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# Optimum crossing cable system in multi-span cable-stayed bridges

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ABSTRACT

This paper presents a strategy to optimize the cable system of multi-span cable-stayed bridges with crossing stay cables. A general approach to minimize the steel volume in cables is performed considering number of cables, cable anchor positions on the deck, cable area and prestressing forces as design variables. Each cable anchor position is associated to an independent design variable allowing overlapping stay cables as well as different spacing along the deck. As the number of cables can vary throughout the bridge, the final design could have different number of cables on each side of the same tower. The possibility of designing a non-conventional cable arrangement leads to significant reductions in cable steel while satisfying structural design constraints. The Queensferry Crossing (UK) was chosen as a real application example to verify the capabilities of the proposed methodology.

## 1. Introduction

Multi-span cable-stayed bridges have experimented a significant development becoming one of the most suitable and aesthetic typologies for long bridges with large span lengths. Relevant examples are the Erqi Yangtze River Bridge, the current worlds longest triple tower cable-stayed bridge, with two main spans of 616 m, the Jiashao Bridge, the longest and widest multi-pylon cable stayed bridge with six towers and five main spans of 428 m. Another well-known examples are the Millau Viaduct, the Ting Kau Bridge or the Queensferry Crossing, which will subsequently be the triple tower cable-stayed bridge with the longest main span, 650 m.

One of the difficulties when designing a multi-span cable-stayed bridge is to control the vertical deflections of the deck due to live loads. In single span bridges, the necessary stiffness is achieved through the backstays cables that connect the top of the towers to the anchor position in piers or abutments. Nevertheless, this objective becomes harder in multiple-span cable-stayed bridges where a significant sway of the interior towers appears as the result of unbalanced live loads applied on deck. Consequently, large moments at the base of these towers appear and the vertical deflection phenomenon in the deck is aggravated. Several strategies have been proposed to reduce the horizontal displacement of the tower head for multi-span cable-stayed bridges, firstly introduced by Gimsing [1] and also summarized in [2].

One approach is to increase the bending stiffness of towers, deck or even both. Some examples are the Maracaibo Bridge or the Rion-Antirion Bridge, where extremely rigid towers were used, being the main drawbacks its high cost and weight. The other approach is based on modifying the cable system. The first technique was inspired from suspension bridges and consists of connecting towers from head to head by horizontal cables in order to stabilize the inner towers, as in the Bridge at Châteauneuf-sur-Loire in France, or using long cables from the top of inner towers to the adjacent tower at the deck level, as in the Ting Kau Bridge.

Another solution is based on the use of crossing stay cables coming from both adjacent towers to the central part of each span, as in the Queensferry Crossing Bridge. This configuration is advantageous since it is efficient in reducing the bending moments in the towers to an acceptable level. It also contributes to reduce the bending moment in the deck thanks to the overlapping stay cables. According to [3], it is convenient that the crossed cables extend for approximately a 20% of span length beyond the span center. A parametric study was carried out by Carter [4] in the Queensferry Crossing Bridge to establish the best number of crossing cables. That study analyzes the effect of increasing the number of crossed cables equally spaced but do not consider variations in the number and the positions of the cables. However, considering both characteristics as variables new cable distributions requiring lower amount of material would be identified.

Since the early 90s extensive research has been carried out to optimize different parameters of single-span cable-stayed bridges. Thus, some studies focused on setting the optimum post-tensioning cable forces under self-weight [5–8], as well as the optimum cross-sectional cable areas given the anchor position of cables on the deck [9]. The cable anchor positions on the deck along with the height, width and plate thickness of a simplified deck and pylon were also considered as design variables [10–12].

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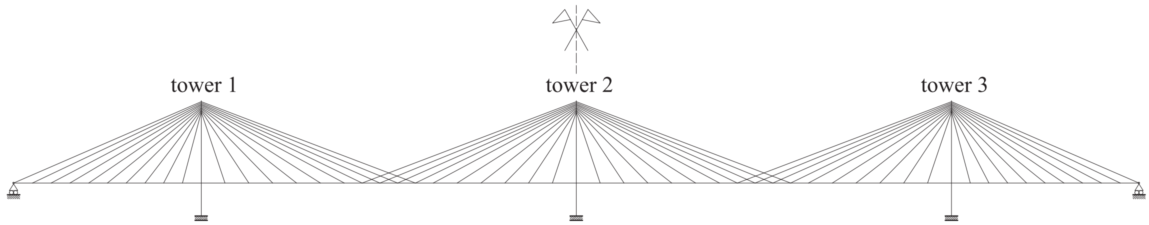


**Fig. 1.** Geometry of the generic finite element model.

In these studies a maximum number of seven stays were considered as well as the same number of cables at each side of the towers. Recent studies have taken into account the construction stages and the time-dependent effects in concrete decks into the optimization problem as presented by Martins [13,14]. Hassan [15,16] proposed an optimization technique using genetic algorithms where the number of cables is considered as a single design variable into the optimization process. Another application in single-span bridges was presented in [17] where the number of cables, anchor positions on the deck, cross-sectional areas and post-tensioning cable forces were simultaneously considered as design variables into the optimization process.

Additionally, new cable distributions have been proposed in single-span cable-stayed bridges. For example, [18] presents a comparison study between the overlapping stay system and the hybrid stay system, in order to provide better static and seismic behavior than the classical cable arrangements. Another example for bridges with main span over 1000 m is the recent typology entitled Partial Ground-Anchored Cable-Stayed Bridge with Crossing Stay Cables [19], with the main advantage of reducing the stress in deck and consequently reducing the total cost of the bridge by 12% approximately.

Even though all the previous studies focused on single-span cable-stayed bridges, some recent research has been conducted to improve the design of multi-span cable-stayed bridges. For instance, FHECOR Consulting Engineers [20] studied the influence of the relationship between main span, side span and tower heights to achieve the demanded stiffness against unbalance live loads. Following this trend, [21] examined the influence of the type of connection between deck and towers, as well as the stiffness of deck, piers and pylons. A new approach proposed by Baldomir [22] considers a multi-model optimization technique to minimize the cable weight with crossing cables and fixed anchor positions.

Although some major enhancements were made on multi-span cable-stayed bridges in the last years, no optimization strategies were performed to improve their cable system, being the cable positions as well as the number of cables fixed design parameters. So no chances were given to know if another cable arrangement would provide a lower amount of steel in cables, which represents a significant percentage of the total cost of the bridge (10% approx.) as presented in [23].

The goal of this research is to propose a methodology to define the optimum cable system in multi-span cable-stayed bridges, allowing crossed cables in the main spans, different number of cables at each side of the towers and different cable areas. For that purpose, an optimization approach is adopted to obtain the optimum number, anchor positions, cross-sectional areas and post-tensioning cable forces in the cable system.

The main contributions of this study are summarized in the following statements:

- Optimization of the cable system in multi-span cable-stayed bridges with crossing cables.
- The number of cables is considered as design variable and the final design can lead to a different number of cables each side of the same tower, unlike pre-existing approaches.
- Each cable anchor position on the deck is associated to an independent design variable allowing overlapping stay cables in main spans. Consequently the cables may have different spacing along the deck.
- A real example of a multi-span cable-stayed bridge has been used to verify the capabilities of the proposed methodology, resulting in an optimization problem with a large number of design variables.

## 2. Problem definition

### 2.1. Bridge structural model

A generic model of a four-span cable-stayed bridge has been considered in this research. The geometry definition of the bridge as well as the nomenclature used are shown in Figs. 1 and 2.

As can be seen in Fig. 2, the main span has been divided into three

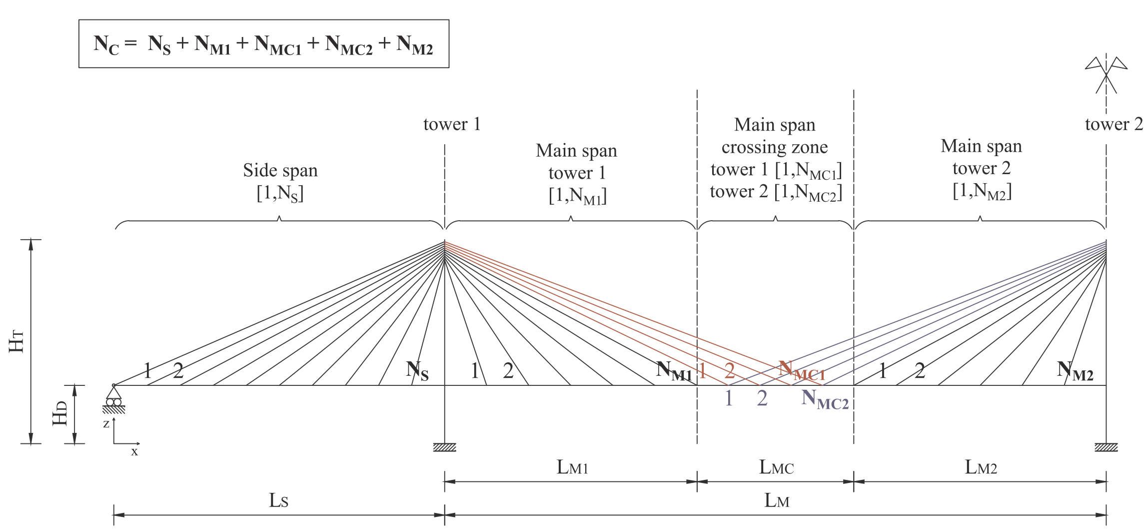


**Fig. 2.** Nomenclature considered for the bridge model.