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Structural behaviour of T-Perfobond shear connectors in composite girders: An experimental approach

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Abstract

This paper presents the results from eighteen push-out tests made at the Civil Engineering Department of the University of Coimbra, Portugal, on T-Perfobond shear connectors. The investigated variables were: concrete slab thickness, concrete compressive strength, connector geometry, relative position of the connector to the direction of loading, shear connector hole number and disposition, among others. The results are presented and discussed, focusing on the T-Perfobond structural response in terms of shear transfer capacity, ductility and collapse modes. Finally, a comparison of the experimental results with existing analytical formulae was also made to develop guidelines for designing the T-Perfobond connectors.

Keywords: T-Perfobond connector; Experimental analysis; Composite structural systems; Composite construction; Structural behaviour; Shear transfer

1. Introduction

The shear connector is the component that assures shear transfer between the steel profile and the reinforced concrete slab, enabling the development of the composite action in composite beams. Several different types of connectors have been studied, proposed, and used in the past. Reference is made to headed or Nelson studs (Fig. 1a), Perfobond (Fig. 1b) and Crestbond (Fig. 1c) shear connectors.

Among these connectors, the most widely used, due to a high degree of automation in workshop or site, is the Nelson stud (Fig. 1a), designed to work as an arc welding electrode and, at the same time, after the welding, as the resisting shear connector. It has a shank and a head that contributes to the shear transfer and prevents the uplift. However, it has some limitations in structures submitted to fatigue, and its use requires specific welding equipment and a high power generator at the construction site. Additionally, in applications where a discrete distribution of the connectors is needed, for example in precast concrete decks or in strengthening, repairing or even retrofitting existing structures taking advantage of the steel and concrete composite action, the stud may be substituted with advantages by stronger shear connectors.

The Perfobond type connector has some common properties with the specific connector studied in this paper. It is formed by a rectangular steel plate with holes welded to the beam flange (Fig. 1b). The Perfobond or Perfobond rib shear connector was developed in the eighties, as referred by Zellner [23], motivated by the need of a system that, under service loads, only involved elastic deformations, with specific bond behaviour and also was associated to higher fatigue strength.

Several authors have recently studied the behaviour of the Perfobond connector, mostly from push-out tests. Among these, reference is made to the studies of Al-Darzi et al. [1], Iwasaki et al. [11], Machacek & Studnika [12], Medberry & Shahrooz [13], Neves & Lima [14], Oguejiofor & Hosain [15], [16], Ushijima et al. [17], and Valente & Cruz [18,19]. These authors concluded that their structural response was influenced by several geometrical properties such as the number

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List of Symbols

A_{cc}	longitudinal concrete shear area per connector (mm^2)
D	connector hole diameter
h	slab height (in the test specimen) from the base up to the the connector (mm)
H_c	slab height
h_{sc}	Perfobond connector height
l	connector length
n_1	number of transverse reinforcement bars used at each slab
P_{Rk}	test characteristic load
$qu_{,\text{test}}$	maximum experimental load
t	connector thickness, for the T-Perfobond the web thickness
t_c	slab thickness
δ_u	connector slip capacity
δ_{uk}	connector characteristic slip
ϕ	reinforcement bars diameter
γ_c	concrete safety factor

of holes, the plate height, length and thickness, the concrete compressive strength, and the percentage of transverse reinforcement provided in the concrete slab.

Ferreira [6] has adapted the Perfobond geometry for thinner slabs, usually used in residential buildings, and isolated the contributions to the overall shear connector strength from the reinforcement bars in shear and from the concrete cylinders formed through the shear connector holes.

The motivation of developing new products for the shear transfer in composite structures is related to issues involving particular technological, economical or structural needs of specific projects. In this context, some other alternative shear connectors have been proposed for composite structures. Reference can be made to the studies of Fink and Petraschek [7], Gündel and Hauke [8], Hechler et al. [9], Hegger and Rauscher [10], Machacek and Studnika [12], Vellasco et al. [20], Veríssimo et al. [21], and Zellner [23].

Also, an alternative connector, named as T-Perfobond (Fig. 2), was presented by Vianna et al. [22], in the scope of a study on Perfobond connectors, where a comparison of the behaviour of these connectors and a limited number of T-Perfobond connectors was made. This connector derives from the Perfobond connector by adding a flange to the plate, acting as a block. The motivation for developing this T-Perfobond connector is to combine the large strength of a block type connector with some ductility and uplift resistance arising from the holes at the Perfobond connector web.


(a) Studs. (b) Perfobond.

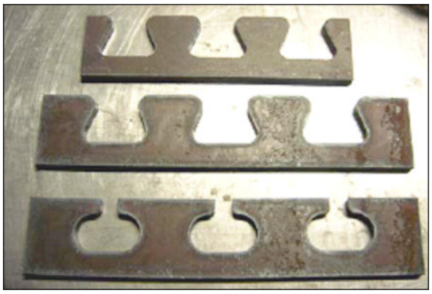
(c) Crestbond.

Fig. 1. Typical shear connector examples.


Fig. 2. T-Perfobond shear connector.

The present work focuses on T-Perfobond connectors and involved eighteen push-out tests performed at the Civil Engineering Department of the University of Coimbra, Portugal. Specimens were fabricated from an IPN 340 section cut at the symmetry axis parallel to the flanges, and were produced without holes, and with, respectively, two or four holes, located in one or two rows in the load transfer direction, with slabs of 120 mm (Fig. 3a) and 200 mm thicknesses, (Fig. 3b). Six tests were made from the nominal C25/35 concrete compressive strength class, and twelve tests from the nominal C35/45 class according to EN-1992-1-1 (Eurocode 2 [2]).

2. Models for the strength prediction of relevant connectors

The T-Perfobond connectors were conceived as a combination of a T-connector or block type connector (Fig. 4) with the perforated Perfobond connector (Fig. 1b). Therefore, any tentative model to predict its resistance should initially be based on existing models for the strength prediction of these two types of connectors.

An evaluation of the shear resistance of Perfobond connectors was proposed by Oguejiofor & Hosain [15,16], adding three contributions for the overall resistance: the bearing concrete resistance at the connector face, the steel

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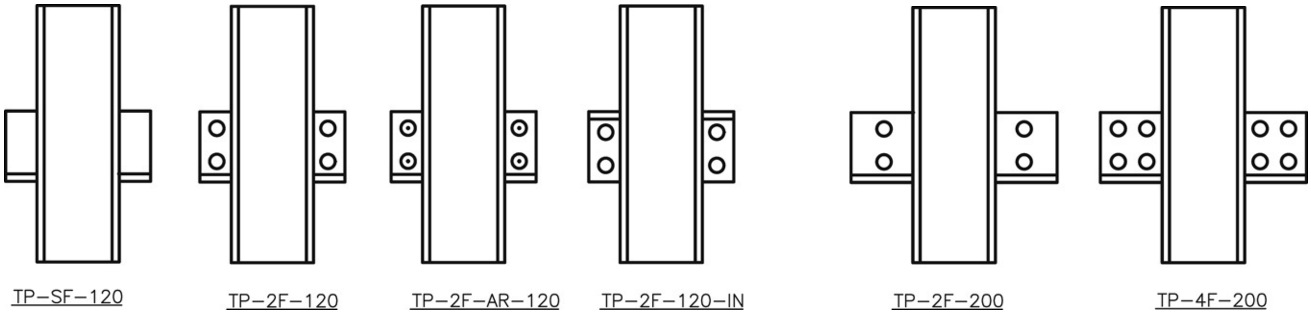
Table 1
Geometrical characteristics of the tested models

Type	Slab			T-Perfobond Rib					Reinforcement bars		
	f_{ck}[a] (MPa)	t_c (mm)	H_c(mm)	h_{sc} (mm)	l (mm)	t (mm)	D (mm)	n	Bars in holes	$n1$	ϕ (mm)
TP-2F-120-A/B	28.3 (C25/30)	120	650	76.2	170	12.2	35	2	0	10	10
TP-2F-200-A/B		200	650	150	170	12.2	35	2	0	10	10
TP-4F-200-A/B		200	650	150	170	12.2	35	4	0	10	10
TP-SF-120-A/B	43.9 (C35/45)	120	650	76.2	170	12.2	35	0	0	10	10
TP-2F-120-A/B		120	650	76.2	170	12.2	35	2	0	10	10
TP-2F-AR-120-A/B		120	650	76.2	170	12.2	35	2	2	12	10
TP-2F-120-A/B-IN		120	650	76.2	170	12.2	35	2	0	10	10
TP-2F-200-A/B		200	650	150	170	12.2	35	2	0	10	10
TP-4F-200-A/B		200	650	150	170	12.2	35	4	0	10	10

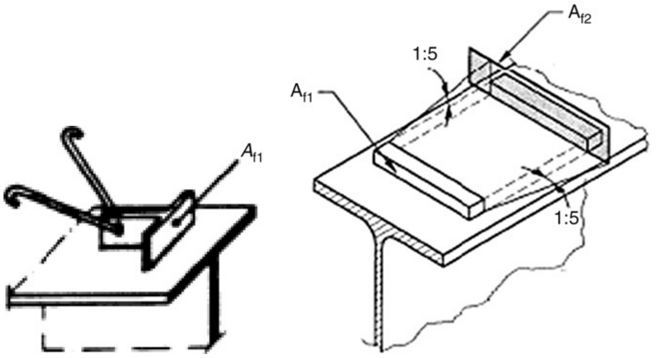
[a] Nominal values are also indicated between round brackets.



(a) T-Perfobond connectors with a 120mm slab thickness.

(b) T-Perfobond connectors with a 200mm slab thickness.

Fig. 3. Typical tested connector geometries.



(a) T-shape block type connectors.

(b) Af1 & Af2 areas definition.

Fig. 4. T-Connector layout and design.

reinforcement bars in the concrete slab, and the concrete cylinders in shear that are formed through the connector's holes — Eq. (1):

$$q_u = 4.50.h_{sc}.t_{sc}.f_{ck} + 0.91.A_{tr}.f_y + 3.31.n.D^2.\sqrt{f_{ck}} \tag{1}$$

where: q_u — Perfobond connector nominal shear strength (N); D — shear connector hole diameter; n — shear connector hole number; h_{sc} — Perfobond connector height; t_{sc} — Perfobond connector thickness; f_{ck} — cylinders concrete compressive strength (MPa); f_y — yield stress of the steel reinforcement bars present in the concrete slab (MPa); A_{tr} — area of transversal steel reinforcement present in the concrete slab, within the connector zone, including any reinforcement passing through the holes (mm^2);

The block connector resistance maybe evaluated from Eq. (2), proposed in the 1992 version of Eurocode 4 [5]:

$$q_u = \eta.A_{f1}.f_{ck}/\gamma_c \tag{2}$$

where: A_{f1} is the connector front bearing area (Fig. 4b); A_{f2} is the connector front bearing area amplified by inclination rate of 1:5 from the previous connector (Fig. 4b) only considering the area inside the concrete; η is equal to; $\sqrt{A_{f2}/A_{f1}} \leq 2.5$ and γ_c is the concrete safety factor equal to 1.5. The connector geometry should be such that the flange width should not exceed ten times the flange thickness, and the height should not exceed ten times the flange thickness or 150 mm.

3. Tests description

The experimental programme consisted of identical twin specimens (A and B), totaling eighteen T-Perfobond push-out tests. The configurations are shown in Figs. 3 and 5 and Table 1, that gives an overview of the specimen's characteristics in the experimental programme. The test variables were: concrete slab thickness, concrete compressive strength, load direction related to the Perfobond flange, and Perfobond holes number. Additionally, specimens without holes were also tested to better assess their particular contribution to the shear connector capacity. Finally, tests with reinforcement bars passing through the holes were made to enhance the shear strength and ductility. The adopted identifying label for each test follows the test

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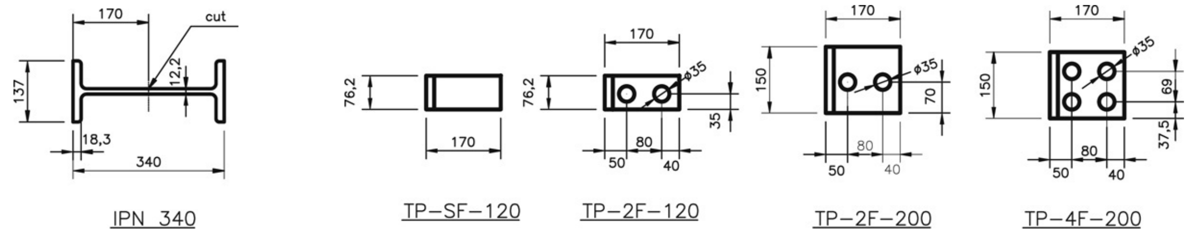

(a) IPN 340 used for the fabrication of T-Perfobond connectors.

(b) T-Perfobond layout.

Fig. 5. Tested connectors layout.

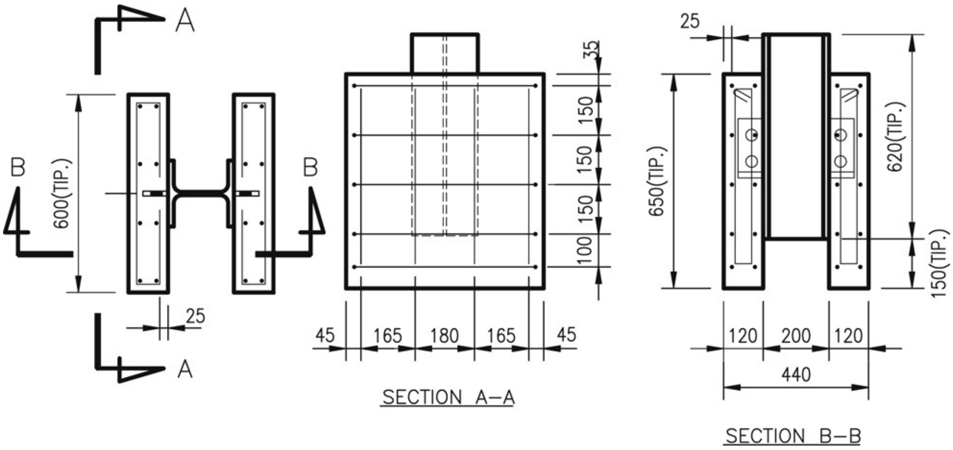

Fig. 6. TP-2F-120-A specimen details.

characteristics: "TP" for T-Perfobond, "SF" for no holes, "2F" or "4F" corresponding to the number of holes in the connector (2 or 4), "AR" when reinforcement bars were used inside the connector's holes, and reference to the concrete slab thickness equal to 120 mm or to 200 mm. Fig. 6 shows, as an example, the configuration of one tested model: TP-2F-120-A. The tests are grouped in two series: six tests with a nominal C25/30 compressive strength class and twelve tests with a nominal C35/45 class. The actual concrete compressive strength for each series, obtained from cubes and corrected for cylinders according to EN 1992-1-1 [2], is depicted in Table 2.

Similarly to the Perfobond connector, the dimensions of the T-Perfobond type connectors were established as a result of the required slab thickness and the hole spacing, adhering to the minimum distance of 2.25d in the horizontal direction according to Oguejiofor & Hosain [15] for Perfobond type connectors. 76.2 mm height connectors were used for 120 mm thick slabs and 150 mm height connectors were used for 200 mm thick slabs. A rolled S275 (nominal yield stress of 275 MPa, according to EN 10025) IPN340 section, cut at the middle of the web, was used to produce a pair of T-Perfobond connectors.

The push-out specimens were fabricated according to the Eurocode 4 [4] specifications adapted to fit the two slab thicknesses. The adopted sections for the beams were S275 HEB200. The reinforcement bars used in the concrete slab and bars passing through the connector's holes were made from 10 mm S500 corrugated bars (nominal yield stress of 500 MPa). The beams steel flanges were previously treated with oil to minimise any contribution from the chemical bond at the steel to concrete interface.

Table 2
T-Perfobond connectors test results

Specimen	Age days	f_{ck}[b] (MPa)	$q_{u,\text{test}}$ (kN)	P_{rk} (kN)	δ_u (mm)	δ_{uk} (mm)
TP_2F_120_A	52	28.37	527.48	474.73	2.80	2.52
TP_2F_120_B	57		520.60	468.54	3.10	2.79
TP_2F_200_A	58		706.28	635.65	6.50	5.85
TP_2F_200_B	58		659.33	593.39	4.44	4.00
TP_4F_200_A	64		705.98	635.38	4.62	4.16
TP_4F_200_B	62		676.30	608.67	4.00	3.60
TP_SF_120_A	33	43.91	621.95	559.76	1.70	1.53
TP_SF_120_B	33		660.55	594.50	2.25	2.03
TP_2F_120_A[a]	33		563.20	506.88	2.18	1.96
TP_2F_120_B	34		647.90	583.11	3.40	3.06
TP_2F_AR_120_A	34		683.38	615.04	2.76	2.48
TP_2F_AR_120_B[a]	34					
TP_2F_120_IN_A[a]	34					
TP_2F_120_IN_B	34		714.68	643.21	4.20	3.78
TP_2F_200_A	34		780.35	702.32	5.18	4.66
TP_2F_200_B	34		804.05	723.65	2.81	2.53
TP_4F_200_A	35		750.28	675.25	5.38	4.84
TP_4F_200_B	35		790.25	711.23	5.42	4.88

[a] Results from these tests were disregarded due to problems with the jack or with the test geometry.
[b] Values for the compressive strength are mean values.

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Fig. 7. Push-out test instrumentation and layout.

The Eurocode 4 [4] recommended procedure was adopted for the tests: the first stage includes 25 cycles of loading/unloading ranging from 5% up to 40% of the expected failure load applied to the specimens. At this stage the procedure was controlled by an applied load at a rate of 5 kN/s. At the subsequent stage, up to the specimen's failure, the control parameter was the relative displacement between the steel beam and the concrete slab, reaching at least a point where the descending load after the peak load was 80% of the peak load.

The slip capacity of the connector δ_u should be taken as the highest measured value at the level of the characteristic load (P_{Rk}). The characteristic load is taken as the least collapse load, divided by the number of connectors, and is reduced by 10%. The characteristic slip is δ_{uk} and should be taken as $0.9\delta_u$.

4. Test layout and instrumentation

Fig. 7 depicts the test layout and the specimen's instrumentation: load displacement transducers (LVDT's) were conveniently located to measure the relative displacement (slip) between steel and concrete. A vertical LVDT was used for control purposes at the specimen's upper part, near to the hydraulic jack. In the TP-4F-200-A (28.3 MPa concrete), TP-2F-AR- 120-A and TP-2F-120-A-IN (43.9 MPa concrete) tests strain gauges were also installed at the connectors flange to evaluate the stress state as shown in Fig. 12. Also shown in this figure is the output from these rosettes, where the equivalent or von Mises stresses are plotted for the connection applied load.

The specimens were supported by neoprene sheets to absorb any imperfections present at the bottom concrete face and to reduce friction, as recommended by Iwasaki et al. [11], and were loaded by a hydraulic testing machine with a maximum capacity of 5000 kN.

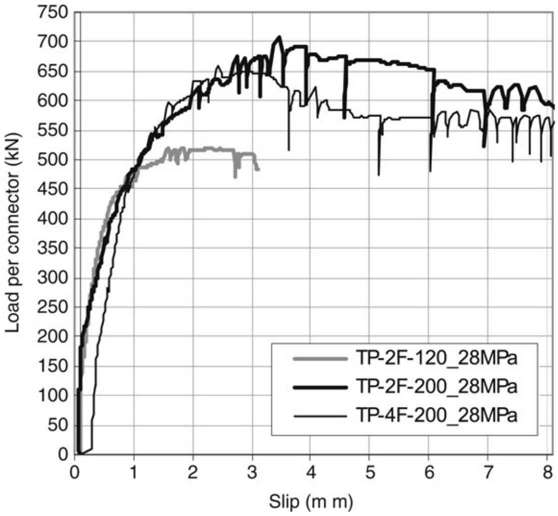

Fig. 8. Load vs. slip curves for T-Perfobond connectors, $f_{ck} = 28.3$ MPa.

5. Results

The results from the tests are summarised in Table 2, where the values for the actual concrete compressive strength, maximum experimental load, test characteristic load, connector slip capacity and connector characteristic slip are reported. The following sections present a comparative interpretation of these results.

5.1. Comparative assessment of the behaviour of different T-Perfobond geometries

Fig. 8 presents the load vs. slip curves resulting from T-Perfobond specimens with a concrete cylinder compressive strength of 28.3 MPa (nominal value of 25 MPa or C25/35 class according to EC2 [2]). Three different geometries are involved: T-Perfobond connectors with two holes in slabs of 120 and 200 mm, and a T-Perfobond connector with four holes in a 200 mm thick slab.

In the tests of T-Perfobond connectors with two holes, increasing the concrete slab thickness from 120 mm (TP-2F-120) to 200 mm (TP-2F-200) led to a 27% increase of the characteristic resistance and an approximately 1.3 mm increase of the slip capacity δ_u.

Increasing the number of holes in the tests from two to four in 200 mm thick slabs did not lead to significant

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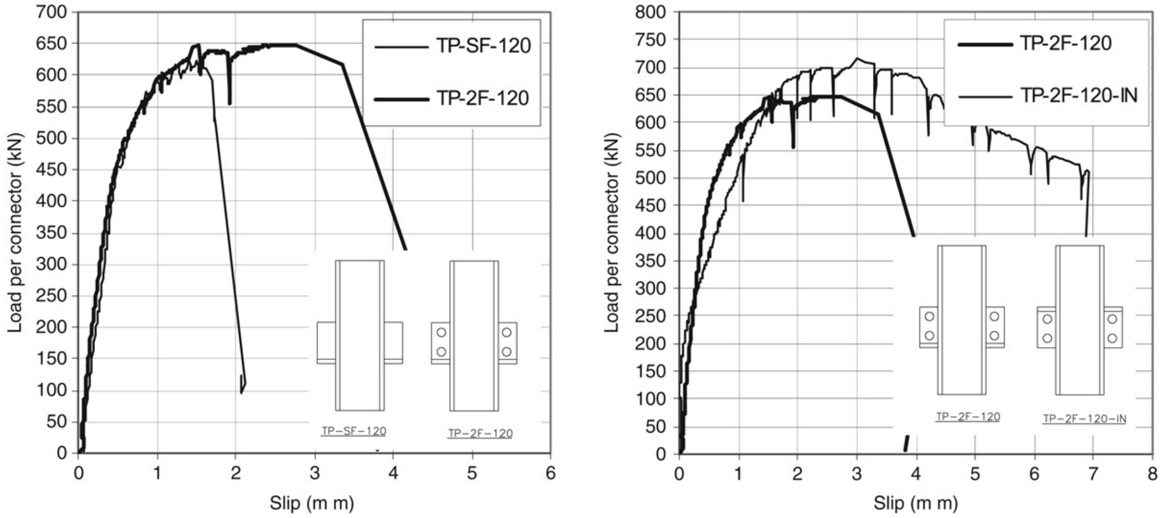

Fig. 9. Load vs. slip curves for T-Perfobond connectors with a 120 mm thick slabs, $f_{ck} = 43.9$ MPa.

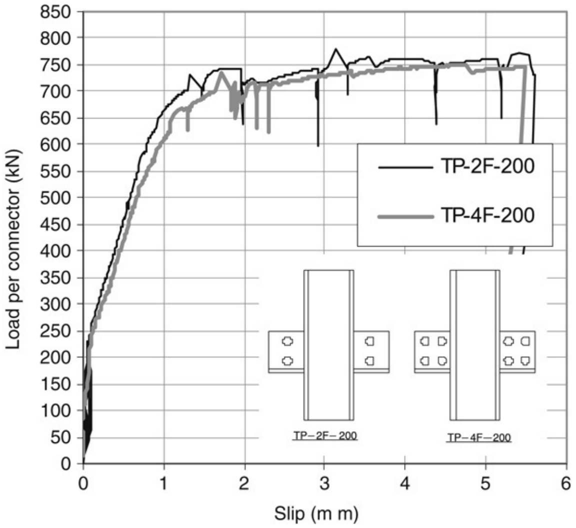

Fig. 10. Influence of the number of holes in T-Perfobond connectors with a 200 mm thick slab. $f_{ck} = 43.9$ MPa.

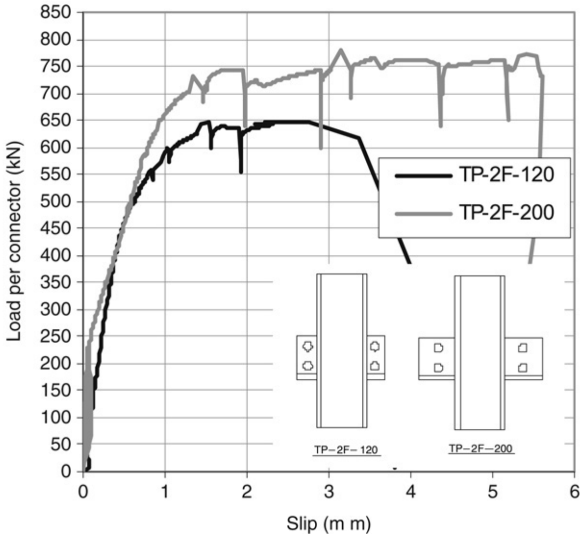

Fig. 11. Influence of the slab thickness and connector height over the T-Perfobond connector response, $f_{ck} = 43.9$ MPa.

changes in the connector behaviour. This is most likely due to stress concentrations generated by the interaction between the stressed areas from concrete cylinders formed at different rows. Concerning this interaction, the minimum distance between holes of 2.25D proposed by Oguejiofor and Hosain [15] was respected in the horizontal direction. However, the vertical distance between the two rows of holes was less than this value, since it was limited by the maximum connector height as a function of the slab thickness and of the minimum concrete cover.

At advanced load stages in these tests, concrete had cracked considerably, suggesting that the bearing capacity was about to be reached. Besides, further loading, if allowed by the concrete, would not be stood by these connections, since the welds connecting the T-Perfobond and the beam flange had started to fail, as observed after dismantling the specimens. This was quite unexpected since the 8 mm fillet weld all round the connector should stand a load of 980 kN, computed according to the conservative simplified method of EC3-1-8 [3], and following the recommendations from EC4-1-1 [5] regarding the eccentricity of the resultant force to the connector's weld. This value is well above the maximum load level of 700 kN reached in the tests. This was therefore an issue that was corrected in the tests performed subsequently.

Figs. 9–11 present the load vs. slip curves resulting from T-Perfobond specimens with a concrete cylinder compressive strength of 43.9 MPa (nominal value of 35 MPa or C35/45 class according to EC2 [2]).

From the left set of curves present in Fig. 9, comparing the tests of 120 mm slabs without and with two holes, it may be concluded that the presence of the holes leads to an approximately 4% increase of the connectors characteristic resistance P_{rk} and an increase of the slip capacity $\delta_{u,}$ of about 1.5 mm, clearly showing that, in this case the block resistance is more significant than the resistance related to concrete dowels formed in the connector holes. However, these dowels/holes,

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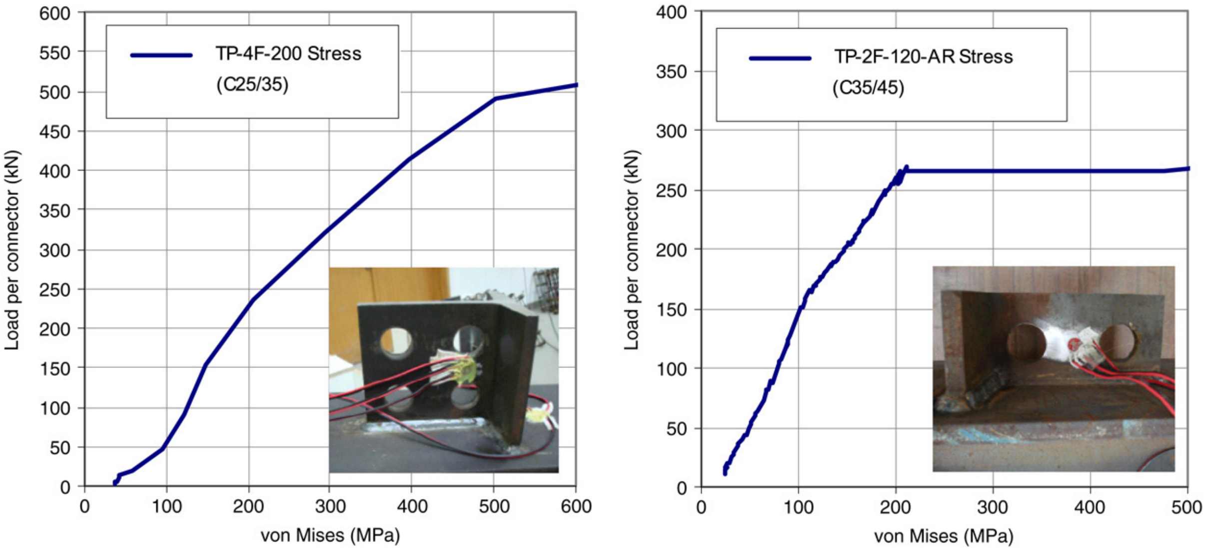

(a) $f_{ck} = 28.3$ MPa.

(b) $f_{ck} = 43.9$ MPa.

Fig. 12. Force vs. von Mises stress curve for the T-Perfobond connector.

in addition to contributing to a higher ductility, provide the connector with the necessary uplift resistance.

The right set of curves in Fig. 9 show the difference in the connections behaviour when changing the position of the connector by 180 degrees: in test TP-2F-120 (the curve represented by a thicker line) the connector's flange is at the bottom and therefore acts almost entirely in bearing on the concrete without a contribution from the dowels/holes. On the other hand in test TP-2F-120-IN the bearing into the concrete is provided firstly by the connector's web, and the holes are surely mobilised. This results in a 10% increase of the connector characteristic resistance P_{rk} and in an approximately 1.8 mm increase of the slip capacity δ_u.

Fig. 10 shows the force–displacement curves resulting from the tests of T-Perfobond connectors with two and four holes in 200 mm thick concrete slabs. The increase from two to four holes in the connector, similarly to T-Perfobond connectors tests with a concrete cylinder compressive strength of 28.3 MPa, did not lead to any significant changes in the connectors behaviour. In fact, the two curves are practically superposed during all the tests.

Fig. 11 shows the influence of the slab thickness and of connector height. The slab thickness varies from 120 mm (test TP-2F-120) to 200 mm (test TP-2F-200) in tests of T-Perfobond connectors with two holes, with height of 76.2 mm and 150 mm respectively. The increase of the slab thickness and of connector height led to a 20% increase of the connector characteristic resistance and an approximately 3 mm increase of the slip capacity δ_u. When comparing these differences to the similar differences from the tests with a concrete cylinder compressive strength of 28.3 MPa (Fig. 8), it may be concluded that for the higher concrete compressive strength the relative gain in resistance is slightly reduced but the relative gain in ductility is also quite important. This ductile capacity may be explained by looking at the force-Von Mises stress curve represented in Fig. 12a for concrete with a strength of 28.3 MPa, where the connector yielding at a load level of 420kN, and its contribution to the connection overall ductility is represented. For a higher strength concrete of 43.9 MPa in Fig. 12b, the strain gauge's values from 200 MPa onwards were not reliable inhibiting any further analysis or conclusions. However, since the load level reached in this test is higher than in the tests presenting a 28.3 MPa concrete compressive strength, it could be concluded that the connector yielding is contributing somewhat to the connector failure mode. It could also be noted, as observed after dismantling the test specimen, that the yielding spread was not enough to be a limit to the connector capacity.

In all tests the onset of failure has involved the formation of a longitudinal crack in the slab most concentrated near the connector (Fig. 13a), that progressed and opened with further loading. This was followed by concrete crushing at the connector's front face. Some tests also presented the connector yielding at advanced load stages. (Fig. 13b) shows a typical test specimen after failure and the shear connector deformed configuration after the concrete removal.

As an overall evaluation of the T-Perfobond performance, it may be stated that this connector presents quite good results in terms of the ultimate shear capacity. However, it does not satisfy the ductility criteria imposed by the Eurocode 4 [4] to perform a plastic distribution of the shear force between different connectors along the beam length. This is particularly important only if the designer wishes to perform a plastic longitudinal shear distribution along the beam length.

5.2. *Influence of steel reinforcement bars*

Steel reinforcement bars passing through the connector holes, when provided, extensively yielded during the tests, as shown in Fig. 14.

Fig. 15 shows the influence of reinforcement bars passing through the holes of T-Perfobond connectors in 120 mm thick slabs. These bars lead to a small increase of only about

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(a) Concrete slab cracking layout.

(b) Connector after collapse.

Fig. 13. T-Perfobond connector failure modes.

5% in the connector characteristic resistance. It was expected that these bars at least could enhance the connector ductility. However this was not the case, most probably because of the connector position, where the flange absorbs most of the force in bearing, not mobilising the holes or the steel reinforcement inside them. The authors expect that if the test was made at the inverse position, i.e the T-Perfobond flange located close to the jack, and a sufficient quantity of reinforcement bars were used at the concrete slabs through the T-Perfobond holes and/or below the T-Perfobond web, the specimens would have their ductile capacity significantly increased.

5.3. *Influence of the concrete compressive strength*

Fig. 16 shows the comparison of load vs. slip curves for T-Perfobond connectors with two holes for 120 mm thick slabs with actual 28.3 MPa and 43.9 MPa cylinder concrete compressive strength (C25/30 and C35/45 nominal strength classes). This relative 55% increase of the concrete compressive strength leads to an increase of the T-Perfobond connection strength of only about 25%.

This strength increase was even smaller when considering connectors with two holes also, but in 200 mm thick slabs. In these tests, the strength increase was of only 11%, as shown in the left set of curves in Fig. 17. This difference reduces to only 7% for the connectors with the same slab thickness but for connectors with four holes. These results are summarised in Fig. 18.

6. Comparison of experimental and analytical results

A preliminary analytical estimation of T-Perfobond strength may be obtained by neglecting the favourable effects of the steel reinforcement bars in the concrete slab and of the holes in the connector by assuming that it behaves like a block or a T-Connector. For these connectors, a strength evaluation was proposed in the 1992 version of Eurocode 4 [5] — Eq. (2). This model was used to evaluate the T-Perfobond resistance and was compared to the corresponding experimental results. For the application of this model, the areas A_{f1} & A_{f2} (Fig. 4) were computed considering the whole available length from the flange of the T-Perfobond to the face of the concrete specimen.

Fig. 14. T-Perfobond connector failure modes with reinforcement bars in the connector holes (TP-2F-120-AR-B).

The results from this comparison for the connectors with a concrete compressive strength of 28.3 MPa show that this model leads to an overestimation of the resistance (Fig. 19) for 200 mm thick slabs, where the average strength overestimation is 25%. In these tests, a premature failure of the connector occurred in the welds, associated with some connector yielding. However, an extensive concrete cracking was observed well

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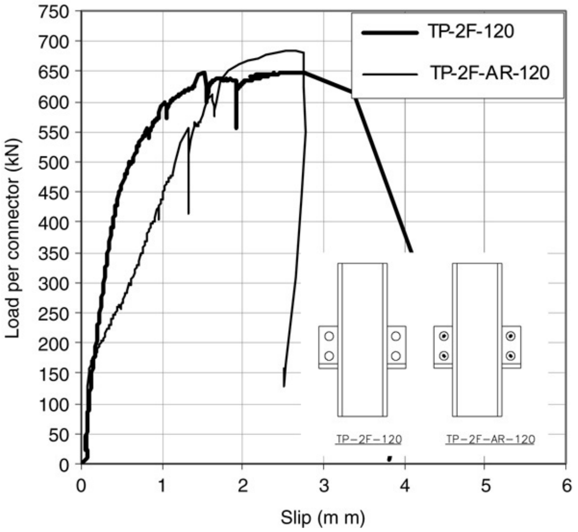

Fig. 15. Influence of the bars in the connector holes for T-Perfobond connectors, $f_{ck} = 43.9$ MPa.

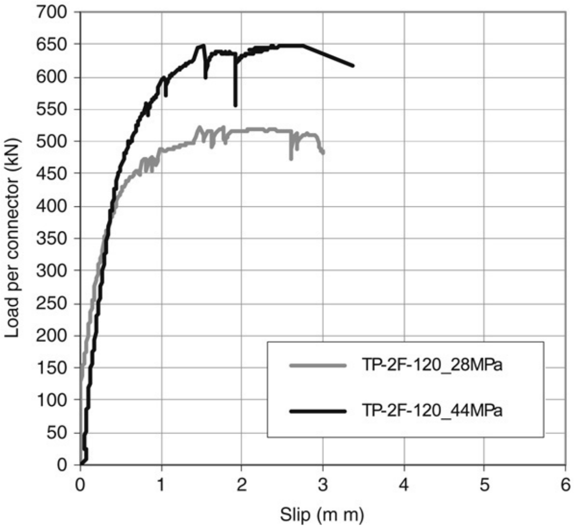

Fig. 16. Comparisons of the load vs. slip curves for T-Perfobond connectors with 28.3 MPa and 43.9 MPa concrete compressive strength.

before, showing that, if maximum bearing capacity of the concrete could not be reached, at least this value was close to this limit. The T-connector resistance seems to depend on the connector height and slab thickness differently from the formulation expressed by Eq. (2). Any development of an analytical model to predict this resistance should consequently look carefully at this issue.

For the connectors with a concrete compressive strength of 43.9 MPa the welds were corrected and therefore no weld failure was observed. As previously mentioned, the connector's yielding was again observed well after an extensive concrete cracking was present in the test specimens. Fig. 20 presents a comparison between the experimental and analytical results, similar to the previous comparison for 28.3 MPa concrete. For the tests with 120 mm thick slabs the experimental resistance is significantly higher than the analytical formulae neglecting the favourable effects of the steel reinforcement bars in the concrete slab and of the holes in the connector, showing that there is a margin for improving the model by introducing these favourable effects. However, for 200 mm thick slabs results were in line with the previous considerations for concrete with a compressive strength of 28.3 MPa. Once again, resistance seems to depend on the connector height and slab thickness differently than in the formulation expressed by Eq. (2).

Since the effect of the holes and the effect of the steel reinforcement in the concrete slab have an influence on the resistance of the connectors, the model proposed by Oguejiofor and Hosain [15,16] – Eq. (1) was used to compute these contributions – the second and third terms in Eq. (1). The comparison between the resulting values and the corresponding experimental values is shown in Fig. 19 and in Fig. 20, and should be regarded not as a prediction of the experimental values, but as a contribution to the connections resistance, that is to be added to the predictions obtained using Eq. (2).

Most certainly there is an interaction between these resistance components, and an analytical expression to predict

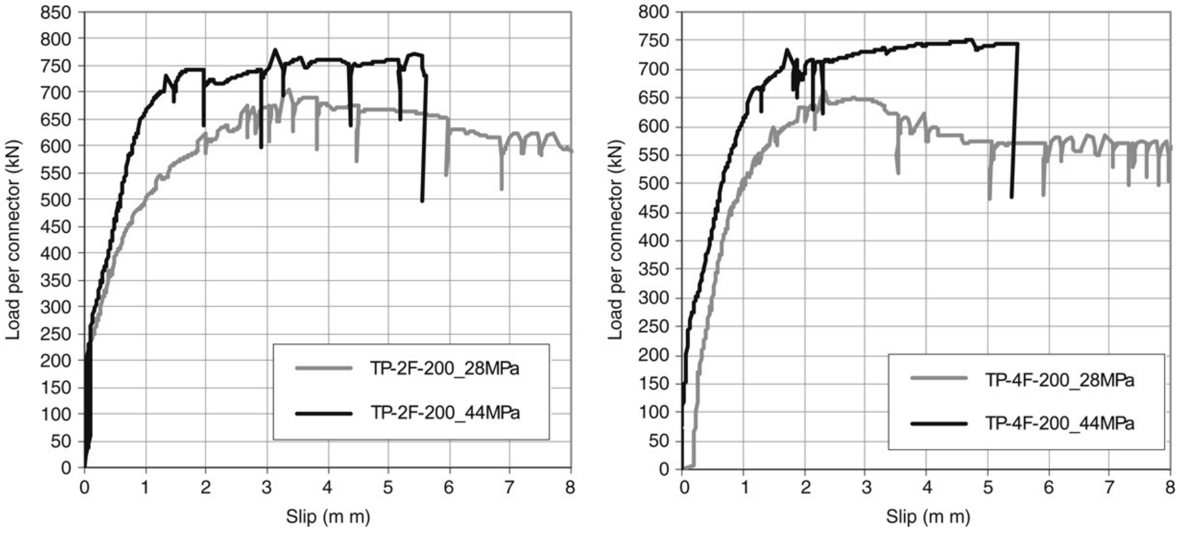

Fig. 17. Comparisons of the load vs. slip curves for T-Perfobond connectors with 28.3 MPa and 43.9 MPa concrete compressive strength.

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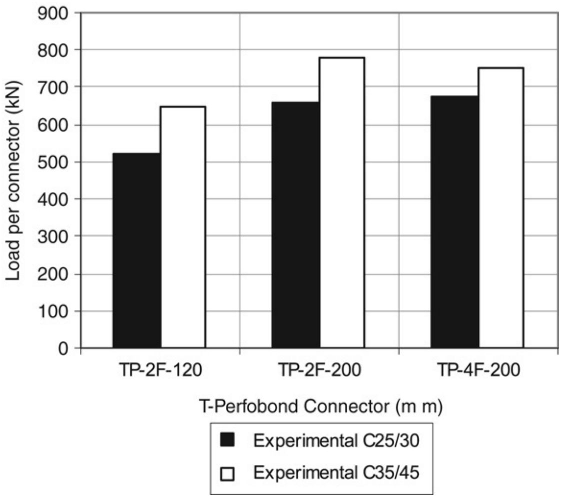

Fig. 18. Influence of the concrete compressive strength on the connector resistance.

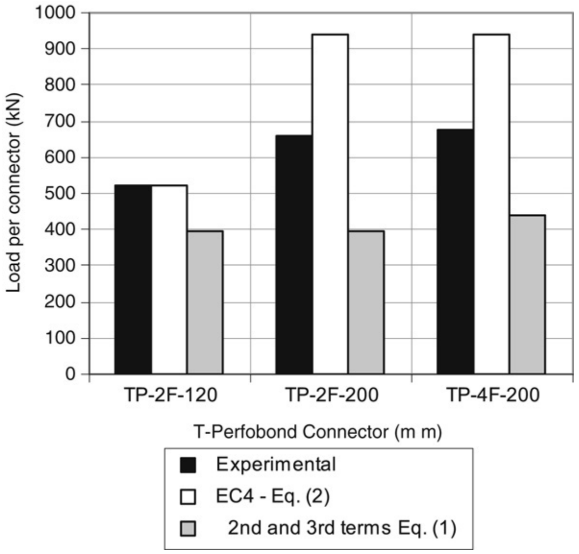

Fig. 19. Comparison of analytical and experimental results, T-Perfobond connector with 28.3MPa concrete compressive strength.

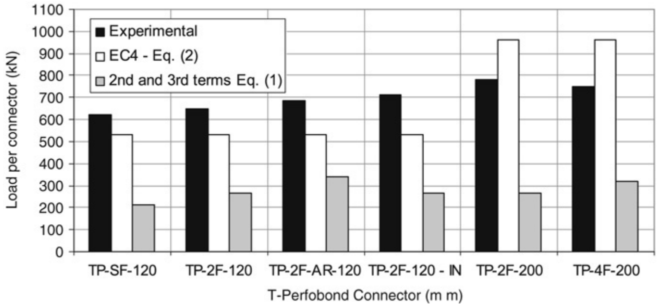

Fig. 20. Comparison of analytical and experimental results, T-Perfobond connector and 43.9 MPa concrete compressive strength.

the global resistance surely should not be based on the linear sum of these contributions. In fact it should be centred on reduction factors affecting each contribution, to take into account the interaction. A similar procedure is proposed in [5] to deal with the contributions from the block resistance and the resistance from a specific type of reinforcement bars. This aspect will be considered in the future stages of the present investigation.

7. Conclusions

The results from a set of experimental tests conducted at the Civil Engineering Department of the University of Coimbra, Portugal, were used to evaluate the behaviour of T-Perfobond connectors, focusing on their resistance and slip capacity.

T-Perfobond connectors have shown to stand high shear loads resulting in a smaller number of connectors in a beam. In addition, they have the additional advantage of being produced with ordinary rolled I or H sections, and may be welded with easily available equipment. These factors contribute to a potential saving of material and workmanship, leading to a more economical design of composite girders.

The onset of failure is related to a slip at the connector-concrete interface, followed by the formation of cracks in the concrete that open and propagate as the load increases, followed by the concrete crushing at the connector's front face. This concrete failure was at later stages of loading accompanied by the connector yielding, and, in some cases by a failure of the connector welds.

The slip observed in the tests was smaller than the minimum required slip capacity of 6 mm according to Eurocode 4 [4]. This value does not satisfy the requirements for a plastic distribution of shear force in the connectors along the structural element. This fact is not significant if an elastic distribution of shear along the beam length is to be adopted in design.

Concrete block resistance was found to be of much greater importance than the resistances related to the holes and to the reinforcement bars. In fact, comparison of test resistances from tests without and with holes, and without and with reinforcement bars in the holes, showed limited gains in resistance for the investigated specimens range.

The authors believe that if the tests were repeated at the inverse position, i.e the Perfobond flange located close to the jack, the connector ductility would be improved. Another improvement in the connector ductility could be achieved if connector positioned at the inverse position could be used with additional reinforcement bars used at the concrete slabs through the Perfobond holes and/or below the Perfobond web the specimens.

Increasing the slab thickness led to a subsequent increase of the characteristic resistance and of the slip capacity δ_u, related to a larger concrete block resistance. When comparing these differences to the similar differences from the tests with a different concrete cylinder compressive strength, it may be concluded that for the higher concrete compressive strength the relative gain in resistance is slightly less significant but the relative gain in ductility is also quite important (about 100%).

An increase of the concrete compressive strength also led to a higher shear connector capacity, but in a comparatively smaller proportion to the concrete resistance in itself. This

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resistance enhancement was observed to be less relevant in thicker slabs.

Application to T-Perfobond connectors of an available model for predicting the shear resistance of T or block connectors [5] was found to be on the safe side for 120 mm thick slab connections (especially for stronger concrete), since it neglects the favourable effects of the steel reinforcement bars in the concrete slab and of the holes in the connector. However, for thicker slabs, this model considerably overestimated the connector's resistance, suggesting that it depends on the connector height and slab thickness differently to the formulation expressed by Eq. (2).

The next steps of the present investigation will consider the development of consistent and accurate formulae for the evaluation of the shear capacity of the investigated T-Perfobond connectors, taking into account the interaction between the block resistance and the contributions from the slab steel reinforcement and the connector's holes. Full scale tests of composite beams using the investigated shear connector will also be the main focus of that study. These new tests will be centred on composite girders with shear connectors evenly spaced or spaced according to the shear force diagram. Their results will help to investigate questions related to the maximum and minimum spacing, its application in a partial interaction design and on hogging moment regions and on its influence over the composite beam effective width.

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