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Numerical prediction of the shear response of semi-prefabricated steel-concrete trussed beams

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HIGHLIGHTS

- Numerical model of the shear behavior of semi-precast steel-concrete trussed beams.
- Validation of the finite element model against experimental results.
- Comparison between cohesive steel-concrete interface vs. perfect bond model.
- Modeling of constitutive behavior of concrete by means of damaged plasticity theory.
- Interpretation of results using the variable strut inclination method of Eurocode 2.

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ABSTRACT

In this study, the shear behavior of hybrid steel-trussed-concrete beams (HSTCBs) realized with prefabricated steel trusses embedded into a concrete core cast *in situ*, is investigated by means of Finite Element (FE) numerical simulations.

HSTCBs do not behave as classical RC elements nor composite beams. Up to now, there are not specific design criteria in the building codes and the calculation of this type of beams is conducted by means of design-by-testing procedures. The knowledge of the material behavior as well as the understanding of the interaction between materials in contact is the first requirement for the definition of proper design procedures and calculation methods for practitioners to be inserted in the international building codes.

In the present study, the numerical simulation of the global beam behavior through the modeling of the local material response and contact properties, allow a detailed knowledge of the shear resisting mechanism aimed at the definition of simplified calculation formula.

The accuracy of the numerical prediction is validated against the results of a reference experimental campaign of three-point bending tests with shear failure carried out by the author in a previous work.

A first analytical approach for the interpretation of the FE results is conducted applying the variable strut inclination method currently prescribed in Eurocode 2 for classical RC beams. Conversely, in the paper it is shown how all information coming from the FE analysis are of paramount importance for the possible development of more proper simplified calculation methods of the shear capacity of this particular beam typology.

1. Introduction

The present study deals with Hybrid Steel Trussed Concrete Beams (HSTCBs) which represent a structural typology of composite beams generally realized with a prefabricated reinforcement in form of truss embedded within a block of concrete cast *in situ*.

Such a beam typology is typically employed as efficient structural solution for light industrialization, providing advantages such as high constructional speed as well as the possibility of covering wide spans with low depths also within seismic framed structures.

Among the large variety of HSTCBs currently produced by the industry, in the present paper, the attention is focused on those realized with bottom steel plate, inclined tensile and compressed web bars, coupled upper rebars and space cross-section, as illustrated in Fig. 1a.

The behavior of HSTCBs is usually investigated with reference to two different operative phases named *phase I* and *phase II* during which the mechanical response of the beam is provided only by

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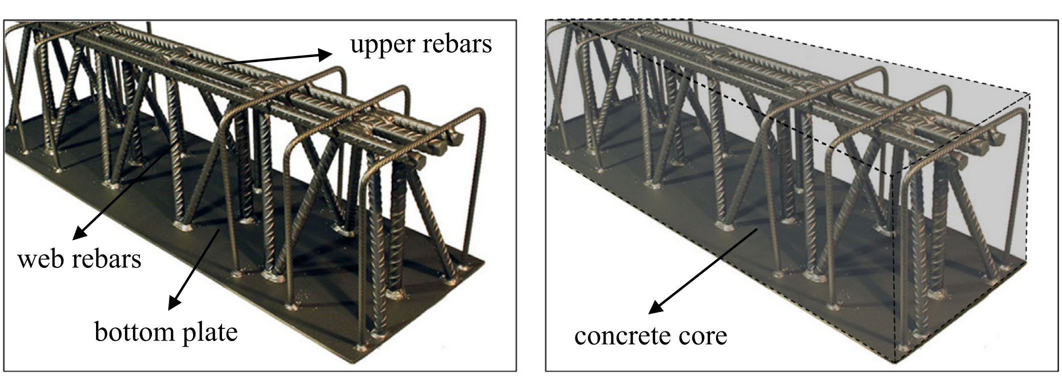
Nomenclature

a	shear span
A_b	longitudinal reinforcement area
A_p	area of the steel plate
A_{sw}	shear reinforcement area
b_w	width of the beam
b_w^*	effective width of the plate
D	damage variable of the cohesive law
$\mathbf{D}_0^{el}$	initial undamaged elasticity matrix
d	effective depth of the beam
d_c	damage variable of concrete in compression
D_i	equivalent diameter of longitudinal reinforcement
E_0	initial elastic modulus
f_c	design compressive strength of concrete
f_{yw}	shear reinforcement yielding stress
f_{yb}	yielding strength of the longitudinal reinforcement
f_{yk}	characteristic yielding stress
f_{yp}	yielding strength of the plate
h_d	depth of diagonal shear cracks
h_v	depth of vertical flexural cracks
$\mathbf{K}$	elastic stiffness matrix of the cohesive law
K_{nn}, K_{ss}, K_{tt}	elastic stiffness components in the local directions n, s, t
$q_{res,b}$	residual bond stresses of the longitudinal rebar
$q_{res,p}$	residual bond stresses of the plate
s	shear reinforcement spacing
$\mathbf{t}$	vector of the nominal cohesive traction stresses
t_n^0, t_s^0, t_t^0	peak values of the contact stress in the local directions n, s, t
T_{wi}	dowel force
V_{cu}	ultimate shear resistance of concrete
V_R	shear resistance
V_{Rc}	concrete contribution in the shear resistance
V_{Rc1}	concrete contribution due to the arch effect
V_{Rc2}	concrete contribution due to the beam action
V_{Rs}	steel contribution in the shear resistance
x_c	neutral axis depth
α	shear reinforcement inclination in the longitudinal direction
β	shear reinforcement inclination in the cross-section plane
α_c	coefficient for prestressed/non-prestressed structures
δ	vector of the cohesive separations
δ_m^0	effective separation at the initiation of damage of the cohesive law
δ_m^f	effective separation at complete failure of the cohesive law
δ_n, δ_s, δ_t	effective separation components in the local directions n, s, t
ε_c	concrete strain
ε_{cu}	peak strain of concrete
$\tilde{\varepsilon}_c^{pl}$	plastic strain of concrete in compression
ϕ	diameter of the diagonal rebar
ν	coefficient of softening
θ	concrete compression strut inclination
σ_c	concrete stress
σ_{cu}	peak stress of concrete
σ_{t0}	failure tensile stress of concrete

the steel truss, in the first phase, or by both collaborating materials, in the second phase (Fig. 1a and b).

The available literature on HSTCBs refers both to the behavior in *phase I* and *phase II*, covering a wide range of topics such as the prediction of the strength of welded joints between web rebar and bottom steel plate [1], the flexural and shear resistance of the beam [2–6], the behavior of beam-to-column joints [2,7–9], the seismic behavior of hybrid beams [10,11], issues related to the creep [12] and the problem of stress transferring from the concrete core to the bottom plate passing through the steel truss [2,13–19].

In the present paper, the attention is particularly focused on the shear response of HSTCBs behaving in *phase II*. To this aim, the results of a reference experimental campaign [2,6] are taken into account in order to generate and calibrate a detailed non-linear finite element (FE) model able to reproduce the salient features of the response, involving 3D geometry, strain-softening damage of the concrete and plasticity of the steel. Actually, the model is based on the implementation of a cohesive constitutive relationship at the steel-concrete interface which is able to take into account the main contributions provided by bond stresses in the tangential direction. Moreover, the non-linear behavior of concrete is modeled by means of the Concrete Damaged Plasticity (CDP) model [20,21] in which the degradation of both compressed and tensile behavior is taken into account. The behavior of the steel constituting the truss of the beam has been described by means of a classical plasticity model with a quadri-linear law [22].



(a) (b)

Fig. 1. Example of HSTCB typology: (a) phase I; (b) phase II.