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Reliability assessment of railway bridges subjected to high-speed trains considering the effects of seasonal temperature changes

P. Salcher [1], H. Pradlwarter [2], C. Adam [*,3]

University of Innsbruck, Unit of Applied Mechanics, Technikerstr. 13, 6020 Innsbruck, Austria

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ABSTRACT

This paper addresses the reliability analysis of high-speed railway bridges with stochastic methods to account for uncertainties in the mechanical model. The emphasis is on ballasted steel bridges. The acceleration response of the bridge deck is assumed to be the governing response quantity for bridge serviceability, and thus, defines in the reliability assessment the limit state of the bridge. The uncertainties for this specific interaction problem are identified and modeled as random variables with appropriate distributions. The effect of uncertain track quality is considered via random rail profiles. A stochastic model is proposed to account for the environmental impact of seasonal temperature changes on the bridge structure. In a parametric study, the contribution of the random variables on the uncertain bridge response of a case study problem is quantified. The probability of exceeding the serviceability limit state is predicted using crude Monte Carlo simulations and Latin Hypercube samples. These predictions are set in contrast to outcomes of a traditional code-based deterministic design procedure.

1. Introduction

Compared to conventional railway lines, in high-speed railway lines the admissible curve radii are much larger, and thus, more bridges must be built, which are crossed by trains with higher speeds and larger capacities. Because worldwide new high-speed railway lines are under development, the demand for reliable dynamic response prediction of railway bridges is steadily increasing. Ballast instability and derailment due to the loss of wheel-rail contact are two major issues caused by excessive bridge deck vibrations, and fatigue problems of the load-bearing structure may arise during the life cycle of a bridge. Passenger safety and passenger comfort must also be ensured when a train crosses a bridge.

The dynamic response prediction in the design process of a railway bridge is usually based on a deterministic analysis, as defined in design codes [1,2]. Upper and lower bounds of bridge stiffness and structural mass are assigned to the corresponding deterministic computational model, supposed to reproduce the worst-case response scenario. The trains are represented by models of real operational trains and specific design train load models, composed of a series of moving single forces. For a few bridges this deterministic approach might be non-conservative although the code design rules are satisfied if, for instance, the considered bridge configurations do not capture all worst-case scenarios. Moreover, at speeds slightly below the maximum admissible speed for which, according to guidelines, a static assessment is sufficient, the actual response may exceed the limit, as it has been shown in [3,4]. Also, material properties and geometry of bridge and train components are subject to natural dispersion, and the bridge-train interaction system is exposed to varying environmental conditions. In this respect, commonly simple mechanical models describe the complex energy dissipation mechanism of railway structures [5], and the temperature dependent behavior of the natural bridge frequencies [6,7] is usually not considered appropriately. Nonlinear dynamic response characteristics [8] such as a nonlinear frequency dependency on the response amplitude [9] may go unnoticed or they are not modeled, leaving uncertainties in the response prediction.

Most of the past research on dynamic response prediction of railway structures is based on deterministic models, however, recently a stochastic treatment of the dynamic response prediction has also been addressed by some researchers. For instance, based on a two-level factorial design, in [10] a statistical analysis of a case study object has been presented. Rocha et al. [11,12] have discussed simulation methods for estimating the bridge reliability due to parameter dispersions, using a planar model of the

* Corresponding author.
E-mail address: christoph.adam@uibk.ac.at (C. Adam).

[1] Dr. techn.
[2] Associate Professor
[3] Professor

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bridge-train interaction system. They have shown that, compared to a deterministic analysis, the outcomes of a stochastic assessment might allow to increase the operational train speed. Additionally, in [12] random track irregularities representing different track qualities have been taken into account. In [13] the efficiency of crude Monte Carlo simulations and Latin Hypercube samples combined with a tail modeling approach and, alternatively, an enhanced simulation technique has been evaluated for assessing the probabilistic safety of the same short high-speed railway bridge investigated in [11,12]. The train running safety has been assessed by Rocha et al. [14] using a probabilistic approach. Au et al. [15] used a two-dimensional bridge-train interaction model to study the significant influence of irregularities on the impact factor of a cable stayed bridge. Johansson et al. [16] conducted Monte Carlo simulations to predict the maximum acceleration amplitudes of more than 1000 railway bridges represented by simplified models in an effort to estimate their reliability considering uncertainties in structural mass and natural frequencies.

The present paper deals with reliable bridge response prediction based on stochastic methods to account for uncertainties in the mechanical model. The particular focus is on ballasted steel bridges. At first, uncertainties of the bridge-train interaction system are identified, and appropriate distributions of the random variables are defined. Irregular random profiles are used to simulate the effect of rail irregularities on the response prediction. Based on outcomes of long-term monitored bridges [6,17,7], a temperature dependent stochastic model is proposed, which represents the environmental impact of seasonal temperature changes on the bridge structure. All random variables are included in a sophisticated three-dimensional mechanical model. The acceleration response of the bridge deck, which is often the limiting factor in dynamic railway bridge design, is assumed to be the governing response quantity for the reliability assessment [7,18,16], and thus, it defines the limit states of the problem. Due to the complexity of the limit state functions and the large number of uncertain parameters, simulation methods such as crude Monte Carlo simulations [19] and Latin Hypercube samples [20] are used to estimate the probability of failure of a case study problem. These predictions are subsequently compared with the outcomes of a code-based deterministic design assessment relying on worst-case parameter combinations.

2. Reliability assessment of railway bridges subjected to dynamic train loads

Standards, design guidelines, and technical notes such as Eurocode 1 [2] specify the requirements and procedure of a detailed dynamic analysis of the bridge-train interaction problem. For instance, according to [2] both a generic high-speed load model (HSLM) set (A or B) and load models of real operating trains with characteristic values of the static axle loads should be utilized. It is also specified that non-exceedance of the ultimate limit state (ULS) and the serviceability limit state (SLS) must be checked for travel speeds up to 120% of the maximum admissible operating speed [2].

When assessing the SLS, the reliability of operation and the fulfillment of comfort criteria for the passengers are examined. The passenger comfort depends primarily on the vertical passenger acceleration. According to [21], up to a vertical passenger acceleration of $b_v = 1.0\,\text{m/s}^2$ the comfort level is a *very good*, and in the acceleration range $1.0\,\text{m/s}^2 < b_v \leqslant 2.0\,\text{m/s}^2$ it is *acceptable*. The maximum bridge deck acceleration is the characteristic response quantity upon which the reliability of operation is assessed. For deck accelerations larger than 0.7 g (g is the acceleration of gravity), in ballasted railway bridges the interlock of the ballast gravel may become unstable, and as a consequence, the risk of derailment increases due to additional settlements of the ballast. For rails supported by concrete tracks, an increase of risk of wheel lift-off is implied if the deck accelerations exceeds 1.0 g. Test data and numerical simulations show, however, that train axle accelerations larger than $10.0\,\text{m/s}^2$ do not necessarily lead to contact loss between wheels and rail and consequently to train derailment [18]. In Eurocode 1 [2] a safety factor of 2.0 is proposed to avoid these effects, resulting in acceleration thresholds of $\gamma_{bt} = 0.35$ g for ballasted tracks, and $\gamma_{ct} = 0.5$ g otherwise. These acceleration criteria are conservative because during the train passage the thresholds may be exceeded only once or twice for an instant of time, and thus, no state of lack of interlock is reached that might lead to derailment. Because these conservative criteria are often decisive for the dynamic assessment of high-speed railway bridges [7,16,18], Zacher and Baeßler [18] propose higher alternative thresholds.

In the present contribution the bridge acceleration is assumed to be the governing response quantity for the stochastic reliability assessment of this dynamic interaction problem. All parameters that may influence the load-bearing capacity of the structure are treated as random variable. Consequently, the safety factor according to Eurocode 1 [2] is eliminated from the design acceleration thresholds, leading to twice the thresholds as defined in [2] for the maximum bridge deck accelerations. That is, $\bar{\gamma}_{bt} = 2\gamma_{bt} = 0.7\text{ g} \approx 7\text{ m/s}^2$ and $\bar{\gamma}_{ct} = 2\gamma_{ct} = 1.0\text{ g} \approx 10\text{ m/s}^2$. Because no data on the physical background of these thresholds are available, they are subsequently considered as deterministic threshold values. Accordingly, assessment of failure at a certain train speed v is based on the safety distance

$$Z = \bar{\gamma}_k - \max|\ddot{u}_z(v)|, \quad k = bt, ct \tag{1}$$

Failure is predicted if the limit state function $g(Z) < 0$.

In some situations, higher acceleration peaks occur at speeds less than the maximum considered speed v_0. An appropriate alternative formulation of the safety distance reads as

$$Z = \bar{\gamma}_k - \max|\ddot{u}_z(v \leqslant v_0)|, \quad k = bt, ct \tag{2}$$

In the presented stochastic approach a limitation or even reduction of the operational speed is not necessary. Probabilities of failure are computed directly for different travel speeds v or speed ranges $0 < v \leqslant v_0$.

According to Eurocode 0 [1] for a system classified into reliability class 2 associated with *medium consequence* for loss of human life and *considerable* economic, social and environmental consequences, the maximum probability of failure for the ULS, $P_f^{(ULS)}$, is 10^{-6}, and for the SLS it is $P_f^{(SLS)} = 10^{-3}$.

The complex formulation of the limit state function requires the application of numerical simulation methods to estimating the probability of failure and the variability of the response. In the present study, a crude direct Monte Carlo simulation approach is used as, for instance, described in [19]. This approach is unaffected by the number of considered random variables, it is always robust, and with increasing sample size also small probabilities of failure in the order of 10^{-3} are predictable. When considering uncertain rail irregularities, the sample size increases drastically. In those cases, Latin Hypercube sampling is used to render reliable estimates of response statistics and variabilities. For details on Latin Hypercube sampling it is referred to [20].

3. Numerical modeling strategy

A reliability prediction can be just as accurate as the underlying stochastic and numerical model. It is assumed that the train-bridge interaction model utilized in this study describes sufficiently accurate the physical system behavior. Model uncertainties, however,