Engineering Structures 107 (2016) 135–150

Contents lists available at ScienceDirect

Engineering Structures

journal homepage: www.elsevier.com/locate/engstruct

Headed steel stud connectors for composite steel beams with precast hollow-core slabs with structural topping

Daniel de Lima Araújo [a,*], Marcel William Reis Sales [a], Silenio Marciano de Paulo [a], Ana Lúcia H. de Cresce El Debs [b]

[a] Escola de Engenharia Civil e Ambiental, Universidade Federal de Goiás, Rua Universitária, n° 1488, Qd 86, Setor Universitário, Goiânia, GO 74605-220, Brazil
[b] Escola de Engenharia de São Carlos, Universidade de São Paulo, Av. Trabalhador São-Carlense, n° 400, Centro, São Carlos, SP 13566-590, Brazil

ARTICLE INFO

Article history:
Received 7 May 2015
Revised 24 October 2015
Accepted 30 October 2015

Keywords:
Precast
Hollow-core slab
Shear connection
Push-out test
Headed stud

ABSTRACT

Composite beams of steel and concrete have been studied for a long time. The transfer of longitudinal shear stresses at the interface between the beam and the slab is a key point in obtaining the composite beam behaviour, which is usually achieved by means of shear connectors. In this case, the joint behaviour of the two materials depends on the strength and stiffness of the interface connector. Headed stud connectors for solid concrete slabs are the most common solution to achieve the composite behaviour. However, there is little information on shear connectors associated with precast concrete hollow-core slabs. This study aims to determine, through push-out tests, the shear strength of headed stud connectors associated with precast hollow-core slabs with a structural concrete topping. The analysed hollow-core slabs have two different heights and a minimum structural concrete topping of 40 mm. The strength of the in situ concrete infill joints and the rate of transverse reinforcement were varied in the present study. The results were compared to code prescriptions, and a proposition to modify an existing design equation for the ultimate shear capacity of headed studs in composite precast hollow-core slab beams is presented, focusing on the influence of the structural concrete topping.

1. Introduction

The association of steel beams and hollow-core slabs as a constructive solution has not been thoroughly researched. Few studies have been conducted to understand the connection between these elements, but this understanding is of great importance for enabling a better use of this system. According to Lam et al. [1], steel and concrete composite beams have been used since 1920. The interaction between the elements to produce a composite behaviour is ensured by mechanical action, friction and adhesion.

In composite beams, the mechanical action provided by the shear connector guarantees the transfer of shear forces at the interface between the steel beam and the concrete slab. Among these connectors, headed studs are the most commonly used due to their flexible behaviour, which allows a high longitudinal slip between the concrete and steel before the ultimate limit state is reached. Moreover, the underside of the head of a stud resists the separation forces and prevents separation between the concrete slab and the steel beam.

Research on the behaviour of these connectors started in 1956 [2]. In 1971, new research was published suggesting an empirical expression to evaluate the resistance of the headed studs, which was incorporated into most of the international standards [3]. Later, Oehlers [4] studied steel and concrete composite beams by analysing the shear flow at the interface due to the shear connectors. In that work, direct shear tests on models with and without transverse reinforcement were performed. The results showed that the presence of a transverse reinforcement limited the slipping at the interface and increased the degree of interaction between the steel beam and the concrete slab.

Several studies have been undertaken to determine expressions for evaluating the shear strength of this type of connector when associated with a solid concrete slab [5–8]. Table 1 presents a summary of the relevant research found in the literature regarding this subject. Table 2 presents the equations proposed by Eurocode 4 [9], the Brazilian Code NBR 8800 [10], the American Institute for Steel Construction (AISC) [11], the American Concrete Institute (ACI 318-08) [12] and the Precast/Pre-stressed Concrete Institute (PCI) [13] to evaluate the shear strength of headed stud connectors

---

[*] Corresponding author. Tel.: +55 62 3209 6504; fax: +55 62 3209 6087.
E-mail addresses: dlaraujo@ufg.br (D.L. Araújo), marcel.engcivil@hotmail.com (M.W.R. Sales), sileniopaulo@terra.com.br (S.M. Paulo), analucia@sc.usp.br (A.L.H.C. El Debs).

http://dx.doi.org/10.1016/j.engstruct.2015.10.050

Table 1
Equations from the literature to determine the shear strength of the headed studs.

Author	Concrete failure	Steel failure
Ollgaard et al. [3] – Eq. (1)	$P_u = 0.5A_s\sqrt{f_cE_c}$	–
Lam [5] – Eq. (2)	$P_u = 0.29\alpha\beta\varepsilon d^2\sqrt{f_cE_c}$ $\alpha = 0.2\ (h/d + 1) \leqslant 1$ $\beta = 0.5\ (g/71 + 1) \leqslant 1$ and $g \geqslant 30$ mm $\varepsilon = 0.5\ (\phi/20 + 1) \leqslant 1$ and $\phi \geqslant 8$ mm	$P_u = 0.8f_uA_s$
Xue et al. [6] – Eq. (3)	$P_u = 0.43A_s\sqrt{f_cE_c}$	$P_u = 3\lambda_pA_sf_u\left(\frac{E_c}{E_s}\right)^{0.4}\left(\frac{f_c}{f_u}\right)^{0.2}$ $\lambda_p = \begin{cases} 6 - \frac{h}{1.05d} & (h/d \leqslant 5) \\ 1 & (5 \leqslant h/d \leqslant 7) \\ \frac{h}{d} - 6 & (h/d \geqslant 7) \end{cases}$
Pallarés and Hajjar [7][a]	Eq. (4) $P_u = 0.0455A_s(f_c)^{0.45}(E_c)^{0.04}$ Eq. (5) $P_u = 0.0197A_s(f_cE_c)^{0.2}$ Eq. (6) $P_u = 0.0247A_s(f_c)^{0.5}(h)^{0.2}$ Eq. (7) $P_u = 0.0236(f_c)^{0.5}(d)^{1.4}(h)^{0.6}$	$P_u = 0.65f_uA_s$
Tanaka and Murakoshi [8] – Eq. (8)	$P_u = 2.5d^2(f_cf_y)^{0.5}$	–

[a] A_s in mm^2, f_c and E_c in MPa, h and d in mm and P_u in kN.

Table 2
Equations from the standards to determine the shear strength of the headed stud connectors.

Reference	Concrete failure	Steel failure
EUROCODE 4 [9] – Eq. (9)	$0.29\alpha d^2\sqrt{f_cE_c}$ $\alpha = 0.2\ (h/d + 1) \leqslant 1$ com $h/d \geqslant 3$	$0.8f_uA_s$
NBR 8800 [10] and AISC [11] – Eq. (10)	$0.5A_s\sqrt{f_cE_c}$	A_sf_u
ACI 318-08 [12][a] – Eq. (11)	$0.66\left(\frac{\ell_e}{d}\right)^{0.2}\sqrt{d}\lambda\sqrt{f_c}(c_{a1})^{1.5}$	$0.65f_uA_s$
PCI [13][a] – Eq. (12)	$0.002915\lambda\sqrt{f_c}(d_{ec1})^{1.53}(d)^{0.75}$	$0.75f_uA_s$

[a] $\lambda = 1$ for normal weight concrete; f_c in MPa, d in mm and P_u in kN; ℓ_e is the height of the connector, discounting the 10-mm thick head; c_{a1} is the distance from the last connector to the end of the hollow-core slab (in this work, adopted as equal to 255 mm according to Fig. 4); d_{ec1} is the distance from the centre of the connector to the edge of the in situ concrete infill joint (in this work, adopted as equal to the depth of the in situ concrete on the void plus half of the gap width, that is, 75 mm).

associated with a solid concrete slab. These standards and design codes give two different expressions: one for the failure of the headed studs and another for concrete crushing failure.

Pre-stressed concrete hollow-core slabs are a good option for composite structures due to the reduced use of formwork, increased spans and ease of assembly. However, despite the widespread use in commercial buildings, international standards do not cover the use of this type of slab in design recommendations for composite systems. Few design recommendations are available [14]. Additionally, there are few studies that encompass the association of headed stud connectors and hollow-core slabs, with the exception of some investigations conducted in the UK [1,5,15–17]. Among these studies, the research conducted by Lam [5] in 2007 is a key reference. In this study, Lam performed 72 full-scale, push-out tests with different parameters, such as stud size, hollow-core slab height (150–300 mm), joint between hollow-core slabs (40–140 mm), end conditions for precast hollow-core units under the steel beams (square end and chamfered end), in situ infill concrete strength (20–50 MPa) and amount of transverse reinforcement (10–20 mm bar diameter). The author observed that the stud capacity increased with the increase of the in situ infill gap between the hollow-core slabs up to a certain limit and recommended a minimum gap width of 80 mm for square-end, hollow-core slabs. He also found that the effect of the hollow-core slab height on the capacity of the shear studs was not significant. Finally, the author proposed a modification to the design equation given by Eurocode 4 [9] to represent the ultimate shear capacity of the headed studs in composite precast, hollow-core slabs, which is shown in Table 1.

The main objective of this paper is to contribute to the study of the association between steel beams and precast concrete hollow-core slabs by determining the shear capacity of the headed stud connectors. The parameters considered in this study were the compressive strength of the in situ concrete infill joint and topping, the height of the hollow-core slabs and the rate of transverse reinforcement. Unlike previous works reported in the literature [1,5,15–17], a structural concrete topping on the hollow-core slabs was considered. Cast in situ concrete toppings are added to the precast slab to make a complete floor finish or to enhance the structural performance of the floor by producing a composite structure. Furthermore, the shear capacity of the headed stud is characterized by the standard push-out test [9], properly adapted for the dimensions of the hollow-core slabs.

2. Experimental programme

Twenty push-out tests were performed, and the considered parameters are shown in Table 3. Eighteen specimens with hollow-core slabs were tested with an additional two specimens with solid concrete slabs for comparison. In Table 3, the first number is the height of the hollow-core slab and the second number is