Journal of Constructional Steel Research 108 (2015) 1–10

Contents lists available at ScienceDirect

Journal of Constructional Steel Research

Torsional behaviour of curved composite beams in construction stage and diaphragm effects

Yanling Zhang [a], Zhongming Hou [b,*], Yunsheng Li [a], Yuanqing Wang [b]

[a] School of Civil Engineering, Shijiazhuang Tiedao University, Shijiazhuang 050043, Hebei Province, China
[b] Department of Civil Engineering, Tsinghua University, Beijing 100084, China

ARTICLE INFO

Article history:
Received 17 September 2014
Accepted 25 January 2015
Available online 18 February 2015

Keywords:
Curved composite beam
Construction stage
Analytical analysis
Restrained torsion
Diaphragm spacing
Warping stress ratio

ABSTRACT

During the concrete-casting process of curved steel–concrete composite beams in construction stage, all loads including the wet concrete weight are carried by the curved open thin-walled steel girder. In order to determine the required diaphragm spacing, firstly the curved girder is simplified to straight one by using the *M*/*r* method, and its torsional behaviour is subsequently derived by solving the restrained torsional differential equation with the initial parameter method, where the discrete diaphragms are treated to be equivalent to a continuous elastic thin plate. Taking the maximum stress ratio of the warping normal stress to the bending normal stress as the control index, effects of the number of diaphragms, the span of the curved girder, the span-to-radius ratio, the girder height and the flange width on the stress ratio are studied. The parametric analysis results indicate that with the increase of the number of diaphragms, the stress ratio decreases exponentially; and with the increase of the span-to-radius ratio, the warping stress ratio increases linearly; additionally, longer span leads to reduced stress ratios, but the variation of the girder height and the flange width has little influence on the stress ratio. Calculation formulae for determining the required diaphragm spacing are obtained eventually by regression analyses. Based on the research outcomes herein, given the limit value of the warping stress ratio in the practical design of curved composite beams under construction, the maximum diaphragm spacing of the open thin-walled steel girder can be determined by using the formulae proposed in this paper.

1. Introduction

Due to the excellent performance in terms of higher loading capacities and larger flexural stiffness, composite beams are widely used in municipal buildings and bridge structures. More and more newly-built high-speed railway bridges also give preference to composite beams in the preliminary design phase just because of their excellent mechanical and economic performance [1,2]. In the construction of such infrastructure, curved composite beams can be always found as bridge and highway interchanges. Combined effects of bending, shear and torsion will occur when the curved composite beams are subjected to external loads. For this reason, the box section, which has great torsional stiffness and is composed of a concrete slab and an open U-shaped steel girder, is usually considered as one of the optimum schemes. Nevertheless, some concerns over the torsional behaviour of such beams in the concrete-casting stage should not be overlooked. When the construction load is only carried by the open U-shaped steel girder with weak torsional stiffness, the steel girder and transverse braces will probably yield prematurely.

Usually, transverse structural members (such as lateral bracing systems between the upper flanges, internal cross frames between the webs, as shown in Fig. 1a) are used to increase the torsional stiffness of the curved composite box beam in the construction stage, and some relative research has been conducted. The lateral braces were modelled by means of virtual steel plates with an equivalent thickness, so as to transform the open U-shaped steel girder to the so-called "quasi-closed box girder" [3,4]. Fan and Helwig conducted detailed analyses on the mechanical mechanism of the lateral bracing systems and the internal cross frames, which proposed a fundamental theory for the subsequent research [5,6]. By using the finite element (FE) method, Kim and Yoo [7] proposed a calculating method for the internal force within K-type transverse braces in box steel girders, afterwards the bending behaviour of the semi-closed trapezoidal box section with X-type internal braces was studied by Kyungsik and Chai [8], and the matrix solution to the internal force of the braces was presented. In general, most of the solutions afore-mentioned were based on the numerical methods, and few theoretical derivations were involved.

In China, the open U-shaped section steel girder with internal diaphragms is more commonly used in the curved composite beams, as shown in Fig. 1b. Some research on the required diaphragm spacing of closed box composite beams and steel girders were carried out (e.g. the work by Oleinik and Heins [9], Park et al. [10,11], Li and

* Corresponding author.
E-mail address: hou.zhong.ming@163.com (Z. Hou).

http://dx.doi.org/10.1016/j.jcsr.2015.01.021
0143-974X/

a

b

Fig. 1. Steel girder with lateral bracing systems. Steel girder with internal diaphragms.

Luo [12], Yabuki and Arizumi [13]). The codes of AASHTO [14] in the USA and HEPC in Japan [15] specified calculation formulae of the diaphragm spacing in curved composite beams, in which the ratio of distortional warping stresses to bending normal stresses is limited. However, all the research results and design guidance concerned the closed section, which may not be applied to the open section.

Up to now, the transverse brace of open I-shaped steel girders has been studied a lot (e.g. the work by Jerome, Dan and Luis [16], Park, Hwang S Y and Hwang M [17], Nguyen, Moon and Le [18], Joo, Moon and Choi [19]); Yoo and Littrell [20] studied the I-shaped curved composite beam by using a three-dimensional FE model, and preliminarily estimated values of the maximum space for brace frames were obtained through regression analyses. Taking the ratio of the warping stress to the bending normal stress as the control parameter, the estimation formulae proposed in the afore-mentioned study were further improved by Davidson, Keller and Yoo through FE analyses [21]. Nevertheless, the corresponding fundamental mechanism of the internal bracing in open I-shaped steel girders is different from that of the diaphragm in the composite beams with open U-shaped steel girders in the construction stage. For I-shaped girders, the effect of the transverse bracing system is just related to the connection between the steel girders, which may hardly increase the sectional stiffness; whilst for the open U-shaped girders, the diaphragms play a more important role for strengthening the sectional stiffness of the open section, which produce in between torsional stiffness, neither that of the open section nor that of the close section. Generally, little research has hitherto concerned the diaphragm effect on the torsional behaviour of the composite beams with open U-shaped steel girders in the construction stage, and the corresponding design guidance is not particularly specified in national standards.

In the paper, the curved composite beam with a thin-walled and open U-shaped steel girder in the concrete-casting stage was studied. Through the M/r theory and initial parameter solution methods, the torsional behaviour was investigated to elucidate the diaphragm effect on the torsional performance of the open thin-walled steel girder. Taking the ratio of warping normal stresses to the bending normal stresses as the control parameter, calculation equations of the diaphragm spacing of the curved composite beams in the construction stage were derived by parametric analyses.

2. Restrained-torsion effect on the curved open thin-walled beam

In the process of concrete-casting for curved steel–concrete composite beams, the wet concrete can be treated as uniformly distributed loads which are completely carried by the steel girder. Hereinafter, a curved simply-supported composite beam with two anti-torque supports, which belongs to a statically indeterminate structure, was focused. Its layout plan and cross-section charts are shown in Fig. 2. Several diaphragms with upper flanges were set along the beam axis. Similar to the steel girder, head-studs were welded on the upper flange of the diaphragms to provide a composite effect after the concrete hardening.

Bending and torsional moments of the statically indeterminate curved simply-supported beam under vertical uniformly distributed load can be solved through the structural mechanics, but the diaphragm effect on the torsional behaviour of the curved beam is not convenient to be obtained by the above method. To solve this problem, in the analysis below the curved beam was transformed into a straight one through the M/r method, then the torsional behaviour and diaphragm effect were analysed by using the initial parameter method.

2.1. Solution to the internal forces of the curved beam based on M/r method

In 1970, Tung and Fountain proposed an approximate method to analyse the torsional behaviour of curved girders, which is very simple and efficient and named after the M/r method [22]. Its computational principles are illustrated in Fig. 3.

In this method, the sectional bending moment of the curved open box beam produced by the vertical load is expressed as a pair of equal axial forces with opposite directions, which act in the upper and lower flanges, respectively [6]. Taking an infinitesimal element ds of the lower flange of the steel girder as the study object, when the bending moment is positive, the tangential tension forces at both sides of the bottom flange of the element are not equal due to the effect of the curvature, so the lateral force $(M/(rh))$ that is perpendicular to the axis and towards the inside of the curve is induced, as shown in Fig. 3(a). Similarly, the equivalent lateral distributed force towards the outside of the curve will also appear at the upper flanges of the steel girder. As a result, the effect of the axial curvature can be equivalent to a pair of antisymmetric forces that act at the upper and lower flanges, respectively, and result in the sectional torque, M/r.

The general steps of the torsional moment calculation for the curved beam by using the M/r method are given as follows:

(1) To straighten the curved beam along the axis with the same boundary conditions being remained, and to calculate the bending moment (M) of the straight beam under vertical loads;
(2) To divide the moment (M) by the radius (r), and the value of M/r being obtained;
(3) Taking the arc length l between the anti-torque supports as the calculation span, the value of M/r as the external distributed torque load of the straight beam, and supposing the boundary condition is simply-supported, and then the internal torsional moment being obtained, which is just the torsional moment of the curved beam.

The bending moment $M(z)$ of the equivalent straight beam (Fig. 4) that is transformed from the curved beam in Fig. 2 is written as

$$M(z) = \frac{q}{2} z(l - z) \tag{1}$$