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Shape optimization of streamlined decks of cable-stayed bridges considering aeroelastic and structural constraints

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ABSTRACT

Structural optimization techniques have the potential to become a powerful tool in the design of long-span bridges. The search for more efficient and reliable designs involves considering shape variations in the deck cross-section, which is one of the key features of the bridge. This affects the deck aerodynamics and its mechanical properties, and consequently to the aeroelastic response of the bridge. A numerical approach pursuing to optimize a long-span bridge needs to explore changes in the deck shape, including structural and aeroelastic responses as design constraints. Therefore, the flutter response of the bridge must be computed numerically for every candidate proposed by the optimization algorithm.

This work presents a novel approach to conduct the optimization of deck shape and cables size of a long-span cable-stayed bridge considering simultaneously aeroelastic and structural constraints. The design variables are the cross-section area and prestressing force of each stay, the deck plates thickness and the width and depth of a streamlined box deck. The aeroelastic constraint is evaluated based on the fully numerical procedure developed in an authors' previous work. A series of parameter variation studies, that are instrumental for the sound interpretation of the optimum designs, are also reported.

1. Introduction

Cable-stayed bridges have been an efficient bridge typology in the 20th century for span lengths between 100 and 500 m. However, the technological advances in the last two decades have allowed to double the range of applicability of this kind of bridges, as it is the case of the Normandie Bridge (Virgoleux, 1992), in France, and the Tatara Bridge (Akiyama, 1999), in Japan, reaching spans surpassing the 800 m. Furthermore, in the last decade, the main span of this kind of bridges is breaking the limit of 1 km, as it is the case of the Stonecutters Bridge (Vejrum et al., 2006) in Hong Kong, China, the Sutong Bridge (Chen et al., 2010), also in China, and the Russky Bridge (Mellier, 2014), in Russia. In addition, several recent research works have reported studies considering bridge models of even 1.5 km (Ge, 2016), ensuring that the main span of this bridge typology will continue growing.

These examples make cable-stayed bridges to gain recognition as super long-span bridges since they present higher overall stiffness than suspension bridges and consequently the aerodynamic stability is beneficed (Gimsins and Goergakis, 2012). Therefore, it is important for the bridge engineering community to improve the design processes by using the most advanced technologies aiming to achieve more efficient designs. Moreover, the high economical cost of building any of these super long-span bridges makes an eventual reduction in materials a top priority.

Structural optimization deals with the application of numerical optimization algorithms to structural models aiming to reduce a target property while satisfying a series of requirements. This allows, for instance, to define an structural design that satisfies the imposed design constraints while reducing its weight, and consequently its cost, to the minimum. This technique was firstly developed in the 1960s by Schmit (1960, 1981), and since then it has been systematically applied in industry and research applications in several engineering fields, such as aerospace (Liu et al., 2016; López et al., 2016) or automotive (Jansson et al., 2003; Cid Montoya et al., 2015). In addition, in the aeroespace engineering field, some recent research works are conducting optimization studies considering structural and aerodynamic or aeroelastic design constraints. For instance, in the work by Elham and van Tooren (2017), the optimum shape of wings is defined based on its aerodynamic quality using gradient-based optimization algorithms. In the same manner, the aeroelastic constraint for the optimization of aircraft wings is considered in the recent works by Robinson et al. (2016) and Doyle et al. (2017). Furthermore, the aerodynamic optimization is currently being addressed

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for obtaining optimum shapes on tall buildings. Remarkable works about this topic can be found in the recent articles by Bernardini et al. (2015) and Elshaer et al. (2017).

However, the implementation of optimization techniques in bridge engineering is scarce, although in the last two decades some advances have taken place at research level. Research efforts in the synthesis of optimization techniques and cable-stayed bridges started with the works by Simões and Negrão (1994, 2000), Negrão and Simões (1997) in the 1990s, where pylons, stay system and deck were optimized imposing structural constraints achieving relevant reductions in the total volume of material. The implementation of the process of defining the optimum values of prestressing forces into the optimum design of a cable-stayed bridge was studied by Baldomir et al. (2010), Hassan et al. (2012) and Martins et al. (2015a, 2015b), once again considering only structural behavior constraints. Furthermore, a first approach to combine the structural optimization with constraints from other disciplines was conducted by Simões and Negrão (1999), where design constraints related to earthquake actions were considered, as well as in the later work by Ferreira and Simões (2011). However, the optimum designs obtained in the aforementioned works do not consider the response of the bridge to aeroelastic phenomena, whose influence is more relevant as the main span of bridges grows and the bridges are more flexible. Some insights about this problem and a historical perspective are provided by Miyata (2003).

The search for optimum designs considering aeroelastic design constraints started with the work by Jurado and Hernández (2004), where sensitivity analyses of some of the most relevant mechanical properties of cable-stayed bridges with respect to the critical flutter velocity were conducted. Later, other works related to sensitivity analyses and parameter variation studies provided valuable information about aeroelastic responses of long-span bridges, such as works by Jurado et al. (2008), Nieto et al. (2011), Omenzetter (2012) and Wang et al. (2014).

The first work reporting the successful application of optimization techniques to the case of a long-span bridge considering aeroelastic constraints was the paper by Nieto et al. (2009). In this work, kinematic and flutter design constraints were considered when the size of the deck plate thicknesses of the Messina Bridge project were modified by an optimization algorithm to reduce the total amount of material in the bridge. This methodology was extended by Kusano et al. (2014, 2015), where the uncertainty associated to the flutter phenomena is also considered in the optimization process.

However, the shape of the deck was kept constant in the aforementioned references, reducing the possible improvements that can be achieved in the bridge design. The present work seeks to be the first application of structural optimization of long-span bridges considering shape and size changes in the deck cross-section, including structural and aeroelastic design constraints. The formulation of the problem is based on the combination of optimization algorithms with the numerical strategy developed in the authors' previous work for obtaining the flutter velocity of a bridge based on a fully computational approach, reported by Cid Montoya et al. (2018). The strategy developed in the latest reference is based on the combination of CFD simulations with surrogate modeling techniques and the quasi-steady formulation. Some preliminary descriptions of the implementation of the technique proposed in this work were reported previously in Hernández et al. (2016) and Cid Montoya et al. (2016).

This article reports the optimum design studies conducted for a super long-span cable-stayed bridge with a mono-box streamlined deck cross-section considering shape design variables for the deck. In first place, the approach proposed for conducting the combined structural and aeroelastic shape optimization of a cable supported bridge is outlined. Then, the formulation of the optimization problem is introduced, focusing on the imposed behavior constraints and the precise identification of the design variables. In the following section, the reference application case chosen for conducting the structural and aeroelastic optimization is presented. Next, a number of parameter variation studies are reported aiming to clarify qualitatively and quantitatively the response of the reference design in terms of flutter speed as different subsets of design variables are modified. This information is of utmost importance for properly understanding the optimization problem results that are latter presented. In Section 6 the results obtained when only structural optimization is carried out for 81 pairs of shape design variables (deck cross-section width *B* and depth *H*) are reported. In these structural optimizations the cross-section areas and prestressing forces of each stay of the bridge are considered as design variables, as well as the thickness of the deck plates. For the 81 pairs of optimum structural designs the critical flutter speed is evaluated and in this way a flutter velocity response surface (FVRS) is defined in the considered shape design space of shape design variables *B* and *H*. This FVRS, when intersected by the plane representative of the flutter velocity constraint allows to understand the feasibility of the shape optimum designs obtained and discussed in Section 8 by the combined structural and aeroelastic optimization. In this process, the amount of material of the deck and stays of the bridge is reduced by searching for the optimum combination of the cross-section area and prestressing forces of each stay, the deck cross-section shape and size, and the thickness of the deck plates, when kinematic, stress and flutter constraints are imposed. Finally, the main findings and conclusions drawn from this research are summarized.

2. Implementation of the combined structural and aeroelastic optimization

This work develops a multidisciplinary approach for the combined aeroelastic and structural optimization of long-span bridges considering deck shape modifications. The fundamental goal is to pose and solve an optimization problem able to identify the bridge design with minimum weight, or material volume, that accomplishes all the required structural constraints as well as the prescribed minimum value of critical flutter velocity. The only way to rigorously address this task is to define a process that allows the evaluation of the flutter velocity of a bridge exclusively by means of numerical methods. Several works have dealt with this issue, for instance, the research reported by Ge (2016), where the flutter velocity of some long-span bridges is numerically obtained. However, in the latest reference the flutter response is obtained for a given section without providing information or methodological alternatives to obtain the flutter response when the shape of the deck cross-section is modified. The most challenging aspect when this problem is formulated is to define a fully computational method that obtains the flutter velocity of any cross-section inside the range of allowable variations of the section geometry. This was addressed in the authors' previous work reported by Cid Montoya et al. (2018), where a numerical strategy based on the combination of CFD simulations with surrogate modeling techniques, the quasi-steady formulation, and the flutter multi-mode analysis, was developed. This technique was applied to obtain the flutter velocity of two bridge models and the results were validated with experimental wind tunnel test data.

The formulation of the optimization problem is sketched in the flowchart of Fig. 1 and relies on this capability for obtaining numerically the flutter velocity of any intermediate design. It is divided into two main stages. The first one consists of the definition of a surrogate model that will provide the force coefficients and their slopes of each design produced by the optimization algorithm as the design process progresses. It is indicated in Fig. 1 as “Aerodynamic surrogate modeling”, and it is conducted previously to the optimization process. In the second stage, the optimization algorithm is implemented in combination with several analyses of multidisciplinary nature. This evaluation, indicated in Fig. 1 as “Bridge Multidisciplinary Analysis” (BMA), consists of obtaining the structural and aeroelastic responses of the bridge for the set of values of the design variables proposed by the optimization algorithm. The design variables considered in this work are the cross-section area **A** and prestressing forces **N** of all the stays of the bridge, the thickness of the deck plates *t*, and the width *B* and depth *H* of the deck cross-section. These