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Finite element models for nonlinear analysis of steel–concrete composite beams with partial interaction in combined bending and shear

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The study in this paper compares three different beam models and relevant finite elements for the nonlinear analysis of composite members with partial interaction. These models are derived by coupling with a deformable shear connection two Euler–Bernoulli beams (only flexural deformability and flexural failure mode of each beam component), an Euler–Bernoulli beam to a Timoshenko beam (addition of shear deformability and shear failure mode for one component only), two Timoshenko beams (addition of shear deformability and shear failure mode for both components). Simply supported and continuous steel–concrete composite beams for which experimental results are available in the literature are used as benchmark problems. Aspects of the structural behaviour considered include: (i) effects of the shear deformability of the steel and slab components at various load levels; (ii) differences in computed collapse loads; (iii) differences in the internal actions, i.e. axial forces, bending moments, vertical shears and interface shear forces at different levels of loading. A study on the convergence rate of the finite element solution and considerations on locking-free finite elements are also presented. Results show that the three models present small differences when composite beams dominated by the bending behaviour are considered. On the other hand differences are significant for beams in which the interaction between bending and shear plays a substantial role; in these cases neglecting the shear behaviour in the composite beam model leads to considerably inaccurate predictions of the structural behaviour.

1. Introduction

Modelling and analysis of steel–concrete composite structures combine many of the challenges encountered in steel structures and reinforced concrete structures, plus specific issues owing to the interaction and load sharing between structural steel and reinforced concrete components [1,2]. In this context, structural engineers involved in the analysis and design of steel–concrete composite structures have to face practical difficulties since procedures which directly handle specific behavioural aspects of composite construction are not generally included in available commercial software. Nevertheless, various models have been proposed in the literature to date in the effort to provide effective and robust tools for the analysis of steel–concrete composite buildings and bridges [3].

Earlier studies on composite beam behaviour highlighted that the relative displacement between the steel beam and the reinforced concrete slab (partial interaction) requires to be included in the numerical model for an adequate representation of the composite response [4]. This relative movement is due to the deformability of the interface shear connection. The latter can also be responsible for the structural collapse and, because of this, its behaviour needs to be included in the modelling. Such considerations are widely accepted [3] and even included in modern structural codes. For example, Eurocode 4 Part 1 [5] in paragraph 5.4.3 (nonlinear global analysis) and Eurocode 4 Part 2 [6] in paragraph 5.4.3 (nonlinear global analysis for bridges) require that the behaviour of the shear connection shall be taken into account. One of the first papers dealing with the analysis of composite beams with partial interaction is the one by Newmark et al. [7]. The Newmark model couples two Euler–Bernoulli beams, i.e. one for the reinforced concrete slab and one for the steel beam, by means of a deformable shear connection distributed along their interface. This shear connection enables longitudinal relative movement to occur between the two components while preventing their vertical separation. The Newmark model has been widely applied for static linear elastic analyses (e.g., [8–10]), and various formulations were presented for nonlinear static analysis under monotonic and cyclic loadings (e.g., [11–22]), as well as for nonlinear dynamic analysis under earthquake ground motions [23,24].

Very recently modifications of the original Newmark model were proposed in order to include the shear deformability of one

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or both components of the composite beam. Berczyński and Wróblewski [25] presented a composite beam model obtained from two Timoshenko beams coupled with a continuous deformable interface connection. With their model Berczyński and Wróblewski studied the dynamic behaviour of composite beams associated with their free vibration. Based on comparisons with experimental results [26], they concluded that their model was the most suitable to depict damage in composite members as shown to be extremely sensitive to higher modes of flexural vibrations. An analytical solution and a finite element formulation for linear static analysis of two Timoshenko beams coupled by means of a longitudinal interface connection were presented by Schnabl et al. [27,28]. In their work [27] vertical deflections were calculated for different values of parameters k (shear connection stiffness), E/G (normal elastic modulus to shear elastic modulus ratio), L/h (span-to-depth ratio) and compared to those obtained using the Newmark model. These comparisons showed that shear deformations are more important for high levels of shear connection stiffness, for short beams with small span-to-depth ratios, and for beams with high E/G ratios. Attention to the composite beam model made of two Timoshenko beams was also given by da Silva and Sousa [29] who presented an alternative finite element formulation by introducing a family of interface elements for linear static analysis. In their study [29] the interest was focused on the convergence of various finite elements and on the discussion of the occurrence of slip and curvature locking. In the following, for ease of notation, the composite beam model made of two Timoshenko beams coupled by a distributed deformable shear connection enabling longitudinal relative movement while preventing vertical separation is referred to as T–T model.

A beam model including the shear deformability of the steel component only was introduced by Ranzi and Zona [30]. This model was obtained by coupling an Euler–Bernoulli beam for the reinforced concrete slab with a Timoshenko beam for the steel member. The composite action was provided by a continuous shear connection which, as in the Newmark model, enabling longitudinal relative displacements while preventing vertical separation. For ease of notation, this model is referred to as EB–T model in the following. Such model was preferred to the T–T model for two reasons: (i) the shear deformability of the slab is commonly very small due to its flexural slenderness while the shear deformability might not be negligible for the steel beam; (ii) it permits a simpler extension to include material nonlinearities in the analysis as a biaxial constitutive law for the concrete is not required. Ranzi and Zona [30] presented an extensive parametric study based on approximately 200 realistic simply supported and continuous composite bridge arrangements. This parametric study was carried out using a locking-free finite element model under the assumption of linear elastic materials and considering the time-dependent behaviour of the concrete. It was found that non-negligible differences between the Newmark and the EB–T models exist, in particular for relatively low values of a dimensionless parameter measuring the importance of the shear stiffness compared to the flexural stiffness of the steel beam. The effects of the shear deformations of the steel beam on the composite deformations were also observed to be more significant for higher shear connection stiffness (in accordance with Schnabl et al. [27]) and for long-term analyses.

In this context, the objective of this paper is to evaluate the ability of finite element formulations of different composite beam models with partial interaction, namely the Newmark, EB–T and T–T models, to predict the nonlinear response of composite structures for which experimental results are available in the literature. In particular, the finite elements presented in [18] are used for the Newmark model, displacement-based finite elements previously introduced for the EB–T model [30] are extended in the nonlinear range, and a novel nonlinear displacement-based finite element for the T–T model is proposed. Even if not producing the same level of sophistication achieved with 3D finite element models using shell and solid elements (e.g., [31–35]), these beam elements represent very efficient tool for the analysis of composite structures (e.g., multi-span bridges and frames) which is expected to be included in the near future in commercial analysis software. Aspects of the composite behaviour evaluated in this study include (i) the effects of the shear deformability of the steel and slab components at various load levels; (ii) the differences in computed collapse loads obtained using the three beam models; (iii) the differences in the internal actions, i.e. axial forces, bending moments, vertical shears and interface shear forces, calculated based on the three beam models at different levels of loading; (iv) which model provides a better estimate of the structural response observed in experimental tests considering both flexural and shear failure modes. A study on the convergence rate of the finite element solution and considerations on locking-free finite elements are also presented. In all simulations realistic constitutive laws for materials and shear connection are adopted.

2. Analytical models

A prismatic steel–concrete composite beam is made of a reinforced concrete slab and a steel beam, as shown in Fig. 1. In its undeformed state, the composite beam occupies the cylindrical region $V = A \times [0,L]$ generated by translating its cross section A, with regular boundary ∂A, along a rectilinear axis orthogonal to the cross section and parallel to the Z-axis of an ortho-normal reference system $\{O;X,Y,Z\}$ where **i**, **j**, **k** are the unit vectors of axis X, Y, Z. The composite cross section domain is formed by the slab,

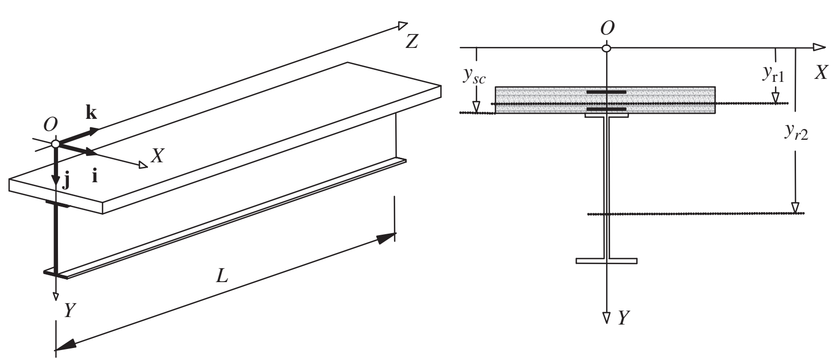

Fig. 1. Typical composite beam and cross section.