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Numerical modelling of the shear-bond behaviour of composite slabs in four and six-point bending tests

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ABSTRACT

An effective finite element model which reproduces the longitudinal shear behaviour of composite steel-concrete slabs with profiled sheeting has been developed. The steel-concrete interface was simulated with a non-linear shear behaviour law (τ-s) which properly defines the shear-bond behaviour of composite slabs. A simple methodology is proposed to calculate the above mentioned law from experimental load-deflection curves and the geometry of the slabs. The numerical model was assessed by comparison with the available experimental results of two different types of composite slabs previously tested to the m-k requirements of Eurocode 4. Since these requirements are for four-point bending tests and to extend the validity of the numerical model for the usual design case of uniform loads, with a non-constant longitudinal shear force acting on the slabs, a new set of composite slab specimens were subjected to six-point bending tests. The results confirm the validity of the model and its simplicity respect to other available models since only two values of the interface τ-s law are necessary to describe the whole behaviour of the slab. Additionally, an interpolation method was applied to obtain the τ-s values in the steel-concrete interface for composite slabs with the same steel deck but different geometry and unknown shear-bond behaviour.

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1. Introduction

The use of composite slabs presents some advantages such as simple, fast and economical construction (referred to costs and time) and they support the applied loads in a very effective manner [1,2]. The most common type of failure in these slabs is longitudinal shear failure [3]. Longitudinal shear forces between the profiled steel sheeting and concrete, which develop during simple bending, produce longitudinal slip in the steel-concrete interface. However, the ultimate load that produces the longitudinal shear failure is usually far from the ultimate bending or vertical shear strength of the slabs. Consequently, the shear strength in the steel-concrete interface governs the behaviour of this type of slab and in the most cases the maximum load capacity is never achieved in the profiled steel sheeting or the concrete block [4].

The longitudinal shear connection between steel and concrete is usually due to three factors: pure bond, mechanical interlocking and friction. The most effective and commonly shear connection device used are pressed embossments on the profiled steel sheeting [5,6]. These embossments are specifically designed and manufactured for each steel deck and consequently, the shear-bond behaviour of these composite slabs is a very complex phenomenon to predict [7]. Thus, the usual standard design methods for composite slabs, the m-k and the partial connection methods [8], are expensive and time consuming semi-empirical methods [9]. Both methods of design need experimental results of full-scale laboratory specimens subjected to four-point bending tests (4PB), carried out to the requirements of the Eurocode 4 (EC-4) or similar [4]. Therefore, a finite element model which simulates the steel-concrete composite action with sufficient accuracy would allow a reduction in the amount of tests and enable interesting parametric analysis leading to an improvement in the design of these slabs [3,9–13]. Furthermore, that model would also allow more detailed research and analysis of shear-bond behaviour in composite slabs, simulate the stresses and strains in the concrete block or the steel decking and make an effective tool to calculate composite slabs in real situations. In the literature, there are few numerical models allowing a global analysis of the mechanical behaviour of a composite slab with embossments. In these models, the definition of the properties of the steel-concrete interface, used to correctly analyse the shear-bond behaviour, has a certain degree of complexity or they are focused on very local aspects of the shear-bond behaviour [3,9,11,14]. Some interesting experimental studies, in which profiled steel sheeting is used [15,16] were useful when

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Nomenclature

A_c	cross area of the concrete block
A_p	cross area of the steel deck
b	width of slab
b_{em}	effective width of the slab
d_p	effective depth of the slab
t	thickness of the steel deck
L	span length
L_0	cantilever length of the composite slab near the support
L_s	shear span length
h	depth of the slab
e	distance from the centroid of the effective area of the steel deck to its underside
e_p	distance of the plastic neutral axis of the steel deck to its underside
x_g	distance of the centroid of the steel deck from bottom
x_{pl}	distance of the plastic neutral axis of the composite section to its upper side
z	level arm
E_c	concrete Young's modulus
E_s	steel Young's modulus
δ	midspan deflection
δ_{1s}	first-slip midspan deflection
δ_{Ls}	crack inducer section deflection
δ_{max}	experimental midspan deflection for maximum applied load
δ_{num}	maximum vertical deflection at midspan obtained with the FEM model
f_{yd}	yield strength of the steel deck
I	moment of the inertia of the steel deck
k	ordinate intercept of shear-bond line, m-k method
m	slope of experimental shear-bond line, m-k method
M_{pa}	plastic moment resistance of the steel deck
M_{pr}	reduced plastic moment resistance of the steel deck
M_{test}	maximum bending moment measured during the test
N_c	compressive normal force applied in concrete with partial shear connection
N_{cf}	compressive normal force applied in concrete with full shear connection
P_{1s}	first-slip load
P_{max}	maximum load
s	longitudinal relative slip
s_1	longitudinal relative slip, first-slip point
s_2	iterated longitudinal relative slip, maximum load point
s_3	longitudinal relative slip, post-crushing point
$s_{2.i}$	longitudinal relative slip for rigid block model
$s_{2.ii}$	longitudinal relative slip taking into account deformation effects in steel deck and concrete
V_t	vertical shear force
W_i	resistant module
Wq	expected value of the characteristic load acting on the slab, (cyclic test)
W_t	maximum load (cyclic test)
ε_c	concrete deformation
ε_s	steel deformation
Δ_c	concrete shortening
Δ_s	steel elongation
η	connection degree of the slab
τ	longitudinal shear-bond stress
τ_u	ultimate shear stress
τ_1	ultimate shear stress, first-slip point
τ_2	ultimate shear stress, maximum load point
τ_3	ultimate shear stress, post-crushing point
μ	steel-concrete friction coefficient

used to study the ultimate capacity of embossments but they are not focused on its shear-bond behaviour.

Ferrer et al. [11] carried out a study on the influence of the geometrical and physical parameters of the composite slabs on the steel-concrete slip mechanisms. This study provided information about the importance of the shape and orientation of the embossments on the longitudinal slip strength. For that, they developed a finite element model where the cross section of the steel deck and its embossments were specifically modelled. Important conclusions were established about the local effects of the embossments on the shear-bond behaviour of the composite slabs and its interaction with the concrete block modelled as a rigid surface. Tsalkatidis and Avdelas [12] performed an experimental and numerical analysis of the unilateral contact problem in composite slabs. For the study of this complex aspect, a finite element model was created in Ansys where the concrete was simulated as a non-linear material with both cracking and crushing failure mode. For the steel deck, a multilinear elastoplastic strain hardening law with a Von Mises yield criterion was used. The friction developed in the steel deck and concrete interface was simulated with a Coulumb friction model. In consideration global aspects, Chen and Shi [9] studied the failure mechanism with a non-linear contact model. They defined the concrete with a multi-linear isotropic hardening behaviour law, and a multi-linear kinematic hardening law was considered for the steel deck. The steel-concrete interface was modelled using surface-to-surface contact elements with a Coulumb friction model. Baskar [13] carried out an experimental and numerical analysis with a finite element model of composite slabs with and without embossments in Ansys. The concrete part was considered as a non-linear material but linear spring elements were used in the steel-concrete interface. Abdullah [17] carried out a finite element model to simulate the global shear-bond behaviour of composite slabs with Abaqus. They compared the numerical results relative to previous small-scale tests. The concrete was modelled as a brittle cracking material and the steel deck was considered as an elastic-plastic material. The steel-concrete interface was modelled with radial-thrust connectors with average bond–slip (τ-s) relationship calculated using the "force equilibrium" method previously developed by An [18]. However, it was carried out as a quasi-static analysis because the brittle cracking material was simulated with Abaqus Explicit only. In a recent paper, Gholamhoseini et al. [3] developed a finite element model with ATENA 3D using interface elements to model the bond properties between the steel deck and the concrete slab, where the bond–slip relationship for each slab was again determined using the "force equilibrium" method.

In this study, a new finite element model in Abaqus 6.12 of profiled steel sheeting composite slabs with embossments, which simulates the global shear-bond behaviour with reliable numerical results, is presented. The concrete is modelled with a concrete damaged plasticity model and the steel deck was considered as an elastic-plastic material, which allows to perform a static analysis with less computation time than other models. The model is versatile since it can be easily adapted to other more complex configurations, such as different distributions of loads, supports, material properties or geometries. Radial-thrust connector elements with a non-linear behaviour law (τ-s) model the contact in the steel-concrete interface. In this way, the full shear connection,

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