ANALYSIS OF THE STRESS STATE OF A RAILWAY SLEEPER USING COUPLED FEM-DEM SIMULATION

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FEM-DEM, coupled analysis, railway ballast, railway sleeper, Yade, ANSYS

ABSTRACT

This paper deals with a coupled finite-discrete element simulation of a railway sleeper. The analysis aimed to show the trends of the stress state of a concrete sleeper during a conventional loading in the case of a crushed stone ballast bed. A typical discrete element analysis helps the engineers to analyze the behavior of the bulk material. The finite element analysis assists in examining the continuum materials. The railway tracks are complex systems, using both of the methods need to understand the interaction between the connected elements. The applied one-way coupled analysis highlighted the trends of the peak stresses on a concrete sleeper caused by the individual stones.

INTRODUCTION

Nowadays, the railway is one of the most popular ways of carrying goods and passengers. Besides the different component systems of the vehicles, the various parts of the railway track, along with their interaction with each other and the surrounding environment, are also in the focus of the researchers, as have been pointed out by Eller and Fischer (2019). The purpose of this paper is to analyze the stress state of sleepers, which are the interface between the rails and the crushed rock ballast as well as to find adequate protection layer.

Numerical simulations are frequently used to obtain data about processes that are hard or cost-demanding to perform experimentally. The finite element method (also known as FEM, Zienkiewicz 1971) gives a tool to the engineers to examine the vehicle and track systems (e.g. Németh et al. 2020) if they are treated as a continuum, while the discrete element method (DEM, Cundall and Strack 1979) helps to understand the role of individual grains on the mechanical behavior of the track system in the virtual space.

For modeling continuum materials, FEM is generally applied. The major fields of application are mechanical (static, dynamic, buckling, fatigue), thermodynamic, and electrodynamic processes. The FEM models consist of a finite number of elements that connect each other with common nodes for which have common degrees-of-freedom (Zienkiewicz 1971). By contrast, however, the DEM models also consist of finite number of elements. These elements (particles) independent from each other, the DoFs are different on the neighboring elements (Bagi 2007). That is why the DEM is the better way to describe bulk materials while FEM for modeling continua.

Several different approaches exist in the literature for modeling the interaction of sleepers and ballast. If the role of individual grains is not important, FEM can be used alone, as Shahraki et al. (2015) and Paixão et al. (2016) did. The motion of grains can be captured by the application of DEM. The simplest element type for representing the stones is the circle or sphere (Irazábal et al. 2017). The effect of shape can be studied by using more complex element shapes, e.g. glued spheres with rigid (*clump*) or deformable/breakable (*cluster*) connection (Kono and Matsushima 2012; Gao et al. 2015; Khatibi et al. 2017; Laryea et al. 2014; Zhang et al. 2017; Jing et al. 2019; Juhasz et al. 2019). Polyhedra (Ferellec et al. 2017; Huang and Tutumluer 2011) are even more accurate at the cost of high computational demand and more complicated contact detection.

There are cases when coupled discrete-continuum methods are needed for valuable results (Shao et al. 2017; Song et al. 2019; Shi et al. 2020b, 2020a). Using a coupled analysis, the stress peaks on the sleepers, caused by the stones in the ballast, can be examined, which can help to understand the crack initiation process on a concrete sleeper. This coupled method also allows the simulation of the effect of different under sleeper pads (between the sleeper and the ballast).

SIMULATION ENVIRONMENT

A typical structure of a trackbed, detailing the different layers, can be seen in Figure 1. One sleeper and the connecting ballast environment have been used during the simulation. The sleeper's geometry was created according to an LM-GEO type prestressed reinforced concrete sleeper's dimensions (Lábatlani Betonipari Zrt. 2020). The load on the sleeper was 225 kN static axle load that is the allowable maximum of the examined sleeper (Lábatlani Betonipari Zrt. 2020). The prestressed state of the sleeper was neglected during the simulation. The geometry of the sleeper can be seen in Figure 2.

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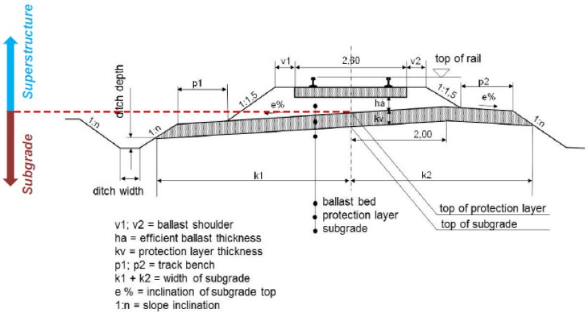

Figure 1: Structure of Trackbed (Fischer et al. 2015)

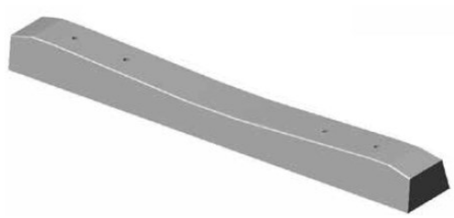

Figure 2: LM-GEO Concrete Sleeper (Lábatlani Betonipari Zrt., 2020)

DEM Model

A 600 mm wide section of the ballast was involved in the model. The boundaries of the model domain were made of *facet* elements (triangle elements with zero thickness). The stones were modeled by polyhedral elements, using Yade (Šmilauer et al. 2016) and the built-in volumetric contact model (Eliáš 2014). Firstly, loose packing was generated with the aid of the Voronoi method (Asahina and Bolander 2011). The size of the elements was set to be between 32 and 50 mm. The assembly consisted 90% compact (size ratio: 2:2:1) and 10% flat (size ratio: 2:1:0.5) elements. The elements fell under the influence of gravity to obtain a dense packing than the shape of the ballast was obtained by deleting sparse elements, including the space for the sleeper. The sleeper was also modeled by facets. It moved downwards with a constant speed until reaching the desired summed load on the sleeper when the acting force on each facet was exported. Falling particles were deleted sequentially. The geometry, after the finishing of the loading process, can be seen in Figure 3.

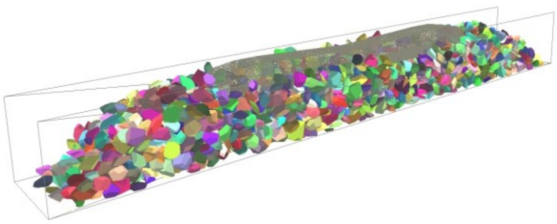

Figure 3: Geometry of the DEM Model

The resultant geometries consisted of 2000-2500 elements, which is lower than in a real ballast domain of the same size. However, it was enough for the authors' purposes: to obtain qualitative results and to test the methodology. Approximately 20-30 grains came into interaction with the sleeper under it, as can be seen in Figure 4 b). The purple (dark gray in greyscale) lines represent polyhedron-polyhedron contacts, and the green (light gray in greyscale) lines show the feasible polyhedron-facet interactions.

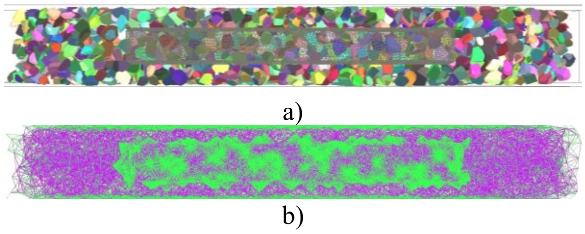

Figure 4: Geometry (a) and Interactions (b) of the DEM Model from Above

The applied model parameters were taken from literature (Eliáš 2014) and can be seen in Table 1. In that paper, the model was calibrated based on oedometric test, which applies similar type of load as in the current study.

Table 1: Micromechanical Parameters of the DEM Model (ρ: density, k_n: volumetric normal stiffness, k_n: shear stiffness, φ: sliding friction angle between elements)

	Stones	Sleeper and walls	Unit
ρ	2600	7800	kg/m^3
k_n	$2{\cdot}10^{13}$	$2{\cdot}10^{14}$	N/m^3
k_s	$2{\cdot}10^{8}$	$2{\cdot}10^{9}$	N/m
φ	0.6	0.4	rad

FEM Model

The finite element analysis created in ANSYS Workbench 2020 R1 environment (ANSYS, Inc. 2020). During the simulation 10-nodes, quadratic tetrahedron elements were applied, which mesh arrangement was the same, used during the DEM simulation. The structure of the sleeper's FEM mesh can be seen in Figure 5.

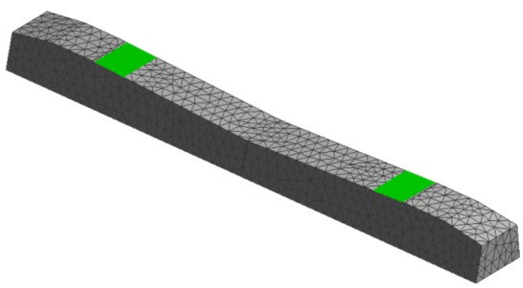

Figure 5: Structure of the Finite Element Mesh Used During the FE Analysis. The Place of the Fix Boundary Conditions Highlighted on the Geometry

Fix boundary conditions were applied on the surfaces where the rails are connecting to the sleeper, neglecting the under sleeper pads (Figure 5). This approach was acceptable because of the acting force came from the DEM simulation on the bottom side of the sleeper. During the simplified simulation, uniform material properties were used. The initial elasticity modulus of the concrete was 37 800 MPa, and the Poisson ratio was 0.2 through the analysis (MSZ 15022-1:1986).

The connection between FEM and DEM

A previously published method (Orosz et al. 2018) was used to establish a one-way connection between Yade and ANSYS. The arising forces on the center of mass of the triangular facets were saved in the appropriate time (when the summarized force on the sleeper exceeded the desired load in more than 100 consecutive timesteps), and were saved in a .csv file with a special format, containing their magnitude (according to components) and coordinates of application. To reduce the effect of numerical errors, the simulation continued for 100 additional timesteps after reaching the maximum force criterion, and the value of force components were avaraged over this time, as it was also done in (Vajda et al. 2019).This file was imported into ANSYS after the creation of the proper geometry. The forces were interpolated onto the FE nodes with the so-called "mapping" technique, which is implemented into ANSYS.

RESULTS

The result of the interaction between the andesite ballast and the concrete railway sleeper can be seen in Figure 6. The figure shows that, because of the non-uniform distribution and shape of the trackbed stones, the surface pressure on the bottom of the sleeper is also non-uniform. However, the value of the average pressure is very small, which matches with the requirements of the sleeper-ballast connection (Sysyn et. al. 2019; Figure 7), but there are some peaks which indicate that the trackbed stones overload the rigid concrete in some small surfaces because of its sharp shape. A highlighted overloaded region can be seen in Figure 8. These peaks can help of the crack initiation process on the surface of the railway sleeper, which results damage in long term period.

In reality, contrarily to the simulation, the corners of the crushed stones break off or even the entire grain can split into multiple pieces (Selig and Waters 1994). That phenomenon reduces the magnitude of peak stresses and increases the number and area of sleeper-stone contacts. Therefore, the results of the simulation can be improved by applying a proper stone breakage model.

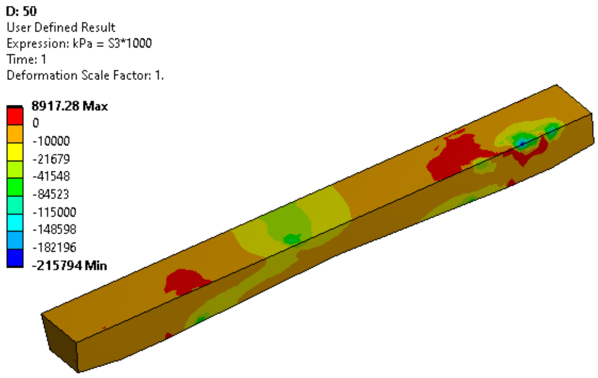

Figure 6: Pressure distribution on the bottom of the examined sleeper (Deformation scale 1:1; unit: kPa)

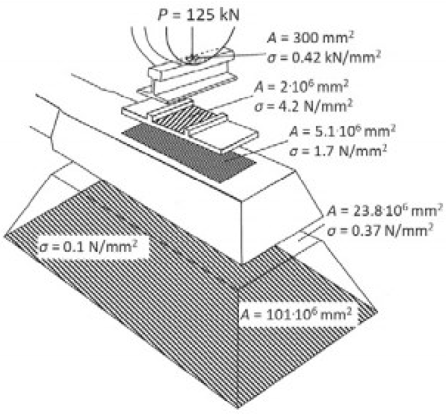

Figure 7: Schematic explanation of the stress distribution of a complete wheel-rail-track connection (Sysyn et. al. 2019, modified after Führer 1978)

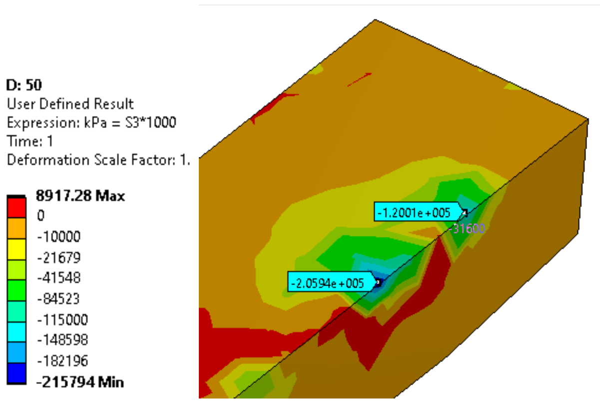

Figure 8: Non-uniform pressure peaks on the bottom of the concrete sleepers (Deformation scale 1:1; unit: kPa)

SUMMARY AND CONCLUSIONS

The examination of the stress field of the railway sleeper due to its interaction with the ballast grains requires a connection between continuum and discrete simulation methods. A simple method was published previously to connect the open-source Yade DEM framework with the commercial ANSYS FEM software without 3rd party extensions. This one-way connection method has created the possibility to take a closer look at a concrete sleeper and ballast connection. The results highlighted that the pressure distribution is non-uniform on the bottom of the sleeper because of the distinct crushed stones. These pressure peaks might initiate cracks on the surface of the sleeper, or can cause the detoriation of the ballast grains. The elaborated model also provides further opportunity to examine the effect of the different under sleeper pads, which reduce noise emission and produce a more uniform pressure distribution on the sleeper. The described results show trends of the interaction and focused on the modeling technique. Further developments and validation tests are needed to be able to obtain reliable, quantitative results. Both in FEM and DEM simulations, the constitutive models and their parameter values need calibration, as well as the effect of mesh resolution, have to be studied in sensitivity tests. Furthermore, the size and shape distribution of the elements, the value of applied timestep, the force criterion, and the length of force averaging has to be carefully validated in the DEM model and a stone breakage has to be included. Nevertheless, the study proved the applicability of the developed method.

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