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Damping Assessment on Railway Bridges Based on an Extensive Experimental Database Framed on the InBridge4EU Project

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Abstract

The structural damping on railway bridges has a very significant effect on the dynamic response at resonance when the loading frequency of the train, or a multiple of, matches the natural frequency of the bridge. However, its estimation is not straightforward, since the literature points to a large scatter in damping coefficients even in similar structures. To tackle the issues associated with this important factor in the evaluation of the effects caused by the bridge vibration under railway traffic, the European Union Agency for Railways (ERA), together with the Europe's Rail Joint Undertaking (EU-Rail), launched a European call for a project whose main objectives consisted on proposing recommendations for improving the current standards that deal with bridge dynamics, namely EN1990-A2 and EN1991-2. In this sense, the project InBridge4EU aims to answer these questions by studying, among other normative topics, the damping on bridges and its normative values currently specified in EN1991-2. This paper presents, therefore, the first results obtained from several measurements carried out in Portuguese and German bridges using the Covariance Driven Stochastic Subspace Identification (SSI-COV) method, including a preliminary analysis of the factors that might influence the damping scatter.

Keywords: railway bridges, damping, SSI-COV method, InBridge4EU Project, Eurocode, assessment.

1 Introduction

At resonance, the dynamic effects on railway bridges induced by traffic loads can reach significant values, especially for speeds higher than 200 km/h [1,2]. The magnitude of these effects, however, depend on several factors, both related with the bridge, such as the stiffness, mass and damping properties, as well as with the train, namely the load values, number of axles and their spacing [3]. Among all these factors, bridge damping stands out given its influence in the bridge response, especially at resonance, but, at the same time, given the large variability that it can assume. The difficulties and uncertainties associated with the determination of values for this factor led to the definition of conservative normative values proposed by the ERRI D214 expert committee [2] based on the lower bound levels of damping estimated for several bridge types with different spans. These damping coefficient values, currently stipulated in EN 1991-2 [1], lead to conservative attenuations of the dynamic response of railway bridges at resonance, which may result, during the design phase, in less cost-efficient bridges.

The difficulties associated with the estimation of damping coefficients in railway bridges arise from the fact that many energy dissipation mechanisms occur during the train passages with different degrees of complexity and importance [4]. Moreover, since these mechanisms can be originated from different subsystems, namely the bridge, train and interfaces, such as the track-bridge, soil-structure or train-bridge interfaces, the difficulties of identifying the origin of damping increase even more.

Regarding the bridge, damping is mostly related with the material damping, but can also be associated with some non-structural components, such as rail expansion joints, bearings or even handrails [5]. As mentioned before, the several interfaces may also contribute for damping. With respect to the track-bridge interface, damping is mainly associated with the longitudinal relative displacements that occur between the deck and the rail at the ballast level that may lead to nonlinear incursions of this component during the train passages [6], as well as with the seasonal effects [7]. Soil-structure interaction is also an important source of damping, in particular radiation damping, in which the energy is dissipated through the adjacent terrain at the abutments or foundations [8]. Finally, the interaction between the moving vehicle and the bridge may also influence the damping associated with the system [9].

Experimental estimation of damping is, therefore, a challenging topic given the high degree of uncertainty associated with the railway bridge system. In this regard, several tests can be performed to access the bridge damping, namely ambient vibration tests [10], where the vibration of the bridge is caused exclusively by ambient effects, such as wind, tests under railway traffic [11,12], in which the levels of vibration are higher and caused by the passage of trains, and forced vibration tests [13], in which the bridge is subjected to an external controlled excitation produced by an equipment, such as an impact hammer or an actuator. Since the former rely on low amplitude vibrations that may not be representative of the real loading conditions caused by train passages, the other two tests are more adequate for the estimation of damping in railway bridges. The most known method for this effect is the Logarithmic Decrement method adopted by several authors [5,10], which is effective in scenarios where the contribution of the predominant mode of vibration for the global response can be easily separated from the others. However, this procedure may not straightforward in some cases, such as in bridges characterized by modes with frequencies closely spaced [14] (e.g. bending and torsion modes). Other methods, such as the Prony-Pisarenko or Autoregressive models, adopted in ERRI D 214/RP3 [2], may overcome these issues.

With the objective of improving the current damping criteria stipulated in the European codes [1] and overcome the degree of conservativeness of the damping values provided there and reported by several authors [5,10,11,15], the European Union Agency for Railways (ERA), together with the Europe's Rail Joint Undertaking (EU-Rail), drafted a Technical Note to propose new normative recommendations in terms of bridge dynamics to close open points in the codes that deal with this topic [1,16,17]. The project InBridge4EU [18] was selected to answer this call and, among other normative topics, to propose revised recommendations related to bridge damping. This paper presents, therefore, the first results obtained from several measurements carried out in Portuguese and German bridges using the Covariance Driven Stochastic Subspace Identification (SSI-COV) method [19], including a preliminary analysis of the factors that might influence the damping scatter.

2 Scope

In 2022, grounded on the results from previous European projects related with bridge dynamics, such as In2Track3 [20], ERA drafted a Technical Note [21] with the objective of closing open points on the codes that deal with railway bridge dynamics. These points identified by ERA were divided in 11 work streams (WS) presented in Table 1, while it is also possible to observe the different work packages (WP) from the project InBridge4EU that address them. This European project is being carried out by a consortium of 11 partners from 6 different countries, including both academic and industrial partners, and aims to perform research to enhance the normative criteria associated with the open topics specified in the aforementioned WS.

The present paper focuses on the preliminary results from WP4 that deals with the enhancement of the current normative criterion stipulated in EN 1991-2 [1] relative to damping on railway bridges. The coefficients specified in this norm arise from a very conservative lower bound envelop of damping estimations carried out in the 90s by the ERRI D214 committee (see Figure 1) and, therefore, should be revised to improve the railway bridge design's cost-efficiency. InBridge4EU will rely on a large database of measurements from bridges from 5 European countries managed by the respective Infrastructure Managers (Germany – DBInfraGo, France – SNCF Reseau, Spain – ADIF, Portugal – IP and Sweden – Trafikverket).

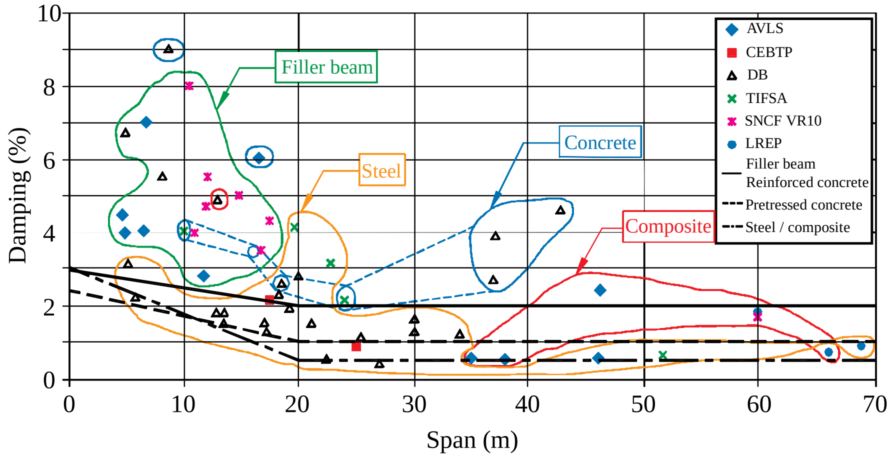


Figure 1: Lower bound of damping proposed by the ERRI D214 committee (adapted from [2]) and adopted in EN 1991-2 [1].

Work Package in InBridge4EU [18]	**Work streams from [21] addressed**
WP1 – Definition of Dynamic Train Categories (DTCs) for ensuring compatibility of the interface between trains and bridges	WS1 - Further development of spectral methods (DER, LIR) WS2 - Definition of dynamic loading interface between vehicles and bridges WS4 - Sensitivity studies on train parameters WS5 - Selection of relevant vehicles in train families
WP2 – Identification of critical bridge parameters for the assessment of the economic impact of the new DTCs	WS3 – Economic evaluation of proposed Dynamic Train Categories (DTCs) WS6 – Identification of realistic critical parameter combinations for existing bridges WS9 – Revision of beam model in parametric study to cover other structural forms
WP3 – Revision of the dynamic factors φ′ and φ″	WS7 - Revision of φ‘ and φ’’
WP4 – Revision of damping in railway bridges	WS8 - Revision of damping
WP5 – Revision of bridge deck acceleration limit	WS10 - Acceleration limit
WP6 – Recommendations for dynamic compatibility checks, TSIs and Eurocodes	WS11 - Revision of limits of validity of static vehicle / bridge compatibility checks (together with WP1)
WP7 – Technical coordination, scientific quality assurance and D&E&C	Coordination

Table 1: Open points (work streams) addressed in the InBridge4EU project.

3 SSI-COV method and its application to estimate damping

As mentioned before, several methods can be used to estimate damping on bridges. The most common method is the Logarithmic Decrement, which consists of determine a damping coefficient based on the exponential decay property of the free response of a damped system. Given its simplicity and ease of implementation, it is a widely used method in structural dynamics, but can only be effective in scenarios where the contribution of the predominant mode of vibration for the global response of the bridge can be easily separated from the others. However, in several cases, this procedure is not straightforward, such as in bridges characterized by coupled modes with frequencies closely spaced [14] (e.g. bending and torsion modes), which makes the Logarithmic Decrement method unfeasible . Other methods, such as the Prony-Pisarenko or Autoregressive models, adopted by the ERRI D214 committee [2] may overcome these issues.

In the present work, the Covariance Driven Stochastic Subspace Identification (SSI-COV) method [19], which is widely used in structural health monitoring (SHM) civil engineering applications, such as bridges [19] or wind turbines [22], was adopted to estimate damping based on the available measurements. This methodology is based on the identification of a state-space model of the recorded response ($\boldsymbol{y}_k$) as [22]

$$\begin{aligned} \boldsymbol{x}_{k+1} &= \mathbf{A} \cdot \boldsymbol{x}_k + \boldsymbol{w}_k \\ \boldsymbol{y}_k &= \mathbf{C} \cdot \boldsymbol{x}_k + \boldsymbol{v}_k \end{aligned} \tag{1}$$

where $\boldsymbol{x}_k$ is the state vector, and $\boldsymbol{w}_k$ and $\boldsymbol{v}_k$ the process and measurement noise, respectively, and where the state matrix $\mathbf{A}$ contains all the relevant dynamic information of the system. Although initially developed for stochastic identification, this method can also be adapted to extract modal parameters from free decays, such as those observed in the bridge response after the train exits it. The observed free decays can be directly used as input of the SSI-COV method, taking the place of the correlation functions calculated from the ambient responses With this technique, after the identification of the modal properties, it is possible to decompose the measured free decays in modal decays using the decomposition of the output correlation matrix:

$$\mathbf{R}_y(j) = \mathbf{C} \cdot \mathbf{A}^{j-1} \cdot \mathbf{G} \tag{2}$$

When the correlation matrix $\mathbf{R}_y$ is replaced by the measured free decays $\boldsymbol{y}_k$ and $\mathbf{A}$ substituted by its modal decomposition, the following expression is obtained:

$$\boldsymbol{y}_k = \mathbf{C} \cdot \boldsymbol{\Psi} \cdot \boldsymbol{\Lambda}^{k-1} \cdot \boldsymbol{\Psi}^{-1} \cdot \mathbf{G} \tag{3}$$

where $\boldsymbol{\Psi}$ contains in its columns the mode shapes, $\boldsymbol{\Lambda}$ is a diagonal matrix, whose elements are equal to $e^{\lambda_i \cdot \Delta t}$, Δt is the time interval between each sample and λ_i are the eigenvalues of the state-space model that are related with the natural frequencies and modal damping ratios of the tested structure. The contribution of a specific mode for the measured decays can be obtained with Eq. (3), considering in the diagonal matrix only the two eigenvalues (complex conjugate pairs) that are associated with that mode. The damping estimates of the less excited modes are expected to be less reliable. A detailed description of the theoretical background of the SSI-COV method and the definition of the contribution of each mode for the measured decay can be found in [22,23].

Based on the above-mentioned SSI-COV method, the damping has been estimated for each bridge based on scenarios where the response is mainly characterized by the fundamental mode of vibration. This approach aims to consider damping values only from responses that are more approximate to a resonant situation because damping has a particular impact in the bridge design under these circumstances [2]. Figure 2 extracted from ERRI D 214/RP3 [2] clearly shows this, where it possible to observe that the maximum acceleration at the midspan of a given simply supported bridge is only clearly affected by damping at the resonance speed, in this particular case around 270 km/h.

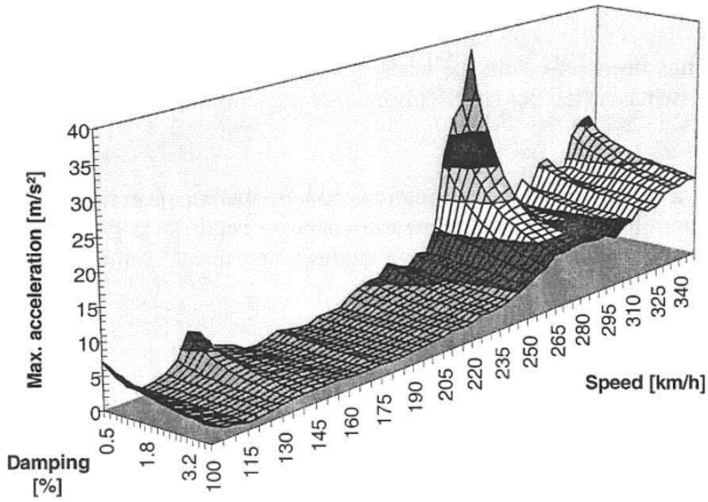


Figure 2: Maximum acceleration at a given bridge as function of damping and train speed (adapted from [2]).

Hence, the following procedure has been followed to estimate the damping on each studied bridges:

1) Estimate fundamental frequency of the bridge based on reports from the Infrastructure Manager and validated through the measurements.
2) Filter each measurement time-series with a band-pass filter around the frequency of the fundamental mode of vibration to isolate this component.
3) Isolate the free decay part of the time-series (bridge response after the train exits the bridge).
4) Estimate damping of the fundamental mode through the SSI-COV method based on the free decay part of each measurement obtained in the previous step.
5) Repeat step 2), but with a low-pass filter with a cutoff frequency of 10 times the frequency of the fundamental mode to get the contribution of more modes.
6) Consider the damping estimations only from the measurements whose contribution of the fundamental mode of vibration is higher. This evaluation is important to ensure that only the measurements more similar to resonant scenarios, usually characterized by responses governed by the fundamental mode of vibration, are considered for damping estimation.

4 Studied bridges

The present work is based on a series of measurements from the database of the project InBridge4EU [18], in particular those obtained in field tests carried out in 8 single-deck simply-supported bridges from the German railway network (5 filler beam, 2 reinforced concrete slab and 1 orthotropic through composite bridge). Figure 3 depicts photos from each of the studied bridges, while Table 2 shows their main structural properties. The data used in this work consist of acceleration responses measured at the midspan of the deck with a sampling frequency of 2400 Hz. All the damping estimations shown in Section 5 were obtained through the SSI-COV method briefly presented in Section 3 considering the free decay period of the response after the train leaves the bridge. The time-series used in this work correspond to the measured bridge response obtained with the accelerometer installed under the deck over which the train is passing (i.e., the responses measured in the opposite track deck are not considered) and their number vary between 9 and 31 valid measurements.

Name	**Deck type**	**Material**	**Span Length (m)**	**Bending stiffness *EI* (GPa.m^4)**	**Number Measurements**
ID #24193	Filler beam	Reinforced concrete with steel profiles	12.90	3.726	22
ID #26496	Filler beam	Reinforced concrete with steel profiles	12.86	3.907	18
ID #20726	Filler beam	Reinforced concrete with steel profiles	15.92	12.425	17
ID #23194	Filler beam	Reinforced concrete with steel profiles	17.70	5.564	21
ID #12391	Filler beam	Reinforced concrete with steel profiles	12.00	2.683	9
ID #5046	Slab beam	Prestressed concrete	22.60	56.067	31
ID #34492	Slab beam	Prestressed concrete	16.73	10.001	13
ID #7341	Orthotropic through	Steel composite	14.71	4.014	15

Table 2: Main mechanical properties of the studied bridges from the German railway network.

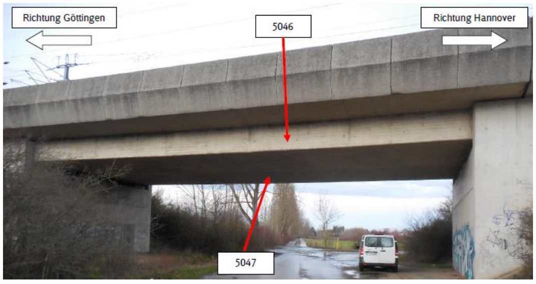
a) ID #24193

b) ID #26496

c) ID #20726

d) ID #23194

e) ID #12391



f) ID #5046

g) ID #34492

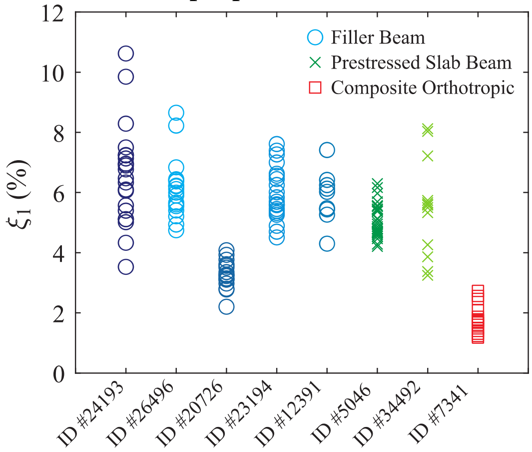
h) ID #7341

Figure 3: Studied bridges form the German railway network.

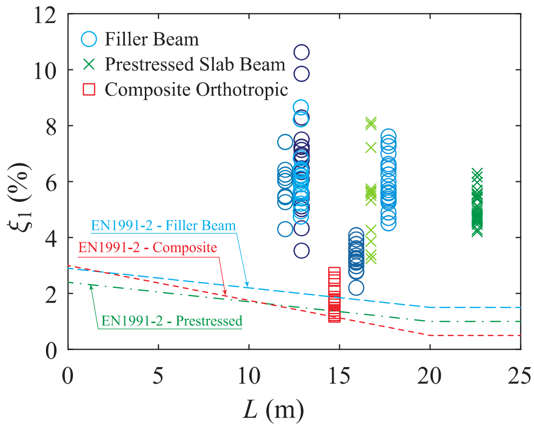
5 Results

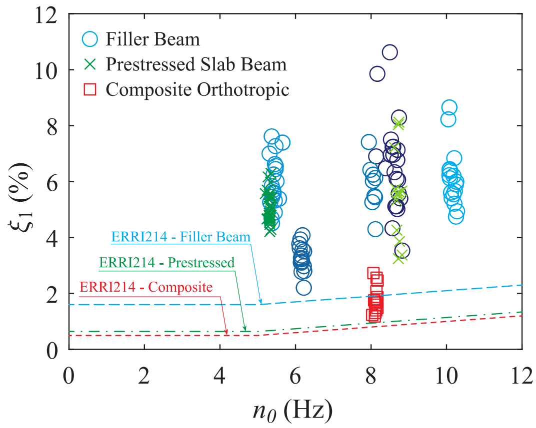
The present section presents the damping estimations for the 8 bridges described in Section 4 taking into consideration the procedure specified in Section 3. Naturally, the number of studied bridges at this point is still low, therefore, the results presented here are still not enough to take final conclusions and proposed the final normative recommendations for damping.

Figure 4a presents the estimated damping coefficients from the fundamental mode of vibration of each bridge ξ_1 considering all the time-series available and without applying step 6) described in Section 3 to disregard estimated values obtained from time-series that are not mainly controlled by the first mode of vibration. This figure also shows the damping values as function of the span L (Figure 4b) superimposed over the normative criterion specified in EN 1991-2 [1], as well as function of the fundamental natural frequency of the bridge n_0 (Figure 4c) together with the NS proposal presented in ERRI D 214/RP3 [2]. As expected, a large scatter can be observed in most of the bridges, but the lower bound of the damping estimations generally agrees with the normative proposal.



a) Damping in each bridge





b) Damping as function of span

c) Damping as function of frequency

Figure 4 – Estimated damping in the studied bridges.

The major goal of the WP4 from the InBridge4EU project consists of understanding the factors that may influence the damping and, consequently, evaluate if some of the estimated values may be disregarded to decrease the scatter and define more objective damping criteria to be adopted in the standards. One of the factors that may be responsible for the typically observed scatter in damping values is the amplitude of the acceleration response used to estimate this damping. To understand if this is the case for these group of bridges, Figure 5 depicts the same damping values previously plotted in Figure 4, but as function of the amplitude of the bridges' free decay responses considering only the fundamental mode of vibration obtained through a bandpass filter applied around the n_0 frequency. It can be observed, there is a trend for the dispersion to decrease with the amplitude of the response. However, more values obtained from more bridges should be analysed to get a clearer idea about the influence of this factor.

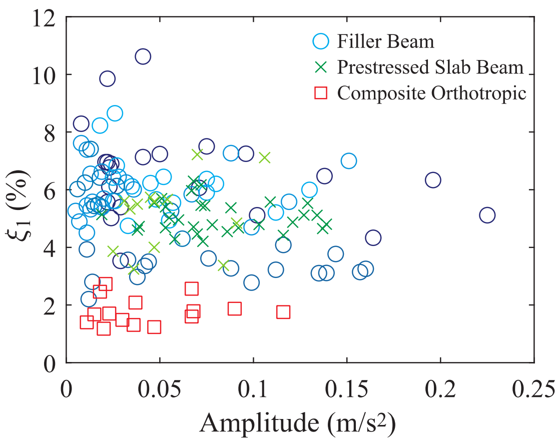
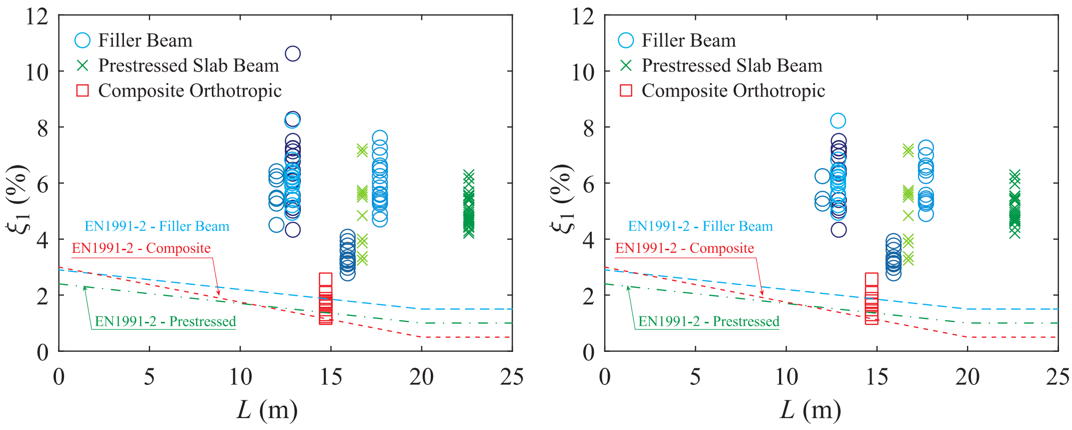


Figure 5 – Estimated damping in the studied bridges as function of the acceleration response amplitude considering only the fundamental mode of vibration.

As mentioned in Section 3 and in the ERRI D 214/RP3 [2], damping has a particular effect in the acceleration response at resonance and barely affects it outside the resonance zones. Therefore, damping values estimated based on measured responses that are clearly outside the resonance zone should not be considered in the definition of a normative criterion. However, the identification of resonance scenarios in field measurements is not simple, since it depends on a specific combination of train speed and regular axle spacing that is not always achieved. To overcome this issue, the present work defines a criterion to disregard some of the damping estimations based on the fact that, at resonance, the bridge response is majorly governed by the fundamental mode of vibration of the bridge. By taking this approach in consideration, the contribution of the fundamental mode for the free decay acceleration response used for each damping estimation has been determined based on Eq. (3). Figure 6a presents the same damping values previously depicted in Figure 4, but disregarding the values obtained from responses whose main contribution did not come from the fundamental mode of the structure (Scenario A). Moreover, Figure 6b analyses how the contribution of the fundamental mode influences the damping by disregarding values obtained through responses whose contribution of the fundamental mode is less than 50% (Scenario B). It can be observed that some of the disregarded values were those with lower damping (e.g. the lower bound of bridge ID #20726 is no longer close to the normative criterion), making the lower bound defined by the normative criterion specified in EN 1991-2 [1] even more conservative. Exception to the composite orthotropic through bridge ID #7341, whose lower damping value coincides with the normative curve even when disregarding the estimations based on responses not governed by the fundamental mode of vibration. More bridges should be analysed in the future to identify more clear trends.



a) Disregarding values from responses not majorly governed by the fundamental mode (Scenario A)

b) Disregarding values from responses with contribution of the fundamental mode less than 50% (Scenario B)

Figure 6 – Estimated damping as function of span disregarding values arising from responses with low contributions from the fundamental mode.

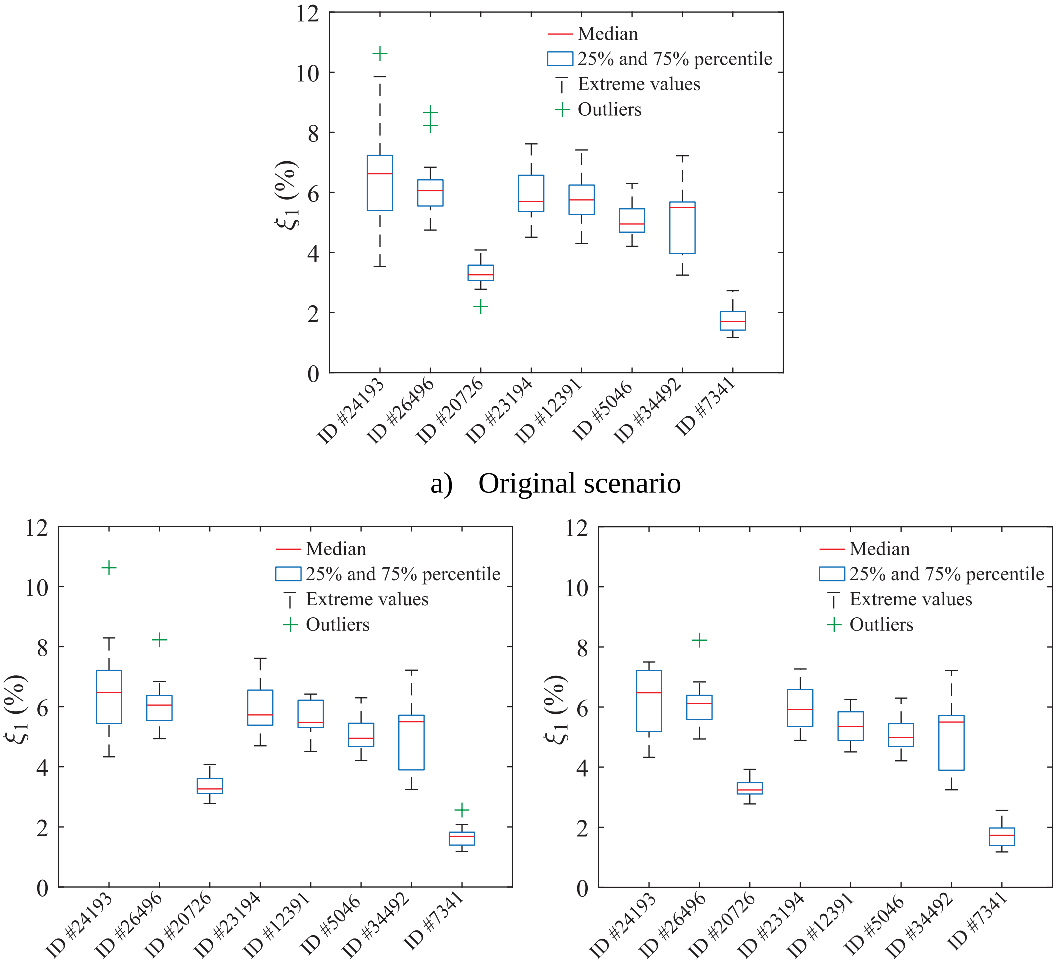
Finally, a statistical evaluation of each of the three analysed scenarios, namely considering the original damping values depicted in Figure 4 and considering the data treatment described above and plotted in Figure 6 (Scenarios A and B), is presented in Figure 7 through a boxplot graphic (the central mark indicates the median, the bottom and top edges of the box indicate the 25th and 75th percentiles, respectively, and the whiskers extend to the most extreme data points not considered outliers, and the outliers are plotted individually using the '+' marker symbol). It can be observed that, by disregarding the damping values justified above in the scenarios A and B, the scatter decreases substantially, leading to more clear damping values. Further studies, however, should be carried out in the future considering more bridge types and spans to extend the conclusions.

6 Conclusions and Contributions

The present paper focuses on the estimation of damping coefficients of railway bridges that will be used in the future, within the European project InBridge4EU, to revise the current normative criterion stipulated in the EN1991-2. The case studied bridges consist of 8 simple-supported bridges belonging to the German railway network, including 5 filler beam, 2 prestressed slab beam and 1 composite orthotropic through bridges.

Damping estimations have been carried out through the SSI-COV method. In a first stage, all the bridge acceleration responses, more precisely their fee decay period, have been used to estimate the fundamental mode damping regardless the importance of this mode in the global response. By analysing the results, it was possible to observe a large scatter in the results and a lower bound of the damping estimated coefficients very close to the normative values. Moreover, an analysis of the influence of the free decay amplitude in the damping value has also been carried out, pointing to a decrease in the dispersion when higher amplitudes are used. Nevertheless, more bridges should be analysed to reinforce this conclusion.

In a second stage, knowing that damping has a particular influence within resonance zones and that under these circumstances the response is mainly characterized by the fundamental mode of vibration, a second analysis of the results has been performed with two scenarios: i) a scenario A, in which the damping values obtained from responses whose main contribution did not come from the fundamental mode of the structure have been disregarded; and ii) a scenario B, where the responses whose contribution of the fundamental mode was less than 50% have been discarded. It was possible to observe that, by disregarding these values obtained through responses that majorly differ from typical resonant ones, the lower bound of the estimated damping coefficients is no longer close to the normative values, pointing to the possibility of a future revision of the normative criterion to increase design damping values and, consequently, avoid overconservative analysis. More bridges should be analysed in the future, however, to identify more clear trends.



a) Original scenario

b) Scenario A

c) Scenario B

Figure 7 – Statistic indicators for damping through boxplot graphic.

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