New Research Developments in the Assessment of the Damping Factor of Railway Bridges

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Abstract To achieve realistic and economical results, dynamic assessments of railway bridges require input parameters in me-chanical models that accurately reflect reality. In this regard, the applied damping properties of the structure play a crucial role in predicting resonance effects and evaluating the compatibility between rolling stock and railway bridges. The EN 1991-2 standard specifies damping factors based on the type and span of the structure, but these values are often highly conservative and do not reflect actual conditions. As a result, in-situ measurements are often needed to reclassify bridges that appear critical in preliminary dynamic assessments as non-critical. However, determining damping factors from in-situ measurements often leads to variable results due to the measurement method used and the individual scope of action of the evaluating person interpreting the data.
This contribution introduces new evaluation methods and analytical tools for determining damping factors from in-situ measurements, aiming to reduce the scatter of results and minimize the influence of the evaluator's individual scope of action. Based on data from a measurement campaign on 15 existing railway bridges, this contribution dis-cusses new evaluation methods for generating damping factors in both the time and frequency domains. The findings demonstrate that a well-defined evaluation algorithm can significantly reduce the scatter of results, and that the excita-tion method substantially impacts the determined damping factors. Additionally, the paper presents a novel approach for calculating the damping factor of railway bridges without requiring in-situ measurements. This mathematical de-termination of the damping factor offers a realistic alternative to overly conservative standards and enables a more accurate assessment of the dynamic behaviour of railway bridges.

1 Introduction

Railway bridges can be subjected to excessive vibrations during high-speed traffic, potentially negatively affecting both the supporting structure and the superstructure. In order to assure the dynamic compatibility between the rolling stock and the bridge structures, railway bridges have to be assessed concerning their dynamic behaviour, where serviceability checks in the form of calculated vertical acceleration limits of the structure have to be fulfilled. In this context, EN 1990/A1 [1] prescribes that calculated vertical structural accelerations due to train crossing must not exceed a limit value of 3.5 m/s².

For dynamic calculations of railway bridges, many different mechanical models for the bridge and the crossing train with varying levels of complexity are available for practical application, which can be both two- and three-dimensional. For a realistic and thus economical prediction of bridge vibrations and potential resonance effects, mechanical models require input parameters that correspond as closely as possible to the properties of the real structure. In this context, the bridge properties applied fundamentally influence the generated calculation results, whereby the damping characteristics, in particular, are of essential importance.

The damping properties of the bridge and all related energy dissipation mechanisms are usually summarised in a structure-related value - Lehr's damping factor ζ. With regard to the damping factor of railway bridges, EN 1991-2 [2] specifies damping factors depending on the type of construction and the span, which must be used in dynamic calculations of railway bridges. However, these normatively prescribed damping factors are regarded as the lower limit value of the damping to be expected in reality, which is why higher damping factors can almost always be generated from dynamic measurements. Figure 1 shows a comparison between the measured damping factors of railway bridges and the normative specifications for 23 concrete and six filler beam bridges (Fig. 1 (a)) as well as for 29 steel bridges (Fig. 1 (b)). The comparison in Figure 1 illustrates the large discrepancy between normative specifications and reality. The consequence of the over-conservative approach of EN 1991-2 [2] is that railway bridges initially classified as dynamically critical can only be classified as dynamically uncritical after extensive and cost-intensive measurements of the structure and determination of the damping properties.

A further uncertainty about the realistic dynamic assessment of railway bridges lies in the measurement-based determination of the damping factor from in-situ tests on the structure. In this context, the vibration excitation and test evaluation method used significantly influences the damping factor generated from measurements, with a considerable scattering of results depending on the method. Furthermore, the individual scope of action of the person analysing the in-situ test is also a critical influencing factor, as this can significantly influence the result (see [4] and [5]).

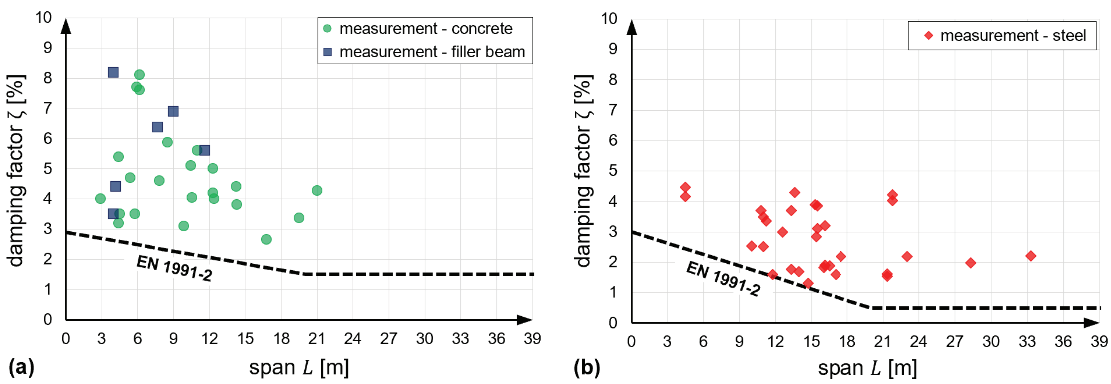

Figure 1: Comparison between measured damping factors and specifications of EN 1991-2 [2] for (a) 23 concrete and 6 filler beam bridges and (b) 29 steel bridges in the Austrian rail network (Source: [3])

For several years now, the research activities of the Institute of Structural Engineering/Research Unit Steel Structures at TU Wien have been focused on the dynamic behaviour of railway bridges and a realistic and, at the same time, computationally efficient prediction of railway bridge vibrations. A central research focus is on the damping properties of railway bridges, with research activities including the development of novel evaluation methods for the determination of the damping factor based on measurements as well as the development of approaches for the realistic mathematical determination of the damping factor as a potential alternative to the normative specifications of EN 1991-2 [2]. This contribution presents the recent research devel-opments in assessing the damping characteristics of railway bridges, whereby section 2 addresses measurement methods and novel evaluation procedures for the determination of realistic damping factors with low scatter of results based on in-situ measurements on the structure. Section 3 then provides an overview of an approach developed as part of the research activi-ties for the mathematical determination of the damping factor of railway bridges with ballast superstructures.

2 Determination of damping factors based on in-situ measurements

Methods are available in the frequency domain and time domain to determine the damping factor of railway bridges on the basis of in-situ measurements of the supporting structure. In the following, novel evaluation methods are presented as an extension of the currently primarily used standard methods in the frequency domain (section 2.1) and the time domain (section 2.2), and their practical application is demonstrated. The novel evaluation methods aim to generate realistic high damping factors with low scatter of results while minimising the individual scope of action of the person evaluating the test. Finally, section 2.3 presents the results of a measurement campaign on 15 existing railway bridges in the Austrian railway network.

2.1 Method in the frequency domain

Determining the damping factor in the frequency domain is based on an amplitude-frequency response generated from measurement data, whereby the vibration amplitude of the system is determined as a function of the excitation frequency, as illustrated in Figure 2. The standard method for determining the damping factor is the bandwidth method, where the damping factor is calculated based on the two frequencies for which the related amplitude has the value $1/\sqrt{2}$ in relation to the maximum (resonance). Strictly speaking, only three points out of all the data are used to determine the damping factor (labelled the 'point method' in this context), which entails uncertainties in the reliability and reproducibility of the results.
Therefore, a novel evaluation method was established at the TU Wien, which takes into account not just a very few selected data points but all data points of the amplitude-frequency response to determine the damping factor (referred to as the 'integral method'). The basic principle is to idealise the investigated system as a single-degree-of-freedom (SDOF) system with harmonic force excitation (see Fig. 2, left) and to adjust the theoretical response of the amplitude response factor R_a (Ω,ζ)

$$R_a(\Omega, \zeta) = \frac{(\frac{\Omega}{\omega_0})^2}{\sqrt{[1-(\frac{\Omega}{\omega_0})^2]^2 + [2\zeta(\frac{\Omega}{\omega_0})]^2}} = \frac{\eta^2}{\sqrt{(1-\eta^2)^2 + (2\zeta\eta)^2}} \quad (1)$$

to the discrete measurement data by varying the damping factor and by using the method of least square error minimisation in such a way that the greatest possible agreement between the theoretical curve and the measurement data is achieved (illustrated in Fig. 2, right). The result of this curve fitting method is a damping factor that is related to the response factor scaled by the factor C (red line in Fig. 2), which approximates the discretely measured data points (blue dots in Fig. 2) as closely as possible (background, see also [4], [6] and [7]).

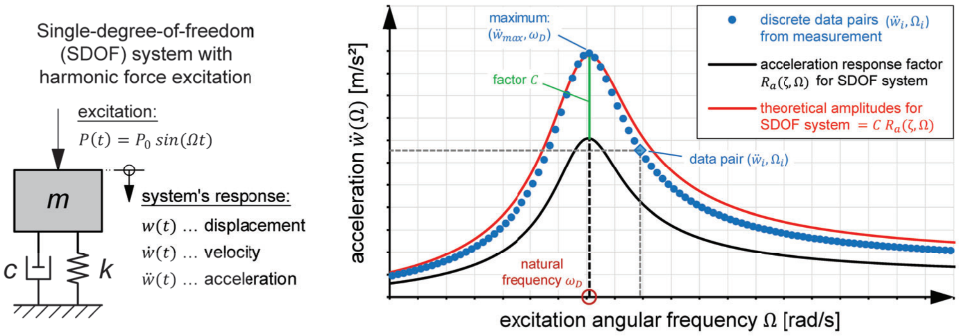

Figure 2: Oscillating system with a single degree of freedom (SDOF-system) and harmonic force excitation and curve fitting of discrete data pairs from measurement by a continuous curve [6]

The damping factor determined on the basis of this integral method depends on the frequency range under consideration in the amplitude-frequency response, whereby the practical application is illustrated in Figure 3. Figure 3 (a) shows an amplitude-frequency response generated from measurement data for an exemplary single-track steel railway bridge. For analysis purposes, energy level lines are introduced, which describe the reduction of the dissipated energy in relation to the energy dissipation at the maximum (horizontal dashed lines in Fig. 3 (a)). The damping factor is subsequently determined as a function of the frequency bandwidth Δf associated with the energy level; the result is shown in Figure 3 (b). Further, the energy level line $E_{\zeta,red}$=50 % (red dotted line in Fig. 3 (a)) is used to define a damping factor as a result. Figuratively speaking, all data points above this line are used to determine the damping factor, which results in a damping factor of 1.72 % for the example shown in Figure 3. Alternatively, the mean value between the energy level lines $E_{\zeta,red}$=50 % and $E_{\zeta,red}$=75 % can also be used, which results in a damping factor of 1.70 % (area marked in green in Fig. 3 (b)).

2.2 Method in the time domain

The method in the time domain is based on the decay process after dynamic excitation, whereby the decay process after train crossings is considered for railway bridges. Figure 4 (a) shows the theoretical course of a decay process after dynamic excitation. The standard method for determining the damping factor in the time domain is the logarithmic decrement method, where the damping

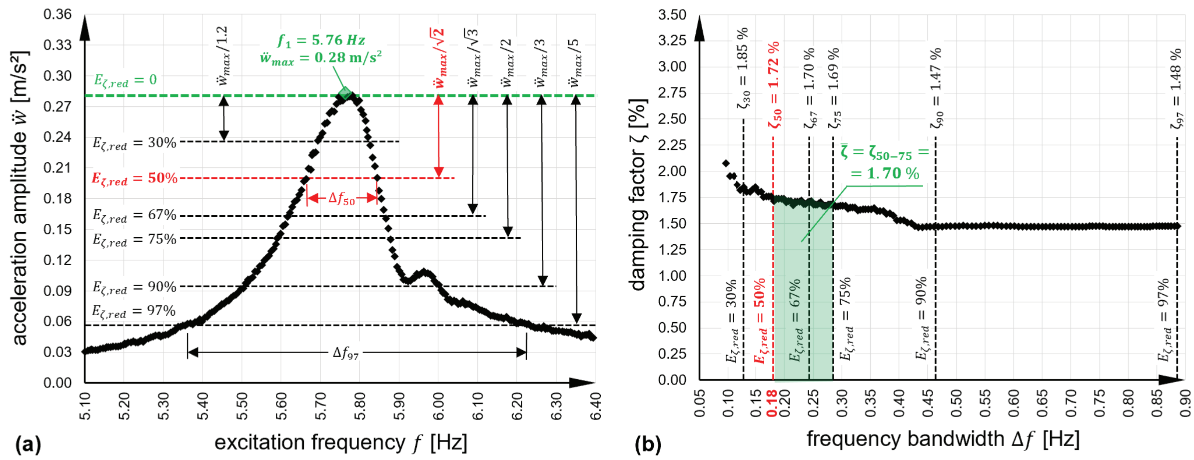

Figure 3: Determination of the damping factor in the frequency domain based on discrete data pairs for one example bridge: (a) amplitude frequency response and (b) damping factor depending on the considered frequency bandwidth [6]

factor is determined using two more or less randomly selected local amplitudes in the decay process (therefore: 'point method'). However, this method is subject to considerable scattering of results and is thus considered problematic. With the aim to reduce the scatter of results, a novel evaluation method for determining the damping factor in the time domain is presented and applied in [5-7]. Analogous to the method in the frequency domain (Fig. 3), an envelope function (blue curve in Fig. 4 (a)) $U(t)$

$$U(t) = re^{-\zeta\omega t} \tag{2}$$

is identified by varying the damping factor, which approximates a measured decay process as accurately as possible. The result is a damping factor related to an envelope function that best approximates the decay behaviour of the local amplitude maxima in the decay process. Figure 4 (b) shows an example of a decay process in the middle of a bridge structure after a train crossing with a total of 21 local acceleration peaks.

The practical application or, rather, the evaluation of the test is carried out in such a way that the damping factor is determined for different starting points (local amplitudes) as a function of the considered oscillation periods j (for further background, see [5-7]). The results are shown in Figure 4 (c), where the damping factors determined using the curve fitting method are shown as a function of the oscillation periods j for different starting points i (see legend). Figure 4 (c) clearly shows that the damping factors vary significantly depending on the starting point of the analyses and the number of considered oscillation periods, which is why it is considered critical to determine the damping factor based on measurements in the time domain. Although the scattering of results can be significantly reduced by specifying a clear procedure for evaluating the test, the scatter of results cannot be sufficiently eliminated. In this regard, reference is made to the studies in [5-7].

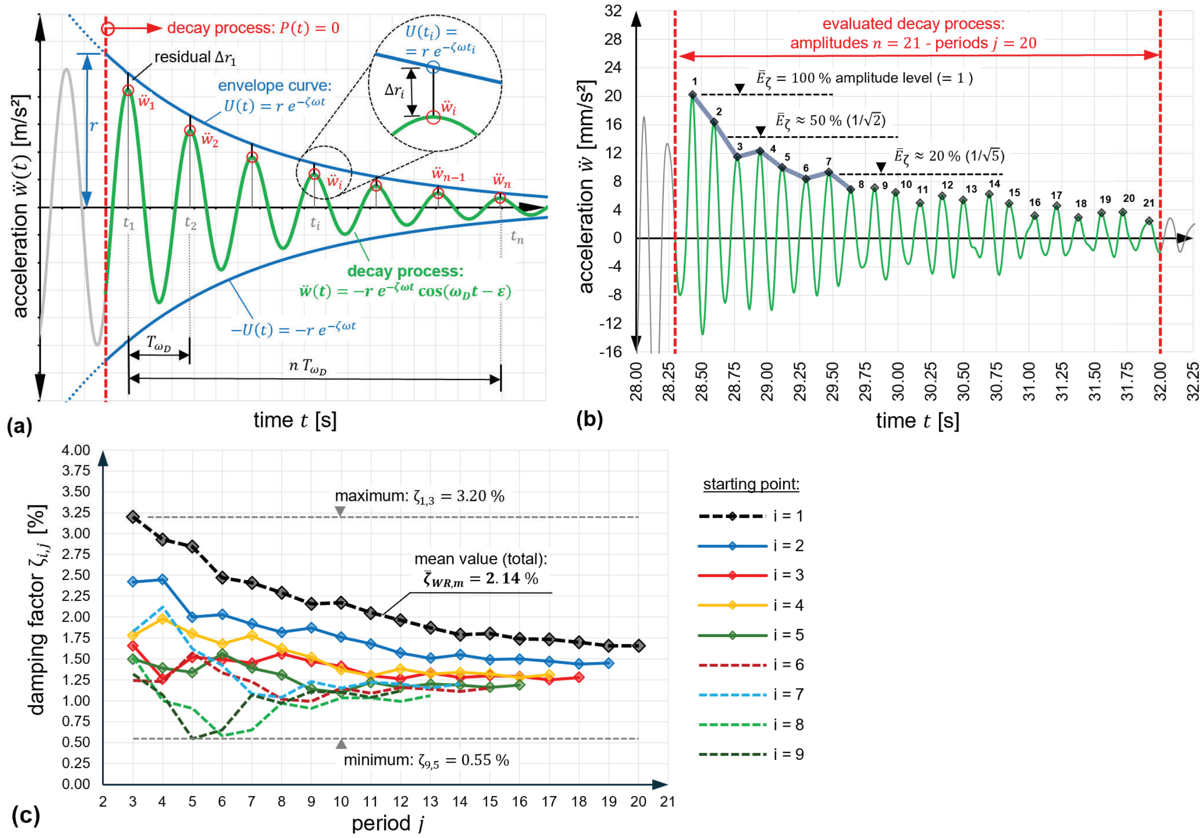

Figure 4: Determination of the damping factor in the time domain based on the decay process after excitation: (a) theoretical course and approximation of the envelope curve, (b) measured decay process for test evaluation and (c) damping factor depending on the starting point and considered periods (Source: [6])

2.3 Measurement campaign on 15 railway bridges

This subsection presents the results of a measurement campaign on 15 existing railway bridges in the context of the measurement-based determination of the damping factor. The measurement campaign is part of a recently concluded research project and includes the measurement-based determination of the damping factor for 15 single-track steel railway bridges in the Austrian rail network using the methods described in sections 2.1 and 2.2 in the frequency and time domain. Figure 5 shows three selected bridges that are part of the measurement campaign.

Figure 6 shows the damping factors determined for all 15 bridges (labelled B1 to B15) based on the methods in the frequency domain. The bridges are sorted by their increasing resonance frequency (first natural bending frequency f_1) along the abscissa, which lies between 4.27 Hz (B1) and 13.68 Hz (B15). For each bridge, several tests were carried out, with the results in Figure 6 containing the damping factors based on the bandwidth method (in grey) and the newly presented curve fitting method (in red). Furthermore, the mean values of the damping factors for each bridge, including the standard deviation and the normative prescribed damping factors according to EN 1991-2 [2], are also depicted (see legend).

Figure 6 demonstrates that the curve fitting method (‘integral method’ - red markings) leads to

Figure 5: Exemplary overview of three selected bridges of the measurement campaign (B2, B4 and B5)

significantly higher damping factors than the bandwidth method ('point method' - grey markings), even though the same measurement data is used to de-termine the damping factor. Furthermore, Figure 6 again illustrates the over-conservative interpretation of the standard (black dashed lines) compared to the real structure-related damping factors. For all 15 bridges, the mean values of the measurements based on the curve fitting method (red diamonds) are above the values prescribed by the standard. In summary, it can be concluded that the evaluation method of curve fitting leads to reliable and reproducible results when determining the damping factor on the basis of in-situ measurements on the supporting structure and that this can also be used to generate beneficial high damping factors that enable a realistic and economical dynamic assessment of railway bridges.

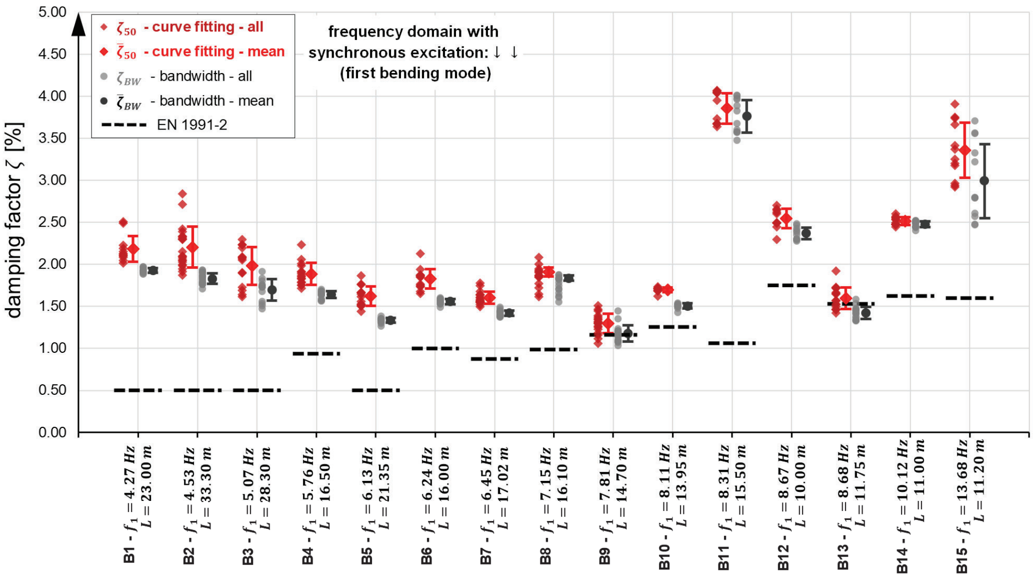

Figure 6: Damping factors identified from measurements in the frequency domain (forced vibration) based on the curve fitting method and the bandwidth method for all 15 bridges (damping factors related to first bending mode)

3 Mathematical calculation of the damping factor

The previous section 2 addresses the determination of the damping factor Lehr on the basis of in-situ measurements on the supporting structure. As part of the further research activities of the

Institute of Structural Engineering at TU Wien in relation to the damping characteristics of railway bridges with ballast superstructures, an approach was developed that enables the math-ematical determination of the damping factor of railway bridges (discussed in detail in [3], [8] and [9]). The basis for this ap-proach is provided by two-dimensional mechanical models of the bridge with varying degrees of complexity, as shown in Figure 7.

The mechanical models in Figure 7 are a continuously damped Euler-Bernoulli beam (Model 1) and a coupling beam model (Model 2), which consists of two beams coupled via horizontal spring-damper elements. In both models, the red spring-damper or damper elements represent the stiffness and damping properties of the ballast superstructure. The basic principle in the model-related calculation of the damping factor is to separately determine the dissipative contributions of the supporting struc-ture and the ballast superstructure and to superpose them as follows:

$$\zeta_{tot} = \zeta_{str} + \Delta\zeta_{bt} \tag{3}$$

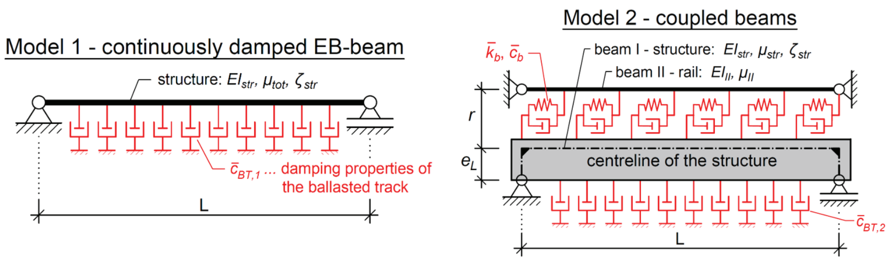

Figure 7: Mechanical models with different levels of detail as a basis for the mathematical determination of the damping factor

The calculated damping factor of the bridge ζ_{tot} is thus determined by a proportion of the supporting structure ζ_{str} and a proportion of the ballast superstructure $\Delta\zeta_{bt}$ according to equation (3). About the damping factor of the supporting structure ζ_{str}, reference values can be used, depending on the structure under consideration, which are given in [10] and [11], for example.

The dissipative contribution of the ballast superstructure $\Delta\zeta_{bt}$ depends on the considered mechanical model (model 1 or model 2, Fig. 7). It depends on the structural properties (span, mass distribution, geometry) and particularly on the damping parameters related to the model. As part of the research activities at the Institute of Structural Engineering/Research Unit Steel Structures at the TU Wien, the dynamic behaviour of the ballasted superstructure is investigated in a targeted and isolated way using special large-scale test facilities (see Fig. 8 and Fig. 9), which enables the precise determination of the damping parameters of the ballasted superstructure and the identification of their dependencies (e. g. frequency and acceleration dependencies). Using the special test facilities, it is thus possible to specifically analyse the energy dissipation mechanisms occurring in the ballast superstructure under dynamic excitation and further derive model-related stiffness and damping parameters as a basis for the approach formulated in equation (3). Corresponding results are published in [12-16]. Initial comparative analyses between mathematically determined damping factors according to equation (3) and damping factors identified from measurements (see [3] and [9]) show that the mathematical approach provides realistic damping factors. Current and future research work is dedicated to further verifying and validating this novel approach for the mathematical determination of the damping factor based on comprehensive in-situ measurements of existing structures.

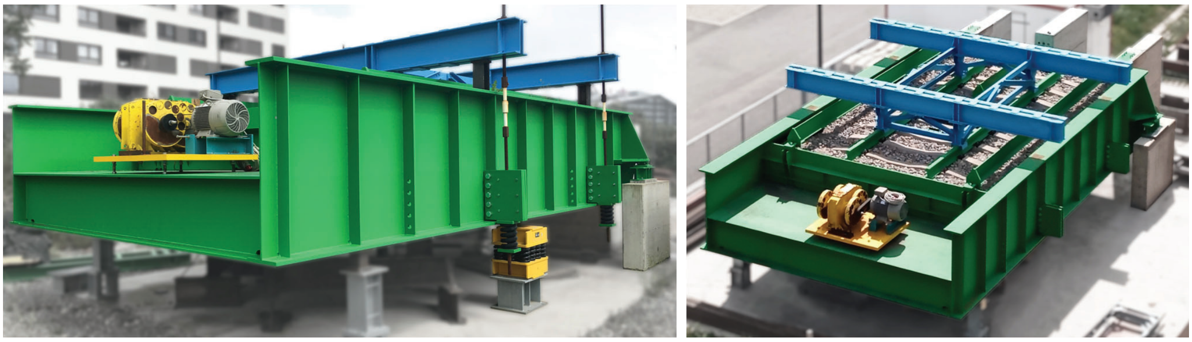

Figure 8: Large-scale test facility for targeted and isolated research of energy dissipation mechanisms in ballasted track under dynamic excitation and for isolated research of the dynamic properties of the longitudinal track-bridge interaction

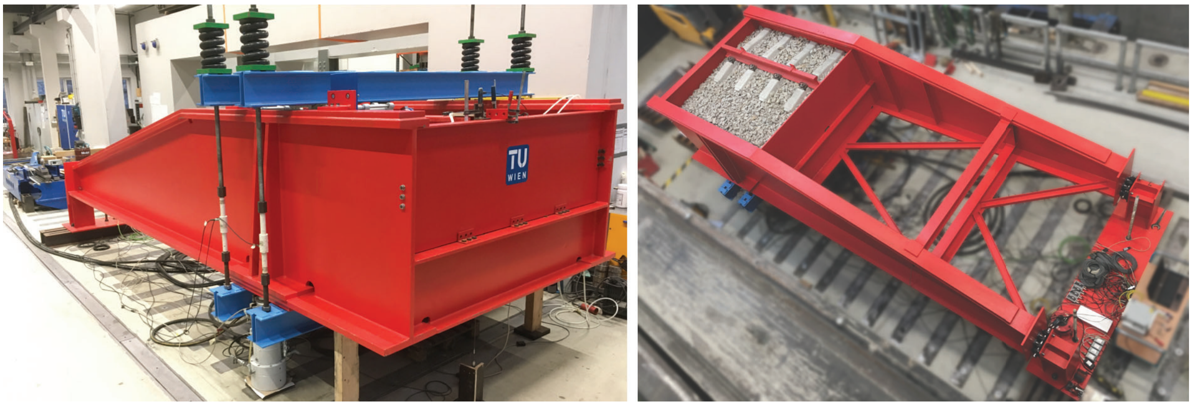

Figure 9: Large-scale test facility for targeted and isolated research of vertical energy dissipation in ballasted track and dynamic properties of the vertical track-bridge interaction

4 Conclusions

This contribution has presented a compact overview of the research work at the Institute of Structural Engineering at TU Wien in the context of assessing the damping properties of railway bridges, focusing on a reliable data-based determination of damp-ing factors based on in-situ measurements of the structure (section 2) and, in addition, on a mathematical determination of the damping factor in an amount corresponding to reality as an alternative to the overly-conservative and thus disadvantageous specifications of EN 1991-2 [2] (section 3). The approaches and methods presented provide a significant contribution to the realistic assessment of damping characteristics of railway bridges based on the combination of measurements and mathemati-cal prediction and thus enable an economic dynamic assessment of railway bridges and the compatibility between rolling stock and infrastructure.

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