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Nonlinear finite element modelling of  
railway prestressed concrete sleeper

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This peer-reviewed conference paper was originally published as Kaewunruen, S and Remennikov, A, Nonlinear finite element modelling of railway prestressed concrete sleeper, in Proceedings of the 10th East Asia-Pacific Conference on Structural Engineering and Construction, 3 - 5 August 2006, Bangkok, Thailand, volume 4, Real Structures: Bridges and Tall Buildings, 323-328. Original conference proceedings are available <a href="http://www.easec10.net">here</a>.

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## **NONLINEAR FINITE ELEMENT MODELLING OF RAILWAY PRESTRESSED CONCRETE SLEEPER**

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**ABSTRACT:** Three-dimensional nonlinear finite element model of railway prestressed concrete sleeper has been developed in this study. The general purpose finite element package, ANSYS 10, is employed for the numerical analyses. Using SOLID65 solid element, the compressive crushing of concrete is facilitated using plasticity algorithm while the concrete cracking in tension zone is accommodated by the nonlinear material model. Since the section of concrete sleeper is fully prestressed by nature, the smeared crack analogy is impracticable. Discrete reinforcement modeling with truss elements, LINK8, is then more suitable to utilize. The pre-tensioning is modeled via an initial strain in the tendon elements. Perfect bonding between concrete and pre-stressing wires is assumed herein. Comparison with experimental load-deflection response is presented for the prestressed concrete sleeper. Convergence of both analytical and experimental results is showed.

**KEYWORDS:** Nonlinear finite element modelling; Railway prestressed concrete sleeper or Railroad tie; Pre-tensioning; and Static analysis.

### **1 INTRODUCTION**

Concrete structural components require the understanding into the responses of those components to a variety of loadings. There are a number of methods for modeling the concrete structures through both analytical and numerical approaches. Finite element analysis (FEA) is a numerical one widely applied to the concrete structures based on the use of the nonlinear behavior of materials. FEA provides a tool that can simulate and predict the responses of reinforced and prestressed concrete members. A number of commercial FEA codes are available in e-markets, along with the advanced modules for complex analyses. The use of FEA has increased because of progressing knowledge and capability of computer package and hardware. Any attempts for engineering analyses can be done conveniently and fast using such versatile FEA packages. These result in the modernization of structural modeling by new-generation practical engineers, in order to verify their structural designs. Nonlinear material models have been integrated in many of general purpose finite element codes, i.e. ABAQUS, ANSYS, STRAND7, or MSC.NASTRAN. Those nonlinear models play a vital role in nonlinear response analyses since each material component tends to possess the complicated stress-strain behaviors. Among those packages, ANSYS [1] provide a three-dimensional element (Solid65) with the nonlinear model of brittle materials similar to the concrete materials. The element features in a smeared crack analogy for cracking in tension zones and a plasticity algorithm to take into account the concrete crushing in compression zones. It is an eight noded solid isoparametric element with the integration points for the cracking and crushing checks. The linear elastic behavior governs the analyses until exceeding either the specified tensile or compressive strengths. Once the principal stresses at the integration points reach the tensile and compressive strength, the cracking or crushing of concrete

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elements can be formed. Then, the cracked or crushed regions will form in perpendicular with the locally redistributed residue stresses to the direction of principal stress. These require the nonlinear iterative solver with high performance computer [2-4]. Railway sleeper is an important component of track structure. It mainly helps distribute loads from the rail foot to underlying ballast bed. It has been found that most of loading on tracks are dynamic loads that have effects on the deterioration of the railway tracks' components and undermine the load resistant performance of the railway concrete sleepers [5-8]. Understanding into relationships between static and dynamic responses is mandatory. There are few studies related to the modeling of prestressed concrete sleepers. Most of them predicted the static sagging behaviors of the concrete sleepers [5, 9]. Prediction of the rotational and translational behaviors under normal track loading, which creates the hogging moment, has rarely been found in literature. The objective of this study was to develop a numerical model where nonlinear material properties of concrete sleepers can be included in the detailed analyses for static and dynamic investigations in the future. Due to its availability to industry, a commercial FEA package is preferable in order to use the model in general design practice. A three-dimensional nonlinear finite element model of a railway prestressed concrete sleeper was developed by a general purpose finite element analysis package, ANSYS10. Concrete section was modeled using SOLID65 solid element where the compressive crushing of concrete is facilitated using plasticity algorithm and the concrete cracking in tension zone is accommodated by the nonlinear material model. In normal practice, the railway concrete sleeper is designed to resist prestressing force fully throughout the whole cross section. 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 modeling, 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 occurs during loading exposure. The static full-scale experiment was conducted to validate this FE model [8]. The experimental details were based on the associated Australian Standards [10, 11]. Comparison with experimental load-deflection response and rotational capacity are presented for a specific type of prestressed concrete sleepers.

## 2 EXPERIMENTS

The prestressed concrete sleeper was supplied by an Australian manufacturer, under a collaborative research project of the Australian Cooperative Research Centre for Railway Engineering and Technologies (Rail CRC). Experimental programs were managed in accordance with the Australian Standards and the negative four-point bending moment test was conducted, see details in ref: [8]. The experimental results, i.e. load-deflection curve, load-rotation curve, and so on, 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. The tested compressive strength of cored concrete is 88.5MPa. This value has been corrected according to AS1012.14 [12]. This information is crucial as the input criteria for the material model in ANSYS. The cross section details of the tested concrete sleeper are given in Figure 1. In addition, sectional analysis of the specimen for ultimate negative moment of middle section was done. The predicted ultimate negative moment is 53 kNm that is quite close to the experimental result, which is about 47 kNm. These static results were used to evaluate the suitability of the sleeper model implemented in ANSYS as to predict the nonlinear responses of the prestressed concrete sleeper to static hogging moment.

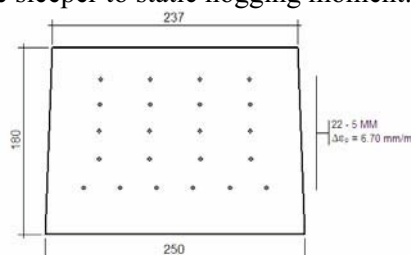


Figure 1. Cross section details for the model sleeper (after [8])

### 3 NONLINEAR MATERIAL BEHAVIOURS

In this study, ANSYS10 is employed for the nonlinear model of prestressed concrete sleeper. Concrete part was modeled using a three-dimensional solid element, SOLID65, which has the material model to predict the failure of brittle elements. 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 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 [13]. To simulate the behaviors 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.

Nonlinear elastic behaviors 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 [14] as given by  $E_c = 5050\sqrt{f'_c}$  and the tensile strength of concrete at 28 days ( $f'_{ct}$ ) is  $0.4\sqrt{f'_c}$ , with the value of  $f'_c$  equal to 88.5 MPa and Poisson’s ratio was assumed to be 0.3. The multi-linear isotropic stress-strain curve for the concrete can be computed by [15]

$$f = \frac{E_c \varepsilon}{1 + \left(\frac{\varepsilon}{\varepsilon_0}\right)^2}, \quad \varepsilon_0 = \frac{2f'_c}{E_c}, \quad \text{and} \quad E_c = \frac{f}{\varepsilon} \quad (1a, b, c)$$

In Equation (1), note that  $f$  is stress at any strain ( $\varepsilon$ ) and  $\varepsilon_0$  is the strain at the ultimate compressive strength at 28 days,  $f'_c$ .

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. Table 1 tabulates the summary of material models used in finite element analysis. Four cases of material models have been investigated in this study.

Load-deflection behavior of concrete structures typically includes three stages. Stage I shows the linear behavior of uncracked elastic section. Stage II allows initiation of concrete cracking and Stage III relies relatively on the yielding of steel reinforcements and the crushing of concrete. This results in the nonlinear response analysis of concrete structures. In nonlinear iterative algorithms, ANSYS10 utilizes Newton-Raphson method for the incremental load analysis.

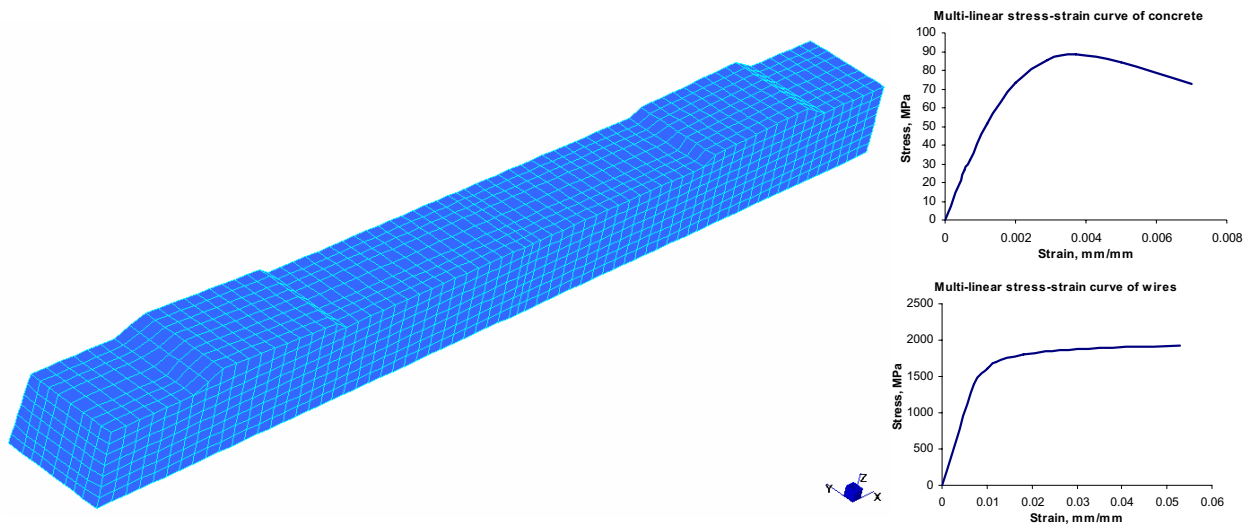
**Table 1 Material models used in finite element analyses.**

Model	Concrete Model		Prestressing Wire Model	
	Tension	Compression	Distribution	Material Properties
MAT1	Linear Elastic	Linear Elastic	Discrete	Linear Elastic
MAT2	Linear Elastic	Multi-linear Isotropic	Discrete	Linear Elastic
MAT3	Linear Elastic	Multi-linear Isotropic	Discrete	Multi-linear Isotropic
MAT4	Cracking	Multi-linear + Crushing	Discrete	Multi-linear Isotropic

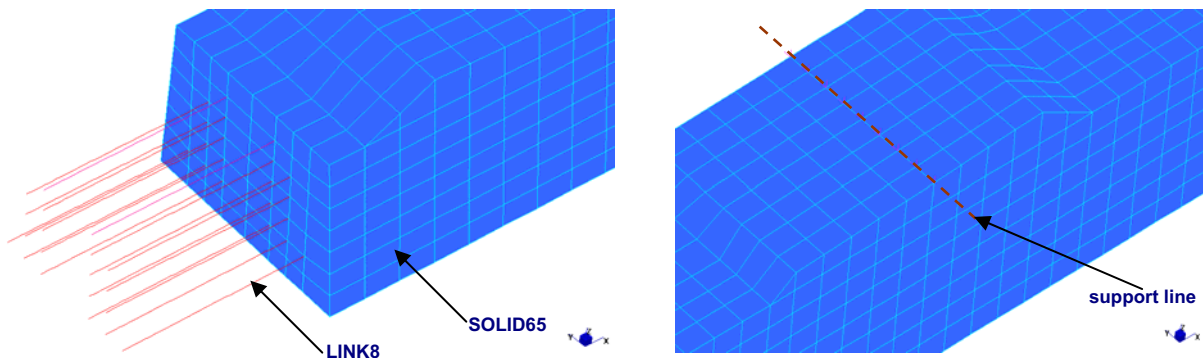
#### 4 FINITE ELEMENT MODELLING

The three-dimensional model of railway prestressed concrete sleeper has been developed in ANSYS10 as illustrated in Figure 2a. Dedicated solid bricks (SOLID65) represent the concrete and the embedded three-dimensional spar elements (LINK8) are used as the prestressing wires, as shown in Figure 2b. The pre-tensioning was modeled using an initial strain in the tendons corresponding to prestressing forces in the preliminary load stage. The nonlinear material models were specified in the ‘*material properties*’ feature, while the initial strain and prestressing wire diameters could be defined in ‘*real constants*’. Figure 2c shows the boundary conditions imposed along the related nodes. The model would be loaded to failure in a manner consistent with the experimental data.

A technique used for load-deflection analysis involves with the use of applied displacements to facilitate the smooth convergence of loading, in accordance with the experimental programs. Then, the maximum displacement at mid span can be calculated. There were three steps towards final solutions. First, no load was applied since the initial strain was defined. The time at the end of the prestrain load step is 1. Second, the self-weight was added in a load step. The uniformly distributed loading is done by applying gravitational acceleration of  $9.81\text{m/s}^2$  in the negative global z direction. The typical mass density of concrete ( $2,400\text{ kg/m}^3$ ) was entered in as a function of the gravitational acceleration (density/g). The last step was to define the load step until failure of the prestressed concrete sleeper, with consistency to the testing data.



a) Three-dimensional full-scale model



b) Connectivity between solid and bar elements

c) Boundary conditions

Figure 2. Finite element mesh of railway prestressed concrete sleeper

## 5 NUMERICAL RESULTLS

The analytical solutions of the concrete sleeper due to only prestressing force (Stage I) are illustrated in Figure 3. 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 this early stage. The effect of self weight in Stage 2 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 4.

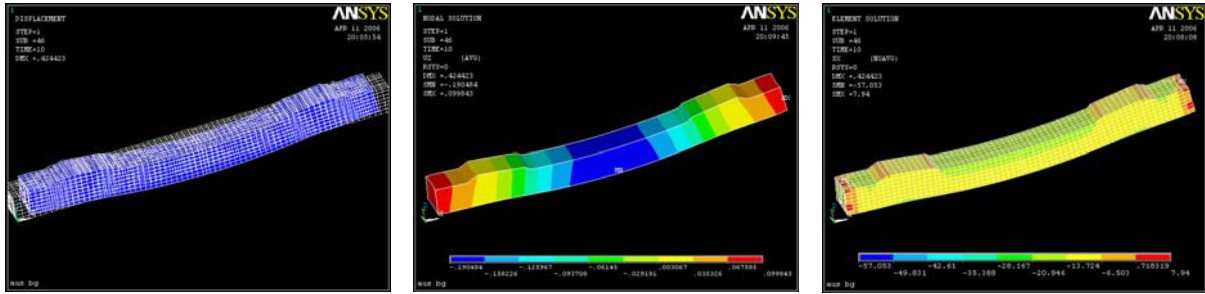


Figure 3. Pre-camber, displacement, and fibre stress diagrams due to pre-tensioned strain.

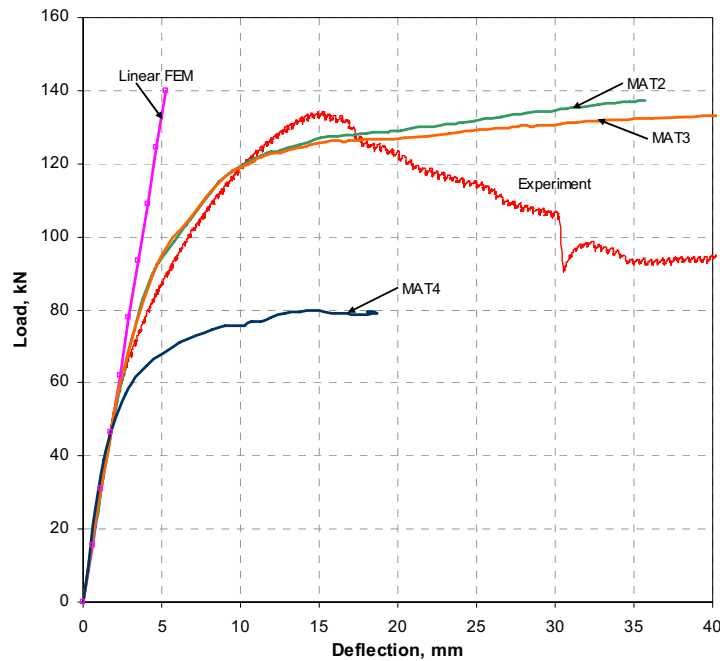


Figure 4. Load-deflection responses.

From Figure 4, it is found that MAT1 model can predict the linear range (from 0 to 65 kN of loading) of static behaviors of the concrete sleeper. The nonlinear material models, MAT2 and MAT3, give similar results in the same loading range. However, it can be found in the nonlinear range that MAT2 model seems to well represent the experimental load-deflection curve, while MAT3 model yields slightly smaller than MAT2 model when subjected to larger displacements (after 10-15mm). To obtain the deflection of 15 mm, the static loads of about 126 and 125 kN are needed in MAT2 and MAT3 models, which are, respectively, at 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.

## 6 CONCLUSION

This paper demonstrates the finite element modeling to investigate the static behaviors of railway prestressed concrete sleeper, with the uses of nonlinear material properties. Commercial package, ANSYS10, was employed in this study, for which it would be benefit for the industry. The finite element model of the prestressed concrete sleeper was developed. The concrete bricks and prestressing wires were modeled using SOLID65 and LINK8 elements, respectively. The prestressing was applied using the initial strain to LINK8 elements in the discrete manner. Applied displacement method was used in the analyses due to the fast and smooth convergence of numerical iterations. The hogging moment test of railway concrete sleeper was 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 nonlinear material models can well capture the nonlinear static behaviors 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.

## ACKNOWLEDGEMENT

The authors are grateful to Australian CRC for Railway Engineering and Technologies (Rail-CRC) for the financial support throughout this study. The authors would also like to thank Dr. Prabuono-Buyung Kosasih of School of Mechanical Engineering, UoW, for his suggestions on ANSYS.

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