Proceedings of the Seventh International Conference on
Railway Technology: Research, Development and Maintenance
Edited by: J. Pombo
Civil-Comp Conferences, Volume 15, Paper 2.7
Civil-Comp Press, Edinburgh, United Kingdom, 2026
ISSN: 2753-3239, doi: 10.4203/ccc.15.2.7

Dynamic Characteristics of Railway Bridges in the European Rail Network: Insights for Future Classification Approaches

A. Stollwitzer[1], M. Reiterer[2] and J. Fink[1]

[1]Institute of Structural Engineering, Technical University of Vienna, Austria
[2]REVOTEC zt gmbh, Vienna, Austria

Abstract

In European high-speed rail, ensuring and verifying compatibility between traffic volume and the existing infrastructure is increasingly challenging for infrastructure operators as traffic volumes steadily rise. To provide a realistic dynamic assessment of railway bridges, it is essential to accurately identify the existing bridge characteristics. In this context, the damping properties of the bridge used in calculations significantly influence the generated results. Eurocode EN 1991-2 classifies railway bridges into three categories; however, due to a lack of reliable damping factors for railway bridges, a very conservative approach is adopted, which is why damping factors identified from in-situ measurements are mostly well above the normative specifications. This contribution provides an overview of the European bridge landscape in the high-speed rail network, using a data set of 379 bridges for which dynamic parameters from in-situ measurements are available. The data set provides insights into the composition of the European bridge landscape. It demonstrates once again that actual damping properties significantly exceed those of normative approaches, highlighting the potential for a redefinition. Finally, a possible recategorization of railway bridges is discussed, with the inclusion of several system parameters enabling the derivation of new approaches to defining damping factors as an alternative to the Eurocode. These novel approaches could make the existing potential of the bridge infrastructure available for realistic dynamic assessment of railway bridges through computational analysis.

Keywords: railway bridges, data set, damping, measurements, reclassification, bridge dynamics.

1 Introduction

The continuous expansion of the European high-speed rail network and the related increase in traffic volumes are subjecting the rail infrastructure to growing demands. Railway bridges are critical components of the rail infrastructure, which are increasingly subjected to higher dynamic demands due to the intensification of traffic (higher axle loads, more frequent trains, new train configurations).

In dynamic assessments of railway bridges, limit values for the vertical acceleration of the bridge are prescribed to ensure compatibility between rolling stock and the structure. The EN 1990 [1] sets this limit value at 3.5 m/s² for bridges with ballast superstructures. At the national level, these limit values may be adapted; for example, the Austrian standard B 4008-2 [2] allows a significantly higher limit acceleration of 6.0 m/s² for existing bridges in the Austrian network. Recent studies on limit states occurring in ballast superstructures in [3] and [4] show that the limit value of EN 1990 [1] can be classified as overly conservative and that an increase in the permissible limit values for vertical acceleration would be appropriate.

In the numerical prediction of vertical bridge accelerations resulting from train passages, the calculation models used and the related input parameters significantly influence the generated results. In this context, the damping properties assumed in the calculations have an essential influence on the intensity of resonance effects and thus on the numerically predicted acceleration. Here, EN 1991-2 [5] defines damping factors to be used in calculations depending on the structural type (steel/composite, prestressed concrete, and concrete/filler beam) and the span. However, these are considered the lower limit of the damping to be expected in reality. Table 1 provides an excerpt from EN 1991-2 [5] and contains the span-dependent definitions of the damping factors for different structural types.

bridge type	**span L < 20 m**	**span L ≥ 20 m**
steel and composite	$\zeta = 0.5 + 0.125\ (20 - L)$	$\zeta = 0.5$
prestressed concrete	$\zeta = 1.0 + 0.07\ (20 - L)$	$\zeta = 1.0$
filler beam and reinforced concrete	$\zeta = 1.5 + 0.07\ (20 - L)$	$\zeta = 1.5$

Table 1: Span-dependent damping factors for railway bridges according to EN 1991-2 [5].

The definitions given in Table 1 are based on studies carried out by the European Rail Research Institute (ERRI) in the 1990s, summarised in [6]. The overly conservative approach of these definitions is consistently apparent when determining damping factors from in-situ tests (see, e.g., [7] or [8]), with the damping factors identified from measurement data exceeding the normative requirements by far.

Furthermore, EN 1991-2 combines different types of structures into one single category. For example, steel and composite bridges are included in one category. Additionally, filler beam bridges and all reinforced concrete bridges are grouped into one category, also including portal frames. Furthermore, no distinction whatsoever is made regarding the type of bearings, even though it is known that energy dissipation also depends on the type of bearing used. The differentiation into only three categories and the specification of lower limit values for damping factors result in many railway bridges being classified as dynamically sensitive and thus critical due to a lack of precise knowledge of the existing damping properties and the use of overly conservative values in calculations. Only through costly measurements on the structure and the identification of damping factors from in-situ tests is it possible to finally classify them as non-critical.

Building on this background, this contribution focuses on the realistic damping characteristics of railway bridges in the European high-speed rail network. It provides an overview of the composition of the European bridge landscape based on a collected data set of bridge parameters derived from in-situ measurements. Furthermore, it suggests a redefinition of the damping factors based on a recategorization of the railway bridges. Studies in [7] and [9], for example, show that for steel bridges, taking several system parameters into account, a redefinition of the damping factor can be provided that is much closer to reality while still following a conservative approach. Furthermore, adapted definitions for the damping factors of railway bridges are also presented in [8]. Below, Section 2 presents an overall view of the data set used, and Section 3 provides an overview of various bridge parameters. Building on this, Section 4 gives an overview of the damping factors identified from in-situ measurements and initiates a possible reclassification into several bridge families. Section 5 closes with several conclusions.

2 Bridge data set and statistical distribution

The data set used in this contribution includes properties derived from in-situ measurements of a total of 379 single-span railway bridges in the European network. The data originates from recent studies and measurement campaigns on railway bridges in the Austrian network, which are available to the authors and have been summarised and partially published in [7] and [10]. Furthermore, the data set includes the bridge data from the InBridge4EU project published in [8] and [11]. In addition, data from the ERRI Report [6], studies and analyses by Fryba [12] in the 1990s, and data on filler beam bridges from [13] are also used.

Figure 1 provides an overview of the composition of the collected bridge data; Figure 1 (a) provides a separation of the bridge data by country, with the bridges located in Austria, France, Germany, Spain, Sweden, and Portugal; however, for 70 bridges, there is no information on their location. As Figure 1 (a) shows, the majority of the bridges considered are located in Austria, France, and Germany. Figure 1 (b) provides a classification of the bridges according to their structural type. In addition to the definitions in Table 1 based on EN 1991-2, the bridges are categorised not into three but into a total of six categories. Relating to the three categories given in Table

1, the data set includes 167 steel and composite bridges (141 steel and 26 composite bridges), 15 prestressed concrete bridges, and 197 reinforced concrete and filler beam bridges (comprising 100 filler beam, 66 reinforced concrete bridges, and 31 portal frames). Figure 1 (b) reveals that only 15 of the 379 bridges (equivalent to 4 %) are prestressed concrete bridges. From the current perspective and based on the available information, a separate categorisation for this bridge type appears questionable.

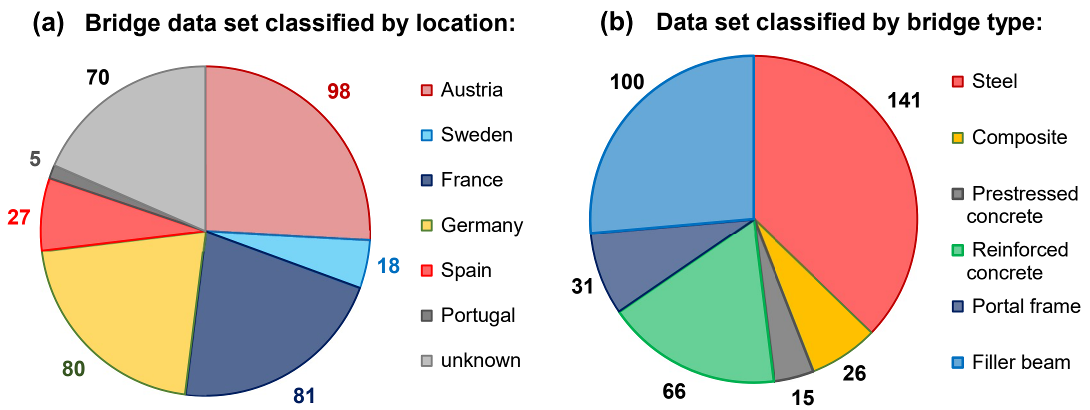

Figure 1: Data set of single-span railway bridges in the European railway network, compiled from [6-13]: (a) classified by location and (b) classified by bridge type.

As mentioned above, the data set used includes a total of 379 railway bridges, for all of which information on the span L and the first natural bending frequency f_1 (derived from measurements) is available. For 287 of these bridges, information on the damping factors ζ derived from in-situ measurements is also available, and for 269 bridges, information on the mass distributions (mass per meter μ) derived from design documents is known. Concerning the evaluation of damping factors, two different methods were applied: decay processes after train passage and forced vibration tests.

Figure 2 provides an overview of the key characteristics of the bridges as a function of span L, showing the natural frequencies f_1 (see Fig. 2 (a)) and damping factors ζ (see Fig. 2 (b)) identified from measurement data, as well as the mass distributions μ (see Fig. 2 (c)) derived from design documents. For differentiation purposes, the three categories according to EN 1991-2 (see Table 1) are distinguished by colour. The spans L range from 2.9 to 68.9 m, and the natural frequencies f_1 range from 1.2 to 73.0 Hz.

The damping factors ζ range between 0.41 and 17.24%. As expected, the overview of bridge data in Figure 2 shows that steel and composite bridges (red markers) generally have higher spans. At the same time, the natural frequencies and mass distributions fall within a comparatively low range. Concrete bridges (green and blue markers) are characterised by shorter spans as well as higher natural frequencies and mass distributions. These relationships are well-documented in numerous studies and analyses. With regard to the damping factors shown in Figure 2 (b) and the mass distributions given in Figure 2 (c), it should be noted here that the reliability of the data is not consistent across all bridges. In particular, the data from the ERRI report [6] should be treated with caution, as the respective damping evaluation method – insofar as it can be ascertained at all – is subject to uncertainties. The damping factors illustrated in Figure 2 (b) are mainly mean values derived from multiple measurements, which may be subject to significant scatter depending on the excitation and evaluation methods, see also [7] and [8] concerning this issue. The natural frequencies identified from measurement data, shown in Figure 2 (a), on the other hand, can be uniformly regarded as reliable values.

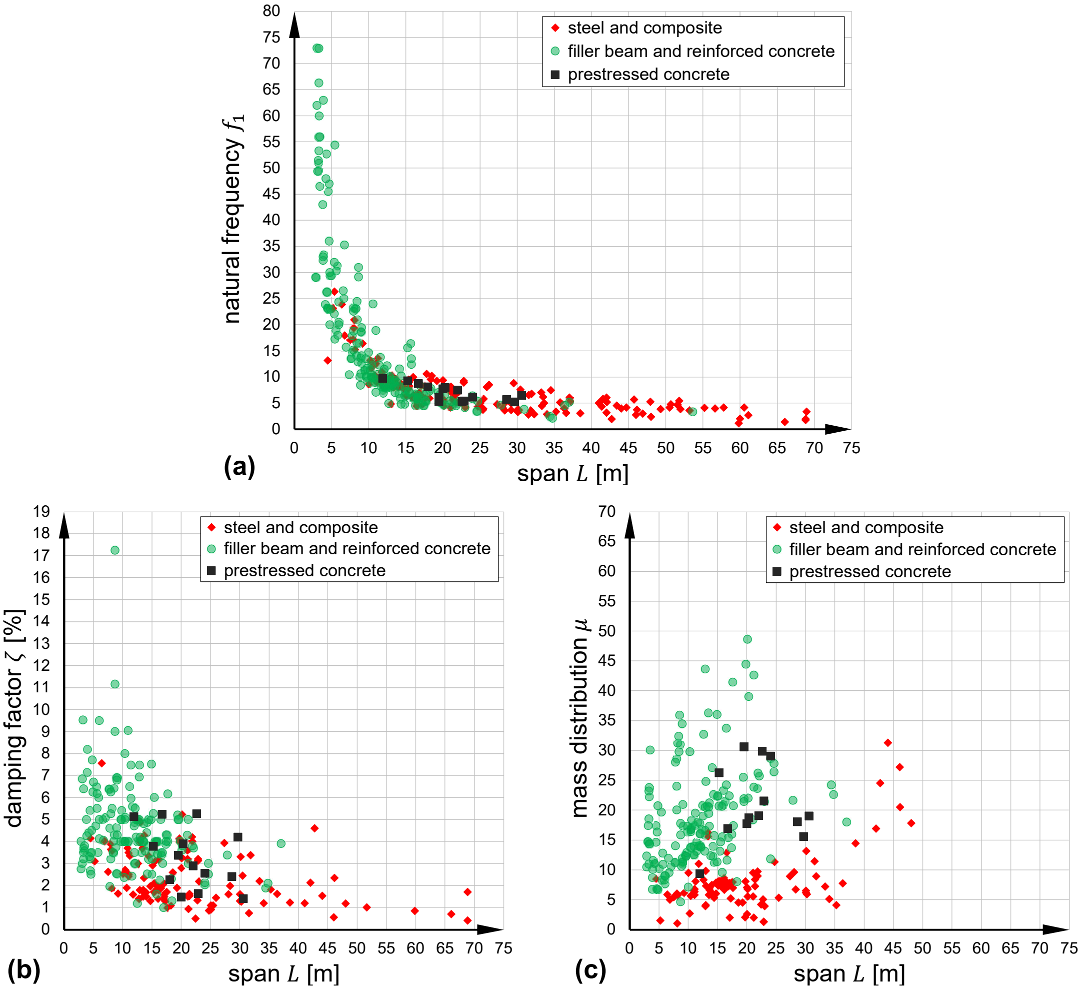

Figure 2: Bridge data set parameters as a function of the span L: (a) natural frequency f_1 (first bending mode), (b) damping factor ζ, and (c) mass distribution μ.

As a further analysis and to illustrate the diversity of bridge parameters, Figure 3 shows a statistical distribution of all spans and natural frequencies. Figure 3 (a) presents the spans L, while Figure 3 (b) presents the analysis of the natural frequencies f_1. In Figure 3, the category including reinforced concrete and filler beam bridges and the category prestressed concrete bridges according to EN 1991-2 are grouped under one parent category “concrete”. In contrast, steel and composite bridges are grouped under the category “steel”. This results in 212 bridges in the concrete category and 167 in the steel category.

Figure 3 shows the normal distribution (continuous lines) and the respective statistical frequency (red and green bars) for both categories, see legend. For concrete bridges, the mean value L_{mean} of all spans is 12.68 m. For steel bridges, the mean value L_{mean} is 26.34 m, which is more than twice as high. The corresponding standard deviations σ_L (related to the span, see Fig. 3 (a)) and σ_{f_1} (related to the natural frequency, see Fig. 3 (b)) are also given. Regarding the natural frequencies, the mean value $f_{1,mean}$ for steel bridges is 7.20 Hz and for concrete bridges 16.35 Hz. Figure 3 clearly illustrates that steel bridges vary greatly in span length. In contrast, for concrete bridges, the natural frequencies are subject to considerable variation (standard deviation σ_{f_1} of 14.97 with a mean value of 16.35 Hz).

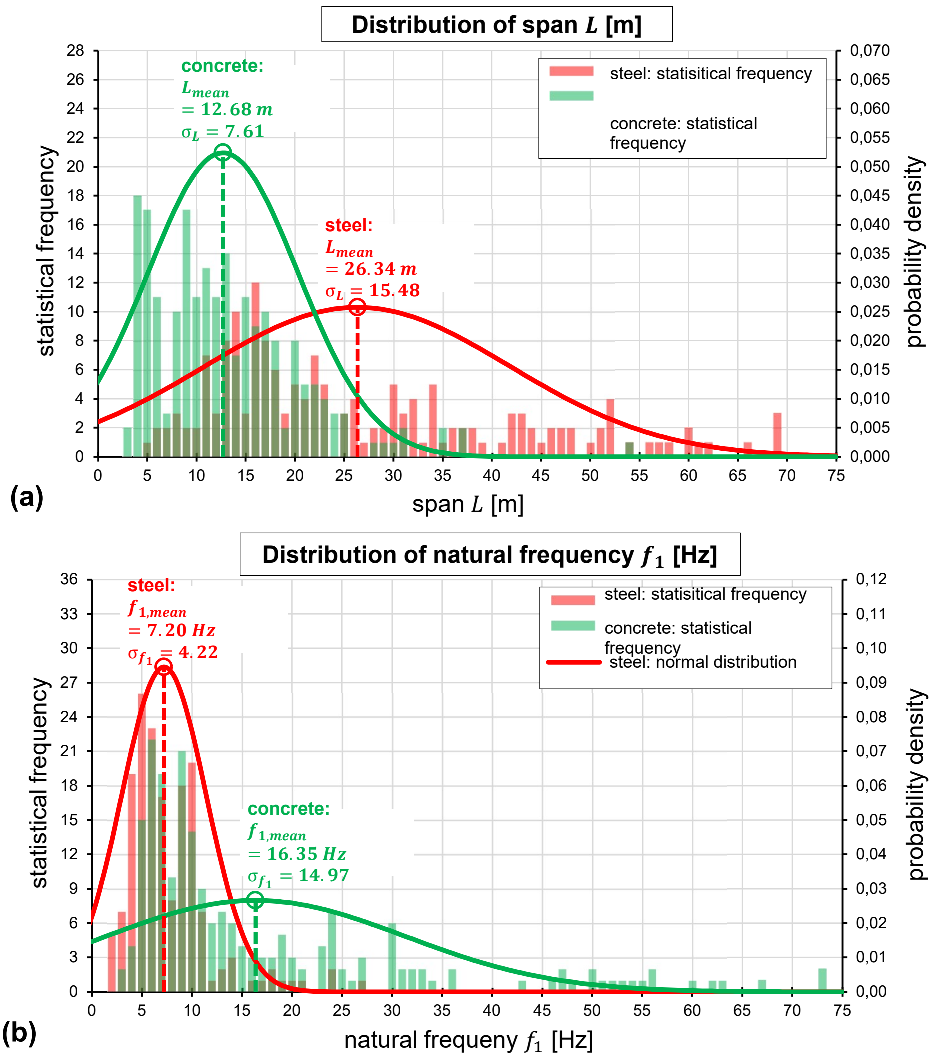

Figure 3: Statistical distribution for the parameters span and natural frequency for 212 concrete and 167 steel bridges: (a) distribution of span L and (b) distribution of natural frequency f_1.

3 Dynamic parameters and recommendations for new categories

The figures in Section 2 present an overview of the parameter distribution of the considered data set comprising 379 railway bridges in the European high-speed rail network. The classification into only three different categories for defining damping factors according to EN 1991-2 thus appears to be an oversimplification. Furthermore, the separate category for prestressed concrete bridges is, given their small number – only 4 % of the bridges in the data set in question – at least questionable.

As a further analysis, Figure 4 illustrates the natural frequencies and damping factors identified from measurement data for all bridges in the considered data set as a function of span. With regard to the classification into three categories, an extension of EN 1991-2 is applied, and following the distinction presented in Figure 1, a total of six categories are considered: steel bridges and composite bridges (Fig. 4 (a) and (b)), portal frames (Fig. 4 (c) and (d)), filler beam bridges (Fig. 4 (e) and (f)), and prestressed and non-prestressed reinforced concrete bridges (Fig. 4 (g) and (h)).

In all diagrams in Figure 4, the dynamic parameters of all bridges are shown for comparison (grey markers, see legend). This comparison provides, on the one hand, a comparison of the respective parameters of individual subcategories within the totality of all bridges and also provides insights into the variation of the parameters. Thus, with regard to natural frequencies for all categories, a very clear relationship between span length and natural frequency is evident. As expected, steel and composite bridges are characterised by larger spans and lower natural frequencies, while portal frames in particular have small spans and high natural frequencies. Filler beams and concrete bridges lie in the middle range.

With regard to the damping factors, Figure 4 also shows the construction- and span-dependent definitions from EN 1991-2 given in Table 1 for comparison (dashed lines, see legends). For the damping factors identified from the measurement data, two significant correlations emerge for the selected categories under consideration. With very few exceptions, the damping factors exceed the normative requirements, in many cases by a significant amount. The definition prescribed by the standard is confirmed as a lower limit, although the actual damping is usually many times higher. This highlights the significant potential entailed by redefining the damping factors for railway bridges. As mentioned above, approaches for redefining damping factors have already been presented in [8] and [9].

Another aspect revealed in Figure 4 regarding the damping factors is that the variation of the damping factors along the ordinate is highly pronounced in all six defined categories. Therefore, a definition of damping factors exclusively depending on the spans for each category represents an oversimplification of reality. Another important circumstance is that in-situ measurements on railway bridges to evaluate damping factors are highly affected by the excitation and evaluation methods used. Studies in [7] demonstrate that forced vibration excitation and evaluation in the frequency domain yield reliable and reproducible results, in contrast to the use of decay processes after train passage.

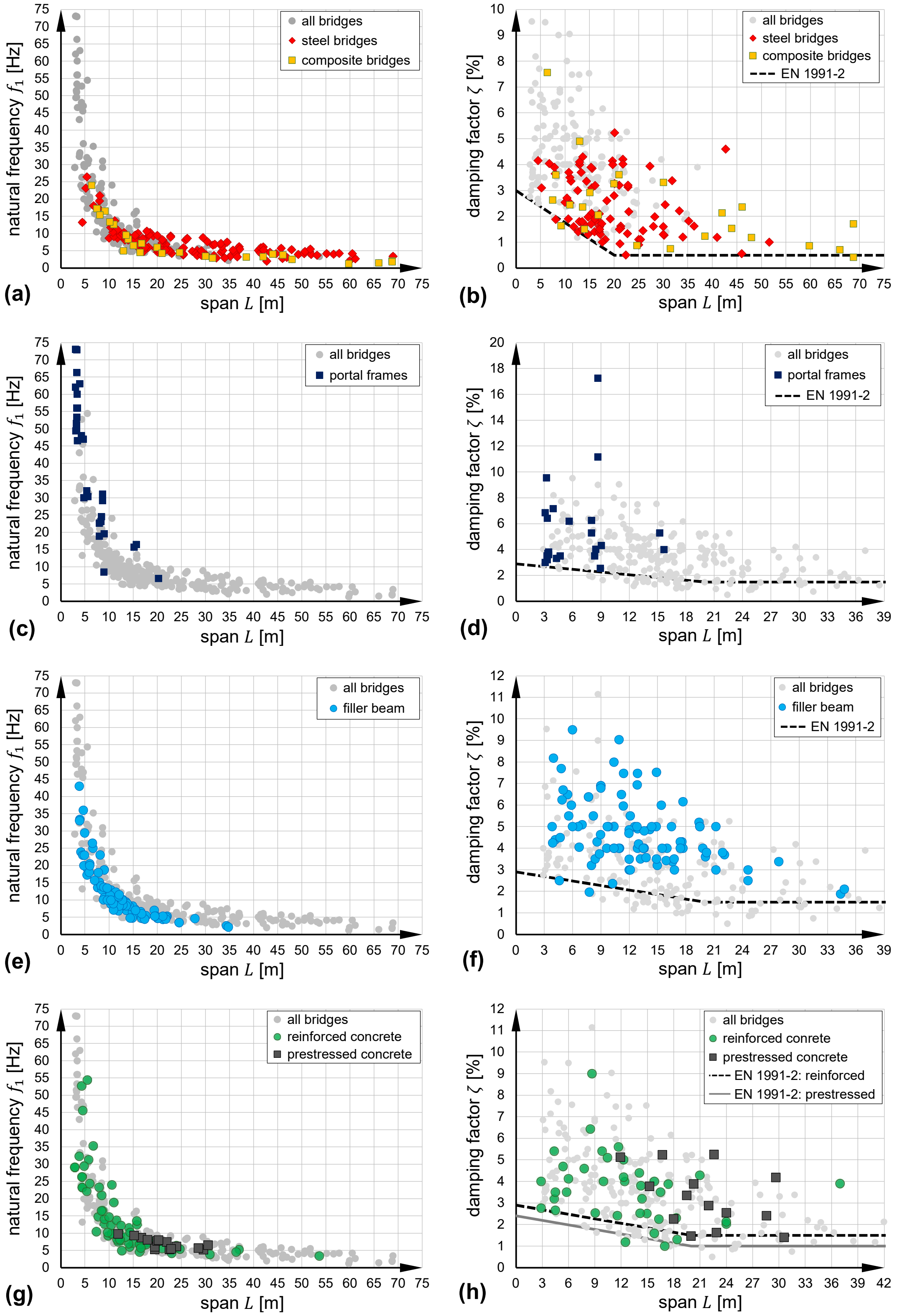

Figure 4: Natural frequency f_1 and damping factor ζ depending on the span L: (a), (b) steel and composite bridges; (c) and (d) portal frames; (e) and (f) filler beam; (g) and (h) reinforced and prestressed concrete bridges.

With regard to redefining the damping factors, it is therefore essential to initially create a reliable data basis of damping factors identified from measurement data using uniform vibration excitation and evaluation methods as far as possible. In addition, the inclusion of multiple system parameters—rather than a formulation based exclusively on the span—is required to define realistic yet still conservative new specifications.

Finally, Figure 5 presents a set of recommendations for a potential recategorization of railway bridges as a basis for a redefinition of structure-related damping factors as well. In this case, the three categories of EN 1991-2 are expanded into a total of seven bridge families. The category of prestressed concrete bridges is thus integrated into reinforced concrete bridges. For a redefinition of damping factors, a solid data basis for a representative number of structures should first be developed for each bridge family. Subsequently, a new definition should be formulated by incorporating multiple system parameters. In [9], this systematic approach is applied, for example, to the family of steel-deck and trough bridges. Furthermore, [8] and [14] present new definitions for the portal frame family, which, however, still remain exclusively span-dependent. In addition, measurement campaigns are currently being carried out in Austria, which are intended to serve as the basis for redefining the damping factors of filler beam bridges. The recommendations in Figure 5, featuring seven bridge families, serve as an initial proposal and can be further expanded by separately considering steel deck and steel trough bridges, for example, as well as potentially creating a separate category for truss bridges.

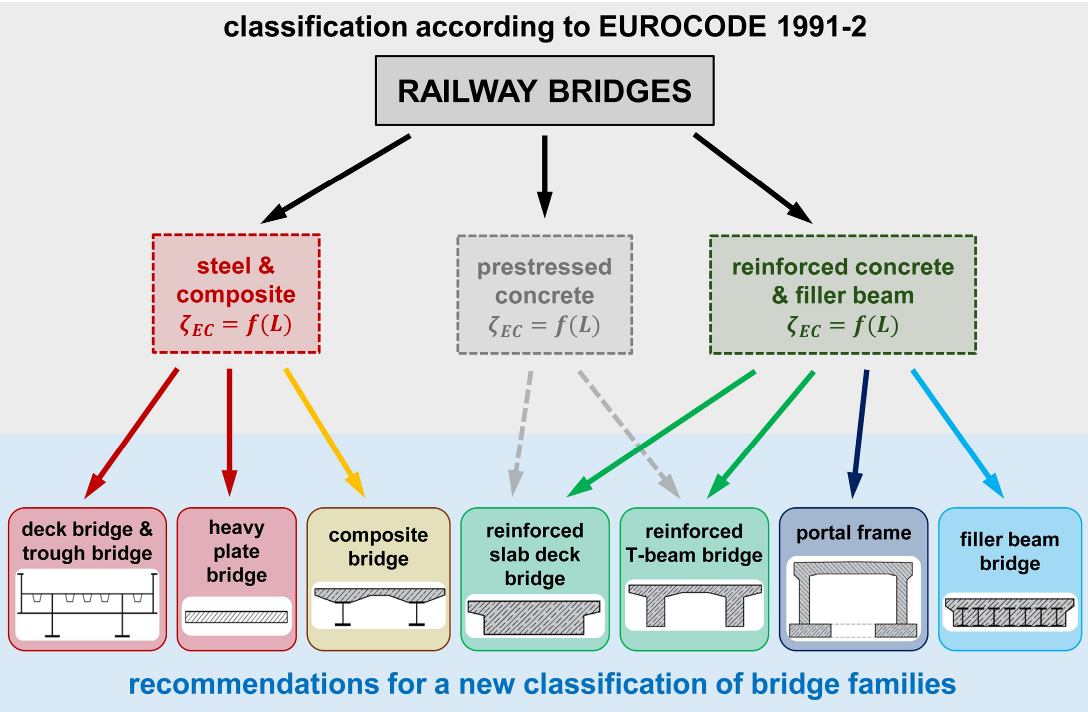

Figure 5: Recommendations for a new classification of bridge families as a basis for a new definition of damping factors for railway bridges.

4 Conclusions and Contributions

This contribution provides an overview of the dynamic properties of 379 single-span railway bridges in the European high-speed rail network based on a comprehensive data set that combines data from in-situ measurements. The evaluations and analyses demonstrate that the actual damping properties significantly exceed the normative specifications defined in EN 1991-2 in the majority of cases. Furthermore, when viewed exclusively in terms of their span, the damping factors are subject to considerable scattering (see Fig. 4).

Moreover, the available bridge data illustrate that the current classification in EN 1991-2, which divides bridges into only three categories with regard to damping factors, does not adequately reflect the actual diversity of the European bridge infrastructure. The analyses demonstrate that defining damping factors exclusively based on the span is an oversimplification of reality and therefore leads to overly conservative dynamic assessments of railway bridges in most cases. The comparisons presented here highlight the potential of new approaches for a more realistic description of the damping properties of railway bridges. To effectively harness this potential by developing new definitions for damping factors, a key step is to recategorise the bridge landscape into multiple bridge families. Figure 5 provides initial proposals based on existing research.

For future work, the establishment of a consistent and expanded data basis appears particularly essential, with consistent measurement and evaluation methods playing a central role in determining the damping factors. Building on this, new definitions of damping factors can be developed for individual bridge families, taking into account multiple system parameters. In [9], this systematic approach is applied to redefine the damping factors of steel trough and deck bridges. The overarching goal of these developments is a more realistic and at the same time secure dynamic assessment of railway bridges, in order to utilise available reserves in the existing stock better and avoid unnecessarily conservative assessments.

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