Engineering Structures 174 (2018) 396–406

Contents lists available at ScienceDirect

Engineering Structures

journal homepage: www.elsevier.com/locate/engstruct

Design of railway bridges for dynamic loads due to high-speed traffic

Sebastian Schneider*, Steffen Marx

Institute of Concrete Construction, Leibniz University Hannover, Appelstraße 9a, 30167 Hannover, Germany

ARTICLE INFO

Keywords:
Continuous beams
Dynamics
Dynamic increase
Railway bridges
Design
High-speed traffic
Resonance

ABSTRACT

This contribution deals with the dynamic behaviour of railway bridges for high-speed traffic and investigates the impact of changes to the structural system on the dynamic response due to crossing trains. Multi-span simply supported beams represent the most unfavourable system for high-speed trains, structurally as well as aesthetically. Therefore, alternative structural systems were analysed to find out whether the dynamic characteristics of railway bridges can be adjusted in the design stage. Because of the strong interaction between the crossing train and the bridge structure the impact of changes to the structure is very difficult to estimate a priori. The internal forces in continuous beams with lengths exceeding 30 m are generally smaller than those in single-span beams with the same cross section and the speeds at which they can be crossed are significantly higher. By adding haunches to the beams those eigenfrequencies whose eigenmodes exhibit curvatures at the supports can be increased. Shortening the end spans leads to an increase in all eigenfrequencies and hence in resonance speeds. Using the findings from this article the dynamic stability of high-speed railway bridges can be improved at the preliminary design stage.

1. Introduction

Railway bridges are subjected to large static and extremely high dynamic loads. The dynamic load is the governing factor for the design of high-speed railway bridges and needs to be taken into account even at the concept design stage, when the fundamental system properties are defined [1,2]. At this stage, the type of structural system, the stiffness and mass distribution and the system damping are of crucial significance. These parameters in particular determine whether a bridge will experience significant vibration or even resonance during train crossings [3,4]. Currently, labour-intensive dynamic investigations are necessary to determine whether the general rules for the optimum static design of bridges (for determining the span lengths of continuous beams, for example, or for deciding where to add haunches) result in a structure which will experience favourable or unfavourable structural effects during train crossings. There are several further parameters that barely affect the static loading of the structure but that have a big impact on its dynamic behaviour due to train crossings, such as the number of spans of continuous beams.

This contribution aims to aid engineers in the concept design of high-speed railway bridges. Based on extensive parameter studies, the main parameters influencing the dynamic stability of bridges under high-speed rail traffic are explained and recommendations for the dynamic optimisation of structures are given. Simply supported single-span beams and continuous beams with varying span lengths and differences in haunch configuration are compared.

2. Dynamic analyses of bridges for high-speed traffic

For road and railway bridges used by moderate-speed traffic the load increase due to dynamic traffic load can generally be estimated sufficiently accurately using system-dependent, particularly span-length-dependent, dynamic coefficients. The forces governing the design are determined with static equivalent load models and multiplied by a dynamic coefficient. But the dynamic coefficients do not apply to railway bridges experiencing resonance. For such bridges it is necessary to carry out more detailed dynamic analyses with calculated simulations of train crossings. Resonance excitation can be caused by a train with relatively uniform axle distances and uniform speed, if the induced excitation frequency corresponds to an eigenfrequency of the structure. The corresponding resonance speeds $v_{res,i,j,k}$, are the product of the j-th flexural eigenfrequencies n_{j-1} and the wavelength of the excitation frequencies $\lambda_{res,i,k}$.

* Corresponding author.
E-mail address: schneider@ifma.uni-hannover.de (S. Schneider).
URL: http://www.massivbau.uni-hannover.de (S. Schneider).

https://doi.org/10.1016/j.engstruct.2018.07.030
Received 5 January 2018; Received in revised form 9 July 2018; Accepted 10 July 2018
0141-0296/

$$v_{res,i,j,k} = n_{j-1} \cdot \lambda_{res,i,k} = n_{j-1} \cdot L_{c,k}/i \quad i = 1, 2, 3, \ldots \text{and} \, j = 1, 2, 3, \ldots \quad n_{j-1} \leqslant n_{max} \tag{1}$$

According to [5], the first flexural eigenfrequency is denoted by n_0. The wavelength of the excitation frequency $\lambda_{res,i,k}$ is defined as the ratio of the almost uniform axle distance (coach length $L_{c,k}$) of the respective train load model k and an integral divisor i. The divisor i takes into account after how many eigenvibrations the j-th eigenmode is excited. For bridges with low-speed traffic and/or with certain eigenfrequency limits as well as for structural systems for which sufficient data on the behaviour during operation is available (for example, single-span frames with certain minimum dimensions), a dynamic analysis does not need to be carried out [5].

2.1. Issues to consider in the concept design stage

The resonant excitation of a railway bridge can result in the criteria for the ultimate and serviceability states not being met. Hence, if the risk of resonance cannot be excluded with simple criteria, a computational simulation of the train crossings is required. To do this, the load models of the currently operating trains and, if considering the interoperability criteria of European high-speed train routes, also the high-speed load models (HSLM) must be taken into account. Fig. 1 shows the configuration and Table 1 shows the specifications of the HSLM-A.

For ultimate limit state analyses the entire range of speeds up to the legal speed limits or the highest possible train speed multiplied by a factor of 1.2 needs to be investigated in small steps. This results in an extremely large number of simulations and a very labour-intensive design process, even with currently available high-performance computers and software. If changes are made based on the results of the simulations, the entire design process has to be repeated. Because of the highly nonlinear behaviour of the reactions of the structure under resonance and the still insufficient knowledge about the impact of the various system parameters it is often necessary to run several iterations to arrive at the optimum design.

Drastic measures are generally required to achieve noticeable improvements in the dynamic behaviour at the design stage, for example changes to the fundamental geometric parameters of the structure such as the span lengths, the span length ratio, the construction height or modifications to the structural system. As these parameters influence the entire design and the structural clearance in particular, the dynamic stability for the range of design speeds of the bridge must be investigated and shown to be adequate at an early stage in the design (concept design).

2.2. Calculation methods and design checks

Several dynamic train simulation methods exist, and they differ considerably with respect to computational effort and the type of input parameters. The simplest model which also yields conservative results uses axle loads of a crossing train expressed as load-time functions. This means that the equations of motion can be solved using modal analysis or the more time-intensive method of linear time-step integration.

Table 1
Specifications of the HSLM-A.

HSLM	Number of coaches N [–]	Coach length L_c [m]	Number of axles [–]	Train length L_{train} [m]	Distance between bogies d [m]	Axle loads P [kN]	Total axle loads ΣP [kN]
A01	18	18	50	397.526	2.0	170	8500
A02	17	19	48	398.526	3.5	200	9600
A03	16	20	46	397.526	2.0	180	8280
A04	15	21	44	394.526	3.0	190	8360
A05	14	22	42	389.526	2.0	170	7140
A06	13	23	40	382.526	2.0	180	7200
A07	13	24	40	397.526	2.0	190	7600
A08	12	25	38	387.526	2.5	190	7220
A09	11	26	36	375.526	2.0	210	7560
A10	11	27	36	388.526	2.0	210	7560

Particularly for bridges that have very high mass compared to the weight of a train this method yields sufficiently accurate results. This applies to any concrete bridges, but also to steel bridges with ballast tracks or slab tracks. Merely for very lightweight open-track steel bridges (for example auxiliary bridges) there can be larger differences between the results of this calculation method and those of the approach where the trains are modelled as mobile mass-spring damper systems [6–8].

The range of design speeds that need to be analysed needs to be determined subject to the design check criteria. According to [5] the guiding speed for determining the range is the speed limit $v_{ö}$, which is the highest speed at which the bridge is to be crossed. This speed is defined either as the design speed of the route (or a smaller value, depending on the alignment on the bridge) or the maximum speed $v_{train,k}$ of the train k. For the serviceability limit state and the fatigue limit state speeds up to $1.0 \cdot v_{ö}$ have to be investigated, whereas for the ultimate limit state speeds of up to $1.2 \cdot v_{ö}$ must be considered.

In estimating the risk of fatigue failure it is extremely important to define the operating program including the train-crossing frequencies, because a high-speed train crossing a bridge at high velocity can cause a high number of damage-inducing load cycles [9]. In practice, however, it is often almost impossible to define a realistic operating program. It is generally not possible for the operator of a high-speed route to reliably predict the type and number of trains crossing the bridge over its lifetime.

Even if there is no risk of resonance, the fatigue limit state analysis does not yield sensible results with the high-speed load models in the sense of a damage accumulation calculation, as they are merely dynamic load models and not real train configurations. Safe fatigue design is currently only possible by restricting the range of maximum stresses induced by the HSLMs to a level close to the endurance limit. It is recommended to use the value of the S-N curve at 10^9 load cycles. The relevant mean stress also has to be taken into account in the design of concrete bridges. Using these design provisions, a bridge with an assumed life span of 100 years can safely be crossed 250 times per day by the most unfavourable high-speed train.

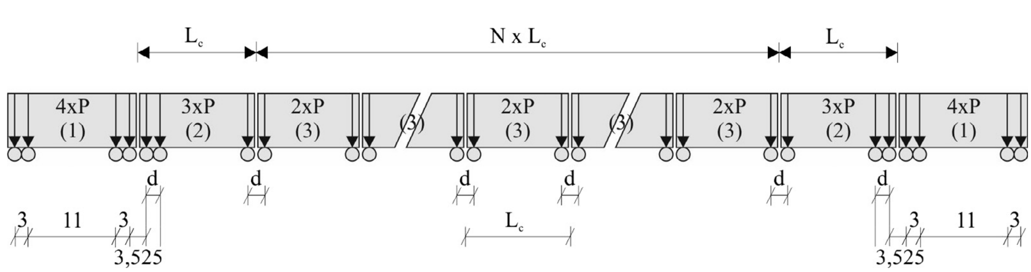

Fig. 1. Configuration of the HSLM-A.