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Analysis of non-uniform torsion in curved incrementally launched bridges

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ABSTRACT

Incremental launching is a common and convenient methodology to build continuous girder bridges on several piers. Although it has mainly been applied to straight bridges with box sections, today it is also used for construction of horizontally curved bridges with concrete and composite steel–concrete closed or open sections like I-girders. In these cases the contribution of torsion to the stress state becomes of primary importance when the construction stages of these bridges are analysed. Moreover, the presence of thin-walled cross-sections, makes the analysis of non-uniform torsion fundamental when the angle of twist per unit length is not constant or warping is prevented in those sections where rigid internal diaphragms occur. Consequently the stress state in the launching phases can be strongly influenced by non-uniform torsion, especially for the evaluation of axial stresses in I-girder bridges, where non-uniform torsion presents its maximum influence. In this paper a methodology for the repetitive analysis of launching steps is proposed, based on the Hamiltonian Structural Analysis method, which takes into account the internal characteristics of non-uniform torsion (warping and bimoment) in order to evaluate the influence of prevented warping on the stress state at each stage of launching. The methodology is convenient because it can be considered a sort of generalised beam theory and presents a reduced computational burden with respect to finite element or boundary element procedures, with fast solution of many bridge launching static schemes. A validation of the method is given through a comparison with finite element procedures and literature data. An application is presented on a bridge with different typologies of cross-section in order to compare the different behaviours of thin-walled sections and the different degree of influence of non-uniform torsion on the stress state. The results are given in the form of envelope graphs of internal forces and stresses for the entire launching sequence and for the different cases examined.

1. Introduction

One of the most common methodologies for construction of continuous girders on piers is the incremental launching technique [1]. Although it is used for bridges with concrete or steel decks with any kind of cross-section, this methodology was initially developed for steel structures by Eiffel (in Evaux and Garabit bridges) and then extended to the construction of concrete box girder bridges by Fritz Leonhardt, who introduced it in the Rio Caronì bridge [2]. The methodology consists in advancing the deck by segments pushed from the abutment towards the piers, launching the spans from one pier to another by using a steel nose in front of the deck, which reduces the bending moment values in the cantilever stages of advancement (Fig. 1). The most convenient section for the construction of incrementally launched bridges is the box section because it has good mechanical performance due to its geometric efficiency and to its effectiveness in resisting torsion and warping. Nowadays bridges with composite steel–concrete box sections and open sections (I-girders) are commonly built through the same technique, extending the field of application of this methodology. Moreover, the technique has generally been applied to straight bridges but it is also used for the construction of horizontally curved bridges [3,4]. In these cases the effects of torsion, always coupled to bending, cannot be neglected, even for the distributed dead loads applied to the girder during launching [5] and construction stages have to be analysed by considering the twisting moment as well as the shear force and the bending moment. All these bridges have thin-walled cross-sections, in the cases of both closed boxes and open I-girders with an upper slab (Π sections); this, associated to the curvature of girders in horizontally curved bridges, makes it important to evaluate the effects of non-uniform torsion, which can influence the stress state. In fact when the angle

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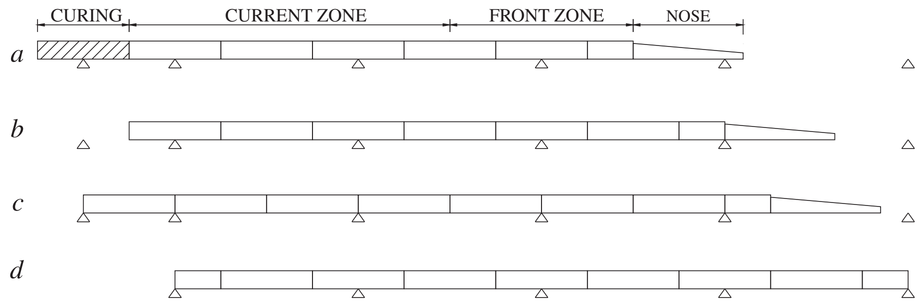

Fig. 1. Stages of bridge launching.

of twist per unit length is constant along the beam and warping is not prevented, uniform torsion is established and it can be studied by the Saint–Venant theory. By contrast, when the angle of twist per unit length is not constant, non-uniform torsion is established and the total twisting moment can be considered as the sum of the primary moment (equivalent to Saint Venant moment) and the secondary one (due to warping). I-girder bridges are more sensitive to non-uniform torsion with significant values of axial stresses induced by the presence of internal diaphragms (which prevent torsional warping) and with the modification of tangential stresses due to the secondary torsional moment with respect to those computed by the Saint–Venant theory. Box girders can present sizable values of stresses due to prevented warping when concentrated actions occur (like those due to the vertical reactions of the sliding bearings over the piers) and in the areas next to diaphragms.

The sequence of prefabrication of segments in the construction yard behind the abutment can follow different procedures but generally the lengths of deck segments vary from the entire span to 1/3 or 1/4 of the span to be launched. This choice depends on the yard length and on the launching equipment and it is convenient to put joints between segments far from the areas of the maximum stresses in the final stage (midspan or over the piers).

Incremental launching leads to the need to compute a large number of static schemes, one for each step of advancement, till the final scheme is achieved, so the designer has to find the envelope diagrams of internal forces in order to evaluate the actual behaviour of the deck at all stages of launching [1,4].

In curved bridges built by incremental launching additional transverse forces rise at the top of piers due to the friction of sliding bearings and to the thrust. The determination of these forces can be generally done through a scheme of a beam on elastic supports, in the horizontal plane, where the stiffness is the transverse stiffness of cross section and the elastic springs are given by the transverse stiffness of piers [5]. Moreover misplacements of supports and errors in positioning the guiding devices can make these forces bigger. By knowing the value of thrust, it is possible to develop a transverse calculus, considering the friction forces and the components in the longitudinal and radial directions, in order to obtain the transverse forces and the related additional internal forces, avoiding the failure of bearing areas through a correct dimensioning.

In this paper a study of the effects of non-uniform torsion in the construction stages of curved incrementally launched bridges is presented. The aim is to extend a methodology, previously applied to straight and curved bridges, to the analysis of non-uniform torsion in order to evaluate whether stresses due to torsional warping have a significant influence on the global state of stress during launching or not and what differences occur between closed concrete or steel box sections and open sections of I-girders, by performing a numerical application in which a comparison of different cross-section typologies is developed.

In order to explain the context in which the proposed approach can be framed, a brief literature review is given here. The first studies on warping effects in thin-walled structures were carried out by Vlasov [6] and Timoshenko and Gere [7], through the so-called "theory of sectorial areas". Important contributions were made by Kollbrunner and Basler [8] while Schardt [9] proposed the Generalised Beam Theory (GBT), as a generalisation of Vlasov's theory. Afterwards Nakai and Yoo [10] proposed different methods of solution for open and closed sections, while Maisel [11] presented a comprehensive approach to the analysis of non-uniform torsion, distortion and shear lag for concrete box girders. The classical solution method found in the literature is the analogy of the beam on elastic foundation (BEF analogy) [12]. Calgaro and Virlogeux [13] instead presented an alternative analytical solution, based on the Transfer Matrix Method (TMM), which is distinct for closed and open sections. Jönsson [14] and Park et al. [15] analysed the behaviour of open and closed sections with a unified approach, by considering the distortion of mono-cell and multi-cell box sections. Razaqpur and Shah presented valuable contributions to the analysis of the beam on two-parameter foundation [16], which are helpful for implementing the BEF analogy, while Razaqpur and Li presented a refined analysis of straight and curved thin-walled box girders through FEM [17]. Sapountzakis and Mokos implemented the Vlasov theory in boundary element procedures [18]. Recently Murìn et al. [19,20] implemented a new effective straight beam finite element for the solution of non-uniform torsion by FEM.

In this paper the solution is found through the Hamiltonian Structural Analysis (HSA) method, which can be considered a generalisation of the TMM based on an energetic approach and on the definition of the Hamiltonian function [21]. The method is fast and useful for repetitive computations, as occurs for incrementally launched bridges, being very competitive with the FEM or BEM solutions, which in these cases could be too onerous, as it will be discussed in the following. Moreover, the methodology has already been applied to curved beams on two-parameter foundations, which present a mathematical form of the solution that is similar to the one of curved girders with non-uniform torsion, deducing the exact solution of the problem.

The solution of straight continuous girders of incrementally launched bridges was developed by Rosignoli [22] through the TMM, by also considering misplacements of launching bearings, temperature effects and prestressing for concrete girders. Contributions to the extensive use of this methodology and to the evaluations of the interaction between nose and deck were made by Sasmal et al. [23,24]. Recently the problem of nose optimisation was also studied with advanced optimisation techniques by Fontan et al. [25,26]. Previous studies extended this methodology of analysis to horizontally curved bridges, disregarding the effects of warping stresses and considering the global behaviour of the curved deck during launching, deducing the envelope diagrams