EXPERIMENTAL STUDIES ON SHEAR CONNECTION BETWEEN STEEL AND LIGHTWEIGHT CONCRETE

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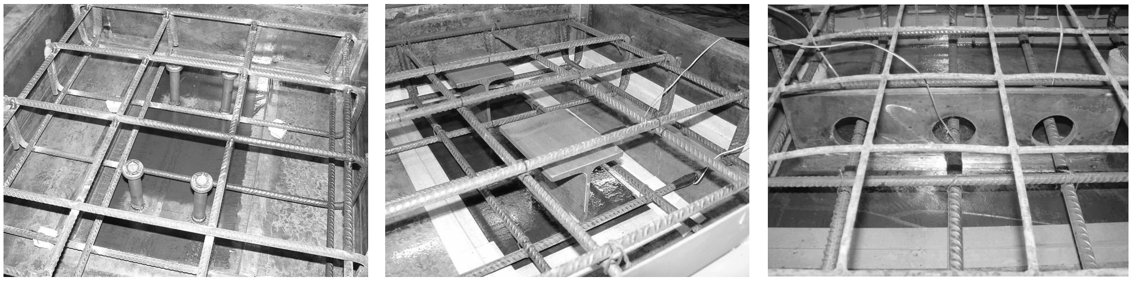
ABSTRACT: This communication describes the experimental tests carried out at University of Minho to study shear connection between steel and high strength lightweight concrete (HSLWC). The test configuration follows the EC4 recommendations and repeats some dispositions referred by other authors. The experimental study involves tests on studs with diameters of 19, 22 and 25 mm, T connectors produced from laminated steel profiles and Perfobond connectors with specific geometry (Figure 1). With these tests it is possible to characterize different types of connection and evaluate load and deformation capacity.

1. INTRODUCTION

On a composite structure, both steel and concrete have to work together. The connection between the two materials is usually achieved by using steel connectors, which may have different shapes. Beside the commonly used headed studs, some investigations proved that the use of Perfobond connectors and T connectors is adequate when dealing with high strength concrete.

Recent experimental campaigns carried out by Oguejiofor & Hosain (1994), Galjaard & Walraven (2000), Hegger et al. (2000,2001), Ferreira (2000), Machacek & Studnicka (2002) made it possible to describe and analyse the steel to concrete connection properties. These studies focused primarily on normal density concrete (NWC), both normal and high strength and were a reference to the work here presented.



Headed stud connector T connector Perfobond connector

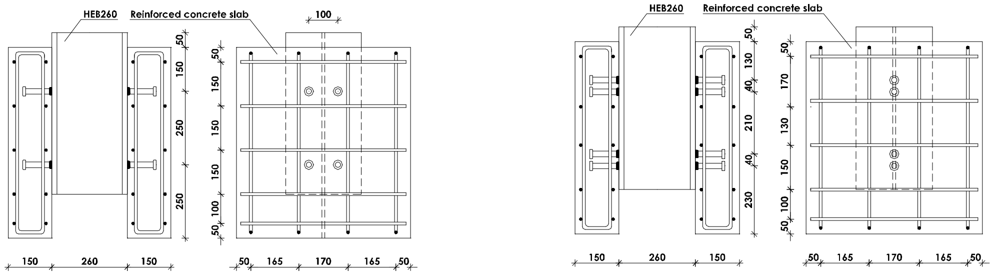
Figure 1. Connector types.

The main objective of these tests is to describe the connection behaviour and to analyse the contribution of the different components to the load capacity and to the slip between the steel profile and the concrete slab. For that reason, the tests are performed with deformation control and the load values and slip between steel profile and concrete slab are measured. Maximum load capacity and maximum slip are defining parameters that allow the analysis of the connections behaviour and ductility.

Shear connection between steel and concrete in a composite beam can be studied with the "Push-out" test. According to the dispositions defined in Eurocode 4, CEN (1994), the push-out specimen consist on a steel beam section held in the vertical position by two identical concrete slabs (Figs. 2-3). The concrete slabs are attached to the beam by shear connectors. The steel profile is subjected to a vertical load, which produces shear load along the interface between the concrete slab and the beam flange on both sides.

2. EXPERIMENTAL SET-UP

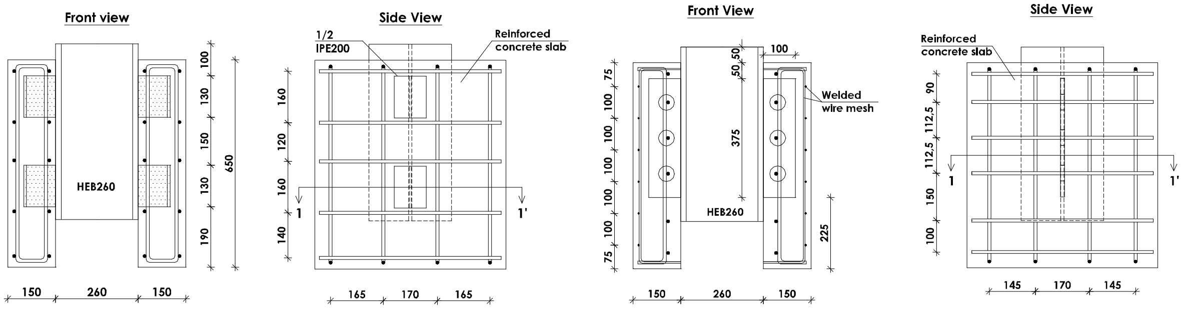
The test set up follows the Eurocode 4 dispositions for shear connection between steel and concrete tests, CEN (1994). For each type of connector, the geometry is always the same, with variation on diameter for studs and transversal reinforcement for Perfobond rib. The slab dimensions is 650×600×150 mm^3. The slab reinforcement represented in Figure 2 and Figure 3 corresponds to 10 mm diameter bars. In the case of Perfobond tests, there are variations on the reinforcement diameter and distribution: principal transversal reinforcement is either 10 mm or 12 mm diameter and a welded wire mesh is positioned on the slab top layer (Fig. 3). Connectors are always welded to the steel profile and later embedded on the concrete slab after concreting.



Isolated stud: ϕ19, ϕ22 and ϕ25 mm

Double stud ϕ19 mm

Figure 2. Geometry of stud connector specimens.



T connector

Perfobond connector

Figure 3. Geometry of T connector and Perfobond connector specimens.

Both slabs are concreted simultaneously in horizontal position to better simulate the conditions in a real structure (composite beam or slab). This implies the cut of the steel beam in two halves. After the concrete hardening it is possible to put both slabs in vertical position and then weld the two HEB260 half webs. To evaluate the reinforcement distribution, the concrete resistance is intended to be approximately the same. This could not be completely accomplished, because the specimens were cast in different days.

The same concrete composition is used in every specimen. Each specimen was concreted in a different day and therefore concrete was tested for compressive strength and elasticity modulus for each case, on the same date as the correspondent push-out test. In average, compressive strength is 55 MPa and elasticity modulus is 25 GPa. Steel specimens were collected from the same reinforcement and stud group used in the "Push-Out" tests and later tested. Table 1 presents the corresponding results.

Table 1. Steel properties.

Type of specimen	Specimen Type	d (mm)	f_y (MPa)	f_u (MPa)
Stud	ϕ19	19	501	596
	ϕ22	22	458	559
	ϕ25	25	466	557
Reinforcement	ϕ10	10	576	675
	ϕ12	12	523	705
	ϕ5	5	583	606

The monotonic load is applied to the specimens using a hydraulic test machine with a 5000 kN capacity. The testing machine consists on a pair of rigid steel plates of 200mm width separated by four steel hollow cylinders of 275mm diameter, 25mm width and 1150mm high. The joint between the cylinders and the plates is pre-stressed. The test setup is presented in Figure 4.

The initial phase of the test is characterized by 25 cycles of loading and unloading, between load values of 5 and 40% of the predicted maximum load. Following this, the test is controlled by deformation, measuring the slip between the steel profile and the concrete slab at a constant rate. Lateral displacement of the slabs is also measured. The test proceeds until failure, and deformation is measured until the load value is at least 80% of maximum load.

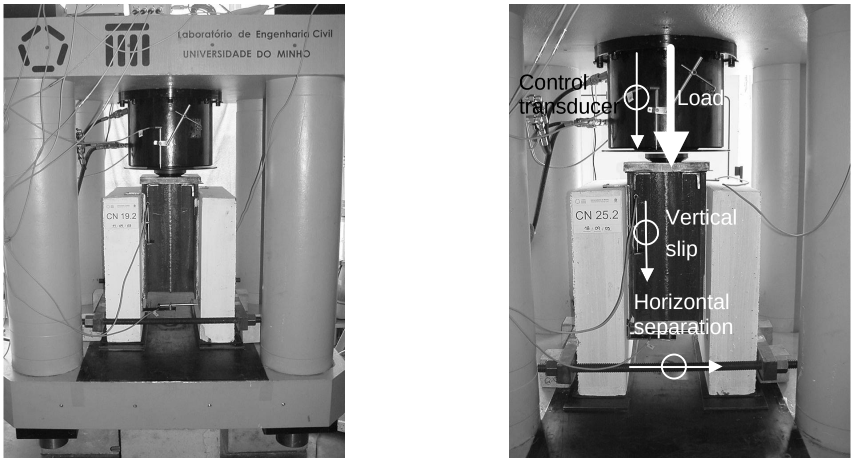


Figure 4. Test setup and dispositions.

3. HEADED STUD CONNECTOR

The headed stud connector load capacity in normal weight concrete results essentially from four components: concrete compression on stud basis around the welded collar, shear and bending on the stud shank, tension on the stud shank and friction between steel and concrete on the connection interface. The load capacity due to friction is not considered in the performed tests because the steel surface was greased before concreting. In case of high strength concrete, tension on the stud shank has a reduced value. Also, this type of concrete makes the bending deformation almost irrelevant. In case of lightweight concrete this behaviour is not well known, making experimental testing necessary.

This type of connection is characterized by a stiffer initial behaviour, with linear evolution, followed by a plastic behaviour, where deformation develops for an approximately constant or slow increasing load value. In general, the connection failure in normal weight concrete is conditioned by shear, and often by tension as a result of the forces that push the slabs to the exterior during the load test. In this case, the metallic bars positioned outside the slabs (Fig. 4) absorb part of these forces, avoiding this type of failure.

For each stud diameter, three specimens are tested. As shown in Table 2, the results are very similar for each group, which proves the validity of the results. In the majority of the performed tests, shear failure is identified on studs. Failure always occurs first on one side of the specimen, even though the specimens are symmetric. The exception comes with the 25 mm diameter studs specimen, the failure of which is determined by concrete in specimens CN25.2 and CN25.3. The high loads lead to severe cracking of the slabs and concrete crushing near the stud positions (Figure 5). Observations on the complete group of tested specimens make it possible to assess the larger damage on concrete slabs as the stud diameter is increased.

As a result, the loss of load capacity is softer on 25 mm diameter specimens, as failure happens with progressive cracking and crushing of the concrete slabs, without shear failure on studs.

Specimen with 19 mm stud diameter

Specimen with 25 mm stud diameter

Figure 5. Concrete crack patterns.

Figure 6 presents load-deformation curves for each diameter of tested stud. The load capacity increases with stud diameter, as expected, as well as deformation for maximum load. Deformation control on CN22.1 was not properly accomplished; therefore, this result was not considered. There is a close relation between maximum load value and corresponding characteristic slip value (value of slip determined for the characteristic load). This is a closely linear relation, as presented in Figure 7.

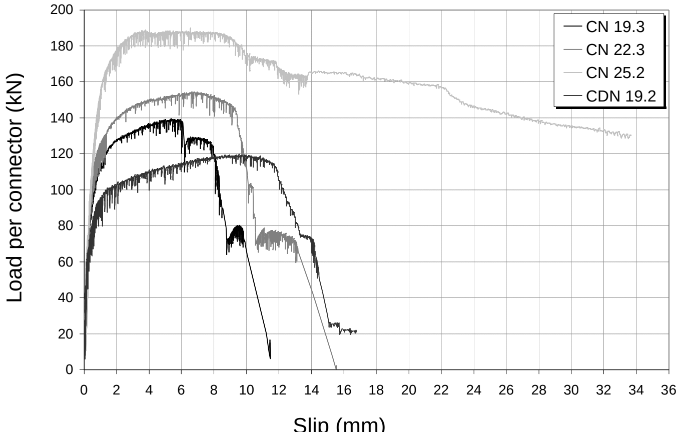


Figure 6: Load vs. slip.

In order to increase the connection deformation capacity, two studs were closely welded in the longitudinal direction (Fig. 2). A loss of load capacity is observed for this second case. However, this comes with an increase of the connection deformation capacity (Figure 6). This disposition results in a reduction of 22% of the maximum load value. On the other way, an increase of 29% is achieved when deformation is considered.

Paragraph 6.1.2(3) of Eurocode 4, CEN (1994), recommends a characteristic deformation value, d_k of 6mm for stud connectors, if a ductile behaviour is intended. This limit is exceeded in every tested specimen, guarantying ductility. Results of tests performed in the RWTH, Hegger et al. (2000,2001), with HSNWC reveal that this minimum deformation value of 6 mm is not always achieved. However, it is important to refer that this aspect is more relevant when the connection elastic-plastic behaviour is assumed. According to Table 2, Table 3 and Table 4,

P_{max} – maximum load
$P_k = 0.9 P_{max}$
$d\ (P_{max})$– slip for maximum load
d_{ki} – slip for load P_k
d_k – minimum slip for a group of three similar specimens
A_s – transversal reinforcement area through holes

Table 2. Experimental results for stud connector.

Specimen Ref[a]	P_{max} (kN)	P_{medium} (kN)	P_k (kN)	d_{ki} (mm)	d_k (mm)
CN 19.1	141.0			8.59	
CN 19.2	140.4	140.2	125.4	8.19	7.01
CN 19.3	139.4			7.79	
CN 22.1	155.1			-	
CN 22.2	156.0	155.2	139.1	8.65	7.79
CN 22.3	154.5			9.39	
CN 25.1	192.1			12.80	
CN 25.2	190.0	192.2	177.0	11.79	10.61
CN 25.3	194.5			13.01	
CDN 19.1	120.3			10.00	
CDN 19.2	119.6	120.6	107.7	11.91	9.00
CDN 19.3	122.0			10.81	

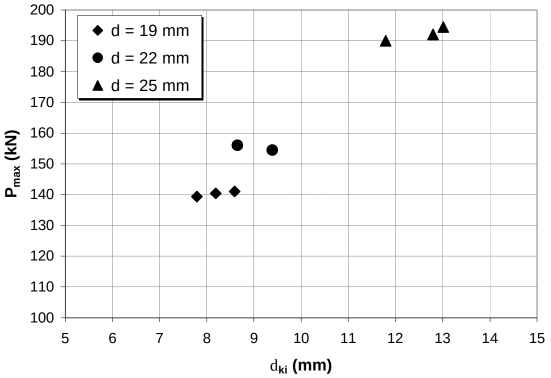


Figure 7. Maximum load and corresponding deformation.

Comparing these results with others presented in the bibliography for HSNWC, it is noticeable that high strength lightweight concrete specimens show higher deformation values. On the other hand, maximum load values are smaller. It is presumable that the observed differences result principally from the differences between concrete elasticity modulus and tensile strength of the two materials. If the elasticity modulus is higher, then the connection behaviour is less ductile and shear failure will occur in the connector. On the other hand, if the elasticity modulus is lower, the behaviour is more ductile and the tensile component tends to increase.

4. T CONNECTOR

The T connector load capacity in normal weight concrete results essentially from three components: concrete compression on T transversal section, shear on the half T web and tension on the T web. In the same way as happened for studs, tension stresses on the T web are reduced because of high strength material. Every tested specimen suffered shear failure, localized near the web basis, right above the welded collar. As presented in Figure 8, concrete showed some cracking, but not as much destruction as for 25 mm diameter studs.

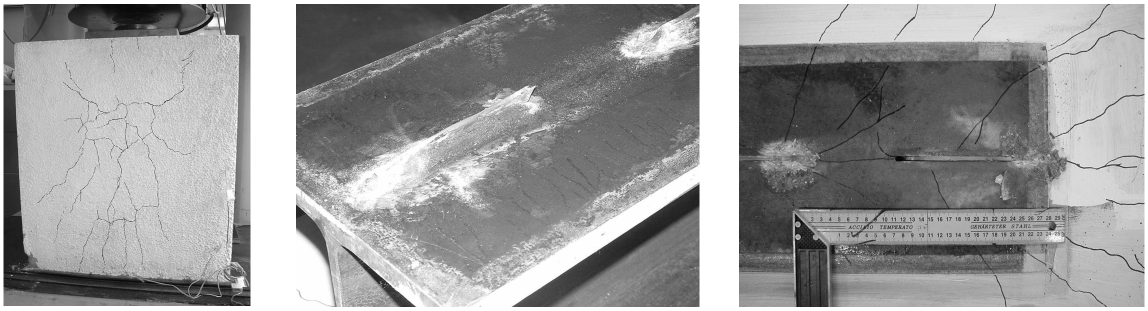


Figure 8: Failure in T connector specimen.

As for the majority of headed stud specimens, this connection suffered shear failure. T connectors show good load and deformation capacity (Table 3). Deformation control on T3 was not properly accomplished; therefore, this result was not considered. Figure 9 compares load capacity for these two types of connection, making it clear that T connectors allow higher load values. For this type of concrete, it would not be possible to achieve such load values with studs, because it would be necessary to have studs with much larger diameters and therefore, failure would occur in concrete. In terms of deformation, T connectors also show higher slip values.

There is an almost linear relation between shear area and load capacity, as well as shear area and slip (Fig. 9). In this way, T connectors allow a better stress distribution on the concrete slab when compared to studs, avoiding concrete crushing for higher loads. A reason for this is probably the localization of the larger concrete compression area on the T flange.

Table 3. Experimental results for T connector.

Specimen Reference	P_{max} (kN)	P_{medium} (kN)	P_k (kN)	d_{ki} (mm)	d_k (mm)
T1	285.8	285.9	254.4	14.94	13.44
T2	282.7			16.49	
T3	289.3			-	

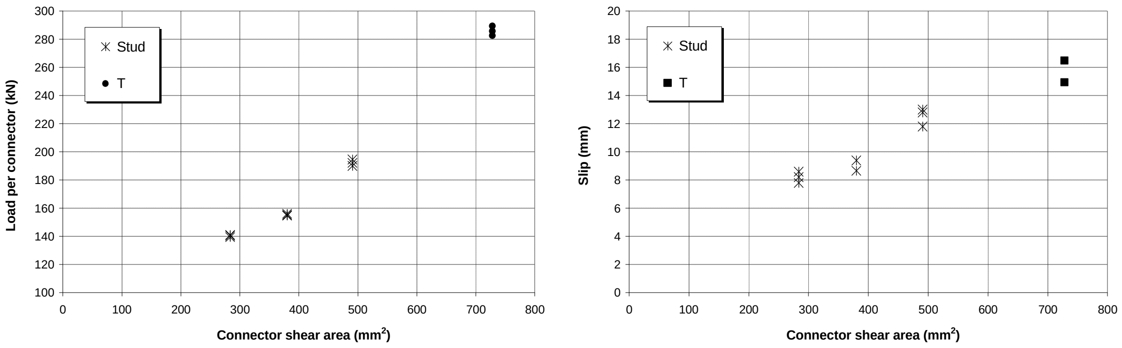


Figure 9. Maximum load and slip vs. connector shear area.

5. PERFOBOND CONNECTOR

Load capacity in Perfobond connection results from concrete slab shear capacity, both through connector holes and outside the connector, and from transversal reinforcement localized on the concrete shear area. In these tests, an evaluation on reinforcement distribution and concrete holes role was intended.

The Perfobond connection failure is characterized by a longitudinal principal crack growing from the bottom of the slab, with enlarging width as the load increases, Valente & Cruz (2004). The presence of the welded wire mesh limits the crack opening and generates other smaller cracks.

Perfobond connection has a much stiffer behaviour during the initial part of the test, until the maximum load is reached, with very small values of slip (Table 4), when compared to stud and T connectors. Following this, the decrease in load capacity is slow and very large deformation values are attained.

Table 4: Experimental results for Perfobond connector.

Specimen Reference	P_{max} (kN)	P_k (kN)	$d\,(P_{max})$ (mm)	d_k (mm)	A_s (mm^2)
CP1.2	375.1	337.6	0.53	18.84	0.0
CP2.2	416.8	375.1	0.61	23.93	78.5
CP4.2	533.6	480.3	1.36	6.67	235.6
CP6.1	559.4	503.5	2.21	12.28	339.3

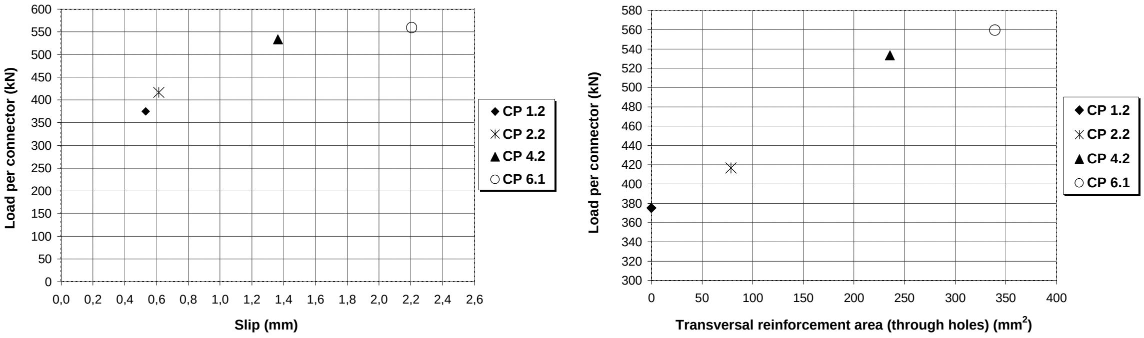


Figure 10. Maximum load vs. slip and transversal reinforcement area.

Figure 10 shows that the increase in load capacity is almost directly dependent on the transversal reinforcement area. This reinforcement also increases the connection deformation capacity until the maximum load is reached. Afterwards, the loss in load capacity is slower for the specimens with less transversal reinforcement. The connection never gets to complete failure, as all the tested specimens maintain considerable load capacity till the end of the test, for very large deformation values. Apart from the longitudinal crack, the slabs only present severe cracks for high deformation values.

6. CONCLUSIONS

The work developed in University of Minho aims to characterize different shear connection typologies, when high strength lightweight concrete is considered. A large number of standard Push-out tests were performed with headed studs, T connectors and Perfobond rib connectors. In every tested specimen, this concrete showed load and deformation values comparable to those verified for normal weight concrete. In general, load capacity is a bit smaller then the ones verified for normal weight concrete but deformation values are higher, which is a good result if a better ductility is intended.

7. AKNOWLEGMENTS

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