Available online at www.sciencedirect.com

ScienceDirect

Engineering Structures 30 (2008) 1160–1177

ENGINEERING STRUCTURES

www.elsevier.com/locate/engstruct

Dynamic impact analysis of long span cable-stayed bridges under moving loads

D. Bruno*, F. Greco, P. Lonetti

Department of Structural Engineering, University of Calabria, 87030 - Rende (CS), Italy

Received 5 September 2006; received in revised form 19 June 2007; accepted 2 July 2007
Available online 21 August 2007

Abstract

The aim of this paper is to investigate the dynamic response of long span cable-stayed bridges subjected to moving loads. The analysis is based on a continuum model of the bridge, in which the stay spacing is assumed to be small in comparison with the whole bridge length. As a consequence, the interaction forces between the girder, towers and cable system are described by means of continuous distributed functions. A direct integration method to solve the governing equilibrium equations has been utilized and numerical results, in the dimensionless context, have been proposed to quantify the dynamic impact factors for displacement and stress variables. Moreover, in order to evaluate, numerically, the influence of coupling effects between bridge deformations and moving loads, the analysis focuses attention on the usually neglected non-standard terms related to both centripetal and Coriolis forces. Finally, results are presented with respect to eccentric loads, which introduce both flexural and torsional deformation modes. Sensitivity analyses have been proposed in terms of dynamic impact factors, emphasizing the effects produced by the external mass of the moving system and the influence of both "A" and "H" shaped tower typologies on the dynamic behaviour of the bridge.

Keywords: Moving loads; Dynamic impact factors; Cable-stayed bridges; "A" and "H" shaped towers

1. Introduction

Cable-stayed systems have been employed, frequently, to overcome long spans, because of their economic and structural advantages. Moreover, improvements in the use of lightweight and high strength materials have been proposed in different applications, and, consequently, more slender girder cross sections have been adopted. As a result, the external loads have become comparable with those involved by the bridge self-weight ones and an accurate description of the effects of the moving loads is needed to properly evaluate dynamic bridge behaviour. At the same time, new developments in rapid transportation systems make it possible to increase the allowable speed range and traffic load capacity; consequently, the moving system can greatly influence the dynamic bridge vibration, by means of non-standard excitation modes. To this end, investigation is needed to quantify the effects produced by the inertial forces of the moving system on the bridge vibration.

The extension of the moving load problem to long span cable-supported bridges requires a consistent approach, appropriately formulated, in order to fully characterize the bridge kinematics and train–girder interaction. In the literature, several studies have been developed, which analyse dynamic bridge behaviour with respect to different assumptions and frameworks. In particular, Fryba and Timoshenko [1,2], provided a comprehensive treatment concerning primarily the dynamic response of simply supported girder structures travelled by vehicles, and analytical as well as numerical solutions for some specific problems have been presented. During the last few decades, with advances in high performance computers and computational technologies, more realistic modelling of the dynamic interaction between a moving system and bridge vibration has become feasible. In particular, Yang et al. [3] presented a closed-form solution for the dynamic response of simple beams subjected to a series of moving loads at high speeds, in which the phenomena of resonance and cancellation have been identified. Moreover, Lei and Noda [4] proposed a dynamic computational model for the vehicle and track coupling system including girder profile irregularity by

---

* Corresponding author. Tel.: +39 0984 496914; fax: +39 0984 494045.
E-mail address: d.bruno@unical.it (D. Bruno).

0141-0296/$ - see front matter
doi:10.1016/j.engstruct.2007.07.001

Nomenclature

α	Longitudinal stay geometric slope
α_0	Longitudinal anchor stay geometric slope
A_s	Stay cross sectional area
A_{s0}	Anchor stay cross sectional area
b	Half girder cross section width
β	Transverse stay geometric slope
c	Moving system speed
Δ	Stay spacing step
e	Eccentricity of the moving loads with respect to the girder geometric axis
E	Cable modulus of elasticity
EI	Flexural girder stiffness
EA	Axial girder stiffness
E_s^*	Stay Dischinger modulus
E_{s0}^*	Anchor stay Dischinger modulus
g	Girder self-weight per unit length
γ	Stay specific weight
GJ_t	Torsional girder stiffness
H	Pylon height
I_0^p	Pylon polar mass moment
K^p	Flexural top pylon stiffness
K_0^p	Torsional top pylon stiffness
l	Lateral bridge span
L	Central bridge span
L_p	Total train length
λ	Mass function of the moving system per unit length
λ_0	Polar mass moment of the moving system with respect to girder geometric axis per unit length
M_p	Lumped top pylon equivalent mass
μ	Girder mass per unit length
μ_0	Polar inertial moment of the girder per unit length
ω	Girder torsional rotation
p	Live loads
σ_a	Allowable stay stress
σ_g	Stay stress under self-weight loading
σ_{g0}	Anchor stay stress under self-weight loading
$\psi_{L(R)}$	Left (L) and right (R) top pylon torsional rotations
$u_{L(R)}$	Left (L) and right (R) horizontal top pylon displacement
v	Girder vertical displacement
w	Girder horizontal displacement

the finite element method, whereas additional references to the influence of AASHTO live-load deflection criteria on the vibration in a railway track under moving vehicles can be found in [5–7].

With reference to cable-stayed bridges, in order to evaluate the amplification effects produced by the moving system, different investigations have been proposed. In particular, Au et al. [8,9] investigated the dynamic impact factors of cable-stayed bridges under railway traffic using various vehicle models, evaluating the effects produced by random road surface roughness and long term deflection of the concrete deck. An efficient numerical modelling has been developed by Yang and Fonder [10] to analyse the dynamic behaviour of cable-stayed bridges subject to railway loads, taking into account nonlinearities involved in the cable system. Dynamic interaction of cable-stayed bridges with reference to railway loads has been investigated in [11], in which strategies to reduce the multiple resonant peaks of cable-stayed bridges that may be excited by high-speed trains have been proposed for a small length bridge structure. Finally, a computational model and a parametric study have been proposed in [12] to investigate bridge vibration produced by vehicular traffic loads. The literature referred to above investigates dynamic bridge behaviour properly taking into account the effects of interaction between bridge vibration and the moving system. However, only a few studies have concentrated on the dynamic responses of long span bridges. This paper, therefore, focuses on the dynamic behaviour of long span cable-stayed bridges, evaluating the effects produced by the moving system on the dynamic bridge behaviour. In particular, the main aims of this paper are to propose a parametric study in a dimensionless context, which describes the relationship between dynamic amplification factors and moving loads and bridge characteristics.

The structural model is based on a continuum approach, which has been widely used in the literature to analyse long span bridges [13–15]. In particular, Meisenholder and Weidlinger [13] have schematized bridge structures as an elastic beam resting on an elastic foundation, whose stiffness is strictly connected to the geometrical and stiffness properties of the stays. Moreover, extended models which generalize the bridge kinematics have been proposed in [14,15], in which the stay spacing is assumed to be small in comparison with the central bridge span. As a result, the interaction forces between the cable system and the girder can be assumed as continuous functions distributed over the whole girder length. The accuracy of the continuum approach has been validated in previous works developed in both static and dynamic frameworks, through comparisons with numerical results obtained by using a finite element model of the discrete cable system bridge [14–16].

In the present paper, the bridge kinematics and the inertial forces have been considered in a tridimensional context, in which both in-plane and out-of-plane deformation modes have been accounted for. Cable-stayed bridges based on both "H" and "A" shaped typologies with a double layer of stays have been considered. However, cable-stayed bridges with one central layer of stays, especially for eccentric railway bridges, are characterized by high deformability, and difficulties verifying the design rules on maximum displacements occur frequently. In particular, the girder torsional stiffness needs to be significantly improved with respect to those involved for "H" and "A" shaped typologies, because contributions arising from the cable system are practically negligible. As a matter of fact, torsional analysis carried out for typical concrete or steel girder cross sections shows that in order to limit torsional rotation to reasonable values (i.e. below 0.02), the maximum allowable central length must be approximately