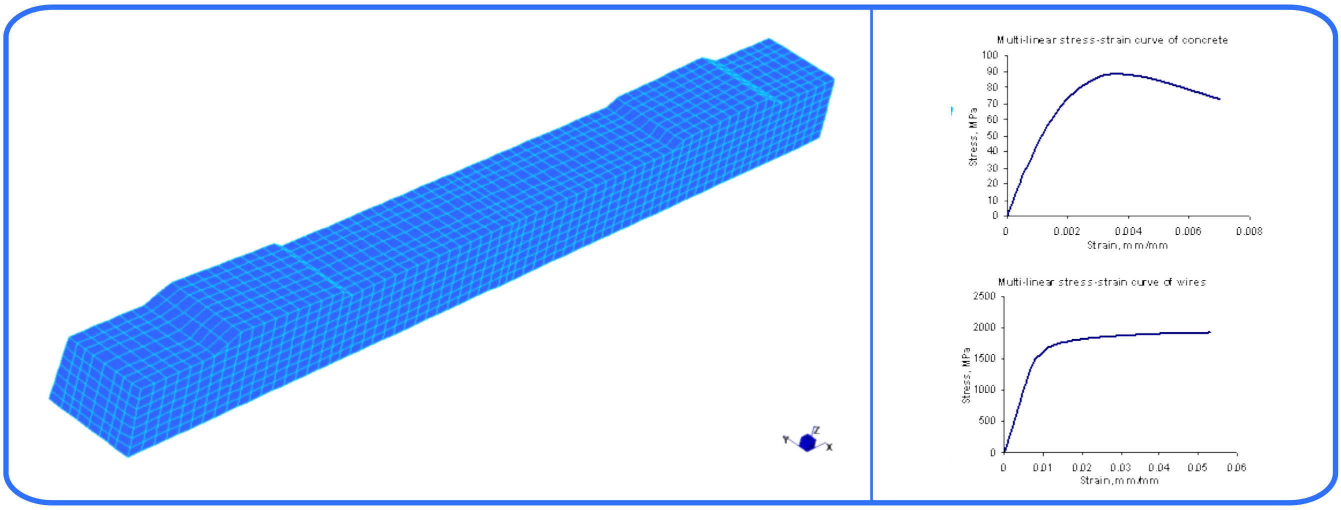

Figure 3: ANSYS finite element mesh of a prestressed concrete sleeper and the material models for concrete and steel used

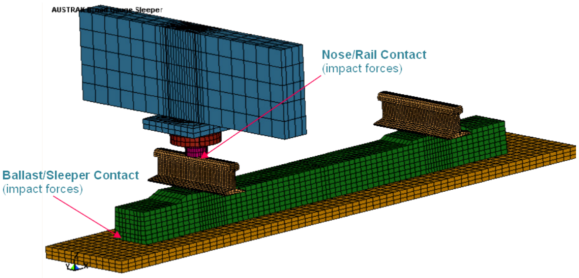

Figure 4: LS-Dyna impact model of railway prestressed concrete sleeper

Results and Discussions

The analytical solutions of the concrete sleeper due to only prestressing force (after losses) are illustrated in Figure 5. Both top and bottom fibre stresses are identical to those calculated manually [8]. The results from various material models are similar since only the initial linear parts of elasticity were employed in the analysis. The effect of self-weight is quite small when added up to the displacement due to the pre-tension. The comparison of experimental load-deflection responses is plotted with the finite element results in Figure 6. The nonlinear material models, MAT2 and MAT3, give similar results in the same loading range. MAT2 and MAT3 models provide respectively 4.5% and 5.3% differences from the experimental results. When using both cracking and crushing model into MAT4, it is noticed that the analytical results are far from the experimental ones because of the low tensile strength of concrete used. This causes the load-deflection response much lower than others.

Figure 7 shows the drop-weight impact experiment and simulation result of the selected railway concrete sleeper. In this case, the falling mass is 600kg and the drop height is 0.2m. 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, see ref: [16].

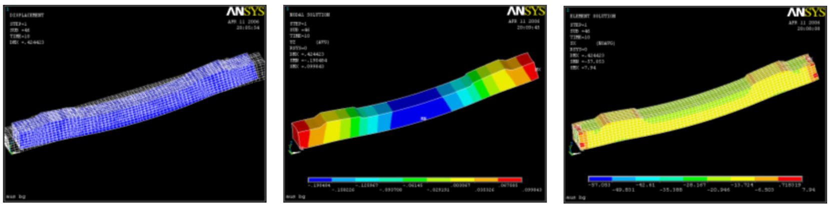

Figure 5: Pre-camber, displacement, and fibre stress diagrams due to pre-tensioned strain

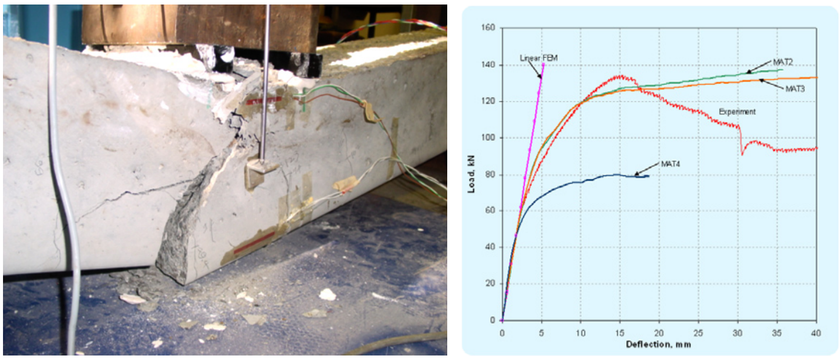

Figure 6: Static behaviour of the concrete sleeper: (left) failure mode; (right) load-deflection responses

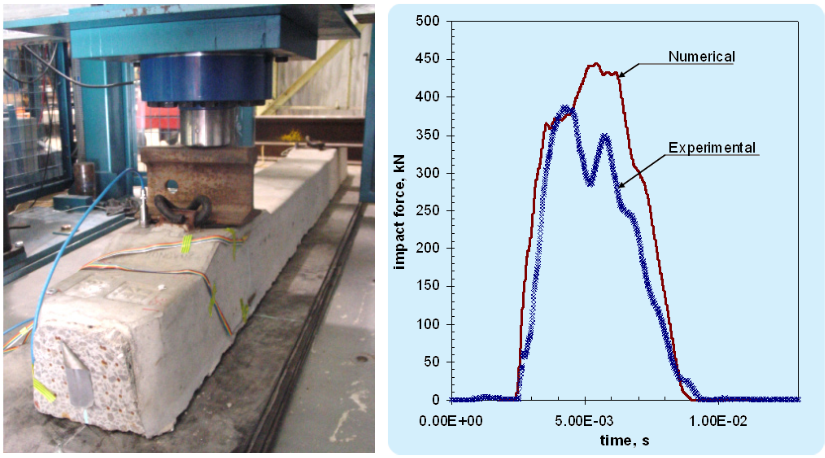

Figure 7: Impact test and shock simulation: (left) experiment; (right) shock load

Conclussions

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 concrete elements and steel prestressing wires were modelled using SOLID65 and LINK8 elements, respectively. The prestressing was applied using an initial strain to LINK8 elements in the discrete manner. Applied displacement method was used in the static analyses due to the fast and smooth convergence of numerical iterations. 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 results also show that the tensile strength based on $0.4\sqrt{f_c'}$ is unsuitable for the high strength concrete. The finite element model was then extended using finite element model updating technique. 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.

Acknowledgement

The authors are grateful to the Australian CRC for Railway Engineering and Technologies (Rail-CRC) for the financial support throughout this study. The authors would also like to thank Professor Brian Uy, Dr. Prabuono-Buyung Kosasih, Ee Loon Tan, Alan Grant, Ian Bridge, Bob Roland, and Jason Knurst, for their assistance during the course of this project.

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