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Long-term deflection of cracked composite beams with nonlinear partial shear interaction: I — Finite element modeling

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Abstract

In this paper, a uniaxial nonlinear finite element procedure for modeling the long-term behavior of composite beams at the serviceability limit state is presented. The finite element procedure follows a displacement-based approach. The nonlinear load–slip relationship of shear connectors as well as the creep, shrinkage, and cracking of concrete slab are accounted for in the proposed finite element procedure. The effects of creep and shrinkage of the concrete slab are considered only for uncracked concrete. The nonlinear iterative procedure adopted for tracking the nonlinear behavior of the composite beam implemented the total nodal deformations, not the incremental deformations, as the independent variables of any iteration. The results of the proposed finite element procedure were compared with the experimental results of four composite beams reported in the literature. The proposed finite element procedure was capable of predicting the deflections and stresses of the four beams with an acceptable degree of accuracy. A parametric study was conducted to study the effect of the nonlinearity of load–slip relationship of shear connectors and the cracking of the concrete deck on the long-term behavior of simply-supported composite beams.

Keywords: Finite element method; Composite beams; Steel; Concrete; Shrinkage; Creep; Serviceability

1. Introduction

Composite steel–concrete beams in which a steel profile supports a concrete slab or deck are commonly used in buildings and bridges. According to current codes of practice, the adequacy of a composite beam against both the ultimate and serviceability limit states must be ensured.

The growing deployment of high-strength materials in construction during the past decade has led to an increase in extreme fiber strains at service loads. As a result, the sizing of composite beams is usually governed by the deflection limit state, a condition set forth in design specifications to reduce the cracking of concrete. Consequently, it is necessary to have an accurate and reliable model for estimating short- and long-term deflections of composite beams.

Relative slip at the steel–concrete interface of a composite beam would be eliminated if the concrete slab and steel profile are rigidly connected to each other. However, in practice, complete shear interaction is assumed to coincide with full shear connection. Full shear connection is only related to beam strength and is reached when there is a sufficient number of shear connectors such that the addition of extra shear connectors do not affect the strength of the composite beam [1]. Even though slip would still be present between the steel and concrete components in composite beams with full shear connection, the influence of this slip on the beam deflection is negligible.

In practical applications, it is not always possible or necessary to reach full shear connection in a composite beam. For instance, the number of shear connectors required to achieve full shear connection may be so large that there are difficulties in accommodating them in the beam, or the applied load carried by a beam may be safely sustained with less shear connectors than required to reach full shear connection. Under these circumstances, the calculation of the composite beam deflection must take into account the effect of partial shear interaction which results in higher deflection values when compared with corresponding beams with complete shear interaction.

An accurate estimation of the long-term deflection of composite beams is a difficult task. Three factors contribute

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to this difficulty. Firstly, there is an incomplete interaction between the concrete slab and the steel profile due to the occurrence of slip at the concrete–steel interface and the deformation of shear connectors. This incomplete interaction is further complicated by the nonlinearity of the slip–shear force relationship even at the early stages of loading. Secondly, the deflection of the composite beam is noticeably affected by creep and shrinkage of the concrete slab. Finally, there is a possibility that cracks may develop in simply-supported composite beams at the bottom fibers of the concrete slab which may continue to grow due to creep and shrinkage. The propagation of cracks is more likely to happen if unpropped construction is used causing the self-weight of the composite beam to be resisted by the steel profile only. For the aforementioned factors, a closed form solution to estimate the deflection of composite beams is available only for the case of rigid connections assuming zero slip at the steel–concrete interface and no cracking of concrete. Available closed form solutions adopt simplified algebraic methods for the evaluation of time-dependent response [2]. These simplified methods are: effective modules method (EM); the mean stress method (MSM); and the age adjusted effective modulus method (AAEMM).

A large number of studies have been devoted to the calculation of short-term deflections of composite beams with partial shear interaction. Analytically, a differential equation was derived by Newmark et al. [3], from which several closed-form solutions for combinations of simple loading cases and simple boundary conditions were developed [4,5]. The major disadvantage of analytical methods is that each problem has to be resolved afresh. Moreover, the mathematics in the final solution may still be quite complex. Alternatively, numerical methods were used [6–10] due to their versatility and generalization in dealing with any combination of loading and boundary conditions. Even though they are very powerful tools for research studies and for analyzing complex structures, their application to everyday design practice may be time consuming and inconvenient to practicing engineers. Considering the plastic behavior of steel and concrete, many approaches using one-dimensional finite element modeling have been proposed in the literature. The uniaxial models are based on displacement [11,12], force [13], or mixed [14] approaches. Two- and three-dimensional modeling have been performed so far to thoroughly evaluate the interaction among the component materials and the local stress state [15,16].

Bradford [2] have introduced methods for calculating the long-term deflection of simply-supported beams based on simplified methods for creep considering no slip at steel–concrete interface. Brodford and Grilbert [17], proposed a method to calculate the deflection of composite beams with partial shear interaction accounting for creep using the method of age-adjusted effective modulus method (AAEMM).

Based on the step-by-step method suggested by Bazant [18] for the calculation of creep, Dezi and Tarantino [19] developed a numerical method for calculating the deflection of composite beams using the finite difference method. Amadio and Fragiacomo [20] proposed a finite element model to study the effects of creep and shrinkage in simply-supported beams with flexible shear connections assuming: (i) no concrete cracks in the lower fibers of concrete and; (ii) connectors with linear stiffness. Fragiacomo et al. [21] modified that model to account for concrete cracks that may develop in the concrete slab assuming shrinkage and creep effects to be identical in both cracked and uncracked concrete. It was shown in an experimental study by Johnson [22] that the free shrinkage dramatically decreases in the cracked phase and the primary shrinkage curvature is halved by cracking of concrete. Eurocode 4 [23] endorses that shrinkage effects should be neglected in any global analysis in regions where the concrete slab is cracked.

In this study, a finite element model for predicting the long-term behavior of composite beams is presented. A step-by-step method for the calculation of creep has been implemented. The nonlinearity of shear connectors and the cracking of the concrete deck are accounted for in order to enable the precise modeling of the behavior of continuous or simply-supported composite beams. The proposed finite element model accounted for shrinkage and creep effects in uncracked concrete but, as per the recommendations of EC4, neglected these effects in cracked concrete.

2. Finite element modeling

Fig. 1 shows a typical cross section of the simply-supported composite beam considered in this study. The beam is modeled as two parallel beam elements representing the steel profile and the concrete deck. The two parallel beam elements are assumed to have identical deflection (v) at any location along the composite beam length; i.e. the uplift phenomenon is neglected as shown in Fig. 2. Johnson and Molenstra [24] showed that accounting for the uplift phenomenon in regular composite beams is only necessary if the beam is carrying a load close to its load carrying capacity. Under service loads, the response of a composite beam is mainly affected by the relative slip between the two components of the composite beam; therefore neglecting the uplift phenomenon is justified. In addition to ignoring the uplift phenomenon, the following assumptions were made during the formulation of the displacement-based uniaxial nonlinear finite element model shown in Fig. 2:

- The two parallel beam elements representing the concrete slab and steel profile are linked together by means of a smeared shear connection of nonlinear stiffness, K_{sec}, in the direction of the beam length as shown in Fig. 2(a);
- Shear deformations of the individual components of the composite beam element are neglected under service loads;
- No slipping occurs between the deck reinforcing steel and the encasing concrete;
- Concrete is assumed to crack immediately if its strain exceeds the critical elastic strain, ε_{cr}, defined as the strain corresponding to the concrete maximum tensile strength, f_{ct}. The closed cracks are assumed to be able to transfer compressive stresses only;
- Shrinkage and creep of cracked concrete layers are negligible; and