Engineering Structures 139 (2017) 120–134

Contents lists available at ScienceDirect

Engineering Structures

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

A higher order model for inelastic response of composite beams with interfacial slip using a dissipation based arc-length method

Md. Alhaz Uddin [a], Abdul Hamid Sheikh [a,*], David Brown [a], Terry Bennett [a], Brian Uy [b]

[a] School of Civil, Environmental and Mining Engineering, The University of Adelaide, Adelaide, SA 5005, Australia
[b] School of Civil Engineering, The University of Sydney, Sydney, NSW 2006, Australia

ARTICLE INFO

Article history:
Received 18 October 2016
Revised 30 January 2017
Accepted 8 February 2017

Keywords:
Steel-concrete composite beam
Partial shear interaction
Higher-order beam theory
Inelastic material behaviour
Dissipation based arc-length method

ABSTRACT

An efficient one dimensional finite element model is developed for an accurate prediction of the inelastic response of steel-concrete composite beams with partial shear interaction using a higher-order beam theory (HBT). This is achieved by taking a third order variation of the longitudinal displacement over the beam depth for the two layers separately. The deformable shear studs used for connecting the concrete slab with the steel girder are modelled as distributed shear springs along the interface between these two material layers. A plasticity model based on von Mises yield criterion and a damage model are used to simulate the inelastic behaviour of beam materials. An arc-length method based on energy dissipation is employed to capture the post peak response successfully. The capability of the proposed model is assessed through its validation and verification using existing experimental results and numerical results produced by detailed finite element modelling of these beams.

1. Introduction

Composite structures are widely used in various engineering activities for their superior structural performances. Steel-concrete composite beams belong to a specific type of composite structures, typically used in bridges, buildings and other civil engineering infrastructure. These structures consist of a concrete slab and a steel girder which are connected by steel shear studs to have composite action. The concrete slab is primarily utilised to carry the compressive stress whereas the steel girder carries the tensile stress to enhance the performance of the overall structural system. The shear connectors transfer shear forces at the interface between concrete and steel material layers. This leads to interfacial shear slip due to shear studs with finite stiffness which is commonly known as partial shear interaction [1]. As the contribution of partial shear interaction on the structural behaviour is found to be significant (e.g. [2,3]), this effect can't be ignored in the analysis of these composite beams. This is an active area of research which is best demonstrated by the large number of studies on different aspects of composite beams. However, the main aim of the present study is to develop an efficient model for accurately predicting the inelastic response of composite beams.

Newmark et al. [4] is one of the earliest researchers who developed an analytical model for composite beams where the effect of partial interaction was considered in the form of shear slip. This is a well-regarded model but only applicable to beams with simply supported boundaries and relatively simple loading due to the analytical nature of the model. In contrast, a numerical model based on finite element approximation can provide adequate generality in the analysis with sufficient accuracy. Thus a number of researchers (e.g. [5–9]) have developed finite element models for composite beams with partial interaction. However all these models [5–9] are based on elastic behaviour of beam materials. In reality, the materials of these beams are having inelastic deformations even with a low to moderate range of loading. In order to address this issue, Yasunori et al. [10] incorporated the effect of inelastic material behaviour in their finite element model of composite beams using the von Mises yield criterion. However, they [10] used a very simple material model based on an elastic perfectly-plastic idealisation for all materials including concrete which is not realistic especially for the tensile response of concrete. Similar studies have been carried out by Salari et al. [11] using a bi-linear elasto-plastic material model with a strain hardening parameter. A further development in this direction is due to Dall'Asta and Zona [12] and Erkmen and Attard [13] who have used realistic stress strain curves for the beam materials but Dall'Asta and Zona [12] have ignored the contribution of concrete in tension whereas Erkmen and Attard [13] have used the concept of tension stiffening for its modelling.

* Corresponding author.
E-mail address: abdul.sheikh@adelaide.edu.au (A.H. Sheikh).

http://dx.doi.org/10.1016/j.engstruct.2017.02.025
0141-0296/

Nomenclature

A_c, A_s	cross-sectional area of concrete and steel layers of the beam
$[B]_l$	strain-displacement matrix for the lth layer ($l = c$ for concrete, $l = s$ for steel)
$[B]_{sh}$	strain-displacement matrix for shear connectors
$\{dR\}$	residual force vector
e_d	prescribed dissipation energy
E_l	elastic modulus for the lth layer
$[E^{cr}]$	tangent damage stiffness matrix for concrete
$[E^{ep}]_l$	elasto-plastic constitutive matrix for the lth layer
f_l	von Mises yield function for the lth layer
$\{F_{ext}\}$	external load vector
G_l	shear modulus for the lth layer
G_f	fracture energy
$[H]_l$	cross-sectional matrix for the lth layer
H_l'	hardening parameter for the lth layer
H_{sc}'	hardening parameter for shear connectors
k_{sh}	elastic stiffness of distributed springs for shear connectors
k_{sh}^{ep}	elasto-plastic tangent stiffness for shear connectors
$[K_T]$	tangent stiffness matrix
l_e	element length
N	shape function
$\{P_{\text{int}}\}$	internal nodal force vector
q	distributed external load
s	interfacial slip between concrete and steel layers
s^e	elastic shear slip between concrete and steel layers
s^p	plastic shear slip between concrete and steel layers
s_{ef}^p	effective plastic shear slip between concrete and steel layers
u_{c0}	longitudinal displacement of the concrete layer at its centroidal or reference axis
$\bar{u}_c$	longitudinal displacement at the bottom fibre of the concrete layer
u_{s0}	longitudinal displacement of the steel layer at its reference axis
$\bar{u}_s$	longitudinal displacement at the top fibre of the lower layer
w	transverse displacement
w_c	crack band width
α, β	higher order terms
$\{\Delta\}$	nodal displacement vector
$\{\boldsymbol{\varepsilon}\}_c$, $\{\boldsymbol{\varepsilon}\}_s$	strain vectors of concrete and steel layers
$\{\varepsilon^e\}_l$	elastic strain vector for the lth layer
$\{\varepsilon^p\}_l$	plastic strain vector for the lth layer
ε_l^p	plastic normal strain for the lth layer
$\varepsilon_{ef,l}^p$	equivalent plastic strain for the lth layer
$\{\bar{\varepsilon}\}_l$	one dimensional strain vector for the lth layer
γ_l^p	plastic shear strain for the lth layer
κ_{ef}	equivalent strain parameter
$d\lambda_l$	incremental plastic strain multiplier for the lth layer
μ	load factor (or multiplier)
θ_c, θ_s	bending rotations of concrete and steel layers
$\{\sigma\}_c$, $\{\sigma\}_s$	stress vectors of concrete and steel layers
$\sigma_{ef,l}$	effective stress for the lth layer
$\sigma_{y,l}$	uniaxial yield stress for the lth layer
σ_l	bending stress for the lth layer
σ_{t0}	uniaxial ultimate tensile stress
$\sigma_{\max}$	maximum principle stress
τ_l	shear stress for the lth layer
τ_{sh}	distributed shear force (per unit length) at the interface between concrete and steel layers
ω	damage parameter

A more comprehensive model is proposed by Liu et al. [14] where the tensile behaviour of concrete is simulated using a damage mechanics model which can precisely model the tensile response of plain concrete without reinforcement. Foraboschi [15] and Foraboschi et al. [16] attempted to solve the composite beam problem analytically but the structure is idealised in a different manner where the shear connector is modelled as a separate material layer with a finite thickness. Moreover, the inelastic material behaviour is consider only for this interfacial layer whereas the primary layers (concrete slab and steel girder) are treated as linear elastic materials. Anyway, all these models [4–16] are based on Euler-Bernoulli beam theory (EBT), which does not consider the effect of transverse shear deformation of the steel and concrete layers. The effect of this shear deformation is significant in some situations such as beams with a small span-to-depth ratio, localized concentrated loads, clamped boundary conditions and some other cases.

Thus there has been a growing interest in recent years to incorporate the effect of shear deformation and the Timoshenko's beam theory (TBT) is typically used for this purpose (e.g., [17–21]). It is observed that all these investigators [17–21] have used linear elastic material behaviour to develop their models except Nguyen et al. [21], who have used a very simple constitutive model specifically for the concrete. Moreover, it should be noted that the actual variation of transverse shear stress over the beam depth is parabolic, whereas an average shear stress having a uniform distribution is taken in TBT to simplify the problem. In order to address this issue, TBT needs an arbitrary shear correction factor which helps to predict the global response such as deflection or vibration frequency well, but it is not sufficient for an accurate prediction of the local response such as the stress distributions within these structures [22–24]. Moreover, the calculation of the exact value of this shear correction factor for a composite beam with partial shear interaction is cumbersome in comparison with that of a single layer homogeneous beam.

In order to address the aforementioned issues related to shear deformation of the beam material layers, a higher-order beam theory (HBT) has recently been developed by Sheikh and co-workers [22–24] for an accurate prediction of global as well as local responses of these composite beams. The cross-sectional warping of the beam layers produced by the transverse shear stress is modelled with a higher order (3rd order) variation of longitudinal displacement of the fibres over the beam depth. This beam theory (HBT) utilised the concept of Reddy's higher order shear deformation theory [25] developed for multi-layered laminated composite plates modelled as single layered plates without interfacial slip. In these investigations [22–24], HBT has been implemented in a one dimensional finite element model which has exhibited very good performance, though these studies are restricted to linear elastic analysis of these composite beams with interfacial slip.

Considering the aforementioned aspects, an attempt is made in this study to develop an efficient numerical model based on HBT for accurately predicting the inelastic response of composite beams. The inelastic material behaviour is responsible for inducing nonlinearity in the structural response, which can be manifested in the form of nonlinear load-deflection curves. These curves can sometimes have a descending branch after attaining the peak load due to the strain-softening of concrete. It is observed that most of the investigations carried out on the inelastic response of composite beams [10–14,21] could not capture the descending branch of