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A Contribution to the Material Behaviour of Ballast on Railway Bridges

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Abstract

Railway bridges are subjected to intensive dynamic stresses due to train crossings. The resulting system response (accelerations) is estimated in advance through dynamic calculations. The basis of the calculations is the knowledge of the natural frequencies. Various studies have shown that a discrepancy between the measured and the numerical determination of these natural frequencies often occurs for short frame bridges. In common practice, the ballast is assumed to be non-supporting regarding the global structural stiffness. In some cases, rheological models of vertical springs and dashpots are used to consider the load distribution in vertical direction.

This publication discusses ballast stiffness on the material level. This leads to a stiffness contribution of the ballast to the horizontal stiffness (fraction of bending stiffness) and thus to a stiffening of the structure. It is shown that ballast can be defined in terms of stress and shear strain dependence. If ballast stresses and expected superstructure accelerations are known, an equivalent ballast stiffness can be determined and taken into account in a dynamic calculation using a linear approach. The material approach is verified by a scaled component test and a parallel numerical reference calculation.

Keywords: bridge dynamics, natural frequencies, ballast stiffness, material approach

1 Introduction

Train crossings on railroad bridges cause high dynamic loads and, in the worst case, may lead to resonance effects. In the construction context of railroad bridges, resonance phenomena are evident in the excessive deformation of the construction slab as well as in the destabilisation of the ballast bed. In the case of existing structures, the determination of the natural frequency can be carried out by in situ measurings and numerical simulations. In construction practice, a discrepancy between the measured and the numerical determination occurs frequently in the case of short frame bridges [1]. To determine the natural frequency of the structure an accurate estimation of the global stiffness as well as the mass is required. The role of the ballast for the vertical load propagation under the sleeper is well known. This paper discusses the mechanics of the ballast in terms of a stiffness contribution with respect to longitudinal and transverse bending stiffness.

The superstructure is essentially composed of rails, sleeper and the ballast. Due to the load-distributing effect of the ballast, applied loads of the train crossing are distributed over a larger load distribution area. Load distribution plays an essential role, especially in the context of excitation at bridge crossings [2]. Observations on the railroad line between Paris and Lyon showed that on dynamic excited short bridges, destabilisation of the ballast can occur due to excessive vertical acceleration [3]. Above accelerations of 0.7 g, ballast starts to shake visibly. This leads to the normative limitation (with double safety) of the maximum superstructure acceleration (3.5 m/s^2) [4].

The ballast is usually only considered in the dead weight load case, even in dynamic calculations. The consideration of the ballast stiffness with a rheological model of spring-damper elements is a special case. The empirical values of the equivalent spring stiffnesses vary by factor of 50 [5]. The scatter range results, among other things, from strongly diverging ballast thicknesses and ballast geometries. Nevertheless, the strongly non-linear behaviour of the ballast is undisputed [6–8].

The presented study describes the ballast by a stress-dependent material behavior, which can be used depending on the acceleration amplitudes using a linear calculation approach in a classical FE application. By the presented approach, stiffening and interaction effects resulting from the mechanisms of the ballast can be taken into account using continuum elements or by using composite cross-sections in the determination of the bending stiffness and modal characteristics.

2 Methods

Material approach from literature

In order to consider the ballast in a dynamic calculation, a rheological model is used in engineering practice. The equivalent ballast stiffness is modelled by vertical springs between the structure and the track. To determine the horizontal (fraction of bending stiffness) and vertical (bedding) stiffness of the ballast, a material approach is developed below.

Prange [6,9], based on Kuribayashi, Iwasaki and Tatsuouka [10] and Woods [11], developed a stress-dependent shear modulus for ballast as a function of the pore number e and the mean normal stress $\bar{\sigma}_0$ for small shear strain $\gamma_{eff} \leq 10^{-6}$:

$$G = \frac{7230\,(2.97 - e)^2}{1 + e} * \bar{\sigma}_0^{\,0.38} \tag{1}$$

with

$$\bar{\sigma}_0 = \frac{1}{3}(\sigma_x + \sigma_y + \sigma_z) \tag{2}$$

The material approach is based on an empirical evaluation of a large-scale resonant column test. In [9], a crushed ortho-gneiss was used as the ballast material.

The average normal stress $\bar{\sigma}_0$ can be determined using the equation (2). Adding the lateral pressure coefficient ($\lambda_0 = 1 - \sin(\phi)$), the relation of the tensions ($\sigma_x = \sigma_y = \lambda_0 * \sigma_z$) and considering plane strain - the average normal stress can be described as a function of σ_z. Another nonlinearity regarding the system stiffness is presented by Reiterer [7]. In Figure 1 the concluded frequency dependence of the superstructure on acceleration is depicted.

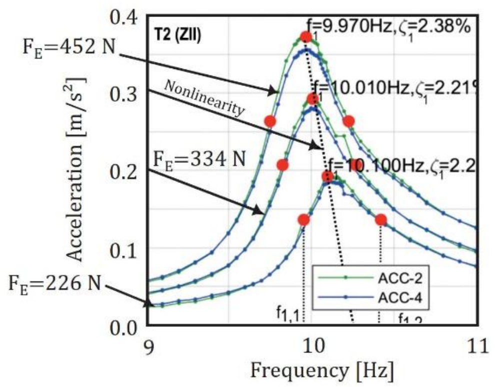

Figure 1: Acceleration dependence of the natural frequency in the frequency-spectrum [7].

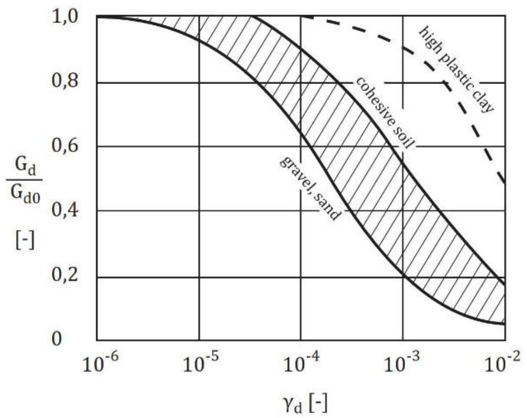

Figure 2: Scatter range of the normalised shear modulus as a function of the shear strain amplitude γ_d according to [12].

Considering the vibration velocity of the superstructure v and the shear wave velocity of the ballast c_S, the shear strain γ_d can be estimated in a first approximation.

$$\gamma_d = \frac{v}{c_s} \tag{3}$$

In the context of soil dynamics, the shear strain dependence is taken into account by the normalised shear modulus as a function of the minimum shear distortion $\gamma_d \leq 10^{-6}$. The normalized shear modulus is mapped for sand, gravel, cohesive soil (scatter range - shaded area) and highly plastic clay (fig. 2). For the ballast track, approximately similar material behavior can be used as for gravel/sand, since Prange [6,9] evaluates the dynamic material parameters of ballast similar to sand. For small strain amplitudes, ballast behaves approximately as an elastic medium with the stiffness ratio $G_d/G_{d0} = 1$. By determining the shear stain and the normalized shear modulus, the approach according to Prange can be extended by the dependence of the shear strain amplitude:

$$G = \frac{G_d}{G_{d0}} \frac{7230\,(2.97 - e)^2}{1 + e} * \bar{\sigma}_0{}^{0.38} \tag{4}$$

3 Results

Verification by own numerical and experimental investigations

To validate the material approach according to equation 6, a finite element model is created in Abaqus [13] using linear elastic material properties (CPE4) and compared with the results of a scale experimental model. The structural slab in the model is a plasterboard (0,2 x 0,6 m). By prestressing the ballast (basalt grit with grain size between 3 and 5 mm), the dependence of the overall system stiffness on the ballast stress can be investigated. By applying different pulse loads, the role of the shear strain amplitude can be determined.

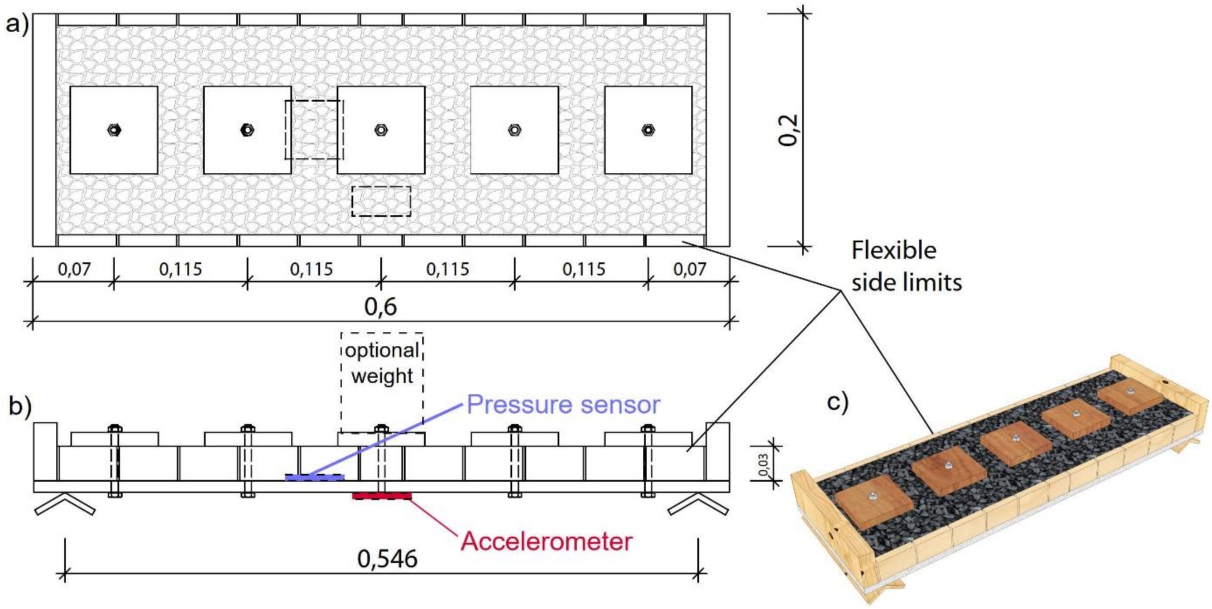

Figure 3: Sketch of the scaled experimental model - dimensions in [m]:

a) top view, b) side view, c) isometry

The preload can be applied independently of the mass using load distribution plates and threaded rods. The acceleration dependence of the ballast stiffness is investigated due to local liquefaction effects by applying defined weights, see figure 3b) and 4b). With the help of a thin-film pressure sensor and an acceleration sensor, the natural frequency can be determined as a function of the vertical ballast stress. The calculation of the first natural frequency on the model is performed by a Fast Fourier Transformation in Matlab [14].

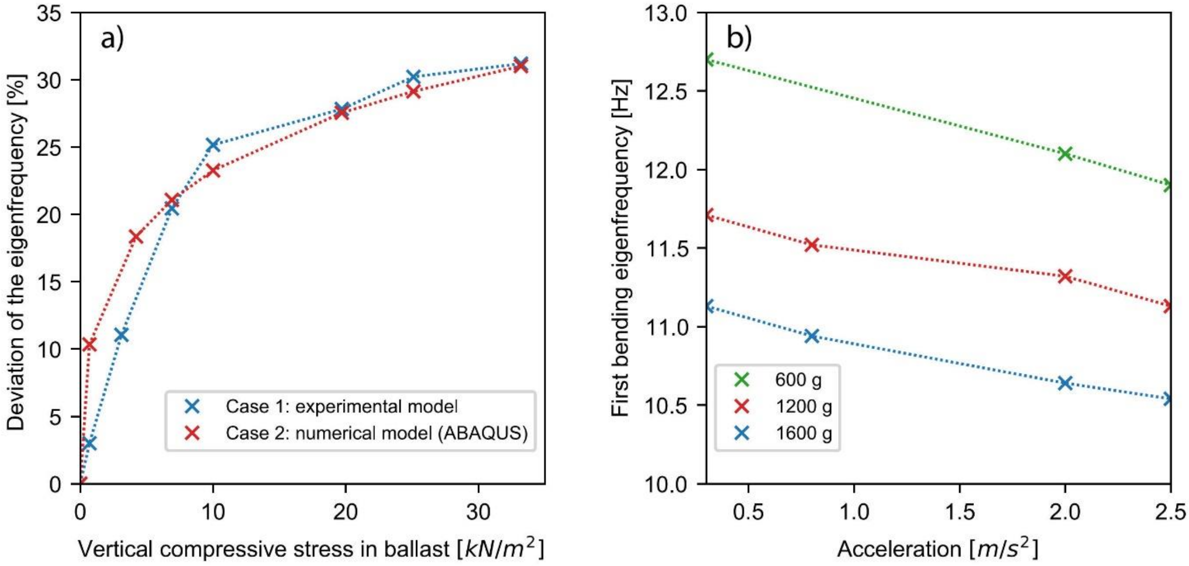

Figure 4: Dependencies of the natural frequency:

a) ... as a function of the ballast stress (reference: σ_V=0)

b) ... as a function of the acceleration

The study of the experimental model shows the expected behavior (fig. 4): an increase of the ballast stresses in the scaled experimental model contributes to a significant stiffness increase (fig. 4a)) of the overall system: $\Delta f_{max} \approx 30\%$. In addition, the acceleration dependence found in [7] can also be demonstrated (fig. 4 b)). Due to material deviations between the experimental model (basalt grit) and the stiffness approach, according to equation 1 (ballast), the presented material approach (equation 6) is calibrated to basalt grit using a prefactor. The comparison of numerical and experiment results shows very good agreement (fig. 4a)).

Further, a parametric study is carried out as a threshold analysis to investigate the effects of a stiffness-effective ballast on the natural frequencies of frame bridges. The first bending frequency of the frame f_R is calculated by extending the frame formula according to [15]. Here, the superstructure stiffness is obtained using the equivalent cross-section method, which increases the slab-stiffness as a function of equation (6). The study points to a stiffening of the first natural frequencies of $\Delta f < 2\%$ for short span bridges.

4 Conclusions and Contributions

This paper develops a material approach for the ballast superstructure that considers the shear strain and stress dependence of the ballast stiffness in a linear calculation (for instance: modal analysis). The ballast stiffness results from the stress-dependent shear modulus in combination with the expected acceleration amplitude. The acceleration dependence of the superstructure (transferred as shear strain amplitude) is taken into account using the nonlinear relationship of the normalised shear modulus. The modeling can be performed either directly via continuum elements in an FE simulation, or indirectly via an equivalent cross-section.

In the parametric study, the consideration of ballast stiffness causes an increase of the first bending natural frequencies of $\Delta f < 2\%$. The deviations of the natural frequency are especially important for short spans L < 10 m. The assumption that the deviation from the natural frequencies measured in practice is mainly due to the contributing bending stiffness of the ballast can therefore not be confirmed.

The influence of higher natural modes through the consideration of ballast stiffnesses and the interaction of adjacent superstructures due to continuous ballast layers will be further investigated. The element-by-element implementation of the discussed material approach for the investigation of train crossings and validation based on component tests is being planned. The presented approach will be further extended to include the material damping of the ballast.

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