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FINITE ELEMENT MODELING OF THERMAL LOADING ON STEEL BOX GIRDERS

MARCO DIVERSI and HANS DE BACKER

Civil Engineering Dept, Ghent University, Ghent, Belgium

Thermal loads are not often considered during the design of steel box girders, but their influence can be quite important. When the thermal gradient within the steel box girders reaches considerable values, a number of other effects are influenced. High thermal gradients will reduce the cohesion of waterproofing layers and surface layers. Therefore, the quantification of the thermal loads acting on the system becomes essential. This is primarily done using detailed finite element models of steel box girders. Modelling all the thermal fluxes within this system, including solar radiation, radiation with the environment, mutual radiation, convective airflow, etc. it becomes possible to study the temperature variations on the bridge structure. The thermal loading is based on the actual revolution of the sun, while the bounds and the orientation angles are the result of a detailed calculation of the position of the sun. The same is true for the respective fluxes. All of these variations are studied along a one year period and this on hourly basis.

Keywords: Bridge codes, Health monitoring, Temperature effects, Eurocode, Temperature load.

1 INTRODUCTION

The Vilvoorde Bridge is a landmark bridge located in Belgium in the suburbs of the capital Brussels. In this paper we will study the temperature effects on comparable steel box girder bridges. These bridges are constantly exposed to a non-uniform, constantly varying, solar radiation and the resulting temperature domain variations, during the seasons as well as daily, can be quite impressive. This can cause problems and stresses that are not included in the initial design, especially when combined with the other loads. The inclination of the sun with respect to the different surfaces of the box girder becomes more complicated when considering yearly cycles of daily variations transmitted to the supporting steel structure. The natural ventilation because of the manholes in these types of girders can never be influential enough to create a cooling airflow substantial enough to balance this effect. This paper describes an accurate model of these temperature distributions, related variations and a quantification of the thermal effect. The objective of the proposed research is to reach new and more fundamental perspectives for the given problem and for the behavior of closed steel box girders with orthotropic steel decks, subjected to a variable thermal load (De Backer *et al*. 2008; 2009).

2 DESIGN LOADS FOR TEMPERATURES

2.1 Differential Temperature

A finite element model has been created (Figure 1), based on the cross-section of the Vilvoorde Bridge in Belgium. It has geometry for the box girder that is 8 m wide and 5 m high, with side flanges with a width of 5 m each. This geometry was introduced into the SAMCEF finite element software. The thickness of the steel plates varies between 18 mm for the deck plate to 48 mm for the bottom plate.

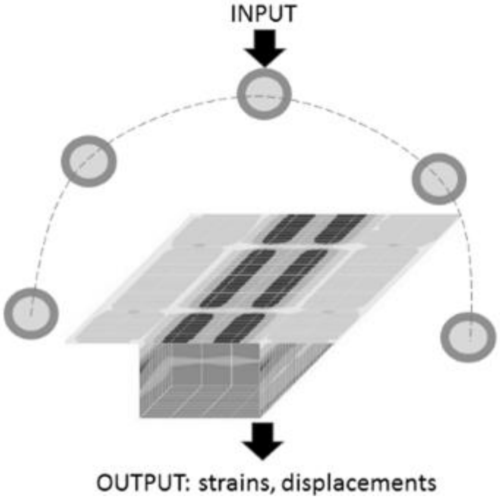

Figure 1. Input and outputs.

An epoxy asphalt layer with a thickness of 15 mm is assumed to be installed on the entire upper surface of the box girder for this calculation (De Backer *et al*. 2008). The thermal effects that need to be studied are:

- Solar radiation, resulting in a positive heat flux on the steel box girder;
- Heat exchange between the internal or external surfaces by convection;
- Heat loss because of the radiation between the structure and the environment;
- Mutual radiation between the external and internal surfaces of the box girder.

2.2 Solar Flux Calculation Method

The sun is actually a continuous fusion reactor. The solar constant is estimated to be a value that averages around 1367 W/m^2 (Kim 2009), although this is just a theoretical value. Ultimately, the estimated transmittance for beam radiation under the standard clear atmosphere on a horizontal surface of the box girder bridge can be calculated as following:

$$G_{cnb} = 1339 \; X \; \tau_b \tag{1}$$

Where:

$$\tau_b = a_0 + a_1 exp(-k/\cos\Theta_z) \tag{2}$$

A is the altitude of the site in kilometres, the constants a_0, a_1 and k are respectively,

$$a_0 = 0.4237 - 0.00821(6 - A)^2 \tag{3}$$

$$a_1 = 0.5055 + 0.00595(6.5 - A)^2 \tag{4}$$

$$k = 0.2711 + 0.01858(2.5 - A)^2 \tag{5}$$

Beam radiation, the major component of solar radiation, is the solar radiation received from the sun that is not scattered by the atmosphere. It is often referred to as direct solar radiation (Recknagel 1974). Diffuse radiation is the solar radiation received from the sun after the atmosphere through a process of scattering changed its direction. Ground-reflected radiation is radiation reflected from the ground cover and bodies of water on the surface of the earth. Ultimately the values that are obtained for the 1-day and 1-year calculations are extremely accurate and assigned as functions to the finite element model giving a realistic overview of the real thermal situation of the bridge (Duffie *et al*. 1974).

2.3 Results for Daily Approach

In this paragraph we will focus on the behavior of the bridge on a daily base, several nodes of the structure are studied but just the most interesting locations are reported in this paper. The day considered is June 21st since it is the day when the solar noon occurs at 13.44 and since it is, theoretically, the hottest day of the year for Brussels.

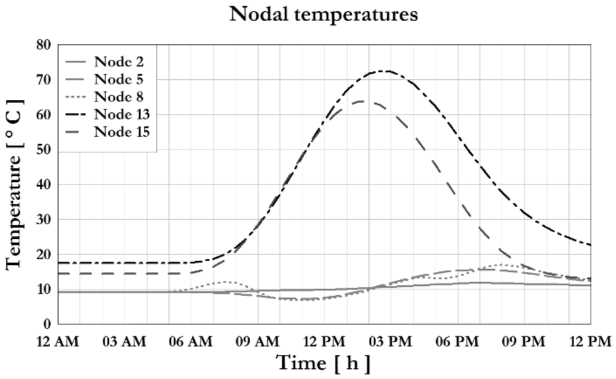

Figure 2. Temperature variations on the side of the box girder for 1-day calculation.

During this day (Figure 2), there are 16.31 hours of daylight and the component of the filtered solar flux on a horizontal plane averages a value of 710 W/m^2. The finite element model is composed of a structure of 2501 nodes, in this paper only 9 are selected nodes from the central cross-section of the steel box girder shown in Figure 3. The reason why we chose these nodes is because the central section of the bridge is the section where the highest values are reached, all the values are along the same line and more easy and visible to compare. There are 6 nodes laying on the central sides which are interesting because they are showing different values since the sun rises east and sets west, and there is a node laying in the bottom and two on the top in between the asphalt layer and the structure. The variation of the temperatures on the sides of the bridge between the sides is mainly due to the heating process that starts earlier on the eastern side where the sun rises. It is quite clear that the two nodes on the asphalt on the top are delivering the maximal values for the temperatures. However, the maximum value does not occur at the same instance as the minimum value because different factors such as position, mutual radiation and heat exchange between the constituting parts are varying the temperature field in the box girder.

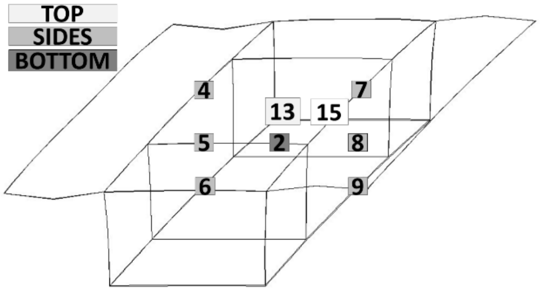

Figure 3. Overview of the position of the more significant nodes of the finite element model of the box girder of the bridge.

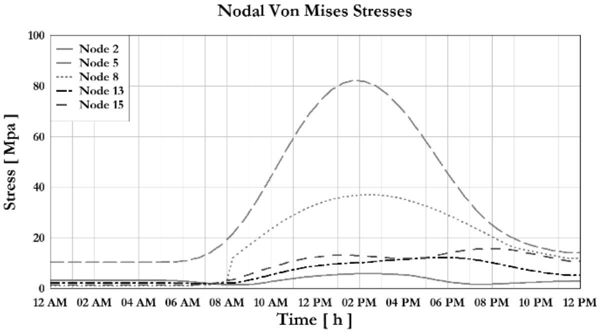

Figure 4. Stress variation considered nodes for a daily calculation.

Also interesting is the fact that the temperatures at the end of the cycle are not going back to the value registered in the morning (Figure 4). This gives a good indicator that the model works in a proper way because the bridge will heat during the day and it will cool down during the night to a temperature that in practice cannot be the same as the one registered in the morning. The model thus correctly represents the influence of successive hot days as an overall heating of the average temperature of the structure. The influence of the diaphragms in the box in conducting the heat flow away from the deck plate is also quite obvious, by the substantially lower temperature of the deck plate. The deck plate (Figure 5) also remains a bit cooler halfway between the sides of the box, since the influence of the secondary radiant heat sources, being the inner surface of the sides of the box girder, is smaller (De Backer *et al*. 2009).

The resulting additional stresses seem to be smallest in the deck plate zone above the diaphragms and above the sides of the box girder, since these parts of the structure help to disperse the solar heating to the cooler parts of the structure, thus resulting in a smaller thermal loading. The study of the temperatures and stresses are processed firstly through a thermal computation and then a mechanical computation that uses the previous thermal values as constraints. We can note that Von Mises stress is at maximum towards the fixed end of the beam, and the value is around 80 MPa. This is less than the yield point value of mild steel. So the design is safe. In short, an engineer task will be to keep the maximum value of Von Mises stress induced in the material less than its strength.

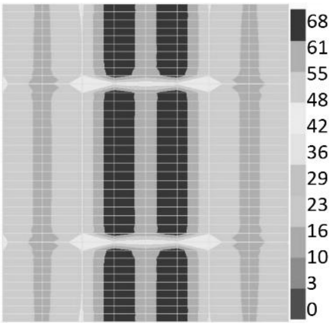

Figure 5. Top view of the temperature distribution in the deck plate during the hottest hour of the day.

2.4 Results for the Yearly Approach

The issue becomes more interesting and complicated for the yearly study, in this paragraph we will focus on the behavior of the bridge on a yearly base. The left part of the structure takes more time to cool down since it is on the eastern side and the sun starts to heat up from early in the morning, both patterns in the winter and in the summer show a consistent variation even though in Belgium the seasonal variations are not as big as in other locations. However, given the large temperature variations found here, it will be even more interesting to re-calculate the solar fluxes for another city with an another climate, be it much hotter or colder.

During the seasonal changes the trends are visible in Figure 6 where the node 13 on the central area of the top deck plate of the box girder bridge is the one that gets more radiations due to the blackened color of the asphalt and its elevated position. During both periods, yearly as well as daily period, the strains increase while the temperatures are rising. In July values of 37 °C, are clearly visible in Figure 6, however the maximal values are not in the same nodes as in the daily calculation. In this calculation other nodes get hotter because the heat will be a sum of all the previous days showing rising temperatures.

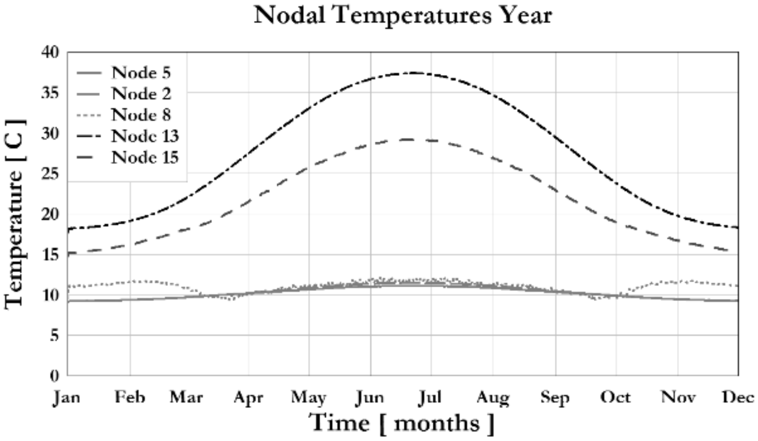

Figure 6. Distribution of the average temperature during a one year period.

3 CONCLUSION

This paper mainly focuses on the importance of temperature effects on structures. The variations of these effects are related to the location of the structure. They are well represented for the Vilvoorde case. The differences between the outer face and inner face are giving a clear map of the situation on the bridge and it is possible to retrieve data and conclusions that confirm the importance of the temperature effects. These effects will have a considerable importance on the cohesion of the different layers of bridge such as the asphalt and the wearing courses, also the stresses combined to the actual loads can be significant. Further research can be done to find a new design code, new materials and connections between the parts of the bridge that allow the displacements and rotations due to thermal effect.

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