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STRUCTURAL DESIGN OF CABLE-STAYED BRIDGES

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Abstract

This thesis describes the structural behavior of cable-stayed bridges, identifies cable-stayed bridge elements, and discusses their role in supporting the structure. It presents methods of pre-sizing the stays and describes a mathematical procedure that allows optimal tensioning of forces in the stays, so that the structure complies with the design criteria.

A parametric study of a structure similar to the "Vasco da Gama" bridge (a cable-stayed bridge that spans the Tagus River in Lisbon), was carried out to understand the suspension, static and longitudinal system.

The study analyzed the level of deformation and stresses in the bridge deck, the stays and in the towers. It took into account the use of various arrangements of stays, the presence of piers in the side span, the size of the approach viaducts and the relationship of the central span to the side span.

Keywords: Cable-stayed bridge, Structural equilibrium, Parametric studies, Static system, Suspension system, Longitudinal configuration

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1. Introduction

Cable-stayed bridges are extremely elegant and very effective structures and they are also architectural landmarks. The combination of multiple simple systems allows for a structure where the role of each of its components is well defined. When a cable-stayed bridge is chosen, the initial design phase is of utmost importance. The characteristics of the structure and whether if it is mainly constrained by structural or architectural reasons must be defined at an early stage in the design process.

The aim of this dissertation is to show what aspects should be taken into consideration during the design phase, in order to see the options that are available and the consequences of choosing each of them. Through this process, an appropriate methodology is obtained to determine the forces on the cables so that the structure is balanced. Through this study a structural relationship is obtained by analyzing the behavior of the various elements that compose the bridge.

2. General Design of Cable Stayed-Bridges

The main structural elements of a cable stayed bridges are the bridge deck, piers, towers and the stays. The deck supports the loads and transfers them to the stays and to the piers through bending and compression. The stays transfer the forces to the towers, which transmit them by compression to the foundations (*Figure 1*).

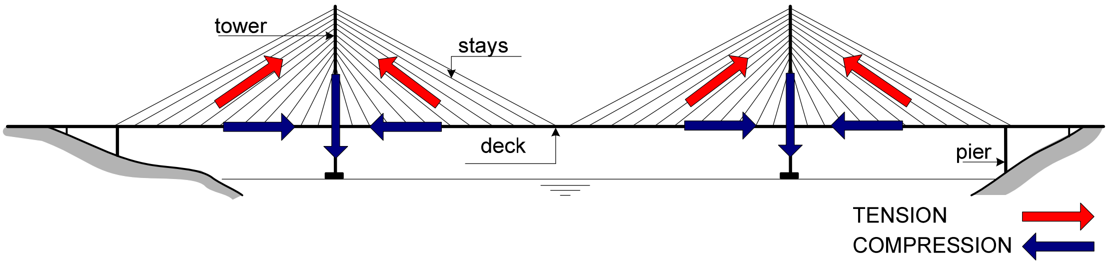


Figure 1 – Behavior of a cable stayed bridge.

The suspension system is usually one of two main types, with the stays anchored to the top of the tower (Fan) or the anchors are distributed along the length of the tower (Semi-Fan and Harp). This system directly affects the level of axial load and the elastic support given to the deck and to the tower.

The static system of a cable-stayed bridge can vary due to the conditions of support of the deck at the abutments and the whether there are piers in the side spans. The connection between the deck and the tower is also of great importance. This system primarily affects how effectively the structure carries live loads.

The longitudinal system is characterized by the ratio of the height of the towers to the central span, the relationship between the central span with the side spans, the connection of the deck to the approach viaduct, and the ratio of stiffness of the deck and the towers.

The geometry of the tower depends on the type of suspension system (Fan, Semi-Fan, or Harp), the form of suspension at the deck (with center or side anchors), whether the deck rests directly on the tower, and the available space for anchoring and tensioning of the stays inside the tower.

The material chosen for the tower depends on the characteristics of the foundation soil, the construction speed, and the construction process.

The cross section of the deck influences the whole structure of a cable-stayed bridge due to its characteristics of self-weight and aerodynamics. Most cable-stayed bridges usually adopts a one way reinforced concrete slab.

When a central suspension is adopted the deck must provide torsional support. In those cases the stiffening girder of the cable stayed bridges will be in a cellular box scheme (*Figure 2*).

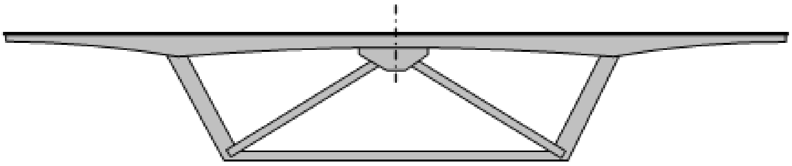


Figure 2 – Bridge deck with box section.

When a multi-cable system is adopted (usually side supported) the deck will be an open girder cross section. Bridges with very long spans should use cross sections with high torsional stiffness (Figure 3).

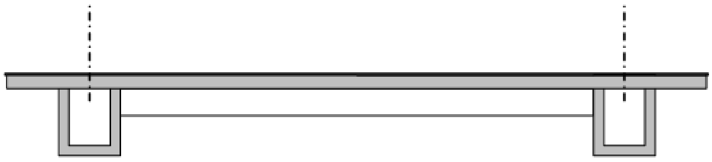


Figure 3 – Bridge deck in open girder cross section.

The anchoring of the stays in the deck is usually made by embedment of the anchors in the concrete stiffening girders. In composite bridges the anchors can be aligned with the stiffening girder or placed in an exterior position (under or in the slab plan).

3. Case Study

The case study is a cable-stayed bridge with a composite deck having a total length of 829 m (the central span is 420 m, and the side spans are 204.7 m) supported by two H-shaped towers that are 95 m above the deck (having a 150 m total height). The stays are spaced at 13.125 m along the sides of the bridge deck and are composed of two sets of sixteen stays.

The composite deck consists of two longitudinal 2.5 m high side girders (suspended only by stays) and a slab of uniform thickness of 0.25 m. The slab is supported by the longitudinal girders and the floor beams (the floor beams are transverse girders spaced at 4.375 m).

To determine the necessary tension forces on the stays, the tension coefficients method is used. This methodology controls the displacement at multiple locations and uses matrices that characterize the structure to obtain the necessary tensioning forces. Using mathematical procedures those forces can be optimized.

The solution with the harp suspension system needed to be modified trough the add of a connection of the bridge deck to the tower and the remove los the first pair of stays, because of their excessive rigidity.

The structure under study was modeled in SAP2000 using frame elements.

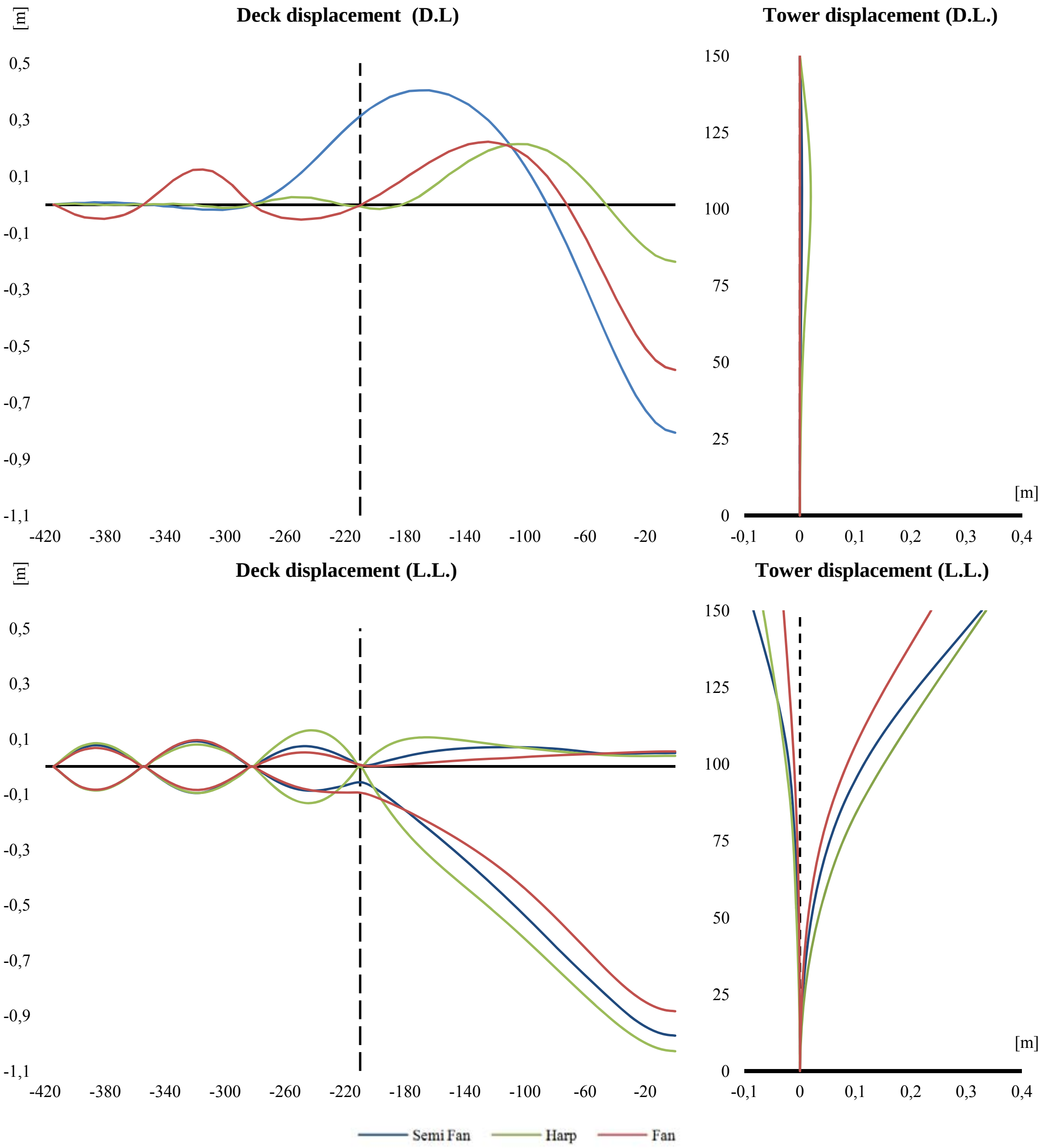
4. Parametric Studies

The change on the suspension system will change the stresses in the structure and it is directly connected to the requirements of strands that compose the stays. It is evident that the design stage has a great influence on the structural and economic performance of the solution adopted. In a successful cable-stayed solution, in the presence of dead load, the structure must have the deck and the tower in an undeformed position.

The Fan solution is the one presenting a best structural behavior.

Regarding the forces on the stays, the Harp suspension system presents higher values. This effect is due mainly to the more unfavorable inclination of the stays.

The axial force on the deck depends directly on the jacking forces applied to the stays, the Fan system has the minimum effort and the Harp system has the maximum effect. For the bending moment, all the system have similar values.


Deck displacement (D.L)

Tower displacement (D.L.)

Deck displacement (L.L.)

Tower displacement (L.L.)

Figure 4 – Bridge deck and tower displacements under dead load (D.L.) and live load (L.L.).

The axial stress at the base of the tower is identical in all systems, but the top of the tower has the largest stresses using the Fan system due to the large concentrated load at one location. The bending moments in the three systems differ greatly, with the Fan system having the best structural behavior.

The main thing to observe with the parameterization of the static system is the effect that side span piers have on the level of stresses and deformation. With or without piers the structure under dead load has the same behavior, but under live load the structure without side span piers has much higher stresses, rotations and deformations (*Figure 5*).

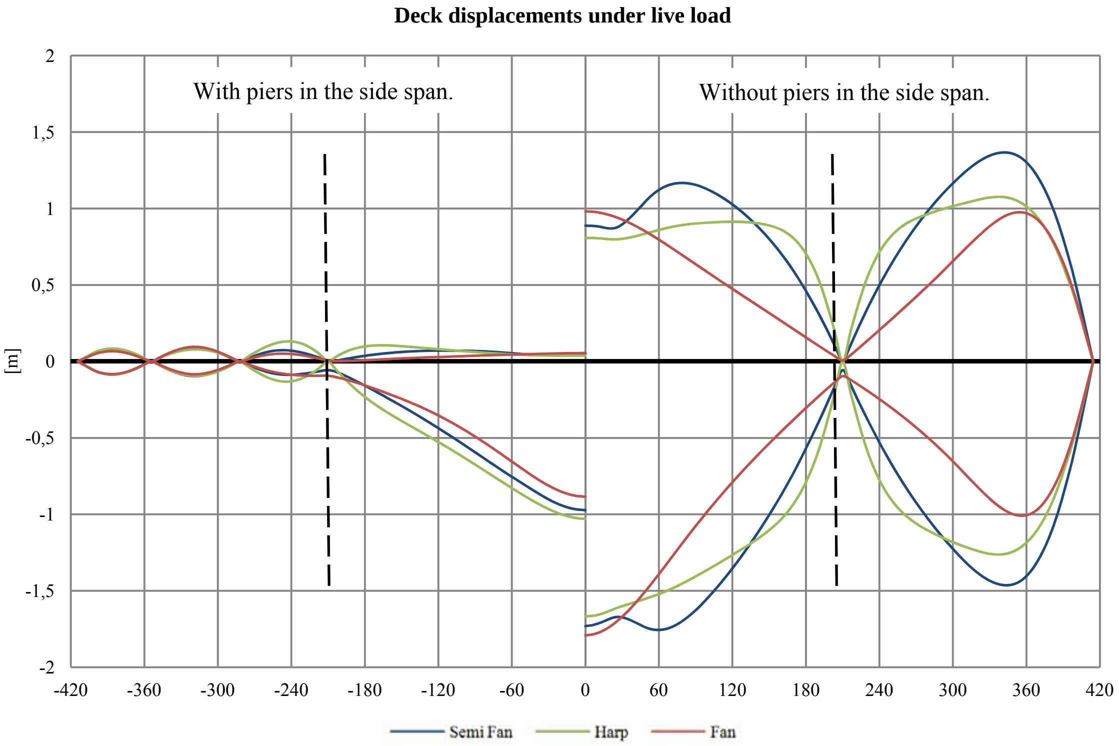


Figure 5 – Bridge deck displacements under live load.

It is concluded that the existence of piers in the side span will considerably decrease the amplitude of displacement of the bridge deck and will also decreases the tower displacements, especially toward the side span.

The stresses in the deck and tower in the case of dead load are not affected by the existence of piers in the side span but in the case of traffic load the stresses on the deck, tower and stays increase greatly without piers.

5. Longitudinal System

In the study of the influence of the longitudinal system the aim is to define how the approach viaduct length and the relationship between the side and central span will affect the structure displacements and stresses. To study the influence of the approach viaduct, five different cases were examined with different span lengths.

The deformations of the deck and the forces on the stays were almost unaffected by the existence of the approach viaduct. The existence of an approach viaduct considerably reduces the rotation at the beginning of the side span (Figure 6).

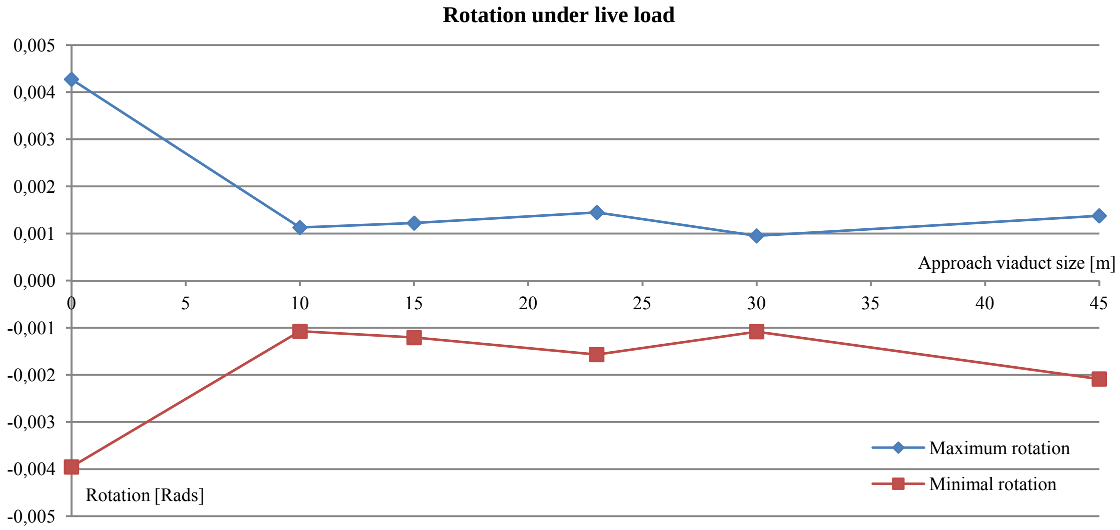


Figure 6 – Rotation in the beginning of the side span due to traffic load.

The decrease in the rotation may be crucial for the bridge deck to comply with design requirements. It was observed that the approach viaduct of 30 m was the one that best reduced the deformation and stresses. Without piers in the side span the rotation is increased about 10 times. The approach viaduct reduces the rotation in the beginning of the bridge deck about 4 times, having the bridge piers in the side span or not.

The relationship between the spans was studied using different side span lengths while keeping the length of the central span constant for the three types of suspension systems. The ratios used for the study (side span / central span) were 48.7%, 41.3% and 33.9%.

In this particular case the change in the relationship of spans did not change the deformation of the deck and towers significantly. In the Harp suspension system the reduction of side span length was beneficial in reducing the level of displacement of the bridge deck and the top of the tower. In the Fan suspension system the reduction of the side span length was harmful because the displacements tended to increase (Figure 7).

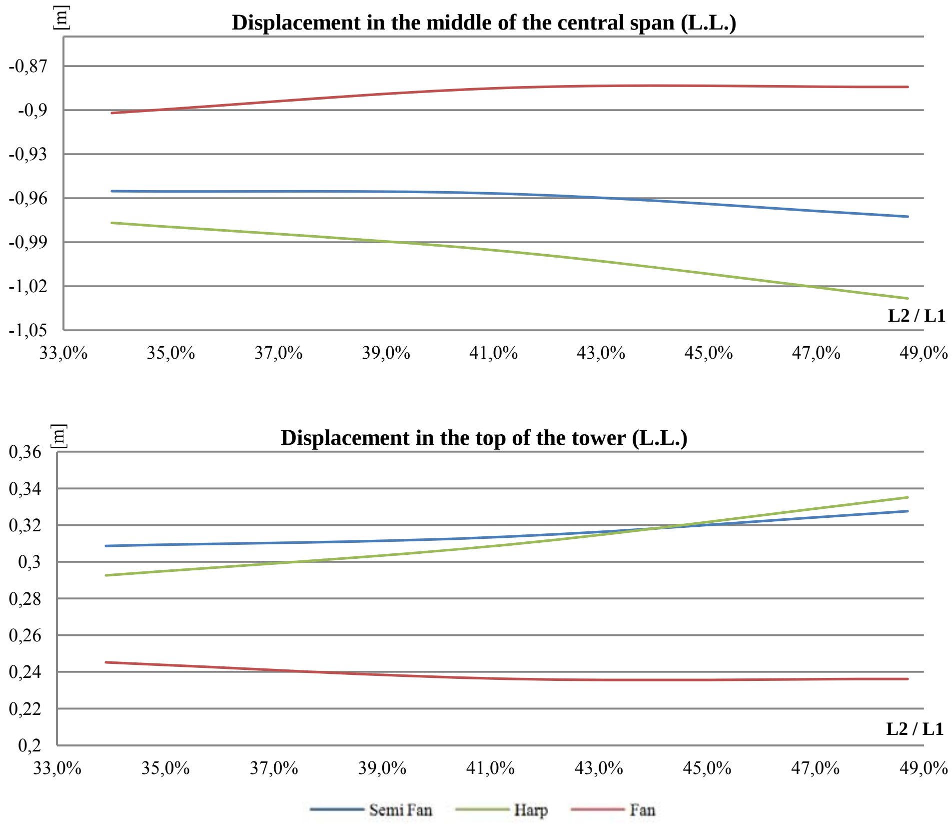


Figure 7 – Displacement due to live load.

6. Future Developments

-*Reformulation of the coefficients method:* there is an interest in whether you can get better results controlling the displacements at the extremities of the stays and the rotations and displacements along the tower and bridge deck.

-*Influence of the longitudinal system:* the relationship between the main span and the height of the towers and the stiffness and rigidity of the deck of the towers, play an important role in the structure. There is interest in conducting a study to determine what kind of influence is produced.

-*Multiple spans:* according several of the references, cable-stayed bridges with multiple spans have a different behavior. There is an interest in adopting to a multiple span cable stayed bridge the coefficients method (an equivalent study to the one made in this dissertation) to observe the behavior of the structure and the influence of the various types of systems that compose it.

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