Engineering Structures 99 (2015) 582–602

Contents lists available at ScienceDirect

Engineering Structures

journal homepage: www.elsevier.com/locate/engstruct

Generalised Beam Theory (GBT) for composite beams with partial shear interaction

Gerard Taig, Gianluca Ranzi *

School of Civil Engineering, The University of Sydney, NSW 2006, Australia

ARTICLE INFO

Article history:
Received 5 August 2014
Revised 18 May 2015
Accepted 18 May 2015
Available online 6 June 2015

Keywords:
Composite beam
Partial interaction
Steel
Concrete
Generalised Beam Theory (GBT)
Dynamic approach

ABSTRACT

This paper presents a theoretical model for the partial interaction analysis of composite steel–concrete beams within the framework of Generalised Beam Theory (GBT). The main contribution of this work relies on its ability to account for the deformability of the longitudinal shear connection between the slab and the steel beam, commonly known as partial shear interaction, in the evaluation of the cross-sectional deformation modes. This approach can handle arbitrary composite cross-sections, in which more than one shear connection can exist between the concrete and steel components, and for which the steel beam can be formed by open, closed or partially closed cross-sections. The proposed GBT approach falls within a category of cross-sectional analyses available in the literature for which a suitable set of deformation modes, including conventional, extension and shear, is determined from dynamic analyses. In particular, the deformation modes are selected as the dynamic eigenmodes of an unrestrained planar frame representing the cross-section. Warping is then evaluated for the conventional modes in a post-processing stage taking account of the kinematic discontinuity at the interface, while in the evaluation of the shear modes the partial interaction behaviour is included in the out-of-plane dynamic analysis. Two numerical composite examples, one where the bottom component consists of an open steel section and one based on a partially closed one, are presented to highlight the ease of use of the proposed partial interaction formulation for different levels of shear connection stiffness. The accuracy of the numerical results is validated against those calculated with a shell finite element model developed in ABAQUS.

1. Introduction

Composite steel–concrete beams are widely used throughout the world for building and bridge applications. Their advantage relies on the ability to couple the contribution of both steel joist and concrete slab by means of an interface shear connection, commonly provided in the form of shear connectors. In this manner, the rigidity and strength of a composite member are higher than those exhibited by the contributions of the two steel and concrete components considered in isolation. With this arrangement, the flexibility of the interface properties plays an important role in the response of the composite member by producing a relative movement between the steel beam and the slab (usually referred to as slip), and needs to be included in the structural modelling for accurate predictions. The first analytical model presented in the open English literature and able to account for the slip behaviour, also commonly referred to as partial shear interaction, is the one by Newmark et al. [1], who highlighted the influence of the longitudinal shear connection rigidity on the flexural composite response. This analytical model is commonly referred to as Newmark model and its formulation relies on the coupling of two Euler–Bernoulli beams by means of a deformable shear connection distributed along their interface. Since then, several researchers have extended the applicability of Newmark model to account for material nonlinearities (e.g. [2–10]), time-dependent behaviour of the concrete (e.g. [11–17]), shear-lag effects (e.g. [18–22]), geometric nonlinearities (e.g. [23,24]), partial interaction perpendicular to the shear connection interface, i.e. transverse partial interaction (e.g. [25–28]) and the use of the Timoshenko beam model for one or both composite components (e.g. [29–36]). Considerations to include higher order beam theory to provide a more accurate representation of the shear deformability of composite members have been presented in the literature, e.g. [37–40]. A composite beam model developed within the framework of the Generalised Beam Theory (GBT) [41–43], therefore able to consider a thin-walled section for the steel beam, has been presented by Goncalves and Camotim [44] in which the partial interaction behaviour has been considered in the analysis by including a rigid mode associated to the

* Corresponding author. Tel.: +61 2 9351 5215; fax: +61 2 9351 3343.
E-mail address: gianluca.ranzi@sydney.edu.au (G. Ranzi).

http://dx.doi.org/10.1016/j.engstruct.2015.05.025
0141-0296/

longitudinal slip. While a number of approaches have been proposed in the literature to describe the behaviour of thin-walled members, including the finite strip method (FSM) [45–50], the finite element method (FEM) [51–53] and the perturbation methods [54–57], the procedure at the basis of the GBT is of particular interest to this paper. Its particularity relies on its ability to capture the deformation of the cross-section which occurs in the structural response of thin-walled members. The displacement field adopted with the GBT approach is described as a linear combination of deformation modes of the cross-section (including both in-plane and warping deformations) and intensity functions (representing the unknowns of the member analysis). With this arrangement, the GBT approach makes use of two analyses: (1) a cross-sectional analysis aimed at evaluating a suitable set of deformation modes, and (2) a member analysis required for the determination of the intensity functions. In this manner, a three-dimensional continuous problem is transformed with the GBT into a vector-valued one-dimensional problem.

In this context, this paper extends the applicability of the dynamic GBT approach proposed in references [58–63] to study the partial shear interaction behaviour of composite steel–concrete members. The novelty of this work relies on the ability of the proposed approach to identify a suitable set of GBT deformation modes, including conventional, extension and shear, which account for the partial shear interaction of the composite member. In particular, the deformation modes are selected as the dynamic eigenmodes of an unrestrained planar frame representing the cross-section. Warping is then evaluated for the conventional modes in a post-processing stage taking account of the kinematic discontinuity at the interface, while in the evaluation of the shear modes the partial interaction behaviour is included in the out-of-plane dynamic analysis. This advancement is particularly useful for composite members in which steel sections have more than one line of shear connectors embedded within the concrete slabs, as it is the case, for example, of composite box girders typically used in bridge applications. In these instances, the development of slip produces a deformation of the cross-section. The material properties are assumed to be isotropic and linear-elastic. Applications are presented to highlight the influence of different shear connection rigidities on the structural response of two composite members, i.e. one with the steel beam being a lipped channel section and one being a closed box section. The accuracy of the numerical results is validated against the values obtained with a shell element model developed using the finite element software ABAQUS [64].

2. Basis of the GBT approach for composite cross-sections

2.1. Displacement and strain fields

A prismatic steel–concrete composite beam is made of a reinforced concrete slab and a steel beam, as shown in Fig. 1. In its undeformed condition, the composite beam occupies the cylindrical region $V = A \times [0, L]$ generated by translating its cross-section A, with regular boundary ∂A, along a rectilinear axis orthogonal to the cross-section and parallel to the Z-axis of an ortho-normal reference system $\{O; X, Y, Z\}$. The composite cross-section domain is formed by the slab referred to as A_1, and by the steel beam, referred to as A_2, where the latter can comprise of thin flat plates with open, closed or partially closed profiles (Fig. 1).

With this approach both slab and steel beam are represented by a set of (generally, but not necessarily, flat) thin plates, free to bend in the plane orthogonal to the member axis. The displacement field $\boldsymbol{u}(s, z)$ of a generic point lying on the mid-surface of the plates forming the cross-section is described by:

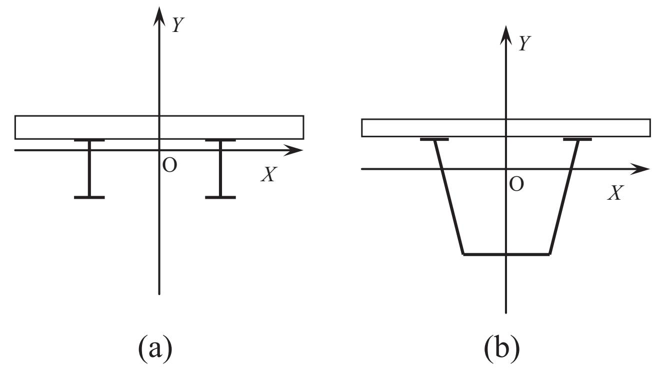

Fig. 1. Typical composite steel–concrete cross-sections.

$$\boldsymbol{u}(s, z) = u(s, z)\boldsymbol{i} + v(s, z)\boldsymbol{j} + w(s, z)\boldsymbol{k} \quad (1)$$

where s is the curvilinear abscissa along the sections mid-line C, z is the coordinate along the member axis, $\boldsymbol{i}, \boldsymbol{j}$ and $\boldsymbol{k}$ are unit vectors in the tangential, transverse and longitudinal directions at the abscissa s, respectively, and $u(s, z)$, $v(s, z)$ and $w(s, z)$ are the displacement components in the same triad (Fig. 2).

The composite action between the two components is provided by N_{SC} continuous deformable shear connections placed along rectilinear lines Λ_n (with $n = 1, \ldots, N_{SC}$) at the interface between the two layers, whose domains in the top and bottom components consists of the points identified by (s_1^n, y_1^n, z) and (s_2^n, y_2^n, z), with subscripts '1' and '2' referring to the (top) reinforced concrete slab and (bottom) steel beam, respectively (Fig. 3a). The curvilinear abscissas s_1^n and s_2^n identify the locations of the n-th shear connection within the mid-planes of the cross-sections of the top and bottom components, respectively, while variables y_1^n and y_2^n depict the distances along the local y-axis between the n-th shear connection interface and the mid-plane of the two components, as illustrated in Fig. 3a and b. The interface connections are assumed to enable only interlayer slip parallel to the beam axis, therefore preventing transverse partial interaction and vertical separation between the two layers.

Using Kirchhoff plate theory, the displacement of an arbitrary point within the plate's thickness is defined as:

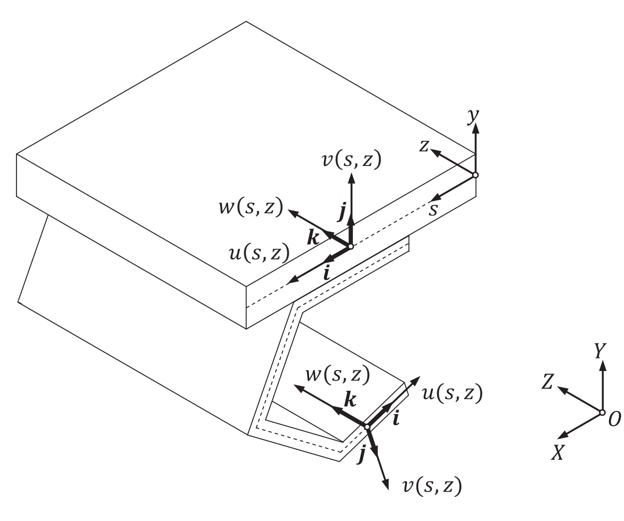

Fig. 2. Displacement field.