USPs on Damage Reduction of Concrete Railway Sleepers

Renga Rao Krishnamoorthy, Zobaer Saleheen

Abstract*: Ballast is the weakest among all of the railway track components due to its latent dynamic shifting and variation of stiffness along and across the track. Sharp Angular shape of the ballast components hinders evenly distribution of loads from sleeper to ballast, which in turn causes the sleepers to deteriorate over time resulting in higher frequency of railway track maintenance. Previous studies have shown that having an under-sleeper pad (USP) in between sleeper and ballast increases the contact area between them significantly. This by itself reduces the long-term damage on sleepers by a substantial amount. However, concrete sleeper is subjected to cracking due to excessive dynamic load from rail wheels. This paper intends to numerically evaluate whether the cracking of concrete sleepers gets reduced due to installing of USPs in the railway track system. The foremost reason behind cracking of concrete sleepers is the induced dynamic loads due to track irregularities and imperfect wheel rail contact. The most affected portion is at the bottom of the rail seat location of sleeper. Thus, two finite element models (one without USP and one with a 20mm thick USP attached at sleeper bottom) were analyzed while incorporating the concrete damage plasticity in the sleepers' material. Results have shown better performance of concrete sleepers with USPs. Sleeper pads have shown a tendency to minimize excessive stress developed within naked concrete sleepers. Substantial advantage of using USPs in terms of damage reduction among sleepers were also perceived during conducting this analysis. Consequential reduction of crack formation was observed after installation of USPs.

Keywords: Under Sleeper Pads, Concrete Damage Plasticity, Railway sleepers, ABAQUS.

I. INTRODUCTION

A railway sleeper acts as a rectangular support for the rails in conventional railway system. It is normally placed at perpendicular to the rails which transfers the wheel load from rail to ballast and subgrade system. It also holds the rails uptight in their designated locations and maintains the gauge spacing. Though wooden sleepers were previously being used all over the world, current practices of adapting prestressed concrete sleepers is widely used in Europe and Asia. Steel sleepers are also common on secondary lines in the UK; plastic composite ties are also employed, although far less than wood or concrete. As of January 2008, the approximate market share in North America for traditional and wood ties was 91.5%, the remainder being concrete, steel, azobé (red ironwood) and plastic composites.

Under Sleeper Pads (USPs) are special pads made of polyurethane rubber which are normally placed between sleeper and ballasts. For economic reasons, thickness of these pads are kept in between 10 to 20 mm for normal purpose railway tracks [1]. In the newly built high speed railway track in central Europe, usage of USPs have been greatly noticed in the recent years. Though USPs are normally made of polyurethane rubber which has a foam like structure [2], sometimes they are also made with two types of materials, whereas the stronger outer thickness gives it protection against abrasive wear and tear, the inner thickness serves the true purpose of USPs. Among other roles, one of the main purposes of USPs is to reduce the damage in sleepers by distributing the wheel loads from sleepers onto ballast evenly. Previous studies have shown that contact area between sleeper and ballast is 3 to 4% of total sleeper area at the bottom. According to Riessberger [3], using USPs in between sleepers and ballast may increase that contact area up to 30%. This leads to a reduced contact pressure as well as stress concentration, also the abrasive wear of the stones is expected to become less. By using sleeper pads, force from the train is expected to be distributed to more sleepers at the same time. This also reduces the wear of the ballast and therefore, the track settlement. Moreover, using USPs in railway track gives better damping properties which reduces the track vibrations due to dynamic effect of wheel loads.

This paper intends to numerically evaluate the effects of USPs in terms of damage reduction in concrete railway sleepers. ABAQUS CAE Version 6.14 was used to conduct the static non linear Finite Element Analysis. Among the two numerical models, one of them was without any USPs and another one had a 20mm thick USP attached at the bottom of the concrete sleeper. Damage of concrete was evaluated using the Lee and Fenves [4] model for Concrete Damage Plasticity (CDP) of ABAQUS which is founded on fracture energy based damage and stiffness degradation concept of continuum damage mechanics.

II. PARAMETERS USED FOR FINITE ELEMENT MODELLING

A. Loading Considerations

The loading on rail tracks is dissimilar for different track geometries and design approach for concrete sleeper and fastening systems. These are iterative, empirical, and based on speed and traffic to meet the design load.

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Different countries have different standard for railway track loading. For example, India uses their own Research Division and Standards Organization (RDSO) for Indian Railway loading system. USA uses American Railroad Engineering and Maintenance-of-way Association (AREMA) loading standards. UK and the other European Countries use Eurocode (BS EN) Standards. As a matter of fact, Malaysia also uses the Eurocode Standards for designing of railway structures. There are several load models in European Standard. For this paper, a 250 kN of axle load is taken from Load Model 71 of Eurocode 1 [5]. As a static analysis proceeds, maximum axle load of Load Model 71 was then multiplied by the dynamic modification factor (φ) and applied as the wheel load over the rail seat of the sleeper.

B. Boundary Condition

The sleeper was modelled as solid element, ballast and subgrade, however, can either be modelled as solid 3D Elastic elements or as discrete spring elements. Different researchers have taken different approaches in choosing the modelling for the sleeper. In this study, discrete spring elements of 20 MN/m^2 uniform stiffness spread across the sleeper at an interval of 75 mm distance were used [6]. The sleeper-ballast interaction is neither fixed nor always uniformly distributed. Four different support conditions were studied depending whether it is a stiff of soft ballast bed. Fig. 1 and Table I show the values of stiffness used in the modelling.

Table I: Stiffness for Different Cases of Support Condition

Case/ Stiffness	Vertical Stiffness (MN/m^2)	
	Side	**Center**
Case 1	20	
Case 2	26	13
Case 3	26	
Case 4	20	

In another study done by Dahlberg [7], it was recommended to use a vertical stiffness of 13 MN/m^2 for soft ballast beds and 26 MN/m^2 for stiff ballast beds. Askarinejad & Dhanasekar [8] used 15MN/m^2 uniform vertical stiffness. Whereas Witt [8] modelled the ballast bed as elastic isotropic material and the soft part of ballast was modelled with a 30 MPa Young Modulus and 20 kN/mm vertical stiffness and for the stiff ballast, 110 MPa Young Modulus and 60 KN/mm vertical spring stiffness was selected [1].

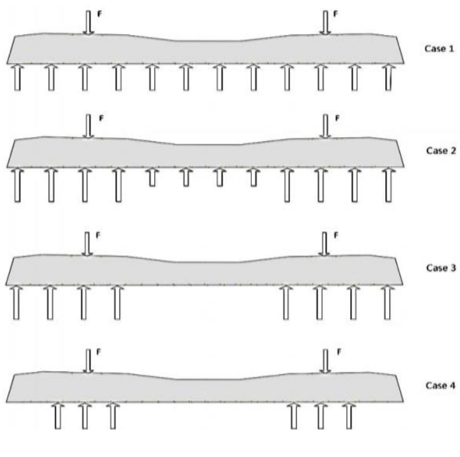


Fig. 1: Four Different Cases of Support Conditions

C. Material Model for USPs

The emphasis of USP development has been initially placed on the ballasted tracks for high speed trains where they induce high dynamic forces onto the track. The ballast could be damaged and densified by this impulsive force. In Europe, it has been reported that the USPs in high speed tracks yield an effective solution combining technical and economic efficiency [9]. Finite Element Modelling of USPs can either be done by using an elastic isotropic material or a hyper-elastic material. For modelling a hyper-elastic material in ABAQUS, at least six experimental test data are required [10]. In order to run a dynamic nonlinear analysis and get accurate results, it is recommended to use proper hyper-elastic and hysteresis data in accordance with the viscoelastic properties of the USP Rubber [11]. On the contrary, Witt [8] evaluated the effects of USPs in railway track dynamics, and the USPs were modelled as elastic isotropic material [1]. Three types of stiffness were used in this study which the details are shown in Table II. Mass density of 500 kg/m^3, Poisson's ratio of 0.1 and Young's Modulus were taken as 100 MPa for modelling USPs.

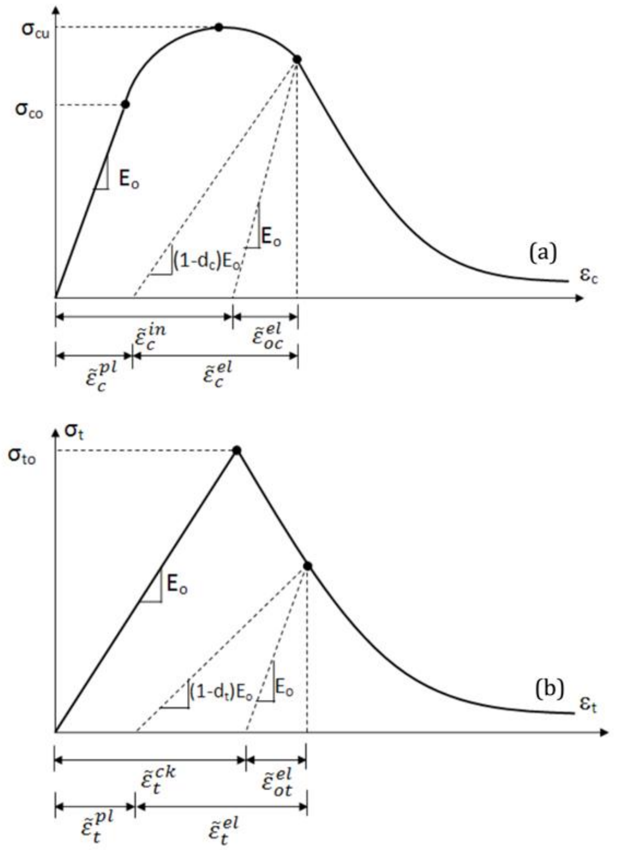
Table II: Stiffness variations of USPs

USPs	Young's Modulus (MPa)	Vertical Stiffness (KN/mm)
Stiff	1000	3000
Medium	100	400
Soft	10	50

D. Concrete Damage Plasticity (CDP) Model for Sleepers

Modelling of reinforced concrete can be quite difficult in the finite element packages due to its complex behavior. The proper reinforced concrete model should be capable of representing the elastic and plastic behavior of concrete in both compression and tension. The complete compressive behavior of concrete should include both elastic and inelastic regions of concrete including strain hardening and strain softening regimes. For the tensile behavior, tension softening, tension stiffening and local bond effects between reinforcement and concrete should be properly taken into account. The plasticity of the concrete can either be modelled using one of three techniques available in ABAQUS namely, Smeared crack concrete model, Concrete damage plasticity model and Brittle crack concrete model [10]. Concrete damage plasticity (CDP) model was selected for this study as CDP can represent the inelastic behavior of concrete in both compression and tension including damage characteristics. CDP model is based on mainly two failure mechanisms which are crushing of concrete during compression and cracking of concrete during tension [12].

As shown in Fig. 2, under uniaxial tension, the concrete has a linear elastic stress strain relationship until it reaches the *failure stress,* σ_{to}*. The failure stress corresponds to the onset* microcracking of the concrete material.



Beyond the failure stress, the microcracking is represented macroscopically with a softening strain branch of the

Fig. 2: Behavior of Concrete under (a) uniaxial compression (b) uniaxial tension

stress strain curve. On the other hand, under uniaxial compression, the concrete behaves elastically until it reaches the initial yield σ_{co}, beyond that point the plastic region starts with a strain hardening branch until it reaches the ultimate stress σ_{cu} and then followed by the strain softening region.

The CDP model used in ABAQUS is a modification of the Drucker-Prager strength hypothesis. According to the modifications, the yield surface on the deviatoric plane need not to be a circle, however, it is governed by the parameter K_c, which is the ratio of the distance between hydrostatic axis to respectively the compressive meridian and tensile meridian in the deviatoric cross section. The value must be greater than 0.5 and less than 1 [10], the default system value of K_c is 2/3, σ_{b0}/σ_{c0} is the initial equibiaxial compressive yield stress to initial uniaxial compressive yield stress. The default system value of 1.16 has been used for this parameter [13] [14]. In the CDP model, the plastic potential surface in the meridian plane assumes a form of parabola, which is adjusted through eccentricity, $\varepsilon = 0.1$ [13]. The last parameter characterizing the performance of concrete under compound stress is dilation angle, ψ i.e. the angle of inclination of the failure surface towards the hydrostatic axis, measured in meridional plane. Physically dilation angle is represented as angle of internal friction in concrete. The value of ψ in common practices can vary from 30º [13] to 45º [14]. As for failure mechanism, it can be defined either as a tabular function of the stress strain data in correspondence with damage parameters [15] or as Hillerborg's cracking energy criteria & [13], [14] & [15].

III. FE MODELLING IN ABAQUS

ABAQUS Version 6.14 was used to numerically evaluate the damage reduction of concrete sleepers due to USPs. For this paper, two models were used. All of the parameters for modelling were same, only the difference between the two models was that the first model contained a naked sleeper and in the second model a 20 mm thick USP was attached at the bottom of the sleeper. Sleeper was modelled as 3D deformable solid element (C3D8R) but the shear stirrups and longitudinal prestressed reinforcements were modelled as wire type T3D2 hybrid elements. The material used for mild steel was a 500 Grade steel, which had a yield strength of 500 MPa and ultimate strength of 640 MPa at 1 % strain. It was defined by putting in the true stress strain values of steel at and beyond elastic limit in a tabular format. For concrete, both the compressive and tensile stress strain data in accordance with the consecutive damage parameters were put in a tabular format in ABAQUS.

Table III: Compressive Stress-Strain data of 51.2 MPa Concrete

Compressive Stress (MPa)	Inelastic Strain	Damage (d_c)
25.60	0.00000	0.00000
36.40	0.00010	0.01050
44.90	0.00028	0.02950
49.70	0.00059	0.06160
51.20	0.00101	0.10600
49.00	0.00176	0.18500
44.30	0.00260	0.27300
38.90	0.00346	0.36300
33.70	0.00431	0.45300
29.20	0.00514	0.54000
25.40	0.00595	0.62500
22.20	0.00674	0.70700
19.50	0.00751	0.78800

Table IV: Tensile Stress-Strain data of 51.2 MPa Concrete

Tensile Stress (MPa)	Cracking Strain	Damage (d_t)
2.36	0.000000	0.000000
1.89	0.000041	0.385000
0.95	0.000293	0.900000
0.21	0.000807	0.991000

Table III and Table show the mechanical properties of concrete in compression and tension respectively that were used to evaluate the damage in sleepers.

These data were taken from Wahalathantri et al. [15], whom got those data from conducting uniaxial compression and tension tests on 51.2 MPa concrete. Later on, those data that obtained from experimental works were validated with ABAQUS model by performing a four-point bending test on a reinforced concrete beam. Needless to say that, the results obtained from ABAQUS and experimental tests were very well matched [15].

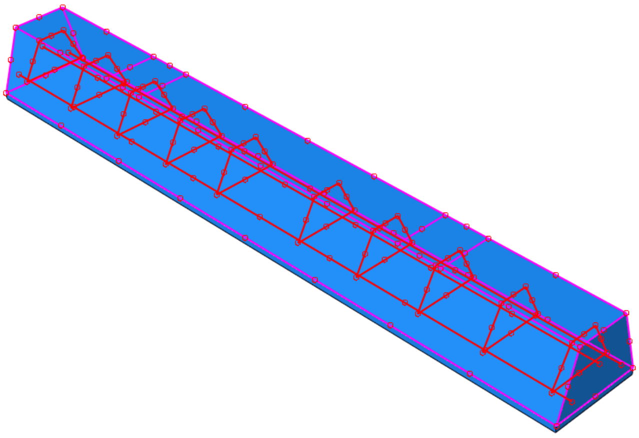


Fig. 3: FEM model in ABAQUS

Both longitudinal and shear reinforcements were modelled using embedded element technique in ABAQUS. Coulomb bilinear friction theorem was used to define the interaction between sleeper and USP, normal interaction was defined as hard contact and for tangential interaction the value of coefficient of static friction was adopted as 0.65. Ballast bed was represented in the model by defining it as an elastic foundation of 20 MN/m^2 stiffness.

IV. RESULTS AND DISCUSSION

There are two models in this phase, one without USP and one with 20 mm USP attached at the bottom of the sleeper. For the easement of comparing the results of both models, the model without USP was designated as Model-1 and the model with 20 mm USP was designated as Model-2. In ABAQUS, the damage of material properties i.e. cracks in concrete can be seen by using either the DAMAGET or DAMAGEC output variables. DAMAGEC stands for damage due to compression crushing of concrete of material. In both models, no apparent damage due to crushing of concrete was observed. Whereas the tensile cracking is represented as DAMAGET output in ABAQUS, which are presented in both models of this phase. The value for both damage outputs varies from 0 to 1, where 0 means no damage of the material and 1 indicates total loss of material strength due to cracking or crushing.

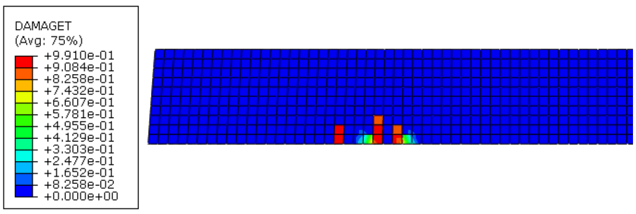


Fig. 4: Crack patterns of concrete sleeper (only half of the sleeper is shown) in Model-1 [No USP]

Fig. 4 and Fig. 5 show the elevation view of tensile cracks on naked concrete sleeper for both models, where a significant area at bottom of sleeper directly below to rail seat was damaged due to static wheel loads at rail seat.

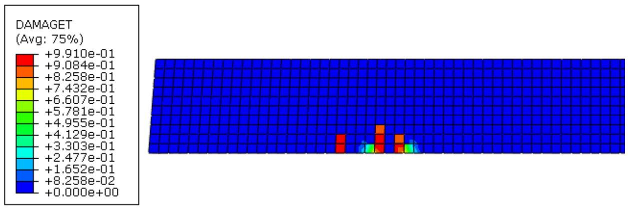


Fig. 5: Crack patterns of concrete sleeper (only half of the sleeper is shown) in Model-2 [20 mm USP]

The maximum tensile damage value of 0.99 were observed in at least two strips at the bottom of sleeper, below each rail seat, damaged area strips were considerably less in the sleeper with USP than the naked sleeper. The maximum damage for both models of this phase were observed at 468.5 mm away from end of the sleeper. So, a section of sleeper was cut in the Y-Z plane at 468.5 mm away in X direction from end of sleeper.

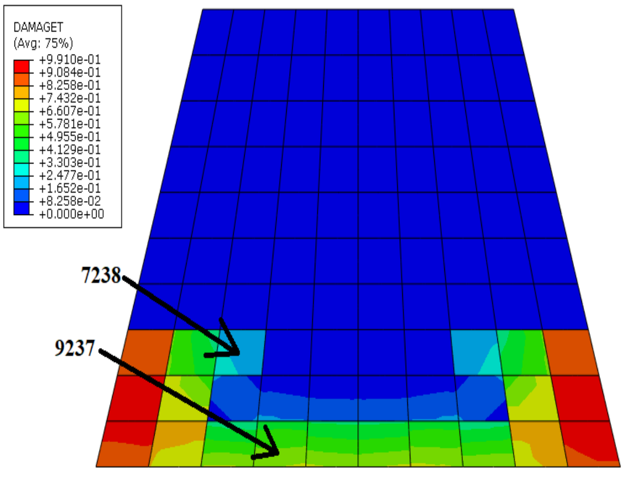


Fig. 6: Cross sectional view of Damage in Model-1

The sections of sleeper without and with USP are shown in Fig. 6 and Fig. 7, respectively. Both models show extensive cracking at the corners of the sleeper bottom. Corner Elements in Model-1 and Model-2 totally loses its strength. Extensive cracks of Model-1 (almost 100% damage), around the corners of sleeper propagate at approximately 60 mm in upward direction from the bottom of the sleeper. The element 7238 looses 31.1% of its strength when there is no USPs but with 20 mm USP, the material of that element remain its strength. Similarly, the maximum and minimum damage for element 9237 and 9239 was 78.97% and 57.83% which reduces to 71.5% and 22.05% respectively after the installation of USPs.

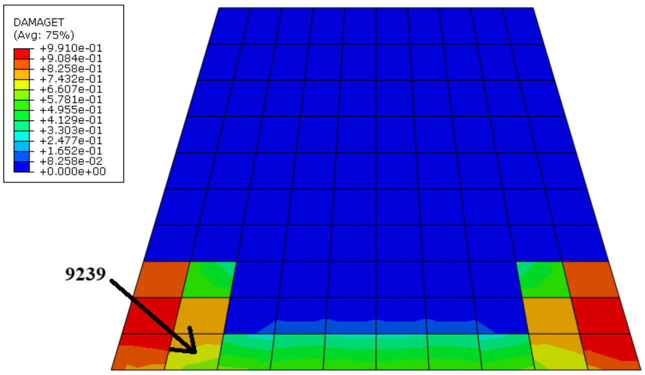


Fig. 7: Cross sectional view of Damage in Model-2

V. CONCLUSION

USPs had some substantial effects toward the extent of cracks in sleeper. Although the crack patterns remain almost same due to the USPs, zones with extensive cracking has shown 7.5% to 35.8% reduction of damages due to installation of USPs. Besides, around some areas, the cracking was seen to be totally eliminated due to USPs. The main advantages of USPs is that it protects sleeper from localized damage due to the sharpened edges of ballast materials by absorbing the energy generated at the USP-ballast contact patches due to dynamic effects of wheel load and impairment to itself. As USPs becomes thicker, damage in sleeper reduces more and more. But due to the cost-benefit ratio, USP thickness for a particular site should be selected by performing several trial and error methods to find the optimum thickness

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