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Practical nonlinear inelastic analysis method of composite steel-concrete beams with partial composite action

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ABSTRACT

This paper presents an efficient computer method for nonlinear inelastic analysis of composite steel-concrete beams with partial composite action. The proposed formulation is intended to model the combined effects of partial composite action and distributed plasticity using only one 2-noded beam-column element per structural member. Based on elasto-plastic cross-sectional analyses the behaviour model is able to take into account the effects of partial composite action between the concrete slab and the steel beam. Gradual yielding throughout the cross-section is described through basic equilibrium, compatibility, material and shear connection nonlinear constitutive equations. Tangent flexural and axial rigidity of the cross-section are derived and then using the flexibility approach the elasto-plastic tangent stiffness matrix and equivalent nodal loads vector of the beam-column element including the shear deformability of the partially connected composite beam has been developed. The proposed nonlinear analysis formulation has been implemented in a general nonlinear static purpose computer program, NEFCAD. Advanced finite element simulations have been conducted by using the specialized software for nonlinear analysis of structures, ABAQUS. Several computational examples are given to validate the accuracy and efficiency of the proposed method by comparing the results predicted by NEFCAD with those given by the ABAQUS software and other results retrieved from the open literature.

1. Introduction

Composite systems have seen widespread use in recent decades due to multiple benefits that occur by combining the individual mechanical properties of the main component materials, steel and concrete. The structural steel experiences high strength and ductility in tension and compression, while the concrete experiences high stiffness and robustness in compression. The *composite action* between the concrete slab and the steel beam is achieved through mechanical connectors such as shear studs. The resulted composite beam-column provides an increase of the rigidity, strength and the ultimate moment capacity of the composite element, compared with the independent use of each material. An important aspect in the structural behaviour of steel-concrete composite beams is represented by the level of shear connection between the concrete slab and steel beam, which is defined as the ratio between the shear connection capacity provided by the studs and the weakest component capacity (concrete slab or steel beam). If the disposed number of shear connectors at the steel-concrete interface of the composite beam is lower than the number that provides full shear connection, then the stiffness and ultimate capacity decreases, while the ductility of the composite beam may be enhanced [1–4].

In recent years, have witnessed significant advances in nonlinear inelastic analysis methods for steel and composite steel-concrete beams and framed structures and integrate them into the new and more rational advanced analysis and design procedures (e.g., [1,5–15]). Reliable nonlinear analysis tools are, for instance, essential in performance-based earthquake engineering and advanced analysis methodologies, that involves accurate predictions of inelastic limit states, up or beyond, to structural collapse.

There currently exist several methods and computer programs devoted to the analysis of composite steel-concrete beams and frame structures, with full and partial composite action, able to reveal both linear-elastic and nonlinear inelastic behaviour of these structures. At one extreme, two- and three dimensional finite elements enhanced with advanced material and shear connection nonlinear constitutive laws were used to investigate the nonlinear response of composite steel-concrete elements with partial composite action (e.g., [3,16–19]). All these available tools for such advanced analyses are general purpose FE programs that require very fine-grained modelling, extensive calibration and mesh

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Nomenclature

αL	non-dimensional partial composite action parameter
γ	elastic degree of composite action
γ_{eff}	inelastic member effective degree of composite action
$f(\gamma_{eff})$	a function of the inelastic member effective degree of composite action
ε	resultant stain under the assumption of full composite action
ε_c, ε_s	resultant stains in concrete slab and steel beam under partial composite action
ε_{slip}	slip strain
η	degree of shear connection
μ	buckling length
$\tau_{xy,\ c(s)}$	shear stress in concrete and steel components respectively
ψ_{eq}	equivalent transverse shear angle
Δ	denotes an incremental quantity
ϕ	common curvature in concrete and steel components
$\mathbf{f}_t$, $\mathbf{k}_t$	tangent flexibility and stiffness matrices of the cross-section
$\mathbf{f}_r$, $\mathbf{k}_r$	instantaneous flexibility and stiffness matrices of beam-column element without rigid body modes
i_c	longitudinal spacing between shear connectors
k	shear connection stiffness
$k_{50\%}$	shear connection stiffness corresponding to a value of connector shear force (P) equal to 50% of shear connector strength capacity (P_{sc})
k_{sec}	secant shear connection stiffness
k_c, k_s	transverse shear coefficients of concrete slab and steel profile
n	effective number of shear connectors
n_f	number of shear connectors that provides full shear connection
r	distance between the centroids of concrete slab and steel profile
s	shear slip
u	axial strain under the assumption of full composite action
u_c, u_s	axial strains in concrete slab and steel beam under partial composite action
A_c, A_s	areas of concrete slab and steel profile respectively
A_{rsi}	area of the *i*-th reinforcement bar
$A_{shear,\ c(s)}$	shear area of concrete slab and steel profile respectively
E_cA_c, E_sA_s	axial rigidity of concrete slab and steel profile respectively
EA^*	ratio between the product and the sum of axial stiffness E_cA_c and E_sA_s
$(EA)_t$	tangent axial rigidity of composite cross-section under partial composite action
E_cI_c, E_sI_s	elastic flexural rigidity of concrete slab and steel profile respectively
$(EI)^0$	elastic flexural rigidity of composite cross-section under no composite action
$(EI)^\infty$	elastic flexural rigidity of composite cross-section under full composite action
$(EI)_{el}$	elastic flexural rigidity of composite cross-section under partial composite action
$(EI)_{eff}$	effective flexural rigidity of composite cross-section under partial composite action
$(EI)_t$	tangent flexural rigidity of composite cross-section under partial composite action
E_t	tangent modulus of elasticity
G_c, G_s	shear modulus of concrete and steel materials
$(GA)_{eq}$	elastic equivalent shear stiffness of composite cross-section
$K_{50\%}$	shear connector stiffness corresponding to a value of connector shear force (P) equal to 50% of shear connector strength capacity (P_{sc})
K_{sec}	secant shear connector stiffness
N^c_{int}, N^s_{int}	internal axial force in concrete slab and steel profile
N_{cf}	internal axial force in concrete slab under full composite action
N^e_{cf}	elastic internal axial force in concrete slab under full composite action
N_{rs}	number of conventional steel reinforcement bars
P_{sc}	shear connector capacity
P	interface shear force attributed to a single shear connector
$S_{shear,\ c(s)}$	first moment of the sheared area of concrete slab and steel profile

generation studies that are often impractical to the structural engineer. At the other extreme, the line elements (1-D) approach in conjunction with either distributed or concentrated plasticity models, have been devoted to the development of nonlinear analysis tools for two-layer composite beams with interlayer slip that provide a desirable balance between accuracy and computational efficiency (e.g., [1,7,10,20–27]) among others.

Analytical procedures based on the key hypothesis of Newmark's model [28] have been proposed, in recent years, for the static response of two-layer beams with interlayer slip in the linear-elastic regime and based on Euler-Bernoulli beam theory (e.g., [21,22,29–31]) among others. Shear flexibility of both concrete slab and steel beam according to Timoshenko's theory has been taken into account, in several analytical and finite element-based procedures to predict linear and nonlinear inelastic behaviour of composite beams with partial composite action (e.g., [1,32–36]) A detailed discussion about various Euler-Bernoulli and Timoshenko-based models that were proposed for the analysis of composite beams with partial composite action can be found in [1,37]. Moreover, the analytical and finite element formulation can be cast within the framework of discrete-bond model (i.e. shear connection is modelled using the concentrated springs at connector locations) [26,38] and continuous-bond model (i.e. shear connection is modelled using the equivalent distributed spring stiffness) [2,39]. A useful brief review about this issue has been given by [38]. There are three main approaches that have been used to model the gradual plastification of partially connected members in a nonlinear inelastic analysis, one based on the displacement method or finite element approach (e.g., [2,23]), the second one based on the force or flexibility method (e.g., [25]), and the third one refers to mixed or hybrid approach (e.g., [24,26,39,40]). Despite of the simplicity and ease of implementation, because displacement-based elements implicitly assumed linear curvatures along the element length, accuracy in this approach when material nonlinearity is taken into account can be obtained only using several elements in a single structural member, thus the computational effort is greatly enhanced and the method becomes prohibited computational in the case of large scale frame structures. Moreover, these formulations may suffer from the shear-locking and slip-locking phenomena [2,25]. On the other hand in the flexibility based approach only one element per physical member can be used to simulate the gradual spread of yielding throughout the volume of the members but the complexity of these methods derives from their implementation in a finite element