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Structural response of a concrete cable-stayed bridge under thermal loads

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ABSTRACT

Daily and seasonal temperature variations have a significant influence on the structural response of bridges, inducing strains, displacements or rotations of the same order of magnitude, or even larger, than those due to dead or live loads. Besides understanding the structural behaviour under the operational loads, the characterization of the structural response induced by the daily and seasonal temperature variations is mandatory for the critical assessment of the bridge structural condition and when proactive conservation is envisaged. In this study, a methodology is proposed for the simulation of the structural response of large concrete bridges under the effects of realistic temperature variations, aiming at the optimum compromise between accuracy and simplicity of the involved procedures. The transient temperature field in a set of representative cross-sections is obtained from the available meteorological data via two-dimensional thermal analyses. The temperature field is decomposed into uniform, linear and non-linear components, the former two being introduced in a mechanical model of the bridge to obtain the transient structural response. The methodology is applied to a concrete cable-stayed bridge equipped with a permanent structural monitoring system. The measured and calculated hourly temperatures, deflections, bearing displacements, rotations and stay-cable forces are compared during a period of 17 months and good agreement is generally found. The consideration of the radiative cooling effects is demonstrated to be essential in other to obtain a good estimation of the thermal field of the bridge. The behaviour of the bridge is discussed and the relative contribution of each temperature component to a given structural response is disclosed. A discussion on the optimal deployment location of a minimum set of embedded temperature sensors in order achieve the best estimators of the temperature components (uniform and linear) is also presented.

1. Introduction

The characterization of the structural response to daily and seasonal temperature variations has an important role in the assessment of the structural condition of bridges. Several long-term monitoring studies have reported that temperature variations can induce strains, displacements or rotations of the same order of magnitude, or even larger, than those due to dead or live loads [1–7]. Taking the example of the Corgo Bridge – the prestressed concrete cable-stayed bridge selected as case study in the present work –, the vertical mid-span displacement measured during the load test when four 30ton trucks crossed the bridge side by side is similar to the daily fluctuations that are consistently measured during the summer period due to the sole effect of the daily temperature variations. Additionally, and contrary to traffic or wind loads, the temperature variations act continuously and the continuous observation of the corresponding structural response provides abundant data that can be used to detect the occurrence of modifications in the structural behaviour, enabling the timely adoption of proactive conservation measures.

Besides a good understanding of the temperature effects [8], the detection of changes in the structural response due to small damages requires suitable algorithms for filtering out the environmental and operational effects from the monitoring data [9,10]. In the scope of structural health monitoring (SHM) this is usually designated as data normalization [11]. One of the commonly adopted approaches relies on regression-based algorithms, which aim to remove the environmental and operational effects by means of relationships between the measured actions and the measured structural responses [12,13]. The effectiveness of these methods relies on the proper characterization of the thermal action on the bridge. The temperature components (uniform and differential) and structural parts that contribute more to a given structural response have to be identified and temperature sensors have to be judiciously placed to obtain the best possible estimates of the relevant temperature components. Moreover, even if the application of the data normalization methods may not strictly require the physical interpretation of the bridge structural behaviour, in many instances it is

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desirable to have a critical assessment of the data, with a physical and quantified interpretation of the measurements.

As reported in [14,15], the temperature distributions inferred from in-situ measurements can be used as input into mechanical finite element models for the simulation of the structural behaviour of real bridges under transient thermal loading. However, this may require a sufficiently dense network of temperature sensors, which is seldom available. In general, the temperature field needs to be computed if an accurate representation is to be achieved.

Many studies can be found focusing on the characterization of the temperature fields at the cross-section level using transient thermal analyses [4,16–24]. The two-dimensional transient temperature field in a cross-section can be computed using numerical methods – most often the finite difference or the finite element method – to solve the heat balance differential equation considering the boundary conditions defined by the ambient temperature, wind velocity, solar and longwave radiation. Fewer studies can be found where the thermal and the structural analysis of the bridge are integrated to provide an insight on the effects of the temperature variations on the structural behaviour. In this case, coupled thermo-mechanical analyses can be performed. This coupling is one-directional in the sense that the thermal field can be assumed to be independent of the state of stress, and the latter can be directly determined from the former via an appropriate mechanical model of the bridge. Following this line of thinking, Westgate et al. [25] studied the temperature distribution and the associated structural response of a steel suspension bridge, the Tamar Bridge. They developed a 3D finite element model of the entire bridge, in which both thermal and mechanical analyses were performed. The thermal boundary conditions were defined using the readings from the structural monitoring system, being the solar radiation estimated from the cloud cover. Recently, Zhu and Meng [26] presented thermo-mechanical analysis of a steel cable-stayed bridge, the Qingling Meng Bridge. A three-dimensional sunlight-sheltering algorithm was used to model complex sheltering effects, being the solar radiation estimated using an empirical model.

In many bridges it is sufficient to perform a 2D thermal analysis of the different cross-sections and to assume that the temperature field is invariant along the longitudinal axis of the elements, thus largely simplifying the problem. Xia et al. [27] presented a study of the temperature distribution and associated structural response of a long-span steel suspension bridge, the Tsing Ma Bridge. A 2D thermal analysis of the main structural elements was developed. The boundary conditions of the thermal problem were established using the ambient temperature and the wind velocity obtained from the monitoring system of the bridge and an empirical solar radiation model. The structural response (strains and displacements) of the bridge was obtained using a global finite element model wherein the calculated temperature distributions were introduced.

No study similar to those referred above could be found in the literature concerning concrete bridges. Given the lower thermal conductivity and higher specific heat of concrete when compared to steel, the spatial distribution and the time evolution of the temperatures within each cross-section are rather complex. The direct use of the temperature readings to characterize the thermal action is not possible unless an unrealistic large number of thermometers is adopted. In this context, an efficient procedure for detailed and realistic analysis of the structural response of concrete bridges subjected to thermal loads is proposed. The thermal and mechanical problems are solved in a sequential manner and resorting to independent numerical models. Accurate models for the conductive, convective and radiative heat transfer mechanisms are described and guidance is provided for the selection of the relevant material properties and definition of the boundary conditions based on field data. The obtained transient temperature fields are decomposed into uniform, differential and nonlinear components. The first two components are introduced into the finite element model of the bridge to obtain the time-histories defining the structural response to the temperature variations, which can be superposed to that due to the long term effects such as concrete creep, shrinkage and relaxation.

In order to demonstrate the effectiveness of the proposed procedure, the Corgo Bridge, a 300 m central span cable-stayed bridge located in northern Portugal, is used as case study. The bridge is equipped with a SHM system and the measured and calculated hourly temperatures, deflections, bearing displacements, rotations and stay-cable forces are compared during a period of 17 months. The long-term behaviour of the bridge is discussed and the relative contribution of each temperature component to a given structural response is disclosed. A discussion on the optimal deployment location of the embedded temperature sensors – considering a few number of sensors per section – in order to have better estimators of the temperature components using the temperature readings is also presented.

2. Methodology

One of the objectives of this work is the systematization of a methodology that is generally applicable to large concrete bridges, with a reasonable balance between accuracy and simplicity of the involved procedures. In general, the global structural analysis of large span concrete bridges is made resorting to beam finite element models. The use of this type of model for the mechanical analysis becomes very attractive, not only due to the reduced number of degrees of freedom, but also because it is generally available from previous design/assessment stages. The thermal analysis is performed separately, as shown in Figs. 1 and 2, which schematically summarize the proposed methodology.

In a first stage, a set of representative cross-sections is selected and the thermal problem is solved as illustrated in Fig. 1 to find the corresponding time-histories of the uniform, $T_u(t)$ and differential, $\Delta T(t)$, temperature components. These are used as inputs into mechanical model. The transient temperature distribution within each cross-section is determined by solving the thermal problem through two-dimensional finite element analyses. The number of analysed cross-sections depends on the geometry of the bridge, on the variation of the geometrical properties along the longitudinal axes of the structural elements (girder, piers, etc.) and on the sheltering effects governing the solar radiation reaching the surfaces of the structural element. The boundary conditions of the thermal problem are defined by the air temperature, effective sky temperature, wind speed and solar radiation on tilted planes. The latter is computed from the solar radiation on horizontal plane, usually available from meteorological stations, through a solar radiation model. The effective sky temperature is obtained through an empirical model of the longwave radiation. The temperature inside the box girder was considered equal to the readings of the air temperature inside the box girder obtained from the structural monitoring system. However, in case these are not available, the air inside the box girder can be simulated with finite elements as discussed in [4,18,28].

The mechanical problem is solved in a second stage, as illustrated in Fig. 2. The time-dependent rheological behaviour of the materials – concrete creep and shrinkage, evolution of the elasticity modulus and prestress steel relaxation – and the construction process must be taken into account and included in the model. If linear structural behaviour is assumed, the principle of superposition of effects can be applied as schematically indicated in the figure. Therefore, the calculated structural responses can be determined based on unit temperature loadings, which are multiplied by the previously obtained uniform and vertical linear temperature gradient components.

In this procedure, the mechanical properties - most notably the elasticity modulus of concrete - are considered independent of the temperature. If this simplification is not acceptable and reliable models relating the elasticity modulus with the temperature are available, this effect can be easily introduced. In addition, if the temperature fields are simulated since the construction, it is possible to refine the calculation of the maturity variable (usually the equivalent time, t_{eq}, determined