Engineering Structures 132 (2017) 733–744

Contents lists available at ScienceDirect

Engineering Structures

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

Service load analysis of composite frames using cracked span length frame element

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

[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, Jaipur 302017, India

ARTICLE INFO

Article history:
Received 14 December 2015
Revised 29 November 2016
Accepted 30 November 2016
Available online 10 December 2016

Keywords:
Composite frames
Cracking
Redistribution
Service load
Tension stiffening
Finite element analysis

ABSTRACT

A cracked span length frame element has been proposed for service load analysis of composite frames consisting of steel columns and steel-concrete composite beams. The element comprises a maximum of three regions (cracked or uncracked) with simplified formulation and is applicable for all types of loading. This element has been used in an analytical-numerical procedure for the inelastic analysis of such composite frames, subjected to service loads. Analytical expressions have been derived for flexibility and stiffness coefficients, end displacements, load vector and mid span deflections of the cracked span length frame element. Average values over the cracked regions have been used for the tension stiffening characteristics, so as to retain the analytical nature of the procedure at the element level. The procedure uses an iterative technique for establishing the cracked region lengths and the distribution coefficients (for tension stiffening), and yields the inelastic deflections and redistributed moments. The procedure using the proposed element has been validated by comparing the results with experimental results available in literature and also with the results obtained from finite element analysis. The procedure requires a fraction of the computational effort that is required for the numerical methods available in literature and gives sufficiently accurate results. Therefore, the reduction in the computational efforts in the case of high-rise composite frames would be considerable.

1. Introduction

Composite beams, with the concrete slab placed above the steel sections and connected by shear connectors, have high structural efficiency in resisting flexure and are widely used. This configuration provides lateral stability to the steel section in sagging moment regions and has the additional advantage that the concrete slab which forms the floor or deck is made use of, in making the steel-concrete composite member. In buildings with composite floors, the propping required during casting of concrete slab can be eliminated which results in faster construction. In addition, the number of floors in a building with a given height can be increased due to the reduced structural depth of composite beams which results in overall economy. Continuous composite beams have the advantages of lesser depth for given spans, lesser deflections, better seismic performance, overall economy, etc. compared to simply supported beams. Hence, these beams are used in multistorey composite frames (along with steel columns) in buildings.

The ends of the beams at the beam-column joints are generally subjected to hogging moments (Fig. 1). Due to the tensile stresses caused by these hogging moments, the concrete slab of composite beams, cracks at service loads. The cracking of concrete, in turn reduces the stiffness of the beam which causes redistribution of moments along the length of the beams and also to other spans and to the columns. This results in inelastic behavior of the frame with increase in the curvatures and deflections in the beams. Due to the presence of reinforcing steel, the phenomenon of tension stiffening occurs, which enables the concrete to carry some stresses even after cracking and contribute to the flexural stiffness of the beam [1–8]. The structural behavior due to cracking of the concrete is observed to be considerably nonlinear even at low stress levels [9–11]. Also, the use of high strength steel and high strength concrete, results in slender and sleeker sections [12–14], for which serviceability conditions, are likely to become the governing criteria. The appropriate inelastic analysis of the composite frames for service load, considering cracking of the concrete is hence desirable for the precise evaluation of forces and deformations.

---

* Corresponding author.

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).

http://dx.doi.org/10.1016/j.engstruct.2016.11.071
0141-0296/

Nomenclature

A, B, I	area, first moment of area and second moment of area of the composite section respectively
A_{sr}	area of the steel reinforcement in the slab
A_{ss}, I_{ss}	area and second moment of area of the steel section respectively
b, D_c, D_s	breadth and depth of the concrete slab and depth of the steel section respectively
C_i	distance from the end A to the centre of the typical i^{th} region
d_m	mid-span deflection
d_{sr}	effective concrete cover to the steel reinforcement from the top fibre
$\{d\}, \{d^{er}\}, \{d^*\}$	displacement vector, error or difference in the displacement vector and revised displacement vector respectively
E	modulus of elasticity
f_{ij}, k_{ij}, $[k]$	flexibility coefficients, stiffness coefficients and stiffness matrix of a skeletal member respectively
f'_c	cylinder compressive strength of the concrete at 28 days
f_t	tensile strength of the concrete
L	span of the beam
L_i	length of the typical i^{th} region (cracked or uncracked)
$L_{i,cr}$	length of the typical i^{th} cracked region
M, N, R	moment, axial force and reaction force respectively
$\{p\}$	revised force vector of element
$\{P^0\}$	fixed end force vector for the uncracked structure
$\{P^{er}\}, \{p^{er}\}$	residual force vector of the structure and element respectively
p	distance between concentrated load and end A
w, W	uniformly distributed load and concentrated load on the span respectively
u	axial displacement
x	distance of the cross-section from end A in an element
x'	distance of the cross-section from C in a typical region
y	distance from the reference axis
θ	end rotation
τ	tolerance value
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
$\sigma_0, \sigma_{un}, \sigma_{un,i}$	stress at the reference axis, stress at the tensile face (top fibre), average of the stress at the tensile face for i^{th} region respectively
$\varepsilon_t, \varepsilon_u$	cracking strain and maximum tensile strain of concrete respectively
$\varepsilon_0, \varepsilon_y$	strain at the reference axis and y from the reference axis respectively
ω	transverse displacement

Subscripts

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
cu	evaluation in cracked zone using the uncracked cross-sectional properties
i	i^{th} region of cracked span length beam element
n, r	net and relative values respectively
y	distance from the reference axis

Superscripts

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

To account for the effect of cracking in the cases of practical design of structures, provisions are available in various codes of practice. For example, EN 1994-1-1 [13] and EN 1994-2 [15] give guidelines for use in general cases and also simplified guidelines for use in specific cases. These guidelines consist of some inherent approximations which may lead to some error in the estimation of the cracked region lengths and consequently in the analysis, in certain cases.

There are various methods available in the literature for the analysis of composite structures, which may be categorized as type 1 (applicable for analysis up to ultimate load stage) and type 2 (applicable for analysis at service load stage). The type 1 methods require too high computational effort than warranted, when used for analysis at service load stage. Type 2 methods [16–19] are analytical in nature. However, either these methods are applicable for simply supported composite beams only [16,17,19] or one or more aspects like progressive cracking of concrete and tension stiffening have been left out [18]. Another method, a hybrid procedure [20–22], considers the effects of cracking and tension stiffening and is computationally efficient. However, this procedure has cumbersome formulation and also it is applicable for only specific types of loading. Recently, Ramnavas et al. [23] have proposed a cracked span length beam element and used it in developing an analytical-numerical procedure for continuous beams in bridges. This procedure has simplified formulation and is also applicable for all types of loading. However, this procedure does not account for axial degrees of freedom and therefore is not applicable for frames, in which the members are subjected to axial forces also.

Thus, for the inelastic service load analysis of composite frames considering cracking of the concrete, there is need for a procedure requiring minimal computational efforts still having accuracy acceptable for practical engineering applications. This requires a procedure with simplified formulation and having generalized applicability to all types of loading.

In this paper, a cracked span length frame element comprising two cracked regions (at the ends of beam) and one uncracked region (at the middle), with six degrees of freedom (including two axial degrees of freedom) has been proposed in which no discretization of the frame element, along the length and/or across the cross-section, is required. The tension stiffening effect in the cracked concrete has also been accounted. This element has simplified formulation and is applicable for all types of loading. The proposed element is used in an analytical-numerical procedure for accurate inelastic analysis of composite frames, considering cracking at service loads and duly accounting for the redistribution of forces. Use of this single frame element for a span, reduces the computational efforts. Also, average values over the cracked regions have been used for the tension stiffening characteristics, so as to retain the analytical nature of the procedure at the element level. For arriving at the flexibility matrix coefficients, stiffness matrix coefficients, end displacements, cracked region lengths and mid-span deflection of the frame element, analytical expressions have been presented. The procedure uses an iterative technique for establishing the cracked region lengths and distribution coefficients (for tension stiffening), and yields the inelastic deflections and redistributed moments. The procedure is validated by