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A beam finite element including shear lag effect for the time-dependent analysis of steel–concrete composite decks

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ABSTRACT

The paper presents a beam finite element for the long-term analysis of steel–concrete composite decks taking into account the shear lag in the slab and the partial shear interaction at the slab–girder interface. Using the displacement approach, beam kinematics is developed from the Newmark model for composite beams with partial shear connection; warping of the slab cross section is caught with the product of an established function which describes the warping shape, and an intensity function that measures the warping magnitude along the beam axis. Time-dependent behaviour is considered through an integral-type viscoelastic creep law for the concrete. The numerical solution is obtained by means of the finite element method and a step-by-step procedure for evolution in time. A refined, locking free, 13-*dof* beam finite element is derived considering second and third order hermitian polynomials in order to ensure consistent interpolation of the displacements. The convergence test results and comparisons with the experimental results of composite beams subjected to sustained loads demonstrate the precision of the proposed method. Further applications to realistic cases show the accuracy of the proposed element and its ability to describe the elastic and the time-dependent behaviour of bridge composite decks.

1. Introduction

Twin-girder decks are widely used in the modern construction of steel–concrete composite bridges even in the case of large viaducts with double carriageway having an upper concrete slab of more than 25 m wide. The analysis of these structures cannot neglect the warping of the slab cross section, and the concentration of stresses in the slab regions around the steel beams (shear lag effect) is usually taken into account for design and verification purposes by adopting the effective slab width [1,2]. In addition to the shear lag effect due to vertical loads, other stress concentrations may arise in the slab due to the application of longitudinal forces as in the case of prestressing cable or stay anchorages, and in the case of differential stress independent deformations (e.g., shrinkage, thermal effects). In all these cases the simplified method of the effective width proposed by the main codes of practice (e.g., EN 1994-2) [3] is not always conservative [4,5] and may lead to significant errors. The stress concentration may then only be caught with refined finite element analyses. Modelling a composite bridge with shell or solid finite elements requires specialised know-how and must be carried out by expert designers; the results of such analyses are not concise and need to be post-processed both to control their reliability and verify the structure. On the contrary, analyses performed by means of one-dimensional finite elements permit easier and faster input and may even furnish stress resultants that are more useful for design purposes.

Shear lag effects have long been investigated by researchers for many decades. Von Kármán [6] introduced the concept of effective width in aeronautical structures; then Reissner [7] introduced the concept of shear lag in structural engineering and analyzed box girders by introducing a parabolic shape function to describe transversal warping due to shear lag. More recently, with regard to composite beams, Gjelsvik [8] investigated shear lag with an analog-beam method while Dezi et al. [9] used the Reissner method to enrich the well-known Newmark model [10] specifically devoted to composite beams with partial shear connection. Many approaches are available to solve the equations governing the problem but nowadays the finite element method is undoubtedly the most used so that defining specific elements capable of taking into account the effects of shear lag becomes important.

In the case of composite beams with flexible shear connection several finite element approaches, based on the Newmark model, are available in the literature: displacement-based elements with

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Notations

The following symbols are used in this paper:

$\boldsymbol{a}$	vector grouping geometrical quantities;
A	cross section area;
$\boldsymbol{A}$	inertia matrix;
$\boldsymbol{b}$	body forces;
B, B_1	half a slab width and half a twin-girder spacing;
C	inertia defined by Eq. (24d);
d	differential operator;
$\boldsymbol{d}$	vector grouping the generalised displacement components;
D	cross section domain;
$\mathcal{D}$	linear differential operator;
E	Young's modulus;
f	shear lag function;
$\boldsymbol{f}$	nodal forces;
$\mathcal{H}$	linear differential operator;
I	generalised second moment of area;
$\boldsymbol{i}, \boldsymbol{j}, \boldsymbol{k}$	unit vectors;
J	creep function;
$\boldsymbol{K}$	stiffness matrix;
L	deck length;
m	bending moment resultant of external loads;
M	bending moment;
n_t	number of time intervals;
$\boldsymbol{n}$	vector grouping the stress resultants;
N	axial force;
$\boldsymbol{N}$	matrix of interpolating polynomials;
O	origin of the frame of reference;
$\boldsymbol{p}$	vector of the resultants of the external loads;
q	force resultant of the external loads;
Q	bi-shear;
r	shear flow at the beam–slab connection;
$\boldsymbol{r}$	vector grouping the stress resultants;
$\boldsymbol{s}$	surface forces;
S	generalised first moment of area;
$\boldsymbol{S}$	Cauchy symmetric stress tensor;
t	actual time;
$\boldsymbol{u}$	displacement field;
v	vertical displacement of the composite cross section;
$\boldsymbol{v}$	vector of nodal displacements;
V	volume integration domain;
w	longitudinal displacement;
W	bi-moment;
x, y, z	coordinates;
X, Y, Z	axes of the reference frame;
γ	shear strain;
Γ	slip at the beam–slab interface;
ε	normal strain;
η	local longitudinal coordinate;
θ	current time;
λ	non-dimensional abscissa of the finite element;
ν	Poisson's ratio;
ξ	curvilinear abscissa;
ρ	stiffness per-unit-length of the shear connection;
σ	normal stress;
τ	shear stress;
φ	rotation;
ψ	slab warping function; and
ω	bi-moment resultant of the external loads.

Subscripts

0	reference value;
c	concrete;
$conn$	shear connection;
e	generic finite element;
r	reinforcement;
s	steel beam; and
si	stress independent.

Superscripts

c	concrete;
r	reinforcement;
s	steel beam; and
T	transposed matrix.

nonpolynomial [11] or polynomial [12,13] shape functions; force-based elements [14] and mixed elements [15,16]. Amongst others, the displacement approach is the most widely used since it permits studying different issues such as nonlinear behaviour [17,18], long-term behaviour [19], and construction sequences [20]. Furthermore, by exploiting closed form solutions for the linear elastic case, direct stiffness approaches were also developed [21].

Beam finite elements for the elastic analysis of the shear lag effect have recently been proposed by some authors. Prokić [22] presented a displacement-based finite element for thin-walled beams; Dezi et al. [23] proposed a 13-*dof* displacement-based finite element for composite beams, while Sun and Bursi [24], using the same displacement approach [9], formulated three displacement-based finite elements and two mixed elements as well as investigating locking problems. Nevertheless specific elements, appropriate for bridge structures, able to catch the effects of the shear lag phenomenon due to each action (e.g., transverse loads, internal prestressing of the slab, and thermal and shrinkage effects), the influence of the shear connection flexibility and, above all, the concrete time-dependent behaviour, are not yet available. The authors propose a finite difference analysis to study the shear lag effect in composite decks accounting for the deformability of shear connection and the long-term behaviour of the concrete slab [9]. Even if the method is general, its application is not straightforward for all kinds of restraints and load layouts.

In this paper a displacement-based 13-*dof* beam finite element for the long-term analysis of twin-girder composite bridge decks is proposed taking into account the warping of the slab cross section, the partial shear interaction between the slab and the girders, and the long-term behaviour of the deck due to concrete creep and shrinkage. The model also considers the effects of imposed longitudinal strains due, for example, to thermal effects and internal prestressing cables in the slab. The slab shear lag is taken into account with the product of a suitable warping function which describes the shape of slab cross section warping, and an intensity function that measures the magnitude of warping along the beam axis [7]. The time-dependent behaviour of the structure is caught by means of an integral type law that describes the viscoelastic behaviour of the concrete. The solving equilibrium condition is obtained in a weak form by enforcing the Virtual Work Theorem and a numerical solution is obtained by introducing a double discretization; the first for the time domain in order to apply the step-by-step general method, and the second for the beam axis in order to apply the finite element method. The proposed 13-*dof* finite element is refined thanks to an internal node and hermitian polynomials are chosen to ensure consistent interpolation [25].