Computers and Structures 157 (2015) 201–208

Contents lists available at ScienceDirect

Computers and Structures

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

Cracked span length beam element for service load analysis of steel concrete composite bridges

M.P. Ramnavas [a,1], K.A. Patel [a,1], Sandeep Chaudhary [b,*], A.K. Nagpal [a,1]

[a] Department of Civil Engineering, Indian Institute of Technology Delhi, Hauz Khas, New Delhi 110016, India
[b] Department of Civil Engineering, Malaviya National Institute of Technology, Jaipur 302017, India

ARTICLE INFO

Article history:
Received 12 March 2015
Accepted 19 May 2015
Available online 12 June 2015

Keywords:
Bridges
Cracking
Finite element analysis
Service load
Steel concrete composite
Tension stiffening

ABSTRACT

For instantaneous non-linear analysis of steel concrete composite bridges that are subjected to a service load, a cracked span length beam element has been proposed. The element consists of two cracked zones at the ends and one uncracked zone between the cracked zones. The element has been used to develop a hybrid analytical–numerical procedure for composite bridges. The procedure yields crack lengths and deflections as well as redistributed moments. The procedure would lead to a considerable reduction in the computational effort in the case of continuous steel concrete composite bridges that consist of a large number of spans.

1. Introduction

Steel concrete composite (SCC) girders are widely used in bridge construction. Bridge superstructure with SCC girders is a preferred option in urban infrastructure, such as grade separators, due to the comparative ease and speed in construction. Continuous SCC girders are gaining popularity owing to (i) the economy due to efficiency in design and (ii) increased riding comfort due to the elimination of joints. Continuous SCC girders are subjected to a hogging moment at the support regions, which causes tensile stresses in the concrete slab. With a service load, the concrete in the tensile zone generally cracks. For example, in an SCC continuous bridge, cracking could occur in the concrete slab near the supports, as shown in Fig. 1, where the cracked zones are shown. This cracking of the concrete at the serviceability limit state causes inelastic behaviour due to the redistribution of moments from the supports to the mid-span [1]. This effect is due to the reduction in the stiffness of the beam over the cracked regions, which causes a considerable moment redistribution along the member length and stress redistribution across the cross-sections. This phenomenon also causes an increase in the deflections. The cracked concrete sections have tension stiffening properties, which enables the concrete to further carry tensile stresses, resulting in stiffness that is more than that of the cracked sections [2]. The appropriate analysis of the SCC bridges when subjected to service loads for cracking is therefore important for obtaining an accurate evaluation of these effects.

Non-linear analysis is required to account for the effects of cracking of the concrete, and conventionally, either incremental or iterative methods are used for this purpose [2]. In these methods, numerical integration is used to obtain the cracked lengths, displacement vectors and load vectors of the beam elements, and the properties of the beam are updated with each iteration or increment. In the case of large structures, the computational efforts that are required in the numerical integration could be substantial.

There are various methods in the literature that are applicable for the non-linear analysis of composite structures (instantaneous and time dependent), at the service load stage. These methods can be further subdivided into two categories: (i) category 1 methods [3–8], which are numerical in nature, and (ii) category 2 methods [9–14], which are analytical in nature. Category 1 methods require discretization of the beam along the axis into a number of elements and therefore require a large computational effort. This arrangement will make the procedure exorbitantly large for large practical structures. On the other hand, category 2 methods are computationally efficient, but one or more aspects, such as progressive cracking of the concrete and tension stiffening, have been left out in some of the methods [13,14]. Furthermore, some of the methods [9–12] are applicable only for simply supported composite beams.

* Corresponding author. Tel.: +91 141 2713273.
E-mail addresses: ram.str.in@gmail.com (M.P. Ramnavas), iitd.kashyap@gmail.com (K.A. Patel), schaudhary.ce@mnit.ac.in, sandeep.nitjaipur@gmail.com (S. Chaudhary), aknagpal@civil.iitd.ac.in (A.K. Nagpal).
[1] Tel./fax: +91 11 26591234.

http://dx.doi.org/10.1016/j.compstruc.2015.05.024
0045-7949/

Nomenclature

A, B, I	area, first moment of area and second moment of area, respectively, of the composite section
A_{sr}	area of the steel reinforcement in the slab
A_{ss}	area of the steel section
b, D_c, D_s, D_{na}	breadth and depth of the concrete slab, depth of the steel section and depth of the neutral axis of the steel section from the top fibre, respectively
C_i	distance from the end A to the centre of the typical zone
$\{d^{er}\}, \{d^*\}$	error or difference in the displacement vector and the revised displacement vector, respectively
d_m, L	mid-span deflection and the span length, respectively
d_{sr}	effective concrete cover to the steel reinforcement from the top fibre
E	modulus of elasticity
$f_{ij}, k_{ij}, [k]$	flexibility, stiffness coefficients and stiffness matrix, respectively, of a member
f'_c	cylinder compressive strength of the concrete at 28 days
f_t	tensile strength of the concrete
L_i	length of the typical zone (cracked or uncracked)
$L_{i,cr}$	length of the cracked zone
M, N	moment and axial force, respectively
$\{P^0\}$	fixed end force vector for the uncracked beam
$\{P^{er}\}, \{p^{er}\}$	residual force vector of the structure and element, respectively
w, W	uniformly distributed load and concentrated load on the span, respectively
x	distance of the cross-section from end A in a beam
x'	distance of the cross-section from C in a typical zone
y	distance from the reference axis
θ, λ	end rotation and tolerance value, respectively
ξ, η	average interpolation coefficients
κ	coefficient that represents the influence of the duration of application or repetition of loading on the interpolation coefficient
$\rho, \varepsilon, \sigma$	curvature, strain and stress, respectively
$\varepsilon_t, \varepsilon_u$	cracking strain and maximum tensile strain of concrete, respectively
$\varepsilon_0, \varepsilon_y$	strain at a distance zero and y from the reference axis

Subscript

A, B	ends A and B of a cracked span length beam element, respectively
c, s	concrete and steel, respectively
cr, un, ts	cracked state, uncracked state and tension stiffening, respectively
i	i^{th} zone
ss	steel section
y	distance from the reference axis

Superscript

C, D, E	locations in a typical zone
m, n	moment and axial force, respectively

Another method, a hybrid procedure [15–18], considers the effects of cracking and tension stiffening; however, the formulations are cumbersome, and there is a scope for simplification.

Eurocode 4 – Part 2 [19] gives a general method and also a simplified method for use in specific cases. As per the general procedure, an 'uncracked analysis' with flexural stiffness of uncracked sections is to be performed, from which the stresses are calculated. In regions in which the extreme fibre tensile stress in the concrete exceeds twice the tensile strength, the properties should be reduced to those of a cracked section, and a cracked analysis is to be performed. A simplified method is given for specific cases of continuous beams with all of the ratios of adjacent spans (shorter/longer) not less than 0.6, in which the effect of cracking is accounted for by using the properties of cracked sections for 15% of the spans on either side of the internal supports and the properties of the uncracked sections elsewhere.

It can be seen that in the general method in Eurocode 4 – Part 2 [19] above, the properties are to be reduced to those of the cracked section in regions in which the extreme fibre stress exceeds twice the tensile strength. In effect, this approach reduces the length of the cracked zones and compensates for the tension stiffening effect; however, it involves an approximation. Hence, both the general and simplified methods in Eurocode 4 – Part 2 [19] could lead to some error in the estimation of the cracked lengths and, hence, in the analysis, in some cases.

From the foregoing discussion, it is clear that for an application to continuous SCC bridges, it is desirable to develop a procedure that requires a minimal computational effort but provides accuracy that is acceptable for practical applications. This approach requires a beam element that accounts for the effect of cracking. Herein, such a cracked span length beam element is proposed, and the same is used to develop a hybrid analytical–numerical procedure that incorporates the effects of cracking, for SCC bridges that are subjected to service loads. The procedure is analytical at the element level, whereas it is numerical at the structural level. For this purpose, a typical bridge span is modelled as a single element and is visualized as consisting of a maximum of three zones (cracked or uncracked). A bridge is visualized as consisting of several cracked span length beam elements, one for each span. Closed form expressions for the flexibility and stiffness coefficients and end displacements of the cracked span length beam elements have been obtained. The stiffness matrix and load vector can be obtained in a computationally efficient manner by using closed form expressions for the flexibility coefficients and end displacements. To keep the procedure analytical at the element level, average tension stiffening characteristics are arrived at for the cracked zones. This hybrid procedure, which involves the proposed element, yields crack lengths and deflections as well as redistributed moments. The developed procedure has been validated by comparisons with experimental results reported elsewhere and also by a comparison with Finite Element Analysis (FEA) results. The procedure requires a computational effort that is a fraction of that required for the category 1 methods that are available in the literature and discussed here.

2. Cross-sectional analysis

Fig. 2 shows a typical cross-section of a SCC bridge girder along with the strain distribution. It is assumed that the plane cross-section remains a plane after the bending of the bridge girder. It is also assumed that shear connectors are at a sufficiently close spacing that the slip between the slab and steel section can be neglected under a sustained service load, as per earlier experiments and studies [10,20]. It is further assumed that there is no slip at the interface of the steel reinforcement and the concrete. Before the cracking of the concrete, under the service load, the stress–strain relationship of the concrete is assumed to be linear