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Active control implementation in cable-stayed bridges for quasi-static loading patterns

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ABSTRACT

The following paper deals with active control implementation in cable-stayed bridges. Recent developments in structural active control of cable-stayed bridges are focused on the adaptability to dynamic effects produced by earthquakes or extreme winds (El Ouni et al., 2012; Pakos and Wójcicki, 2014; Domaneschi et al., 2015a,b). Nevertheless, no attention has been paid to the static or quasi-static case. As stated by Housner et al. (1996), Song et al. (2006) or Gilewski and Al Sabouni-Zawadzka (2015), active control could also be useful to diminish fatigue in the day-to-day performance of this type of bridges by decreasing stresses adaptively. Indeed, the following paper shows that excitation periods produced by traffic loads and natural periods of vibration of this type of bridges are sufficiently distant one another so as to conclude that a quasi-static analysis can be performed. Filling this gap, the following paper proposes a structural analysis procedure to include active control systems in the design process of cable-stayed bridges, as well as suggestions which ought to be considered in order to include these cases into codes. The results of the paper, studying both non-cumulative and cumulative load cases, show a reduction in unbalanced bending moment referred to the Neutral Moment State of around 25%, depending on the load case. As a result, active control systems compensating quasi-static loading patterns can certainly help engineers optimise the design of these emblematic structures.

1. Introduction

Cable-stayed bridges, used in long spans since the 1970s, have been gathering significant interest in the recent years. Virlogeux [36] shows the rapid development of this type of bridges during the second half of the 20th century.

Cable-stayed bridges are bridges supported by a set of straight cables connecting the deck to the pylons in a balanced multispan arrangement [17, chapter 3]. The sizing and geometry optimisation of these bridges was thoroughly analysed by Simões and Negrão [33]. Besides these orthodox designs, some heterodox designs can also be found, such as the Alamillo bridge [2]. In these cases, the pylon is inclined so as to compensate dead loads with its own weight. Also, more modern designs have been proposed in the early 2000s, like under-deck single-span [31] and multispan [32] cable-stayed bridges.

The idea of active control of a structural response was first introduced by Kobori and Minai [23], and was adopted in Bridge Engineering in the 1980s [1,40]. In historic concordance, when cable-stayed bridges started to be used in very long spans [36], active control was considered to improve the behaviour of these bridges against earthquakes and extreme winds. Several theoretical [22,27,28,30,41] and experimental [5,15] studies for these cases were rapidly proposed. The appearance of more modern devices [35,38] and algorithms [24,25] improved significantly these active systems in the early 2000s. In recent years, researchers have been using detailed bridge models to analyse active control in the same dynamic scenarios [4,11,12,14,29]. Nonetheless, no attention has been paid to the static or quasi-static analysis.

As a completely new approach to the topic, the authors propose to use active control also with quasi-static loading patterns, merging the classical ideas by Housner et al. [20] with the modern ideas by Gilewski and Al Sabouni-Zawadzka [16].

According to the following study, one can show that, for traffic loads and cable-stayed road bridges, the excitation periods and the natural periods of vibration are significantly distant one another, and thus dynamic excitations become irrelevant (Section 2). As a consequence, the present paper proposes a structural active control system for cable-stayed road bridges so as to decrease stresses adaptively in a quasi-static manner. The detailed algorithm based

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on bending moment compensation is presented with detail for the control system (Section 3). Finally, the paper tests the former developments in a cable-stayed bridge designed by the authors (Section 4), including the analysis of two load cases (non-cumulative and cumulative) where the use and absence of the control system are compared. The results of these load cases show that the bending moment distribution of the bridge can be efficiently modified, reaching a reduction in unbalanced bending moments of around 25%, depending on the load case.

Therefore, a structural active control can be applied successfully to react to quasi-static loading, with a significant unbalanced bending moment reduction. Because the bending moment distribution is adaptively modified, displacements decrease and fatigue can be reduced.

2. A quasi-static approach to traffic loads in cable-stayed bridges

To begin with, it is important to draw a conceptual line between static or quasi-static, and dynamic loading of cable-stayed bridges. Theoretically speaking, all real physical structures behave dynamically when subjected to loads or displacements. It's only when these loads or displacements are applied *very slowly*, and do not produce significant oscillations, that the inertia forces can be neglected. In this case, a quasi-static analysis can be performed [39, chapter 12], as loads and displacements can be related sufficiently accurately via a static analysis. The question that arises is what *slow* means in this context.

Setting aside extreme winds and earthquake excitations, which clearly provoke dynamic effects, the most relevant actions on bridges are traffic loads. Traffic theory establishes that the more dense the traffic is, the slower the velocity of the flow becomes [19, chapter 4]. As a result, one can use three representative velocities for a cable-stayed road bridge: *in-city bridges* (assume 50 km/h), *medium-speed bridges* (assume 75 km/h) and *highways* (assume 100 km/h). Table 1 shows the traffic excitation periods, T, for these velocities, v, and for several cable-stayed bridge spans, L, according to the simplest approximation $T = L/v$ [9, example 3.4].

Therefore, one wants to judge whether these excitation periods are capable of generating significant oscillations. Two types of analysis procedures are typically adopted to verify vibration behaviour due to traffic loads [7]: deflection-based and acceleration-based methods. The most common one (deflection-based) follows the ideas by Smith [34], which assume that the response is governed by the first period of vibration. Therefore, one has to establish how distant the excitation periods are to the first natural period of vibration.

Camara [6, chapter 4] studies the first two natural periods of vibration for two different cable assemblies. This analysis compares the experimental data obtained by Kawashima et al. [22] with two finite-element models. Camara concludes that, if T is the period in seconds and L, the span in meters, an accurate approximation for the first mode of vibration for a Lateral Cable Arrangement (LCP) is:

$$T_{LCP} = 0.088L^{0.592}\ [\mathrm{s}] \quad (1)$$

And that an accurate approximation for the first mode of vibration for a Central Cable Arrangement (CCP) is:

$$T_{CCP} = 0.08L^{0.583}\ [\mathrm{s}] \quad (2)$$

Table 2 shows the approximated natural periods of these two cable arrangements and the spans considered in Table 1.

From these figures, it is readily seen that natural periods of vibration are significantly smaller than their correspondent excitations, thus if one defines the frequency ratio $f_r = \frac{\omega}{\omega_n}$, and recalling that $\omega = \frac{2\pi}{T}$, one can use the approximation $f_r \approx 0$. As studied by Chopra [9], Figs. 3.2.6 and 3.5.1, for harmonic excitations it is concluded that the transmissibility $TR \to 1$ and the deformation response factor $\frac{u_0}{(u_{st})_0} \to 1$ when $f_r \to 0$. Therefore, the response of the structure can be statically approximated.

Table 1
Excitation period T for traffic loads and a combination of speed v and span L.

$v \backslash L$	150 m	300 m	400 m	500 m
50 km/h	10.8 s	21.6 s	28.8 s	36 s
75 km/h	7.2 s	14.4 s	19.2 s	24 s
100 km/h	5.4 s	10.8 s	14.4 s	18 s

Table 2
Approximated natural periods of vibration for LCP and CCP arrangements, and span L.

L	150 m	300 m	400 m	500 m
LCP	1.7 s	2.6 s	3.1 s	3.5 s
CCP	1.5 s	2.2 s	2.6 s	3.0 s

In conclusion, traffic loads do not produce significant oscillations, and can thus be considered with a quasi-static approach. However, it is important to note that this fact need not mean that there are no variables that depend on time [18], as there will exist registers of data that will have to be processed by the system. Instead, a quasi-static structural analysis guarantees that this time dependency can be decoupled from the structural response.

It is also relevant to note that Camara's expressions are for vertical modes of vibration. Often, transversal modes have longer periods for long spans and shorter periods for short spans [6]. Nevertheless, these modes are typically not excited in straight cable-stayed bridges.

As a matter of fact, a new way of taking advantage of structural active control in cable-stayed bridges arises from the precedent discussion. Indeed, an appropriate active control system can be introduced to reduce bridge stresses and displacements for traffic loads, which represent the main source of fatigue.

3. Proposal of an active control system in quasi-static analysis

To begin with, one has to clearly identify the control objective of the system. In the proposed case, the main goal of the active control system is to monitor the deformation of the bridge and react adaptively. As a result, stresses and displacements will be decreased adaptively, and hence fatigue will be reduced.

Consequently, the system will need to obtain data from the structure, process it logically and actuate a mechanical system to reduce some targeted stresses. The most natural way to induce a change in the stresses in a cable-stayed bridge is by means of the cables [7,11,27,29,30]. This procedure was experimentally verified for the dynamic case by Bossens and Preumont [5]. In this study, Bossens and Preumont use a large-scale mock-up bridge model equipped with hydraulic actuators in order to demonstrate the control of the parametric vibration due to deck vibration. To this end, the paper is focused on the root locations of the transfer function, and constitutes an experimental framework for the present analysis.

The idealised system consists of a closed-loop active control system as shown in Fig. 1, where i is a point in the bridge deck where a cable is anchored, M_i represents the reference bending moment that is to be achieved by the system at point i, M_i^m is the bending moment measured at point i, q_i is the axial force of the cable anchored at point i and e_i is the error between the reference bending moment and the real bending moment in the structure. It is important to note that this setup only allows measuring points