Journal of Physics:
Conference Series

PAPER • OPEN ACCESS

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To cite this article: Y Wang *et al* 2025 *J. Phys.: Conf. Ser.* **3071** 012005

Journal of Physics: Conference Series **3071** (2025) 012005 doi:10.1088/1742-6596/3071/1/012005

FEM-based study of temperature-induced changes in a railway bridge in cold regions

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Abstract. Natural frequencies of engineering structures often vary with environmental temperature changes. For bridges, these variations can affect structural performance and potentially compromise the safety of pedestrian and vehicular traffic. The extent of this impact depends on bridge type and boundary conditions. One simply supported steel–concrete composite railway bridge in northern Sweden, where temperatures range from –40 °C to 30 °C, is investigated in this study. Using finite element analysis (FEA), the effects of temperature-induced changes in concrete properties, boundary constraints, and ballast stiffness on the bridge's natural frequencies and modes are examined. Results show that: (1) As temperature decreases, the first, second and third natural frequencies increase by 12.41%, 20.08% and 16.92%, respectively; (2) the frequency–temperature relationship exhibits a trilinear behavior; and (3) temperature variations have a more pronounced effect on torsional modes than on bending modes. This study attempts to provide advice for the scheme and maintenance of railway bridges in cold regions.

1. Intruduction

Bridges are critical components of transportation infrastructure, ensuring connectivity and economic development. However, environmental factors such as temperature fluctuations pose challenges to their structural integrity. Changes in temperature can alter material properties, affect boundary conditions, and influence modal parameters, ultimately affecting the natural frequency of bridges.

Establishing a comprehensive and effective structural health monitoring (SHM) system provides substantial social and economic benefits by ensuring structural safety. Engineers use SHM data to detect potential damage and evaluate overall structural conditions [1]. Common structural health monitoring systems come in different types based on response, such as those based on vibration response, those based on strain response, and those assisted by artificial intelligence. Vibration-based SHM focuses on vibration parameters, such as natural frequency, modal shape, and damping ratio, to detect structural damage or changes in state.

Among the many factors that influence bridge modal parameters, temperature is especially critical. Numerous existing studies and cases have shown that temperature has a important influence on the modal parameters of bridge structures, even much greater than changes caused by structural damage. When analyzing the health status of bridges, this may mask the true changes in modal frequencies caused by certain structural damages [2]. This makes it not easy to distinguish whether changes in modal frequency of bridge are caused by structural damage or temperature variations. Therefore, it is essential to study the effect of temperature on natural frequency.

Many researchers have studied the changes in the natural frequency of bridge under temperature changes. For instance, Zabel et al. [3] conducted field tests and analysis on a 9-meter span simply supported railway bridge located in northern Germany. The study found that when ambient temperature varied from -3 ℃ to 21 ℃, the first, second, third natural frequencies of the bridge decreased by 23%, 25.5%, and 24.4%, respectively, with no correlation observed between damping ratio and temperature changes. Liu and Dewolf [4] analyzed five-year experimental vibration data and finite element simulations of a continuous rigid-frame bridge with spans of 58 + 88 + 88 meters. It was found that within the temperature range of -1 ℃ to 38 ℃, the first natural frequency decreased by 10.92%, the second by 10.92%, and the third by 9.36% as the temperature increased. Furthermore, the first two modes were bending-dominated, while the third was torsional, exhibiting smoother frequency changes with temperature, a finding that implies higher modes can be less sensitive to temperature than lower modes.

Most existing research examines temperature ranges of around -10 ℃ to 35 ℃ [3-9]. Relatively fewer studies focus on bridge structures in cold regions (environmental temperature below -20 ℃). Therefore, this study investigates a railway bridge located in the northern Sweden, where temperatures range from -40 ℃ to 30 ℃. A combination of theoretical analysis and finite element simulations is used to determine the temperature-induced changes in the bridge’s modal behavior.

2. Theoretical analysis

2.1. Factors affecting natural frequency under temperature changes

As reported in previous research [10], the natural frequencies of simply supported beams can be calculated as

$$f_n = \frac{n^2\pi}{2}\left(\frac{Ebh^3}{12ml^3}\right)^{1/2} \tag{1}$$

where f_n is the n-th natural frequency, l is length, b is width, and h is the height of the beam. m is the mass per unit length, and E is the elastic modulus of the beam material. For the first vertical mode, $n = 1$.

Taking the differential of equation (1) yields the rate of change of the natural frequency:

$$\frac{\delta f_n}{f_n} = \frac{1}{2}\frac{\delta E}{E} + \frac{1}{2}\frac{\delta b}{b} + \frac{3}{2}\frac{\delta h}{h} - \frac{3}{2}\frac{\delta l}{l} \tag{2}$$

where δE, δl, δb, and δh represent changes in the elastic modulus, length, width, and height, respectively. The thermal expansion coefficient of concrete, α_t, and its temperature-dependent coefficient of elastic modulus, α_E, are defined as:

$$\alpha_t = \frac{\delta l}{L \times \delta t}, \qquad \alpha_E = \frac{\delta E}{E \times \delta t} \tag{3}$$

Let δt denote the temperature change, then:

$$\frac{\delta E}{E} = \alpha_E \, \delta t, \qquad \frac{\delta b}{b} = \alpha_t \, \delta t, \qquad \frac{\delta h}{h} = \alpha_T \, \delta t, \qquad \frac{\delta l}{l} = \alpha_t \, \delta t \tag{4}$$

Substituting equation (4) into equation (2) can obtain:

$$\frac{\delta f_n}{f_n} = \frac{1}{2}(\alpha_t + \alpha_E)\delta t \tag{5}$$

According to this relationship, the effect of geometric dimensions and concrete elastic modulus changes is governed by α_t and α_E. Because $\alpha_E \approx -4.31 \times 10^{-3}$ °C^{-1}, and $\alpha_t \approx 1.0 \times 10^{-5}$ °C^{-1}, changes in the elastic modulus dominate over geometric changes for reinforced concrete beams.

In addition, when snow accumulates on the ballast and subsequently melts and refreezes, it can change the ballast stiffness and effectively freeze the ballast to the bridge and its surroundings, thereby modifying the boundary conditions.

This study focus on three factors that significantly affect a bridge's natural frequencies with temperature: (1) changes in the concrete elastic modulus; (2) changes in ballast stiffness; and (3) changes in boundary conditions due frozen ballast.

2.2. Finite element parameter settings

Based on the discussion above, three parameters were identified that may significantly affect the natural frequency of the bridge under temperature changes: (1) concrete elastic modulus, (2) ballast stiffness, and bridge boundary constraints influenced by ballast freezing.

According to fib Model Code 2010 [11], the elastic modulus of concrete at temperature T (°C) can be approximated by:

$$E_T = E_{20} \cdot (1.06 - 0.003\mathrm{T}) \tag{6}$$

where E_{20} represents the elastic modulus of concrete at 20 °C. Equation (6) is applicable to concrete C20 - C50. Figure 1(a) shows how E_T changes with temperature.

When the temperature is low, melted snow will freeze with the ballast, changing the stiffness of the ballast and thus altering the overall stiffness, affecting the natural frequency of the bridge. According to [12], when the temperature is above 0 °C, the ballast maintains an elastic modulus of approximately 550 MPa. However, as temperature drops below 0 °C, any meltwater or slush within the ballast can freeze, drastically increasing its effective stiffness. Below the freezing point, the elastic modulus of the ballast can reach up to 1750 MPa (Figure 1b).

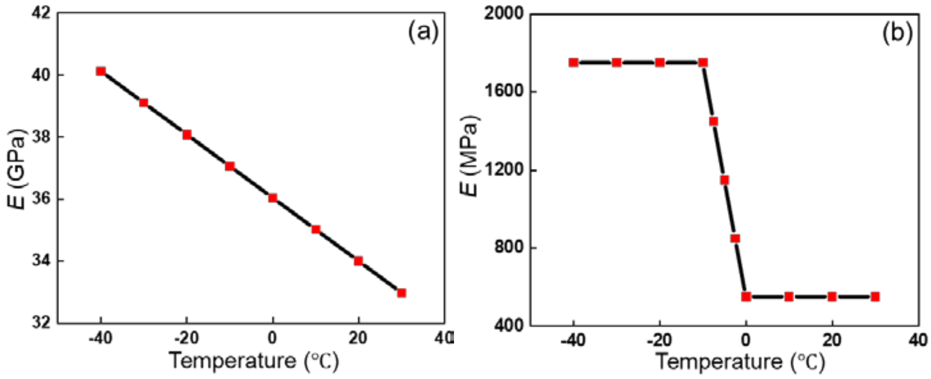


Figure 1. The variation of elastic modulus with temperature. (a) Concrete, (b) Road ballast.

When the ballast freezes, the ballast on the bridge will freeze tightly with the ballast outside the bridge, which will have a certain impact on the boundary conditions of the bridge. To capture this effect, the model extends the ballast and rails longitudinally on both sides of the bridge, thereby simulating the additional restraining effects.

3. Numerical modeling

3.1. Case description

The bridge in this study is a simply supported steel-concrete composite railway bridge located in northern Sweden (Figure 2). The bridge structure is composed of lower steel beams and upper reinforced concrete deck with railway ballast on the top surface.

Figure 2. A railway bridge located in northern Sweden.

The total length of the bridge structure is 21.80 m, with a width of 4.50 m, and it is covered by UIC 60 rails. The lower steel structures consist of two variable cross-section I-girders with the length of 21.60 m beam connected by steel batten plates. The top of the steel girders is riveted to the concrete deck. One abutment is hinged, and the other permits longitudinal displacement. The elastic modulus of concrete is E_{cm}=34 GPa, the standard value of axial compressive strength f_{ck}=35 MPa, and the density is 25 kNm^{-3}. The elastic modulus of steel is E_s=200 GPa, and the density is 78.5 kN·m^{-3}. The dimension of the bridge superstructure is shown in Figure 3.

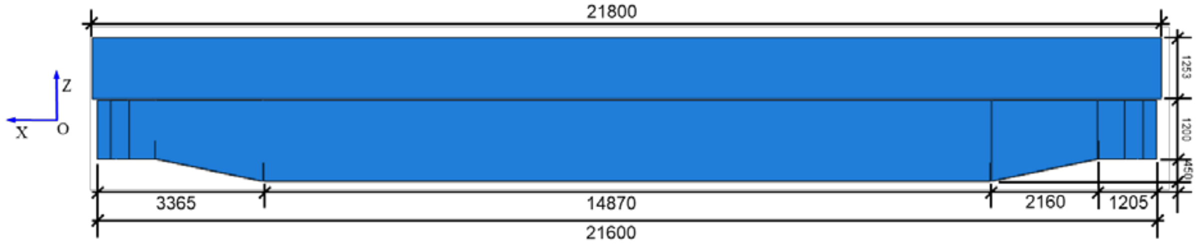


Figure 3. Dimension of bridge superstructure (Unit: mm).

3.2. Finite element modeling

A finite element model of the bridge was constructed to investigate how its natural frequencies respond to temperature variation. The concrete deck was modeled with solid (continuum) elements. The ballast, considered as a homogenized medium, was also discretized with solid elements. A "tie" connection was used between the ballast and the concrete deck. The UIC60 rail was likewise modeled using solid elements, extended and connected to the ballast with a tie to prevent relative slip. The steel girders and their connecting batten plates were modeled using shell elements. The girders were then "tied" to the lower surface of the concrete deck. To simulate boundary effects due to frozen ballast, the ballast and rails were extended by one bridge length (21.8 m) on both sides, with the bottom of the extended ballast constrained to remain fixed.

All continuum elements were discretized with an 8-node linear hexahedral element (C3D8R), whose mesh size is 100 mm. The steel girders were discretized with a 4-node shell element (S4R), whose mesh size is 20 mm. The final FE mesh is shown in Figure 4.

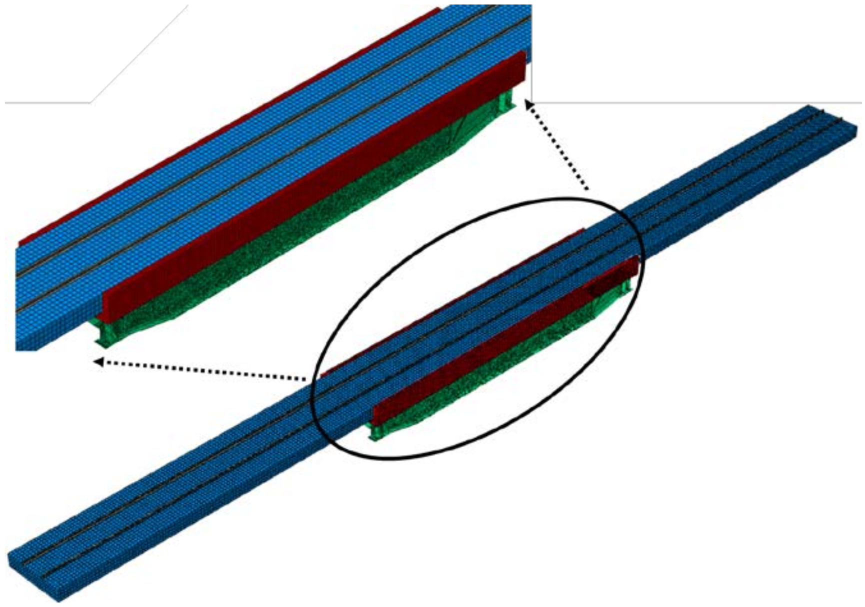


Figure 4. Finite element mesh of the bridge structure.

Eigenvalue analysis was performed using the *Lanczos* solver in a linear perturbation step, extracting the first three global modes and their corresponding natural frequencies.

4. Results and discussion

This part presents the changes in the natural frequencies and corresponding at 15 different temperatures ranging from -40 ℃ to 30 ℃ in increments of 5 ℃.

4.1. Variation in natural frequencies

Figure 5 shows the first three natural frequencies of the bridge under variations of temperature.

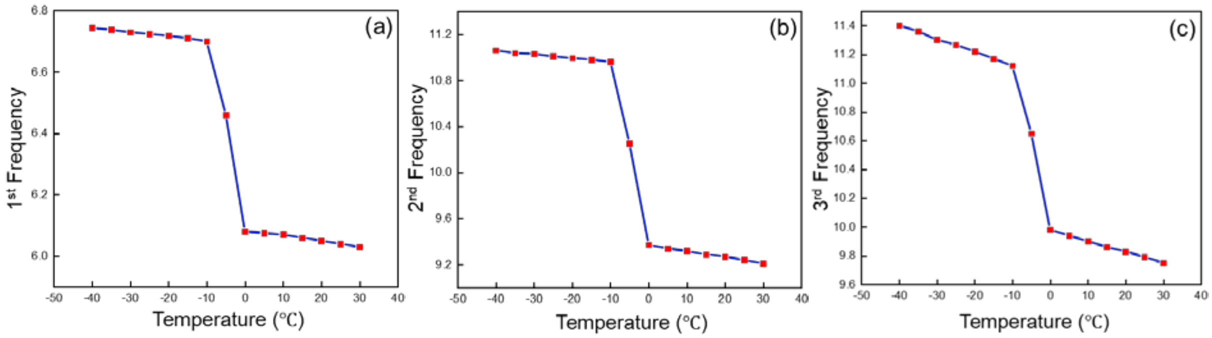


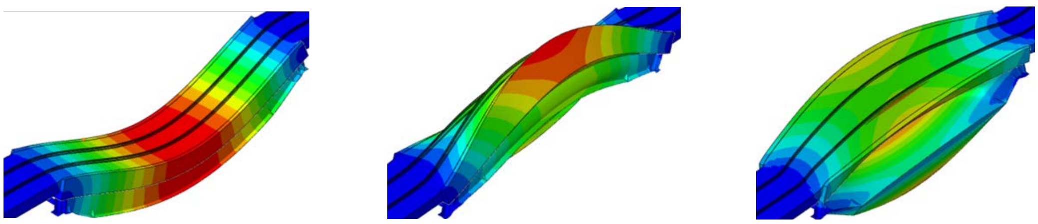
Figure 5. Variation of the first three natural frequencies with temperature. (a) First order, (b) Second order (c) Third order.

It is found that all three natural frequencies of the structure increase with the decrease of temperature. The first natural frequency increases by 12.41%, the second increases by 20.08%, and the third increases by 16.92%. The second mode shows the largest relative change.

Notably, in the range of 0 ℃ to -10 ℃, the rapid change in ballast stiffness and consequently, the boundary constraints result in a steep increase in the bridge's natural frequencies. Outside that range, the natural frequency-temperature relationship remains approximately linear, but with different slopes before and after ballast freezing, resulting in an overall trilinear relationship. These findings are consistent with the measurements reported by Peeters and De Roeck [13] and Salcher et al. [14] on other railway bridges.

4.2. Structural modal shape

The first three natural modes of the bridge structure under different temperatures are shown below (Figure 6).



(a) First order (b) Second order (c) Third order

Figure 6. First three modal shapes of the bridge. (a)First order, (b)second order, (c) third order.

By analyzing the first three modal shapes of the structure, it is found that the first modal shape is vertical bending mode, the second modal shape is torsional mode, and the third modal shape is bending torsional mode.

Comparing these modes with their frequencies confirm that temperature changes affect torsional modes more than bending modes, what is consistent with the findings of Salcher P [14].

5. Conclusions and work in the future

This study examined how temperature variations influence the natural frequency and mode shapes of a railway bridge in a cold region. Three key factors were identified: (1) the temperature dependence of the concrete elastic modulus; (2) the change in ballast stiffness; and (3) the alteration of boundary conditions due to frozen ballast. These factors were incorporated into a finite element model of a simply supported ballasted railway bridge in northern Sweden. The main conclusions are:

1. The natural frequency of bridge structure increases when temperature decreases, with a trilinear trend associated with ballast freezing. Across the -40 ℃ to 30 ℃ range, the first, second, third natural frequencies increase by 12.41%, 20.08% and 16.92%, respectively.

2. The first natural mode of the bridge structure is bending mode, the second is torsional mode, and the third is bending-torsional mode. Torsional modes exhibit greater frequency shifts under temperature changes compared to bending modes.

In future work, the authors plan to collect long-term vibration monitoring data of the bridge to validate the finite element results. By comparing measured frequencies and mode shapes with the FE predictions, the model can be calibrated and refined. Additional factors influencing modal parameters under temperature changes will also be explored. Finally, a mathematical model describing the relationship between the bridge's natural frequencies and temperature will be proposed and validated against field data from this and other studies.

Acknowledgement

The authors acknowledge the support from Luleå University of Technology and Southeast University for this research.

6. References

[1] Deng L, Wang W and Yu Y 2016. State-of-the-art review on the causes and mechanisms of bridge collapse. *J. Perform. Constr. Facil.* **30(2)** 04015005

[2] Modares M and Waksmanski N 2013. Overview of structural health monitoring for steel bridges. *Pract. Period. Struct. Des. Constr.* **18(3)** 187–91

[3] Zabel V, Brehm M and Nikulla S 2010. The influence of temperature varying material parameters on the dynamic behavior of short span railway bridges *Proc. Int. Conf. on Noise and Vibration Engineering (Leuven)* p 74

[4] Liu C and DeWolf J T 2007. Effect of temperature on modal variability of a curved concrete bridge under ambient loads. *J. Struct. Eng.* **133(12)** 1742–51

[5] Yu Y, Zong Z H and Chen B C 2014. Influence of ambient temperature on modal frequency of

Journal of Physics: Conference Series **3071** (2025) 012005 doi:10.1088/1742-6596/3071/1/012005

continuous rigid frame bridge. *Vib. Test. Diag.* **34(01)** 69–76+190

[6] Jiao Z Q, Hu L P and Han D 2010. Research on the influence of temperature on dynamic characteristics of bridges. *Sci. Technol. Eng.* **10(31)** 7685–89

[7] Wang Z, Huang M and Gu J 2020. Temperature effects on vibration-based damage detection of a reinforced concrete slab. *Appl. Sci.* **10(8)** 2869

[8] Yang S Z, Liu B T and Yang M Z 2017. Influence of ambient temperature and boundary conditions on natural frequency of concrete beam bridge. *Vib. Shock.* **36(08)** 164–72

[9] Daró P, De Cicco B and La Mazza D 2023. Thermal effects on bridges dynamic behaviour. *Int. Conf. on Experimental Vibration Analysis for Civil Engineering Structures* (Cham: Springer Nature Switzerland) 748–57

[10] Xia Y, Hao H and Zanardo G 2006. Long term vibration monitoring of an RC slab: temperature and humidity effect. *Eng. Struct.* **28(3)** 441–52

[11] Fib MC 2010. Model Code for Concrete Structures 2010. fib, Larsanne, Switzerland, Berlin: Wilhelm Ernst & Sohn. 2013.

[12] Anastasopoulos D, Maes K and De Roeck G 2022. Influence of frost and local stiffness variations on the strain mode shapes of a steel arch bridge. *Eng. Struct.* **273** 115097

[13] Peeters B and De Roeck G 2001. One-year monitoring of the Z24-Bridge: environmental effects versus damage events. *Earthq. Eng. Struct. D.* **30(2)** 149–71

[14] Salcher P, Pradlwarter H and Adam C 2016. Reliability assessment of railway bridges subjected to high-speed trains considering the effects of seasonal temperature changes. *Eng. Struct.* **126** 712–24