An update on the acceleration limit criterion for railway bridges in high speed lines with ballasted track

Patrick Simon[1*[0000-0002-1538-177X]] and Matthias Baeßler[1[0000-0002-5182-7310]]

[1] Bundesanstalt für Materialforschung und -prüfung (BAM),
Division 7.2 Buildings and Structures, Unter den Eichen 87, 12205 Berlin, Germany
[*patrick.simon, matthias.baessler]@bam.de

Abstract. As Europe undergoes a transition towards climate-neutral mobility, the strategic role of railways—and especially bridges—demands a deeper understanding of their dynamic behavior. In particular, the widely used 3.5 m/s² deck acceleration limit for ballasted bridges, though central to current standards, is based on limited empirical evidence and may be overly conservative. This contribution presents experimental and analytical advancements from the InBridge4EU project that are aimed at revising this acceleration limit criterion. A series of shake table tests were conducted to quantify the reduction in lateral resistance and aspects of vibration-induced creep in ballast under vertical dynamic excitation and concurrent lateral load. Complementing the experiments, a scenario-based assessment framework was developed to evaluate the impact of reduced lateral resistance and vibration-induced creep on the track safety and serviceability. This approach enables infrastructure operators to assess the consequences of new and existing railway bridges which exceed the acceleration limit criterion.

Keywords: infrastructure, bridge deck acceleration, ballasted track, ballast destabilization, lateral track stability.

1 Introduction

As Europe accelerates its shift to climate-neutral mobility, rail infrastructure – particularly bridges – will bear a larger share of passenger and freight movement. In high-speed rail, the dynamic combability of each new train & bridge combination has to be checked [1, 2]. The limit criterion of a maximum bridge acceleration amplitude of 3.5 m/s² of EN 1990 [3] is employed in the process. However, this criterion based on empirical evidence [4] of damage in some cases and may be overly conservative, some standards e.g. ÖNORM B- 4008-2 [5] already allow exemptions of this criterion for existing bridges under certain conditions.

This highlights the need to address exceedances of this criterion for existing bridges, providing principled approaches that take into account the specific scenario at hand. The InBridge4EU project targeted at providing a more comprehensive approach, aiming to enable going beyond this blanket criterion. It is based on the physical principles at hand and the actual failure modes of ballast.

The detrimental effects are caused by the influence of one engineering structure – the bridge – on another – the track. Ballast is part of the track structure and supports the sleepers both vertically and horizontally. On a bridge, ballast itself is supported by the bridge deck. As the bridge deck experiences vibrations, the ballast also experiences the same vibrations. These vertical vibrations have detrimental effects on ballast, which in turn causes problems for the track. Figure 1 illustrates this chain of effects.

The failure modes of ballasted track subject to vertical vibrations are found in the literature [4, 6–9]. Vertical vibrations compact and rearrange ballast particles, increasing vertical track settlement, which poses a maintenance issue. During vibration cycles, downward accelerations temporarily reduce the particles' effective self-weight, weakening inter-particle friction and interlock. This promotes lateral creep deformation and lowers the sleepers' lateral resistance within the ballast bed. Both mechanisms affect operational safety and heighten the risk of track buckling [10, 11].

In this contribution, we highlight two aspects that were investigated: Regarding the physical effects of degraded ballast the reduction of lateral resistance due to vertical vibrations was examined via shake table tests (see Section 2). For cases where the acceleration criterion is exceeded, a deterministic scenario-based framework was developed and is introduced in Section 3.

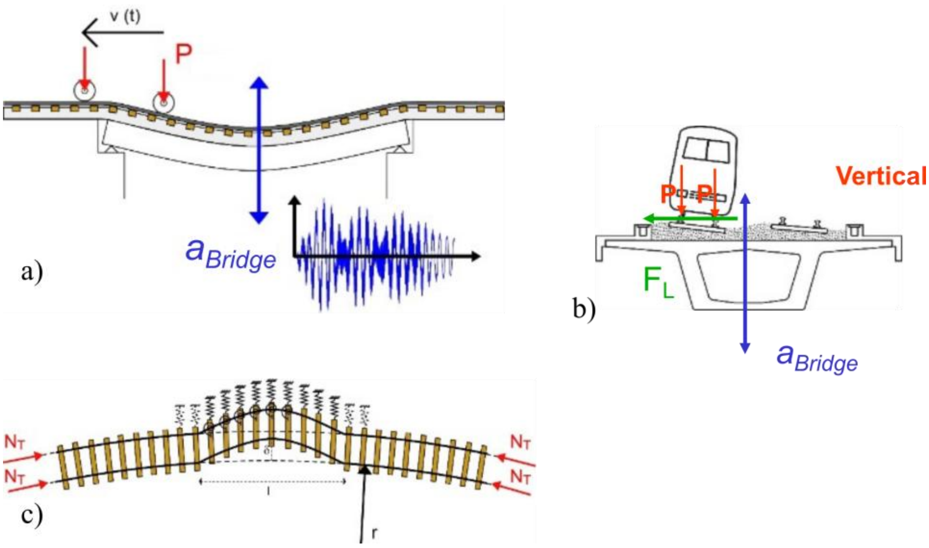


Fig. 1. The chain of effects: a) A bridge is dynamically excited by a passing train, resulting in vertical vibrations. b) The ballasted track experiences these vibrations, while at the same time being subject to vertical train loads and lateral loads. c) The track is subject to longitudinal forces and imperfections resulting in lateral forces which are supported by the ballast (here modelled as springs).

2 Shake table tests

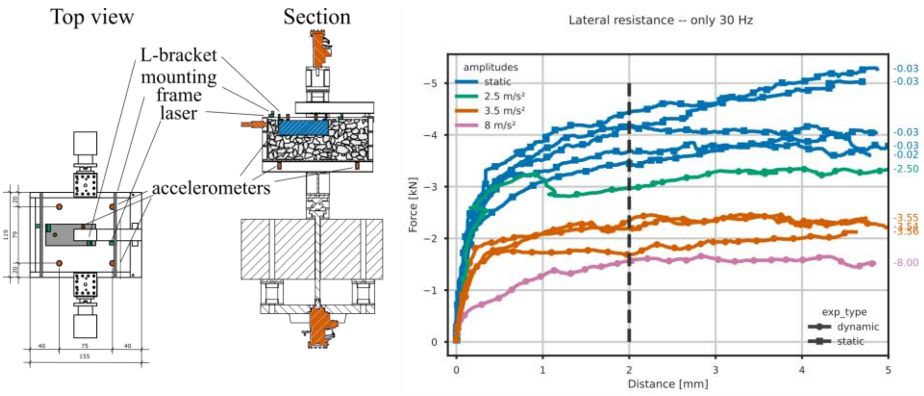
The question to be answered with shake table tests is the influence of vertical vibrations on the lateral resistance of sleepers in ballasted track. The experimental setup was thus designed to model the scenario of a sleeper subject to a lateral load inside ballast, all of which rests on a vibrating bridge deck.

To this end, a concrete model sleeper (0.6m× 0.3m× 0.22 m) is placed inside a box (1.40 m × 1.04 m × 0.60 m) filled with ballast. This ballast box is mounted inside an enclosing steel frame which vertically rests on a pole connected to an actuator mounted below the floor plate. The frame is laterally supported by steel columns via sliding bearings. This enables applying purely vertical vibrations on the ballast box. On the side of the box, a lateral actuator is mounted which applies lateral loads on the model sleeper. Four accelerometers (Metra MMF KD41V) are mounted on the floor plate of the box, and two laser distance sensors (Micro-Epsilon optoNCDT 1401) are mounted on a frame on top of the box, measuring the distance to L-brackets mounted on the model sleepers. This setup enables the application of vertical vibrations on the whole system and lateral forces on the model sleeper while measuring the applied accelerations and force as well as the experienced displacement of the sleeper. Figure 2a) shows the setup and sensor layout of the experiment.

The experimental procedure includes preconditioning of the ballast and sleeper with an actuator applying a vertical force on top of the model sleeper. Harmonic vertical accelerations with different combinations of frequency and amplitude were examined in the experiments. The lateral actuator was displacement-controlled with a constant displacement rate of 0.1 mm/s, while measuring the applied force. This procedure allowed to record the lateral resistance diagrams.

Figure 2b) shows excerpts of the results: the lateral resistance of experiments conducted with vertical vibrations with a frequency of 30 Hz alongside the results for static cases where no vibration was applied. A reduction in lateral resistance for higher acceleration amplitudes is evident. Full results are shown in the report [9], where it is also concluded that acceleration amplitude is driving factor, regardless of the frequency.

These results give an indication on how to model reduced lateral resistance for track models for ballasted track on vibrating bridge decks. The limitations of experiments are that this is a specific system investigated while there are various configurations of ballasted track used in praxis. These results can be used in conjunction with other data [12] and knowledge and insights of lateral resistance [13].



a) b)

Fig. 2. a) Experimental setup and results. b) Lateral resistance diagrams of the dynamic tests at 30Hz with varying acceleration amplitudes. Results of the static tests are plotted as reference. The numbers on the right side of the diagram show the achieved acceleration amplitudes in m/s². Both from[9].

3 Scenario-based assessment

It is established that excessive vertical bridge vibration led to reduced safety of the track and maintenance issues. On the various aspects there exists research mainly conducted in laboratory experiments [4, 6, 7, 9]. What is missing is a way of translating this knowledge into actionable insights and decision tools for track managers applicable when measurements on existing bridges exceed the acceleration limit criterion or the compatibility of a new train on an existing bridge fails to comply with the limit criterion.

The three main failure modes of ballasted track subject to vertical vibrations are 1. vertical settlement, 2. lateral vibration-induced creep, and 3. an increased propensity for track buckling. The implications of these failure modes are now discussed:

Vertical settlement is mainly a maintenance issue. Existing regimes for track alignment monitoring address this issue [14]. Especially for existing bridges exceeding the limit criterion, track managers already implicitly address this issue via the existing maintenance regimes.

For the assessment of lateral vibration-induced creep (both a maintenance and operational safety issue) the work from the project already proposed a framework [8]. First, based on maintenance standards, a limit state for the permissible lateral deflections within a reference time frame is defined. A lateral finite element track model is established with scenarios for applied temperature differences to generate lateral forces acting on the sleepers. With a train-bridge dynamic analysis, timeseries of accelerations of specific trains are calculated. For all sleeper locations on the bridge, peak identification or cycle count algorithms are applied to these timeseries. The formula for vibration-induced creep [6] is applied for each cycle and the resulting displacements are superposed. This leads to the accumulated lateral displacement which is then evaluated against its limit criterion within the reference time frame.

However, the assessment of the increased propensity for track buckling is still not addressed. In this contribution, we propose a framework of assessing it. We accomplish this by listing the key influences of track, material and bridge models and working our way backwards from the track buckling:

- The influences on track buckling are: The longitudinal forces due to temperature [10], lateral resistance [11], and the current imperfections.
- The influences on current imperfections are: vibration-induced creep [8].
- The influences on vibration-induced creep are: vertical acceleration amplitudes and lateral forces of the sleepers [6–8].
- The influences on the lateral resistance are: vertical acceleration amplitudes [9].
- The influences on the lateral forces of the sleepers are: The longitudinal forces in the rails due to temperature differences of the rails and the initial imperfections.
- The influences on the vertical acceleration amplitudes are: the dynamic effects of trains passing the bridge
- The influences on rail temperature differences are: The neutral temperature and environmental influences.

With these influences listed, it is now possible to construct a framework for evaluation: A rail temperature model informs the longitudinal forces present in the track. The track model uses these temperatures alongside assumptions of the initial imperfections to predict lateral forces of the sleepers. A train-bridge dynamic analysis predicts vertical accelerations. These accelerations are used to predict a) the reduced lateral resistance and b) the vibration-induced creep in conjunction with the lateral forces of the sleepers. The displacements of the track due to vibration-induced creep predict the current imperfections of the track. These imperfections and the reduced lateral resistance are applied on the track model which is then used for track buckling analysis. Figure 3 shows this framework.

To address the track managers' need for assessment of increased propensity of track buckling due to excessive vertical vibrations on bridges, it was necessary to show all interdependencies between track model, material model, and bridge-train model. By listing all dependencies, a framework for assessment of track buckling was constructed. In combination with considerations on vertical settlements and lateral vibration-induced creep, it is now possible to assess the reduced safety of a track given excessive vertical vibration.

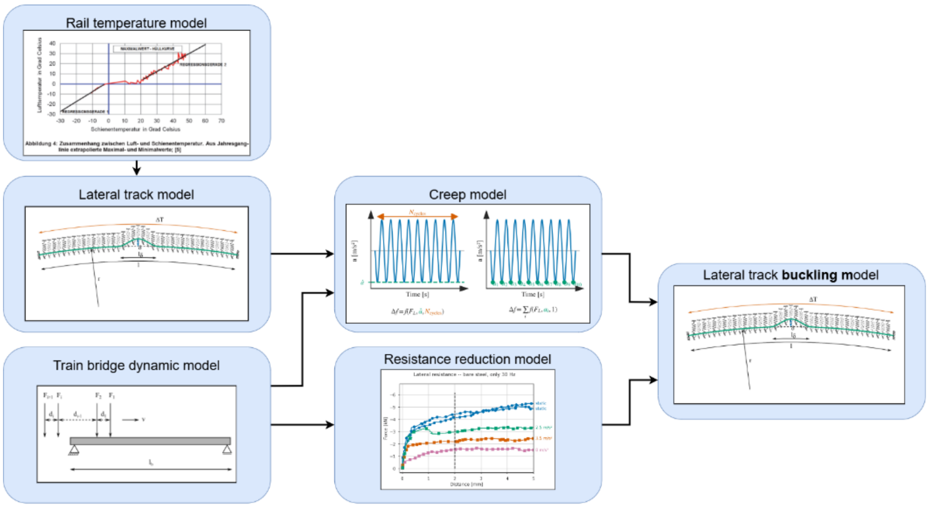


Fig. 3. The proposed framework for assessing track buckling by looking at all influences of track, ballast, and bridge.

4 Concluding remarks

The current acceleration limit of 3.5 m/s² in EN 1990 [3] is conservative in some cases. A more nuanced, physics-based framework is needed to evaluate cases of exceedances of this blanket criterion. Vertical bridge vibrations adversely affect ballast increasing risks of settlement, lateral vibration-induced creep, and track buckling. To this end experiments were undertaken and a framework for assessment developed.

Shake table tests confirmed that the acceleration amplitude is the key influence for reduced lateral resistance, independent of vibration frequency. The experiments provide quantitative evidence of lateral resistance reduction under vertical vibration. While system-specific, these results can be integrated with other datasets and modeling approaches to generalize the findings.

A structured framework was proposed to translate laboratory insights into actionable tools for track managers. It addresses three failure modes:

- Vertical settlement, which is mainly a maintenance issue, manageable with existing regimes.
- Lateral vibration-induced creep, which is both safety and maintenance issue, modeled with cycle-based creep accumulation, introduced in [8].
- Track buckling, which is addressed with a new framework developed, tracing interdependencies between rail temperature, imperfections, creep, lateral resistance, and vertical bridge accelerations.

Future research can translate this scenario-based assessment framework into a probabilistic risk-based assessment.

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