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Behaviour of Perfobond shear connectors at high temperatures

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ABSTRACT

In composite steel and concrete construction, the most extensively used and known shear connector is the Nelson or stud connector, automatically welded to the beam flange. Some alternative connectors account for the contribution of the mechanical interlock of the concrete in holes or other indentations drilled in steel plates welded to the beam flange. This is the case of the Perfobond and Crestebond shear connectors recently studied by several authors. However, there is a lack of studies of their performance in fire.

In this paper, we describe a research study on the behaviour of the Perfobond shear connectors under fire conditions. The specimens were first heated from room temperature up to a target temperature and then they were loaded up to failure as a way to assess the connector's shear resistance and its ductility at high temperatures.

The main purpose of this research was to investigate the influence of the number of holes in the Perfobond shear connectors, the presence of transversal reinforcement bars passing through these holes, and the behaviour of two connectors placed side by side at high temperatures. We also compared the behaviour of these connectors at room temperature and at high temperature.

The results of this research showed mainly that the load capacity at high temperatures of these connectors was not as good as at room temperature.

1. Introduction

Steel and composite steel–concrete beams have been extensively used in buildings and bridges. The element that assures the shear transfer between the steel profile and the concrete deck, enabling the composite action to develop, is the shear connector.

The most widely used shear connector is the Nelson or stud (Fig. 1(a)). This type of connector is used worldwide, mainly due to a high degree of automation in workshops or construction sites. However, such connectors have some limitations in structures subjected to fatigue, and their use requires specific welding equipment and a high-power generator in the construction site. In addition, their resistance is somewhat limited, compared to other types of connector, leading quite often to girders designed with partial interaction.

Some alternative shear connectors have been proposed for composite structures, namely by Zellner [1], Machácek and Studnicka [2], and Veríssimo et al. [3], but some of them presented some restrictions in their industrial production, installation, or structural behaviour.

Dealing with the particular technological, economical, or structural needs of specific projects has led to the motivation of developing new products for shear transfer in composite structures. In this context, Perfobond (Fig. 1(b)) is an alternative connector with higher resistance than a stud; it was developed in the 1980s by the German company Leonhardt, Andråand Partners for the design of the third bridge over the Caroni river, in Venezuela [4]. Its development was based on the need for a system that involved only elastic deformations under service loads, with some specific bond behaviour. It is formed by a rectangular steel plate with holes drilled in it, and is welded to the beam flange.

In the recent past, several authors have studied the behaviour of Perfobond connectors at room temperature, namely by the evaluation of results from push-out tests or by the development of numerical models. It was concluded that their structural response is influenced by several geometrical properties, such as the number of holes, the width, length, and thickness of the steel plate, the concrete compressive strength, and the percentage of transverse steel reinforcement present in the concrete slab. Reference is made to the studies of Cândido-Martins et al. [5], Iwasaki et al. [6], Valente and Cruz [7], and Vianna et al. [4,8].

In addition, some analytical models have been proposed to predict the resistance of Perfobond shear connectors. The most relevant models were proposed by Al-Darzi et al. [9], Marecek et al. [10], Oguejiofor and Hosain [11], Ushijima et al. [12], and Veríssimo et al. [3].

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Notation

D	Diameter of the holes in the connector
P_{Rk}	Characteristic value of the load capacity of the specimen
P_{test}	Ultimate load capacity of the specimen
P_{θ}	Load at temperature θ
$P_{20\,°C}$	Load at room temperature
h	Connector width
l	Connector length
l_c	Concrete slab length
n	Number of holes in the connector
re	Reinforcing bar in the connector holes
s	Sample standard deviation
t	Connector thickness, time
t_c	Concrete slab thickness
$\bar{x}$	Sample mean value
w_c	Concrete slab width
δ	Relative displacement between the short steel beam and the concrete slab
δ_u	Slip capacity of the connector
θ	Furnace temperature
θ_S	Steel temperature
θ_C	Concrete temperature.

Also, this connector presents an economical alternative to studs, according to a study comparing the costs of girders with both connectors [4]. These authors concluded that Perfobond connectors may lead to an economy, compared to traditional studs, of up to 64% of the connector cost, corresponding to an overall saving of up to 5% of the total girder cost.

In spite of the relatively large number of studies on composite girders, and particularly on connectors, very few studies have been performed on the behaviour of these structural elements at high temperatures. Reference may be made to the works of Choi et al. [13] and Mirza [14] on the behaviour of studs and to the study of Zhao and Kruppa [15] on the behaviour of composite steel and concrete beams using headed shear studs in fire conditions.

In this paper, the results of an innovative study to characterise the behaviour of different types of Perfobond connector at elevated temperatures are presented. This study was based on several modified push-out tests to provide information concerning the general behaviour and suitability for practical applications of Perfobond connectors in fire conditions. The experimental programme was made in accordance with the recommendations of EN1994-1-1, annex B [16], changing some features in order that tests at high temperatures were enabled. A key issue dealt with was the number of holes in the Perfobond plate and how this characteristic affects the connector shear resistance and ductility. Another investigated issue was the presence of transversal steel reinforcement passing through the holes of the Perfobond plate. Finally, a test with two identical connectors, side by side, was carried out to evaluate the magnitude of the interaction of two Perfobond connectors.

2. Experimental tests

2.1. Specimens

The experimental tests on the Perfobond shear connectors were conducted in the Laboratory of Testing Materials and Structures (LEME) of the University of Coimbra, in Portugal. The experimental programme consisted of 32 modified push-out tests, 8 of which were performed at room temperature and 24 at high temperature.

The test specimens were fabricated in accordance to EN1994-1-1 annex B [16], but to apply heat to one side of the short beam, one of the concrete slabs of the standard push-out test had to be removed (Fig. 2). This resulted in specimens whose geometry is shown in Fig. 3. The number of holes in the connectors was varied from 0 to 4 (Fig. 3(a)) and, in some, 12 or 20 mm diameter transversal rebars were placed inside the holes of the connectors (Fig. 3(b)), or two identical connectors were placed side by side (Fig. 3(c)).

The geometrical characteristics of the specimens tested are summarised in Table 1. The notation Pnh corresponds to a Perfobond connector with n holes. Also, re corresponds to the provision of reinforcing bars within the connectors holes: 12re is for 12 mm rebars and 20re is for 20 mm rebars. The geometry of the Perfobond connectors tested is shown in Fig. 4.

All connectors were made with S355 steel plates and the beam was an HEA 200 type beam of S355 steel [17], as well. The slab reinforcement was made with 10 mm diameter bars in S500 and with a mesh around #150 mm, as established in EN1994-1-1, annex B [16]. All specimens presented a similar concrete compressive strength of approximately 28 MPa, obtained from cubes of edge dimension 150 mm at 28 days old and so corresponding to a C20/25 class according to EN 206-1 [18]. It is noticed that EN1994-1-1 recommends an HEB 260 steel profile for the short steel beam. This section was not used in specimens because the HEA 200 profile is the one often used in steel building construction in Portugal.

2.2. Test set-up

In Fig. 5, the test layout is illustrated, showing a new test set-up for modified push-out tests at room temperature and at high temperature. One of the slabs of the standard specimen was replaced (1) by the furnace (2), and a restraining structure (3) was built to re-establish the symmetry of the loading and to keep the specimen in position during the tests. The loading was applied by a 1 MN servo-controlled hydraulic actuator (4). The data acquisition system was assured by a data logger and the loads were measured by the actuator load cell, while the relative displacement between the short steel beam and the concrete slab were measured by linear variable displacement transducers (LVDTs) (5). In order to register any slip of the specimen with the base, two LVDTs were mounted (6).

2.3. Test plan

Eight modified push-out tests at room temperature, for specimens made with the connectors referred to in Table 1, were conducted to assess the reference force–slip curves, failure modes, ultimate load, and slip capacity of the specimens. Eight modified push-out tests at high temperature, for each temperature level tested, were also conducted to assess the force–slip curves, failure modes, ultimate load,and slip capacity of the specimens. It was intended to test the same type of specimens that were used for room-temperature tests, but under elevated temperatures. The temperature levels tested were 840, 950, and 1005 °C (furnace temperatures), corresponding to 30, 60, and 90 min of the ISO 834 fire curve, respectively.

2.4. Test procedure

2.4.1. Room-temperature tests

These experimental tests were loaded in two stages according to EN1994-1-1, annex B [16]. At the first stage, a cyclic loading between 5% and 30% of the expected ultimate load capacity was applied in 25 cycles at a rate of 1 kN/s. The ultimate load