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Stress transfer and failure mechanisms in steel-concrete trussed beams: Experimental investigation on slab-thick and full-thick beams

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HIGHLIGHTS

- Experimental investigation on the failure modes of hybrid steel-concrete beams.
- Full-strength connection for Slab Thick Beams (STBs) and Full Thick Beams (FTBs).
- Execution of four-point bending tests with different shear span values.
- Analytical interpretation of the failure load for different collapse mechanisms.

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ABSTRACT

This study presents the results of an experimental investigation on semi-precast Hybrid Steel Trussed-Concrete Beams (HSTCBs) for analyzing the failure modes and the stress transfer mechanism between concrete and embedded steel elements (plate and truss). The available literature presents previous studies carried out by the authors mainly focused on the understanding of the local transfer mechanism by means of push-out tests. Conversely, in this paper original the results of laboratory tests conducted on six specimens of full-size HSTCBs subjected to four-point bending, with variation in the shear span, are reported on. From these results, the authors are able to assess the failure modes of each beam and, finally, the transfer length necessary to ensure a full-strength connection. In the experimental campaign, two beam typologies are considered: Slab Thick Beams (STBs) and Full Thick Beams (FTBs). Both global and local response are monitored, the former in terms of load-midspan deflection curves and the latter in terms of strain measurements from Strain Gauges (SGs) placed on steel elements and concrete. Finally, some of the most relevant analytical models available in the literature and/or deduced from codes are used for interpreting the load-carrying capacity of slab and full thick beams as well as the failure modes experimentally observed, i.e. failure due either to flexure or shear, or failure of connections.

1. Introduction

This study concerns semi-prefabricated composite beams widely employed in framed buildings for light industrialization of civil constructions. As is done in the existing literature, such beams may be indicated as Hybrid Steel Trussed-Concrete Beams (HSTCBs) because they are realized by embedding a steel truss within a concrete core. In particular, the truss is made up of inclined web rebars welded to the longitudinal coupled rebars constituting the top chord and to the smooth steel plates constituting the bottom chord, which act as a mold during concrete casting.

The studies present in the technical literature on HSTCBs are almost all recent. Few studies concern the strength of welded joints [1] and the capacity of bare trusses under pure slippage force [2]. In particular, with regard to the first topic, in Ref. [1] butt and fillet welding are considered and experimental tests are performed for evaluating the bearing capacity. The latter is also assessed utilizing the calculation formula provided in Eurocode 3 [3]. The second topic, instead, concerns the behavior of the bare truss in so-called phase I, i.e. the transient time before concrete casting, when one of the most important issues is buckling of diagonal and longitudinal compressed rebars of the upper chord of the steel truss. In Ref. [2] experimental push-out tests are performed, deducing the testing procedure from that prescribed in Eurocode 4 [4] for classical composite beams. The moment-axial force interaction non-linear domain for a typical diagonal rebar is calculated, and the slippage ultimate load of the beam is predicted. Buckling is also studied with regard to the beam in phase II, i.e. the behavior of the composite beam after concrete curing. The researchers in

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List of symbols

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	effective depth of the beam
D_i	equivalent diameter of longitudinal reinforcement
E_{cm}	average elastic modulus of concrete
E_s	elastic modulus of steel
f_b	bearing stress of the concrete
f_{cm}	average compressive strength of concrete
f'_c	reduced compressive strength of concrete
f_y	yielding strength
f_{yb}	yielding strength of the longitudinal reinforcement
f_{yp}	yielding strength of the plate
f_{yw}	shear reinforcement yielding stress
f_u	ultimate strength
h_{pl}	length of the plastic hinge
M_y	yielding bending moment
M_t	ultimate bending moment at rupture
N_{cu}	maximum compression in the concrete strut
n_{st}	number of diagonal rebars
$P_{conn,1}$	connection failure load according to EC4 model [4]
$P_{conn,2}$	shear failure load according to Colajanni et al. model [19]
$P_{fl,1}$	flexural yielding failure load
$P_{fl,2}$	flexural failure load at rupture
$P_{sh,1}$	shear failure load according to EC2 model [30]
$P_{sh,2}$	shear failure load according to Campione et al. model [11]
P_y	yielding load
$q_{res,b}$	residual bond stresses of the longitudinal rebar
$q_{res,p}$	residual bond stresses of the plate
s	shear reinforcement spacing
T_{wi}	dowel force
V_{c1}	concrete contribution due to the arch effect
V_{c2}	concrete contribution due to the beam action
V_R	shear resistance
V_{Rc}	concrete contribution in the shear resistance
V_{Rs}, V_{sw}	steel contribution in the shear resistance
x_c	neutral axis depth
α	web rebar inclination in the longitudinal direction
β	web rebar inclination in the cross-section plane
α_c	coefficient for prestressed/non-prestressed structures
ε_y	yielding strain
ε_u	ultimate steel strain
ϕ	diameter of the diagonal rebar
ν	coefficient of softening
θ	concrete compression strut inclination

Ref. [5] develop an analytical model for the evaluation of the elastic critical moment, which is required to calculate the lateral-torsional buckling resistance moment in accordance with the current technical standards. They also propose a simplified analysis procedure, which makes it possible to derive a closed-form solution that can be assumed as a rapid tool for hand calculation. Lateral-torsional buckling of the steel reinforcement is also studied in Ref. [6] where the main mechanical models and verification principles to be used in design are illustrated with reference to static load conditions, also taking into account the specific ultimate limit states for the lower plate.

However, most studies in the literature concern the flexural and shear capacity of beams in phase II [7–16] while other researches deal with the characteristics of connections [2,17–21]. Both experimental and theoretical studies are available. In particular, experimental three-point bending tests designed for attaining shear failure are discussed in Refs. [12,13], where the researchers also develop and calibrate finite element models of the beam, and utilize analytical formula for prediction of shear strength. Effectiveness of both truss-models and additive models provided by the current building code or also derived in specific research works [16,18] are investigated.

The authors of the present paper developed a calculation model for the prediction of the shear strength of HSTCBs in Ref. [11] where an additive formulation is proposed (also in non-dimensional form) by considering the resisting contribution of concrete as the sum of arc effect and beam effect, and then the contribution of the spatial truss as as well as that of the inclined stirrups. The model also takes into account the contribution of the bottom steel plate and added longitudinal reinforcement if present. The analytical model is validated against the experimental results presented in Refs. [12,13] and also against the numerical results provided in Ref. [14] where a finite element modeling of the shear failure of HSTCBs is developed and discussed, taking into account the actual superficial finishing of the spatial truss (i.e. ribbed or smooth steel truss). The failure modes of HSTCBs of different sizes are studied in Ref. [15] by a computational method using well-established constitutive models for materials (non-linear concrete and steel) and adopting a simplified contact condition at the interface between steel and concrete. Finally, the behavior of connections was studied both experimentally and theoretically analyzing both push-out test response of specimens of HSTCBs in phase II for studying local mechanisms [2,19,21] and beam-to column connections for investigating the global flexural capacity [17,18,20]. In particular, the study on the local response consists in the investigation of the stress transfer mechanisms between steel and concrete, which can be evaluated by means of push-out tests according to Eurocode 4 [4]. Finite element models were also developed in [21] taking into account the influence of steel-concrete interface on the development of the effective length for transfer of stresses between materials. Ref. [21] also proposes a parametric study for evaluating the effect of other relevant parameters such as steel and concrete strength, diameter of spatial truss and thickness of bottom plate. In the same paper a regression model is proposed for the calculation of the shear conne capacity in the case of smooth and ribbed steel truss. Subsequently, the same researchers also developed an efficient analytical model for this kind of calculation, based on the equilibrium of forces involved in a plastic collapse mechanism conceptually derived from the mechanics of embedded dowels loaded against concrete and free-headed piles in cohesive soils [21].

Furthermore, the behavior of beam-to-column joints [17,18,22,23] and the seismic performance of hybrid systems [24,25] represent relevant issues investigated by the scientific community. With regard to the behavior of joints, cyclic tests were performed in Ref. [22] on specimens representing both internal and external joints composed by HSTCBs and RC columns. The results were also interpreted by means of analytical models available in the literature for prediction of the shear strength of joints in RC structures, obtaining conservative results that are more reliable for exterior joint configuration.