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Simulation of thermal load distribution in portal frame bridges

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ABSTRACT

Uneven exposure to e.g. solar radiation can cause temperature differences between various structural parts of a bridge, which leads to tensile stresses if the parts cannot move freely. In this study, thermal simulations and stress calculations on a model of a portal frame bridge are performed with the aim of evaluating the temperature difference between the bridge parts. Factorial design is used in a parametric study to determine the influence of different factors on the temperature difference and the largest reasonable temperature difference obtainable for the chosen weather data. The study shows that the quasi-permanent temperature difference between parts which is proposed by Eurocode 1 is overestimated, causing tensile stresses in the transverse direction to be exaggerated significantly. Using the design method proposed by Eurocode 1 is therefore likely to overestimate the required reinforcement in crack width limit design, which in turn would lead to unnecessary costs and environmental impacts. The results also indicate that the temperature distribution within the bridge is different from what is given in Eurocode load cases, and consequently, the largest tensile stresses appear in other areas of the bridge. A simplified temperature distribution is therefore investigated and shown to give similar results as the detailed thermal simulations.

1. Introduction

Temperature variations in bridges can occur both over time and space, due to changes in weather conditions such as air temperature, wind speed and solar radiation. The temperature changes due to three modes of heat transfer, namely conduction, convection and radiation. Air temperature affects the temperature of the structure by conduction and convection. Conduction describes heat transfer within a medium or between two media in direct contact with each other. The heat energy is transmitted directly between molecules in either solid, liquid or gas state. Convection on the other hand takes place in either a gas or a liquid, and combines the molecular heat transfer of conduction with a mixing effect, which speeds up the heat transfer. In the case of heat transfer between a gas and a solid, the mixing constantly replaces the gas molecules closest to the surface of the solid, which increases the speed of the conduction at the surface. Thereby, wind speed increases the heat transfer at a bridge surface [1].

Radiation describes heat transfer between objects separated by a transparent medium. The radiant heat can be described as an electro-magnetic wave, and its wavelength depends on the temperature of the emitting body. The higher the temperature of the surface, the shorter the wavelength of the emitted energy [1]. Short wave radiation relates to heat energy emitted by the sun, and long wave radiation relates to heat energy emitted by objects with a temperature similar to that on earth. Long wave radiation reaches the earth from the sky, emitted by various objects and particles in the atmosphere and in space [2].

The temperature in a bridge can at a given time vary in different ways. One possible way is by temperature gradients over cross sections, investigated by i.e. Larsson [3], Peiretti et al. [4]. Another type of temperature variation is temperature differences between structural parts, e.g. between the flange and the web in a box-section bridge [5,6], the box-girder and the bridge deck in a girder bridge [7,8], or between deck and abutment in a portal frame bridge. Temperature variations cause the volume of structural parts to vary, and in structural members prevented from changing their shape, (e.g. by expanding, contracting or bending) restraint stresses therefore appear.

Constant temperature loads and linear temperature gradients in cross sections cause restraint stresses if an outer restraint is present, i.e. if an adjacent structure is preventing the desired expansion or contraction [9]. The cross section itself causes stresses to appear if nonlinear temperature gradients are present, since the strain varies linearly over the cross sectional height. The sum of

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the stresses over the cross section must be zero if no outer restraint is present [10]. Fig. 1 shows an example of a nonlinear temperature distribution, and the resulting stresses, over a beam cross section which is not prevented from bending. This type of restraint is called inner restraint, since it is caused by the structural part itself [9]. In real structures, both inner and outer restraint situations occur simultaneously although they are generally treated as separate loads in design.

The restraint stresses alone, or in combination with other stresses, may cause cracking of a concrete bridge. Cracking in turn reduces the durability of the structure, and increases the need for maintenance. Crack widths are limited in bridge design in order to reduce their negative impact on the structure. On the other hand, cracking reduces the stiffness of the structure, which leads to increased deformations. This in turn causes the restraint stresses to decrease. Structures close to collapse are often so deformed that restraint stresses become very small, which is why restraint effects are often only considered in serviceability limit state in design, and not in ultimate limit state. In Eurocode, quasi-permanent loads are used when limiting crack widths. These loads shall correspond to load values that are exceeded 50% of the time. The load values are obtained by multiplying the characteristic loads with the ψ_2-coefficient, which equals 0.5 for thermal loads on bridges [11]. The thermal loads themselves are presented in EN 1991-1-5 [12].

Three main types of thermal loads which always shall be considered in design are uniform thermal load over the entire structure, linear or bilinear temperature gradient over cross sections, and temperature differences between structural parts. The uniform thermal load shall be combined with the gradient and temperature difference between structural parts, one at a time. Temperature gradients are however not supposed to be combined with temperature differences between structural parts. Nor are gradients applied in more than one structural part at a time. The level of these three different thermal load types are determined based on different factors. For the uniform thermal load, the characteristic load value depends on the bridge type and the geographical location of the bridge. The temperature gradients in bridge decks are determined based on the bridge type, thickness of asphalt layer and cross sectional height. For abutments, a linear temperature gradient of 15 °C is assigned. In the case of temperature difference between structural parts, a recommended value of 15 °C is given. Although not specifically stated in the code, the values for gradients and temperature differences between structural parts are here assumed to be characteristic values.

The background document to thermal loads in Eurocode 1, ENV 1991-2-5 [13], does not state the motivation of the choice of 15 °C as temperature difference between structural parts. It is however stated that the previous Spanish code used the value of 5 °C for concrete structures, and that the German code also considered the load case. According to Římal and Šindler [14], the German load value was given in DIN 1072 as 5 °C between structural parts of concrete and 15 °C for other materials.

Applying the Eurocode 1 temperature difference between structural parts causes large stresses in the transversal direction for some bridge types. Especially the crack width limitation design can lead to large reinforcement requirements, if the thermal loads are applied in simplified ways and no consideration is taken to the reduction of restraint stresses due to cracking. Since the large stresses are appearing in the transverse direction, models which do not consider the transverse direction, such as simple 2D frame models, do not show the large stress values. But with the use of 3D-models the effect in transverse direction is captured by the design model. The use of the more advanced 3D-models is thereby in turn requiring more detailed thermal load distributions.

In this paper, the temperature difference between structural parts in portal frame bridges is investigated using thermal simulations with climate data from a two-year period in Stockholm, Sweden. The resulting transversal stresses are calculated and compared with stresses obtained when applying thermal load cases from Eurocode 1. Also, the influence of various material and geometry parameters on the maximum temperature difference between structural parts is analyzed in a parametric study using factorial design. Portal frame bridges were chosen for this study due to their simple geometry and rigid connections between bridge parts, which generates restraint effects. Also, the bridge type is very common in Sweden.

2. Temperature effects on portal frame bridges

In the case of a portal frame bridge as in Fig. 2, the bridge deck and abutments are rigidly connected. Each structural part can therefore be considered to be restrained from expanding or contracting in the transverse direction by the adjacent part, since the transverse length of the bridge deck and the abutments must remain equal at the corners. Therefore, restraint stresses will appear in the transverse direction if the structural parts have different temperatures. In the longitudinal direction, restraint stresses will be smaller, due to a lower degree of restraint. If for example the bridge deck is cooled and strives to contract, the abutments will curve and thus only prevent a relatively small part of the longitudinal contraction.

Theoretically, at least three simple reasons for temperature differences between the structural parts can be found for the bridge type shown in Fig. 2: difference in short wave radiation influx, long wave radiation and heat exchange between abutment and soil. The difference in short wave radiation is due to the top side of the bridge deck being directly exposed to sunshine, while the abutments are mostly shaded by the bridge deck. The difference in heat influx between the parts is in this case largest when the sun is at its highest position in the sky, indicating that the largest temperature differences due to solar radiation will appear during summer.

A difference in long wave heat radiation appears when there is a large amount of outgoing long wave radiation from the bridge to the sky. This situation is most likely to appear during clear nights, often during winter. A large amount of outgoing radiation will lower the bridge deck temperature more than the abutment temperature, since the abutments are not facing the sky to the same extent.

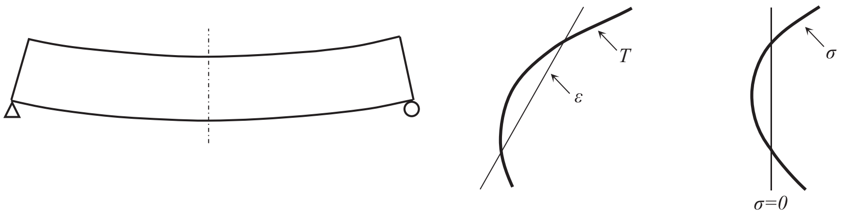

Fig. 1. Stresses and strains caused by a non-linear temperature distribution over the height of a simply supported beam. Figure after Jokela [10].