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# MODELLING STRATEGIES FOR THE SEASONAL EFFECTS ON DYNAMIC BRIDGE PARAMETERS

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**Key words:** Bridge Dynamics, Natural Frequency Variation, Seasonal Temperature.

**Abstract.** *This paper proposes two stochastic approaches for numerical prediction of the effect of seasonal temperature changes on dynamic bridge parameters. The first simpler approach, appropriate for bridges modeled as Euler-Bernoulli beam, assumes that the fundamental bridge frequency is a bilinear (or multi-linear) function of the environmental temperature, specified as random variable. In the second more sophisticated approach used in elaborate finite element bridge models, the seasonal frequency change is related to the frost depth in subsoil and ballast (in case of railway bridges). Here it is assumed that the unfrozen and the fully frozen condition, both modeled as stochastic variables, are correlated with the daily minimum temperature at the ground. Monte Carlo simulation of a case study railway bridge shows that this environmental model captures qualitatively the seasonal temperature changes of the natural bridge frequencies, as observed in monitored bridges.*

## 1 INTRODUCTION

In structural dynamics the modal structural parameters, i.e., natural frequencies, mode shapes and damping coefficients, are commonly considered as constant quantities. This implies that the structural stiffness remains constant throughout the life cycle of the building.

It has, however, been recognized that changes of the environmental conditions may modify the dynamic behavior of certain structures. For instance, under severe earthquake excitation non-structural elements such as in-fill walls or partition walls may fail, reducing significantly the lateral stiffness of the building. In the long term, the structure may be subject of environmental induced corrosion, which gradually decreases the stiffness of structural components. Sedimentary depositions (for instance, in the ballast of railway bridges, or at the supports) may lead to a stiffening of the structure. In some buildings also wind (Xu et al.[1]) and humidity (Moser and Moaveni[2]) may affect the stiffness. In particular, the natural frequencies of bridge structures are vulnerable to seasonal temperature changes. For instance, Moser and Moaveni[2] observed during a 16 weeks monitoring period of a footbridge variations of the first natural frequencies between 4% and 8% in the air temperature range from −14 °*C* to 39 °*C*. While above freezing the effect of the environmental temperature on the natural frequencies is small, a drop of temperature below freezing increases significantly - and in some cases even stepwise - the natural frequencies. Peeters and De Roeck[3] report on a 17% maximum variation of the first natural frequencies of a highway bridge during a one-year monitoring campaign, and Gonzalez et al.[4] found an increase of 12% of the first and an increase of 20% of the second natural frequency of a ballasted single-span railway bridge if temperature drops below the freezing point of water. This behavior can be attributed to the increase of stiffness through the formation of ice, frozen water in the ballast, ground, abutments, and supports, and it is confirmed by other studies such as Alampalli[5]. In contrast to the bridge stiffness (and consequently the natural frequencies), seasonal temperature variations do, however, not change noticeably the damping behavior, as reported by Moser and Moaveni[2]. Frequency changes due to material deterioration (i.e. stiffness reduction) are in general lower than temperature induced frequency variations, but may be according to Alampalli[5] also in the order of 3% to 8%.

Neglecting the variation of natural frequencies may have a grave effect on the numerically predicted structural safety. For instance, tuned mass dampers aimed at protecting a building against prohibitively large vibration amplitudes may become detuned, and thus, loosing much of their efficacy. Other examples are railway bridges, where resonance speeds may be shifted to operating speeds of high-speed trains, thus exciting the structure to unexpected large vibrations. Consequently, for a reliable prediction of the failure probability of the serviceability limit state respectively the ultimate limit state of affected buildings, the environmental impact on the dynamic structural parameters must be considered. However, there is a lack of appropriate models that are able to capture this effect in numerical analyses.

In an effort to overcome this shortage, based on previous accomplishments of the authors (Salcher et al.[6,7], Salcher[8]), in the present contribution two stochastic approaches are proposed, aiming at modeling the seasonal variation of natural frequencies and mode shapes of ballasted railway bridges for numerical analyses.

## 2 OBSERVED ENVIRONMANTAL EFFECTS ON BRIDGE PARAMETERS

As an example presented in Gonzales et al.[4], in Figure 1 the first vertical bending frequency and the first torsional frequency of a simply supported single-span ballasted railway bridge located in Skidträsk, Sweden, are plotted against the environmental temperature $T$. The natural frequencies have been identified from vibration data recorded during a one-year measurement campaign. It is readily observed that, globally, with dropping temperature the frequencies become larger. While at temperatures above zero degree Celsius the dependence of the frequencies on $T$ is small, at temperatures close to the freezing point of water, $T = 0\ °C$, a significant frequency discontinuity is observed. This behavior can be attributed the stiffness change of ballast and subsoil due to phase shift of water from liquid to solid and vice versa. In the considered bridge, according to Gonzales et al.[4], the vertical bending mode is more affected by the subsoil stiffness, while the frozen ballast contributes more to the torsional stiffness of the bridge structure. The first vertical natural bending frequency is at temperatures below the freezing point on an average about 12% larger than at positive temperatures. The first torsional frequency shows even a difference of about 27%. Similar temperature dependent discontinuous behavior of the natural frequencies of bridges has been detected by Moser and Moaveni[2] and Peeters and De Roeck[3], among others. In some bridges the frequency-temperature relation is bilinear with a kink at the freezing point, while in others this relation shows a step-wise discontinuity close to zero degree Celsius (Figure 1).

In an alternative representation, Figure 2 depicts the natural frequencies and the corresponding environmental temperature of the previously discussed bridge located in Skidträsk, Sweden, as a function of the season. This representation reveals that there is no direct relation between the environmental temperature and the natural frequencies. While the temperature shows a large fluctuation throughout the year, the frequencies remain at two more or less constant levels, the higher one from the end of November to April, and the lower one in the remaining period of the year. Based on this observation, Gonzales et al.[4] conclude that the seasonal frequency shift depends on the frost depth in subsoil and ballast, and it is not a direct function of the environmental temperature.

From this discussion it becomes obvious that modeling of the seasonal impact on dynamic bridge parameters is not straightforward.

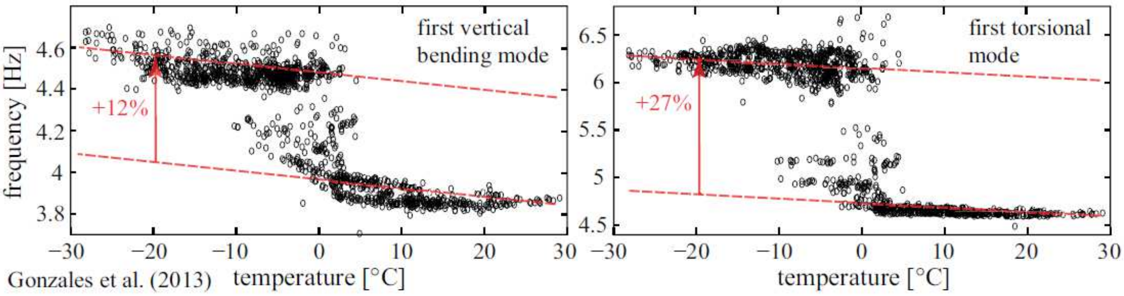


Figure 1: Natural frequency-temperature relationship of a simply supported ballasted railway bridge located in Skidträsk, Sweden. Modified from Gonzales et al.[4].

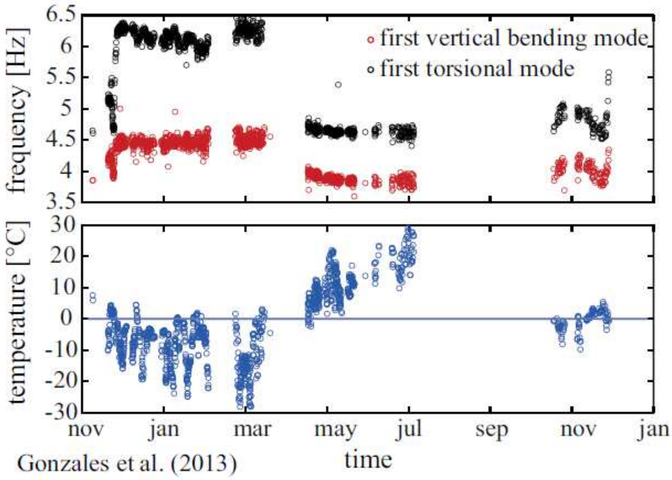


Figure 2: Natural frequencies identified from one-year monitoring of a ballasted railway bridge located in Skidträsk, Sweden, and corresponding environmental temperature. Modified from Gonzales et al.[4].

## 3 BLACK BOX APPROACH FOR SEASONAL EFFECTS ON BRIDGES

The in several bridges observed, in essence, bilinear natural frequency-seasonal temperature relationship is the basis of a phenomenological *black box* environmental model, appropriate for simple bridge structures that are approximated as Euler-Bernoulli beam (Salcher et al.[6]). In this approach the fundamental bridge frequency $f_1$ is assumed to be a bilinear function of the daily mean temperature $T$, i.e., $f_1(T) = f_{T0} + k(T)\left(T - T_0\right)$, $k(T) = k_1 \,\forall\, T \leq T_0$ and $k(T) = k_0 \,\forall\, T > T_0$, as shown in Figure 3. Deterministic input parameters that need to be defined are slopes $k_1$ and $k_0$ (with $k_1 > k_0$) of the linear branches, the initial fundamental frequency $f_{ini}$ at temperature $T_{ini}$, and temperature $T_0$ (close to 0 °*C*) at the kink of this function. From these data the fundamental frequency $f_{T0}$ at $T_0$ is deduced. In numerical simulations, bending stiffness $EJ(T)$ is considered as temperature dependent variable, derived from the fundamental frequency $f_1(T)$ of the Euler-Bernoulli beam as $EJ(T) = f_1^2(T)\rho A / \alpha_1^2$. $\alpha_1$ is a parameter depending on the boundary conditions of the beam model. For a simply supported beam $\alpha_1 = \pi / (2L^2)$.

The daily mean temperature $T$ is considered as a random variable, specified by a Gaussian or extreme value distribution (Salcher[8]). The distribution is calibrated to temperature data recorded close to the site of the bridge.

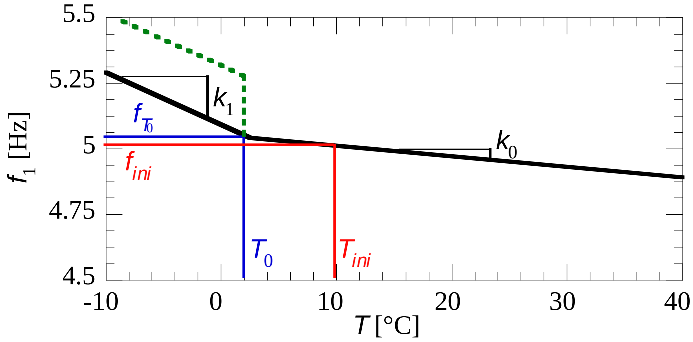


Figure 3: Bilinear natural frequency-temperature relation of a black box environmental model for beam bridges.

It should be noted that this approach is not limited to a bilinear fundamental frequency-temperature function, but any relation can be prescribed. As an example, in Figure 3 at temperature $T_0$ a stepwise discontinuity is introduced, as it has been observed in some monitored bridge structures. That is, in the temperature range up to $T_0$ the dashed line governs the $f_1$-$T$ relation, and in the temperature range $T > T_0$ frequency $f_1$ follows the linear function with slope $k_0$.

## 4 STOCHASTIC MODELING OF SEASONAL EFFECTS ON BRIDGES

The approach based on a bilinear (respectively multi-linear) natural frequency-temperature relation cannot be applied to a more sophisticated two- or three-dimensional finite element model of a bridge structure, because no global stiffness parameter (such as the bending stiffness in a beam) does exist. Therefore, for finite element models a more elaborate stochastic approach is proposed to describe the seasonal impact on the dynamic parameters, related to the frost depth of the adjacent subsoil and (in case of railway bridges) the ballast.

As in the previous approach, the daily mean temperature $T$ is a random variable with suitable distribution, calibrated to temperature data recorded close to the bridge site. The frost depth, which has the most distinct and instant influence on the seasonal frequency change, is modeled simplified, defined by the limits states fully frozen respectively unfrozen. It is assumed that the fully frozen state, where up to the maximum frost depth all water is in the phase of ice, is attained at a daily minimum temperature measured at ground level, $T_g$, less than 10 °$C$ (i.e., $T_g < 10°C$). In the unfrozen state, $T_g$ is assumed to be equal or larger than -1 °$C$ (i.e., $T_g \geq -1°C$), implying that freezing is initiated if $T_g$ drops below $-1°C$. The fully frozen state is governed by random temperature variable $T_1$, defined by the conditional distribution of the daily mean temperature $T$ with respect to the daily minimum temperature at ground level $T_g < 10°C$: $\varphi_{T1}(T \,|\, T_g < -10°C)$. Random temperature variable $T_0$ for the unfrozen state is described by the conditional distribution $\varphi_{T0}(T \,|\, T_g < -1°C)$. $\varphi_{T1}$ and $\varphi_{T0}$ are fitted to temperature data of the bridge site. Thus, in this model the two limit states of the frost depth are described probabilistically as a function of temperature data only. Transitional phases between the fully frozen and the unfrozen state are linearly interpolated. Since in the fully frozen state the temperature must be lower than at freeze initiation, the transition from fully frozen to unfrozen condition follows a step function if $\varphi_{T1} \leq \varphi_{T0}$.

Fully frozen ballast is stiffer than in the unfrozen condition, approaching Young's modulus of ice. Thus, in the fully frozen state to the ballast Young's modulus of ice is assigned, modeled as a random variable. The material properties of ice vary in a quite large range because they depend on ice formation, temperature, temperature changes, humidity, load speed, etc. (Hobbs[9]). In the proposed environmental model, Young's modulus of the ballast is modeled as a Gaussian distributed random variable with a mean of 9.45 GPa and a coefficient of variation of 0.05 GPa (see Hobbs[9]). In the fully frozen condition the stiffness of the modeled subsoil domain is increased proportionally according to the increase of the ballast Young's modulus. The unfrozen state is defined by the unmodified (in some circumstances random) variables of the ballast and subsoil.

If the bridge is built of steel components, the effect of the surrounding air temperature on Young's modulus of steel, $E_{sT}(T)$, is captured through a linear temperature dependent function as proposed in ASME[10], i.e., $E_{sT}(T) = E_s - 1.67 \times 10^8 (T - T_{E0})$. Reference value $E_s$ corresponds to Young's modulus of steel at temperature $T_{E0} = 20\,°C$.

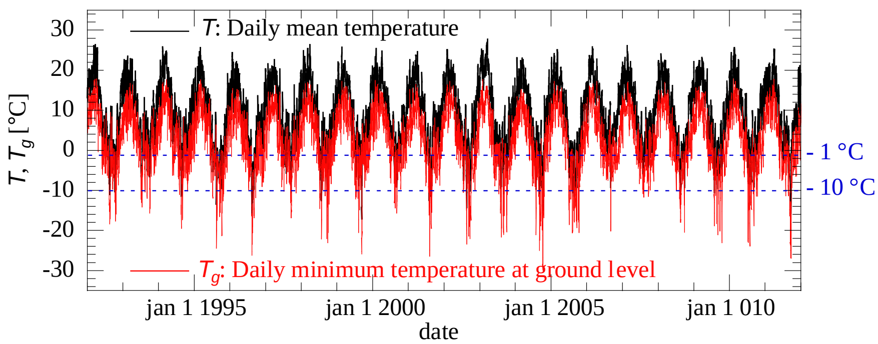


Figure 4: Time history of the daily mean temperature $T$ and the daily minimum temperature $T_g$, recorded at the ground recorded at Munich Airport, Germany. Modified from Salcher et al.[7].

## 5 APPLICATION

In an example application the Munich Airport, Germany, is selected as location of a bridge structure to be studied, internationally known and representative for the climate at the latitude of Central Europe. Public available temperature data for this particular site (DWD[11]) are used to define the distribution of the daily mean temperature $T$, which serves both for the black box and the more elaborate stochastic seasonal model as random variable. In Figure 4 the black graph represents the time history of the daily mean temperature $T$ measured at a height of 2 m above ground in the 20-year period from 1992 to 2012. The histogram shown in Figure 5(a) is the corresponding relative frequency of $T$, and the gray graph in Figure 5(b) the cumulative frequency of $T$. Now a suitable distribution is selected to describe appropriately the statistics of $T$ as random variable. In Figure 5(a) the dashed red line corresponds to a Gaussian distribution fitted to the histogram. After testing the assumption of a Gaussian distribution for the data representation using a $\chi^2$ and a Lilliefors test, this hypothesis has been rejected at a significance level of 5%. The extreme value distribution shown in Figure 5 by a black graph, and with mean of 9.00 °$C$ and coefficient of variation (CV) of 1.01 °$C$, is, thus, a more appropriate representation of temperature data $T$.

For the second proposed seasonal model, in the subsequent step the conditional distributions $\varphi_{T1}(T\,|\,T_g < -10\,°C)$ and $\varphi_{T0}(T\,|\,T_g < -1°C)$ are derived. In Figure 4 additionally to $T$ also the corresponding time history of the daily minimum temperature at ground, $T_g$, (i.e., measured at 0.05 m above ground level) is depicted in red. Dashed horizontal lines indicate the limit temperature levels $-1\,°C$ and $-10\,°C$, defining the unfrozen and the fully frozen ballast. The two histograms shown in Figure 6 represent the distribution of the daily mean temperature $T$ of those days in the 20-year observation period, where the daily minimum temperature at ground $T_g$ was less than $-10\,°C$ respectively $-1\,°C$. These histograms can be accurately approximated by conditional Gaussian distributions $\varphi_{T1}$ (mean -6.33 °$C$, CV 0.54 °$C$) respectively $\varphi_{T0}$ (mean 0.69 °$C$, CV 7.38 °$C$), as depicted in Figure 6. Based on these distributions, Figure 7 shows the freezing condition of 100 random samples with respect to the daily mean air temperature $T$ determined in a Monte Carlo simulation. The transition from fully frozen to unfrozen substruction is linear, as assumed in the model. Vertical lines indicate that in some cases freezing is initiated at the same temperature as the fully frozen state is attained. This model does, however, not allow freeze initiation at temperatures lower than for the maximum frost depth.

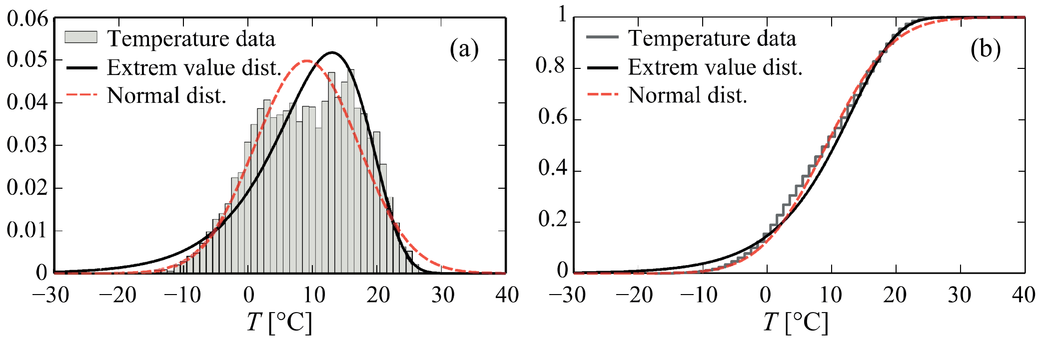


Figure 5: (a) Histogram of the daily mean temperature $T$ and corresponding fitted distributions. (b) Cumulative frequency and corresponding cumulative distribution functions. Modified from Salcher[8].

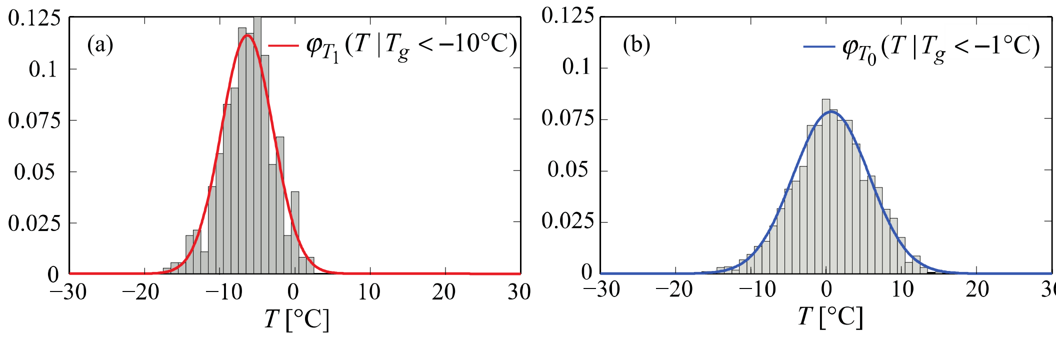


Figure 6: Conditional histograms of $T$ for given $T_g$, and fitted normal distributions. Munich Airport, Germany. (a) $T_g$ < -10 °C (b) $T_g$ < -1 °C. Modified from Salcher[8].

A simply supported single-span ballasted railway bridge located close to the Munich Airport, Germany, is considered as case study object to test the proposed stochastic environmental model. The steel bridge with cross-section depicted in Figure 8(a), span $L$ =16.48 m, and width $b_1$ = 4.67 m carries a single track. The fundamental frequency $f_1$ of this bridge at temperature $T$ = 9.0 °$C$ is 9.28 Hz. The detailed geometry of structure and track, and the material parameters of its components are complied in Salcher[8]. A full three-dimensional finite element model of the bridge with six degrees of freedom per node is built. The rails resting on the bridge and the adjacent subsoil (with excess length of 5.2 m at both sides) are discretized by means of Euler-Bernoulli finite beam elements. Linear elastic springs support the rails in the domain outside of the bridge to capture the behavior of the ballast and subsoil properties. For details on the numerical model it is referred to Salcher[8].

Based on the proposed environmental model with random variables specified before, a direct Monte Carlo simulation with 1000 random bridge samples has been performed to reveal the temperature induced dispersion of the natural bridge frequencies. Figure 8(b) shows the resulting histogram for the first and the second natural frequency. The dispersion left of the mean frequency results mainly from uncertain material parameters of the structure, while the lower densities larger than the mean frequency can be led back to the random environment model. Subsequently, the computed frequencies are plotted against the corresponding daily mean temperature $T$, resulting in the scatter plot shown in Figure 9. These outcomes prove that the proposed stochastic environmental model captures qualitatively the virtually stepwise change of the natural frequencies around the freezing temperature of water.

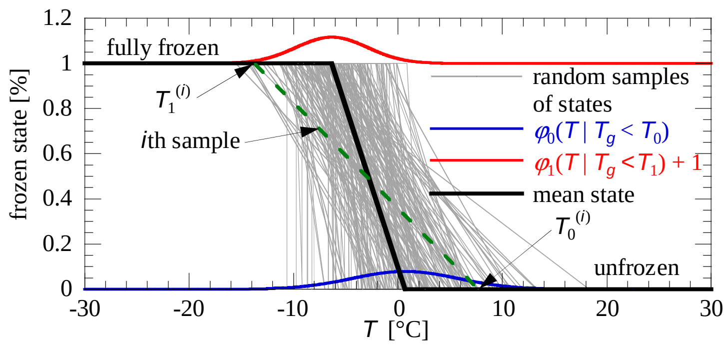


Figure 7: Frozen state as a function of daily mean air temperature for 100 random samples, based on temperature data recorded at Munich Airport, Germany. Modified from Salcher et al.[7].

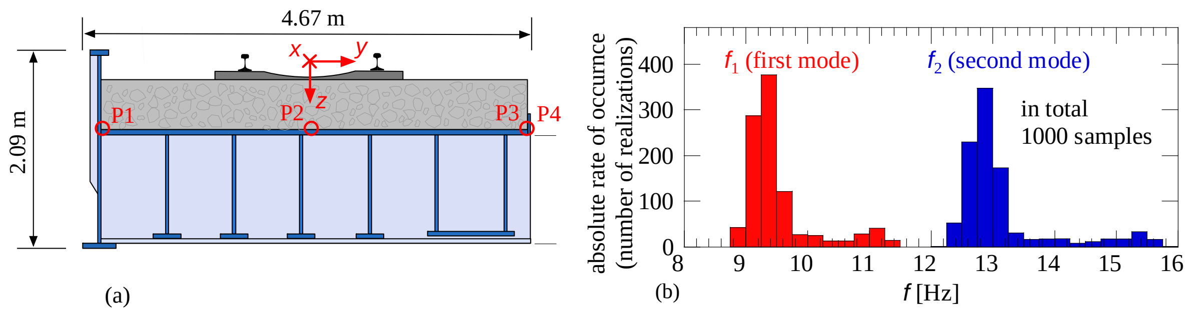


Figure 8: (a) Cross-section of the case study bridge. (b) Distribution of the first and the second natural frequency of 1000 bridge samples due to seasonal temperature variations. Ballasted railway bridge located at Munich Airport. Modified from Salcher[8].

## 6 SUMMARY AND CONCLUSIONS

Two approaches for capturing in numerical simulations the seasonal effect on natural frequencies and mode shapes of bridge structures have been described. In the first black box-like model an appropriate relation between fundamental frequency and environmental temperature has been established. This approach can be used for reliability assessment of bridges, based on Euler-Bernoulli beam models. The second approach relates the frost depth in subsoil and ballast and the natural frequency variation in a stochastic manner. Two limit states of the frost depth, i.e. the fully frozen state and the frozen state, are expressed in terms of random variables with conditional distributions of the daily mean air temperature for defined thresholds of the daily minimum temperature recorded at ground level. Application of this approach to a ballasted railway bridge shows that the predicted scatter of natural frequencies with respect to the environmental temperature reflects qualitatively the stepwise scatter around the freezing point of water, as it has been observed in monitored bridges.

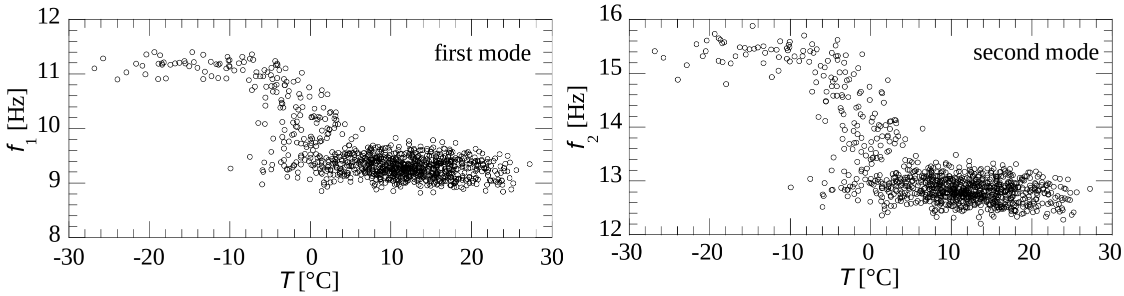


Figure 9: First and second natural frequency of 1000 bridge samples plotted against temperature *T*. Ballasted railway bridge located at Munich Airport, Germany. Modified from Salcher et al.[7].

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