The effect of confining forces on the resistance of Headed bars in tension in Reinforced Concrete Elements

El efecto de las fuerzas de confinamiento en la resistencia de barras ancladas con placa utilizadas en elementos de hormigón armado

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RESUMEN

El uso de barras ancladas con placa ofrece importantes ventajas en estructuras de hormigón armado comunes, como la reducción de las longitudes de anclaje requeridas, la mejora del confinamiento de los nudos y la reducción de la congestión en la armadura, lo que facilita la colocación en obra de la ferralla y del encofrado. La norma EN 1992-1-1:2023 incluye una nueva formulación para calcular la tensión máxima a tracción que puede desarrollarse en una barra de acero para armar para una geometría de cabeza y un detalle de armado dados. Esta formulación, sin embargo, no considera el efecto del confinamiento de la barra, que puede presentarse en forma de soporte o zona de carga aplicada. Este documento presenta los resultados de un estudio experimental realizado para estudiar el efecto del confinamiento en elementos de hormigón armado. En total se fabricaron y ensayaron 24 probetas con 3 variaciones paramétricas para estudiar el efecto del confinamiento, el efecto del recubrimiento y el efecto de la adherencia entre el hormigón y el acero. Los resultados indican que las probetas con confinamiento total tienen mayor resistencia que plas probetas con un confinamiento parcial. Los ensayos también muestran que la resistencia aumenta con el aumento del recubrimiento, con la adherencia y con la presencia de capas adicionales de armadura.

ABSTRACT

The use of headed reinforcing bars offers distinct advantages in ordinary reinforced concrete structures such as reducing the required development lengths, enhancing the confinement of joints, and reducing reinforcement congestion, thereby facilitating the placement of reinforcing bars on-site and concreting. EN 1992-1-1:2023 includes a new formulation to calculate the maximum tensile stress that can be developed in a reinforcing steel bar for a given head geometry and reinforcement layout. The formulation does not consider the effect of confinement around the bar, which can be present in the form of a support or zone of applied load. This paper presents the findings of an experimental study conducted to test the effect of confinement in reinforced concrete elements. A total of 24 specimens were cast with 3 parametrical variations to observe the effect of confinement, the effect of the edge cover, and the effect of the bond between concrete and reinforcement. The results indicate that the specimens with full confinement provide more resistance than those with partial confinement. The tests also show that the resistance increases with the increase in cover, the presence of bond, and with the presence of additional layers of reinforcement.

PALABRAS CLAVE: Barras ancladas con placa, recubrimiento, confinamiento, adherencia.
KEYWORDS: Headed bars, cover, confinement, bond.

1. Introduction

The primary failure mode for headed bars used in reinforced concrete structures is concrete blow-out failure, which becomes more critical as the cover and spacing between reinforcement bars decrease. In the new formulation of EN 1992-1-1:2023 [1], the methodology outlined in this provision aligns with the minimum mandrel diameter requirements for hooked bars and considers various parameters that differ from those specified in EN 1992-4-2018 [2].

2 Model description

Concrete Blow-out failure (see Figure 1) is one of the significant failures observed in structures with headed reinforcement bars. As per EN 1992-4-2018, it is defined as spalling of concrete elements at the level of the embedded head with no significant breakout at the top concrete surface.

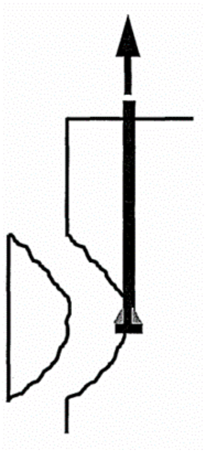

Figure 1. Side Blow-out failure.

The resistance of the concrete element with headed bars can be computed as per 7.2.1.8 of EN 1992-4:2018 and 11.4.7 of EN 1992-1-1:2023. The model of EN 1992-4: 2018 is empirical and has the form of the multiplication of different factors. However, in this paper the focus will be on the formulation of EN 1992-1-1:2023 which is based on a model developed for minimum mandrel diameters which is described in detail in reference [1]. Full background is available from reference [2]. With respect to the formulation of EN 1992-1-4:2018, three factors have different effects:

- The distance to edges and corners
- The group effect (spacing and effect of non-uniform loading of grouped bars)
- The influence of compressive concrete strength.

The formulation of EN 1992-1-1:2023 is given in the following equation:

$$\sigma'_{sd} = k_{h,A} \cdot f_{cd} + \upsilon_{part} \frac{\sqrt{f_{ck}}}{\gamma_c} \cdot \frac{a_d}{\phi} \cdot \left(\frac{\phi_h}{\phi}\right)^{\frac{5}{6}} \cdot \left(\frac{d_{dg}}{\phi}\right)^{\frac{1}{3}} \leq k_{h,A} \cdot \upsilon_{part} \cdot f_{cd} \tag{1}$$

where (see Figure 2):

$k_{h,A}$ is the ratio between the net area of the head and the cross-sectional area of the reinforcement:

$$k_{h,A} = \frac{A_h - A_s}{A_s} = \left(\frac{\phi_h}{\phi}\right)^2 - 1$$

υ_{part} is the strength factor to consider state of the concrete. As per 11.4.7(2) of EN 1992-1-1:2023, It can be taken as 11 for uncracked concrete in the region of the head and 8 for the cracked concrete in the region of the head.

a_d is the nominal value of the distance between the bar and free surface, which can be computed as follows for different cases:

Case (a):

$$a_d = a_y \tag{2}$$

for the following cases

(i) Single bars are present near an edge.
(ii) Corner bars are present at a minimum distance of $a_x \geq 2a_y + 1.2\phi_h$.
(iii) Group of bars along an edge at spacing $s_x \geq 4a_y$ and with $a_x \geq 2a_y$.

Case (b)

$$a_d = 0.5a_y + 0.25a_x - 0.3\phi_h \tag{3}$$

For single bars near to a corner at a distance $a_x < 2a_y + 1.2\phi_h$.

Case (c)

$$a_d = a_y \frac{s_x - \phi_h}{4a_y - \phi_h} + 0.23(a_y - \frac{\phi_h}{2}) \frac{4a_y - s_x}{4a_y - \phi_h} (1 - \frac{1}{(\frac{\phi_h}{\phi})^2}) \tag{4}$$

If the group of bars along the edge at spacing $s_x < 4a_y$.

d_{dg} is a size perimeter describing the failure zone roughness, which depends on the concrete type and its aggregate properties.

For Concrete with $f_{ck} \leq 60\ MPa$

$$d_{dg} = 16mm + D_{lower} \leq 40mm \tag{5}$$

For Concrete with $f_{ck} > 60\ MPa$

$$d_{dg} = 16mm + D_{lower} (\frac{60}{f_{ck}})^2 \leq 40mm \tag{6}$$

ϕ_h is the diameter of a circular head or the diameter of a circle with the same area as that of the actual head:

$$\phi_h = 2\sqrt{\frac{A_h}{\pi}} \tag{7}$$

a_x and a_y are the distance between the bar axis and the nearest edge as defined in **Figure** 2.

s_x is the bar spacing of a group of bars.

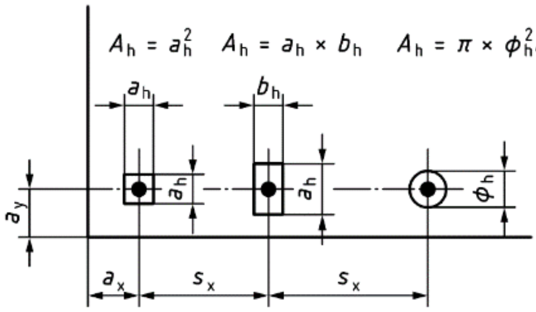

Figure 2. Definition of head dimensions and bar spacing.

3. Effect of confinement

In reinforced structures, the presence of tension forces implies the existence of corresponding compression forces to achieve equilibrium, as exemplified in Strut & Tie models. Because of this, the presence of confining forces in the zone of the head of headed bars is not uncommon. Compressive forces can have a favourable effect, as observed for example in Marchetto's tests [5] which are described below with the help of Figure 3.

The new formulation given 11.4.7(2) provided by EN 1992-1-1:2023 does not include the effect of confinement, but as per 11.4.7 (5) of EN 1992-1-1:2023 *if there are external compressive forces from supports or forces due to opposed active headed bars acting in the zone of the head sufficient to balance the tensile-blow-out in their direction the resistance can be enhanced according to more refined model.*

The confinement can also come from a support or from a zone of load application, etc. In the tests conducted by Marchetto, it is observed that in the presence of two opposite plates, one set of headed bars acts as confinement and transforms the corner problem into an edge problem. It signifies that the presence of confinement (in the form of plates for the tests by Marchetto – Figure 9 b) – prevents the failure in the plane of the figure that is shown in Figure 9 c). This leads to ultimate loads that are much higher than expected by the formulations of both EN 1992-4:2018 [3] and EN 1992-1-1:2023 [4].

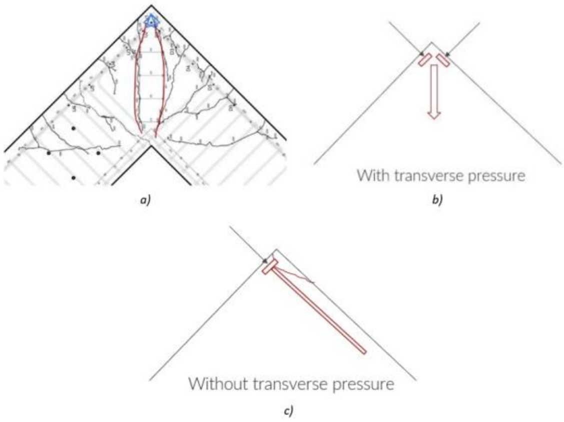

Figure 3. a) Confinement effect by opposite plates b) Model that shows how the load is centred in case of opposite plates c) Blow-out failure in case of absence of transverse pressure.

Further investigation is required to deepen our understanding of the phenomenon under examination. The experimental campaign presented in this paper, which was carried out as part of a Master Thesis [6], includes a test setup to induce the confinement effect by applying compressive forces. The two series of tests are conducted involving partially confined areas and fully confined areas.

4. Anchorage capacity

As per *11.4.7(3)* of EN 1992-1-1:2023, the resistance provided by the anchorage length and the head can both be considered to determine the maximum tensile stress in the reinforcing steel, which provides a significant increase in the resistance of headed bars.

As per *11.4.2 (3)* of EN 1992-1-1:2023 – *Anchorage of a straight bars,* the anchorage length l_{bd} , which can safely transfer the forces from the bar to the surrounding concrete without spalling or bond failures, is the one given in the following equation:

$$l_{bd} = k_{lb}.k_{cp}.\phi.\left(\frac{\sigma_{sd}}{435}\right)^{n\sigma}.\left(\frac{25}{f_{ck}}\right)^{\frac{1}{2}}.\left(\frac{\phi}{20}\right)^{\frac{1}{3}}.\left(\frac{1.5\phi}{c_d}\right)^{\frac{1}{2}} \geq 10\phi \quad \textbf{(8)}$$

where the ratios are limited to $(\frac{\phi}{20}) \geq 0.6$, $(\frac{1.5\phi}{c_d}) \geq 0.4$, $(\frac{25}{f_{ck}}) \geq 0.3$, whereas the parameters involved in the formula are defined in section *11.4.2 (3)* of EN 1992-1-1:2023.

5. Experimental campaign

Based on above motivation, to analyse the confinement effect and to verify new formulation provided by EN 1992-1-1:2023, an experimental campaign was carefully designed, considering the following parameters:

b) Edge and corner covers (of 10, 20, and 30 mm)
c) Variation in Test Setup: partially and fully confined
d) Reinforcement layouts with 1 and 2 layers
e) Interaction between head capacity and bonded length.

A total of 24 specimens were fabricated. The failure in concrete was targeted in all cases, necessitating the use of 20 mm reinforcement bars. This selection was based on empirical evidence demonstrating an increased probability of thread failure for smaller diameters, as depicted in **Figure** 3. Additionally, diameters exceeding 20 mm were not feasible due to the mismatch between the commercial diameters of nuts and washers (M24, M30) and the standard reinforcement diameters (25, 32 mm) of reinforcement bars.

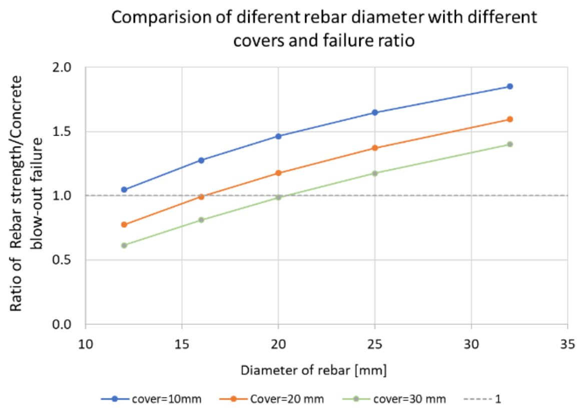

Figure 3. Rebar diameter and failure ratio

Figure 3 presents a comparative analysis of the failure ratio (determined by the strength of the threaded rebar and the resistance of the concrete for blow-out failure according to EN1992-1-2-2023) for concrete covers of 10 mm, 20 mm, and 30 mm. The study focuses on comparing diameters ranging from 12 mm to 32 mm. Notably, the figure clearly illustrates that for diameters smaller than 20 mm, the failure ratio is below 1, indicating the failure of the threaded bar, which leads to the choice of using rebar of 20 mm.

The parameters considered in the experimental campaign are the following:

a) **Edge and corner covers:** The specimens are designed with 10-, 20-, and 30-mm edge distances to ensure the failure in concrete. Although the 10- and 20-mm covers may be unrealistic, these tests are conceived to maximize the probability of obtaining a concrete failure. **Figure** 3 shows that for a rebar diameter of 20 mm and a concrete cover depth of 30 mm, Steel yielding and failure by concrete are equally probable. However, for cover depths of 10 mm and 20 mm, failure of the specimen is predicted to be in concrete. These findings led to the limitation of the variation in the study to a maximum concrete cover depth of 30 mm.

b) **Variation in Test Setup- partial and full confinement:** The effect of compressions coming from points of load application and anchoring of structural nodes is intrinsic to the test setup and present in real structures, but not explicitly accounted for in current code formulations. The selection of partially and fully confined areas is grounded in the understanding that both types of confinement can occur in practice, depending on the dimensions of the loaded areas. The difference between the partially and fully confined area is illustrated in the test-setup section **¡Error! No se encuentra el origen de la referencia.**.

c) **Reinforcement layout-1 and 2 layers:** The effect of small spacing between the heads in case of multiple bars was tested to understand the group effect on the resistance of headed bars in the absence of confinement. The bar spacing in the critical case is the diameter of the washer plus 20 mm in all cases, representing the smallest possible spacing that can be practically applied. This is logical because, in practice, anchor bars are placed in situations where there is congestion of reinforcement, and minimum bar spacing is commonly used.

d) **Interaction between head capacity and bonded length -** Both specimens, in which the reinforcement bars are inside a PVC sheath to prevent direct contact between concrete and reinforcement, and direct contact with the concrete, were built to observe the additional capacity provided by anchor length.

Figure 4 shows the working concept for the specimen, which could be representative of a corbel. The load is self-equilibrating.

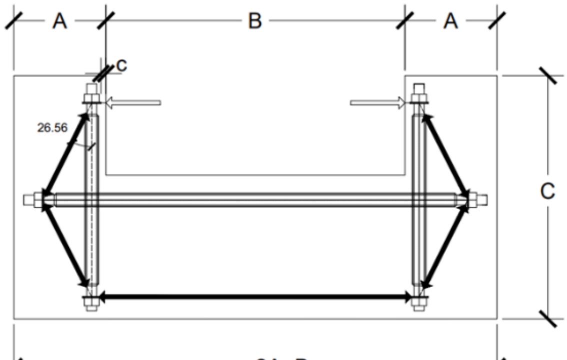

Figure 4. Typical specimen geometry showing bars with PVC tube to avoid bond

The Specimen ID nomenclature is as follows:

ϕ20-cXX-Y-ZL-n

where:

20 is the headed bar diameter in mm.

XX is the cover from the edge of the washer to the closest concrete surface in mm.

Y is equal to U (unbonded) if the bar is covered with a PVC sheath and to B (bonded) if the bar is in contact with concrete.

Z is equal to 1 if there is a single layer of reinforcement and equal to 2 if there are 2 layers.

n is equal to (a) if partially confined and equal to (b) if fully confined.

The specimens are concreted horizontally (the plane shown in **Figure 5** is to be parallel to the floor). This should minimize the resistance of the headed bars on the upper surface and provide more conservative results, as aggregates settle down and make poor concrete on the top, even though this effect is expected to be small given the width of the specimens.

Figure 5 shows a typical definition of the reinforcement in a specimen having a single layer of reinforcement.

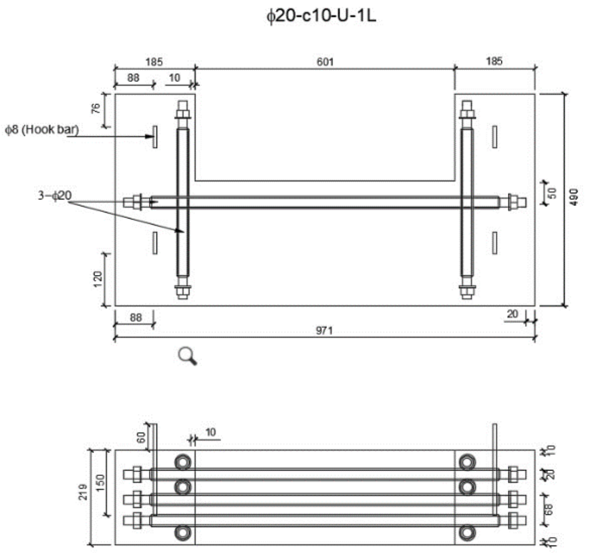

Figure 5. Typical reinforcement in specimens with a single layer of reinforcement

The materials used in the test were as follows:

- Concrete Class C25/30 (CEM I 42.5, 330 kk/m3, W/C = 0.55, Plasticizer: POZZOLITH 427N-BASF, Consistency: fluid. The mean strength measured at the time of the tests was only 21 MPa.
- Reinforcing steel B 500 C (f_{ym} ~575 MPa, f_{um} ~ 661 MPa)
- PVC pipe, ϕ=23 mm

2.1 Monitoring

The specimens were monitored using the following techniques:

1. DIC (Digital image correlation)
2. LVDT (to measure deflections)
3. Load cells
4. Deflectometer
5. Strain gauges
6. Extensometer bases

2.2 Construction of specimens

The specimens were prepared and concreted in the Laboratory of Structures at the Universidad Politécnica de Madrid by the following procedure.

1. **Gluing of encapsulated strain gauges**- The procedure is described in the **Figure 6.**
2. **Elaboration of headed bars**-
The procedure used to place the nut and washer on the threaded bars is detailed in **Figure 7** and **Figure 8.**
3. **Formation of headed bars for unbonded specimens:** The reinforcement bar is covered with a PVC sheath. The other steps remain unchanged from the procedure used for bonded bars (see **Figure 9**).
4. **Setting-up of formwork and placement of rebars:** A wooden framework is prepared, according to the geometry specified above, using 20 mm thick laminated wood. Then rebars are placed at the determined positions. A picture demonstrating the arrangement for ϕ20-c10-U-1L can be seen in **Figure 11.**
5. **Concreting:** A concrete mixture with a design strength of C25/30 and a slump value of 135 mm was effectively placed

using a vibrator while not disturbing the interlocking of reinforcement bars. The casting was done on 1st March 2023.

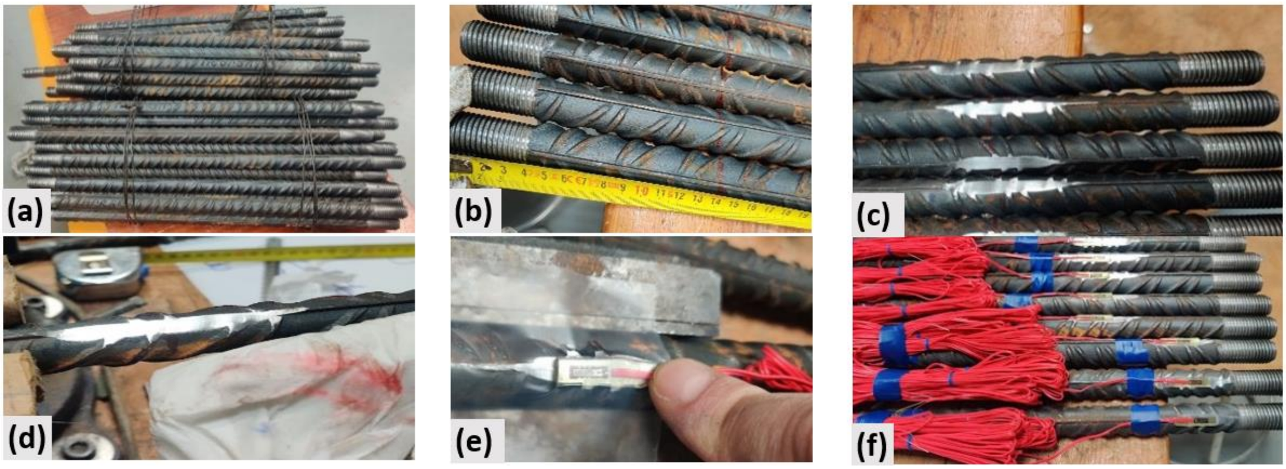

Figure 6. a) Threaded rebars from the factory b) Gauge location marking on the rebar c) trimmed surface e) cleaning of the trimmed surface e) glued strain gauge on the location f) Rebars with strain gauges

Figure 7. a) M20 Nut and Washer b) Nut and washer placement for hot glue connection c) Glued Nut and bolt d) Positioning of nut and washer on rebar.

Figure 8. e) Resin application for the connection to rebar f) Prepared headed bars.

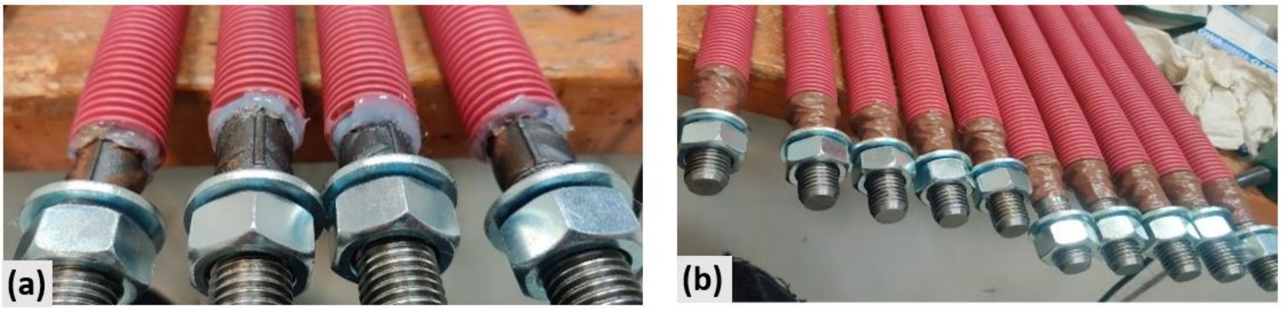

Figure **9**. a) PVC tube glued to rebar b) Duct tape at the ends to ensure waterproofing.

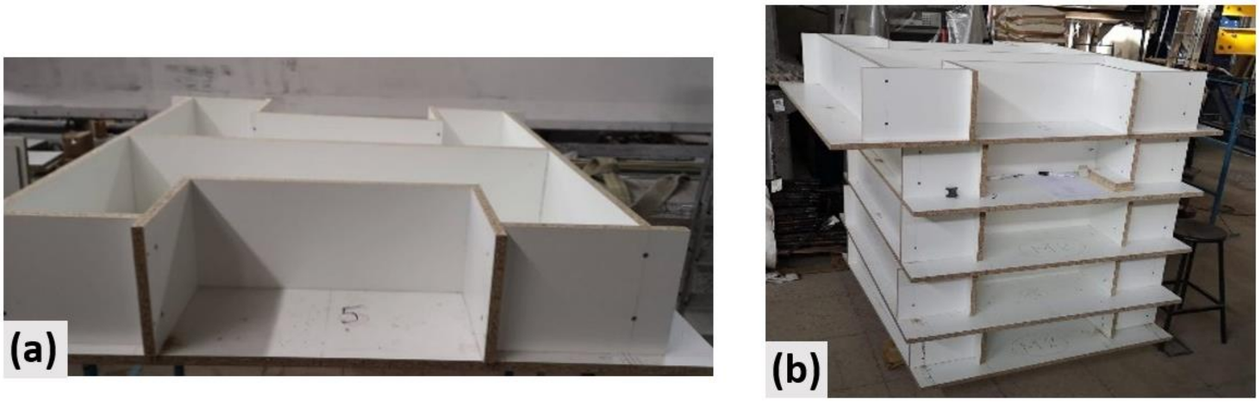

Figure **10**. a) Formwork for 1 specimen b) Finished formwork for several specimens.

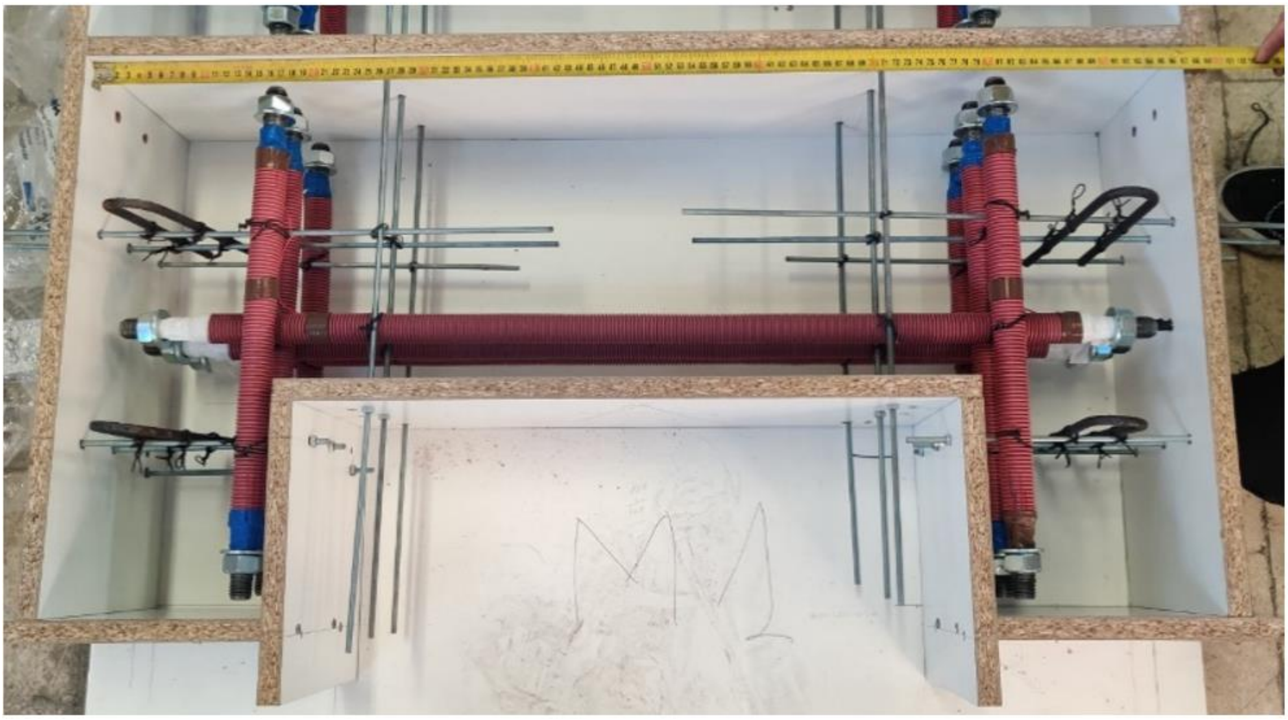

Figure **11**.ϕ20-c20-U-1L with completed reinforcement

6. **Surface Preparation:** A week from the casting, the demoulding procedure was carried out with due diligence to prevent damage to the strain gauge wires. Subsequently, surface preparation activities were initiated by the predetermined plan as previously described. The position of the steel pins utilized in the extensometer gauges was marked, and the surface was trimmed to obtain a level surface. The pin was bonded using a quick-setting adhesive, and the surrounding area was coated with resin to ensure long-term adhesion.

In the case of DIC, the surface was coated with three coats of paint to create a consistent and uniform surface, following which dots were marked, using a roller to produce a random pattern.

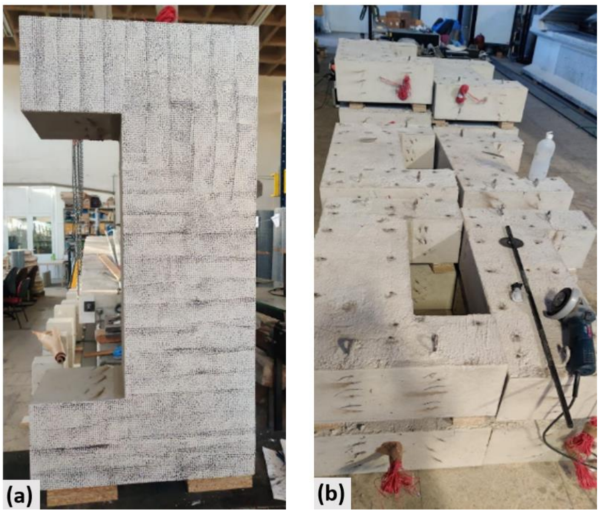

Figure 12. a) Prepared DIC surface b) Prepared top concreting face with steel pins for extensometer gauges.

6. Test Setup

Two different setups with slight variations were used to perform the test. The entire test setup can be seen in **Figure 13** and **Figure 14**

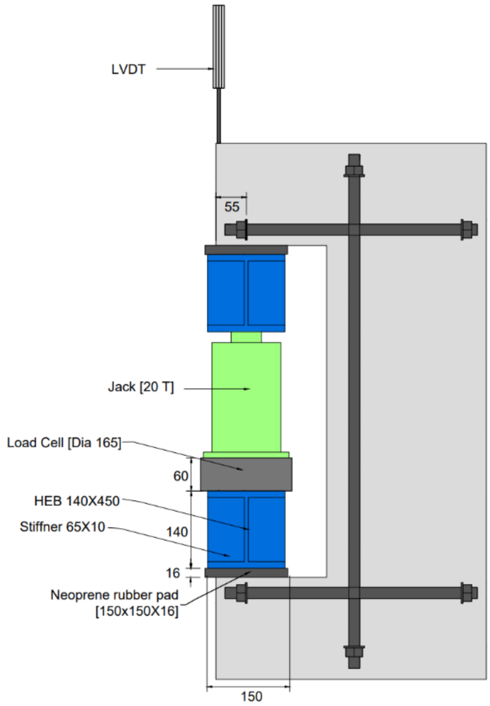

Figure 13.Typical test set-up

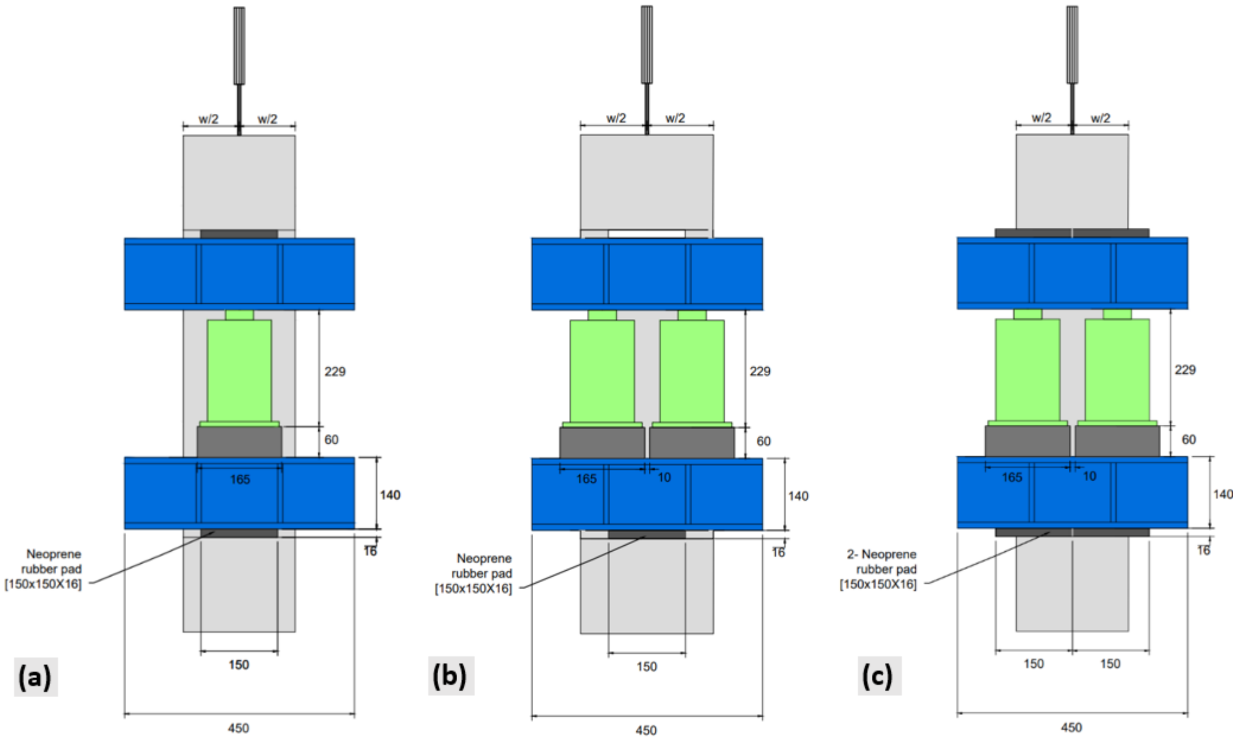

Figure 14. Side view of test setup a) Partially confined(1-Neoprene pad) b) Partially confined using 2 jacks us ed for c20,c30 – 2 layers of reinforcement(1-Neoprene pad) c) fully confined(2-Neoprene pad).

The specimens with partially confined area were tested with one jack with 20 tonnes of capacity, as shown in **Figure 14** (a), except for the 2-layer reinforcement with 20 mm and 30 mm covers, which were tested with 2 jacks as shown in **Figure 14** (b). For specimens with fully confined area, as shown in **Figure 14**(c), 2 jacks were used in all the cases.

The manually operated jacks (displacement-controlled) were loaded until the failure of the specimen in steps. During the test, applied load and deflection (at the edge of the specimen - see **Figure 13**) were continuously recorded by load cells and the LVDT, respectively. The change of resistance in the strain gauges was recoded with the help of a Datataker 615 series with the frequency of 10 sec. Also, cracks were marked on the top concrete face with each loading step, and extensometer gauge measurements were taken at the established load stages. For the DIC face, a camera was set at an appropriate position to record one picture per minute.

After failure, the jacks were unloaded, during which a video recording was taken to observe the recovery capacity.

7. Theoretical specimen resistance

Table 1 and Table 2 show the expected resistance of the specimens with one and two layers of reinforcement respectively, according to EN 1992-1-1:2023 and EN 1992-4:2018. The resistance is significantly higher for the EN 1992-1-1:2023 in the case of bonded reinforcement, because this standard allows adding the effect of bond to the plate resistance and, in the case of confined specimens, it is considered in the calculation that there is no corner effect. For specimens with one layer, the critical bar is assumed to be an edge bar, due to the confinement provided by the neoprene in the vertical direction, while for the specimen with two layers a group effect is considered, because of the interaction of the heads in the lower and upper layers. For the estimation of the contributing bond length, this has been taken as shown in **Figure 15**.This criterion provides a bond length of 92 mm for the 10 mm cover, 102 mm for the 20 mm cover, and 112 mm for the 30 mm cover.

Table 1. Theoretical resistance for 1 layer.

Specimen_ID	EN 1992-1-1: 2023 [kN]	EN 1992-4:2018 [kN]
ϕ20-c10-U-1L-a	49	41
ϕ20-c20-U-1L-a	67	49
ϕ20-c30-U-1L-a	85	56
ϕ20-c10-B-1L-a	102	41
ϕ20-c20-B-1L-a	124	49
ϕ20-c30-B-1L-a	145	56
ϕ20-c10-U-1L-b	93	49
ϕ20-c20-U-1L-b	117	57
ϕ20-c30-U-1L-b	141	66
ϕ20-c10-B-1L-b	146	49
ϕ20-c20-B-1L-b	174	57
ϕ20-c30-B-1L-b	202	66

Table 2. Theoretical resistance for 2 layers.

Specimen_ID	EN 1992-1-1: 2023 [kN]	EN 1992-4:2018 [kN]
ϕ20-c10-U-2L-a	90	83
ϕ20-c20-U-2L-a	93	92
ϕ20-c30-U-2L-a	99	101
ϕ20-c10-B-2L-a	195	83
ϕ20-c20-B-2L-a	206	92
ϕ20-c30-B-2L-a	219	101
ϕ20-c10-U-2L-b	90	98
ϕ20-c20-U-2L-b	93	108
ϕ20-c30-U-2L-b	99	119
ϕ20-c10-B-2L-b	195	98
ϕ20-c20-B-2L-b	206	108
ϕ20-c30-B-2L-b	219	119

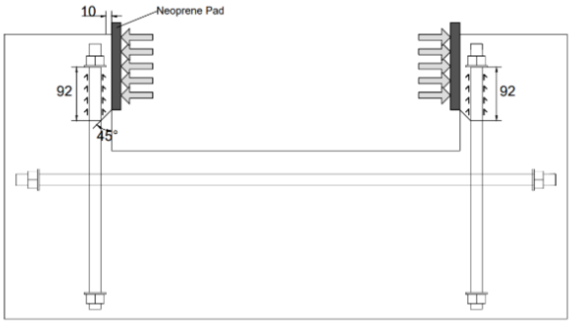

Figure 15. Bond length considered for theoretical evaluation of bond contribution

8. Results and analysis

The results show a clear influence of the cover, a clear contribution of bond to resistance, and also an effect from confinement. **Figure 16** summarizes the results in terms of ultimate load for bonded specimens, while **Figure 17** summarizes the results for unbonded specimens. To make tests with one and two layers comparable, the results are given per layer, dividing by a factor of two the ultimate load of specimens with two layers. By comparing both figures it is clear that bonded specimens have a significantly higher resistance than unbonded specimens. It is also easy to see that resistance grows with cover, even though the growth is not linear, as the growth in capacity slows down when increasing the cover from 20 to 30 mm, with the exception of unbonded specimens with one layer of reinforcement. Finally, in all cases the load increases when going from partially confined (PC) to fully confined (FC) specimens.

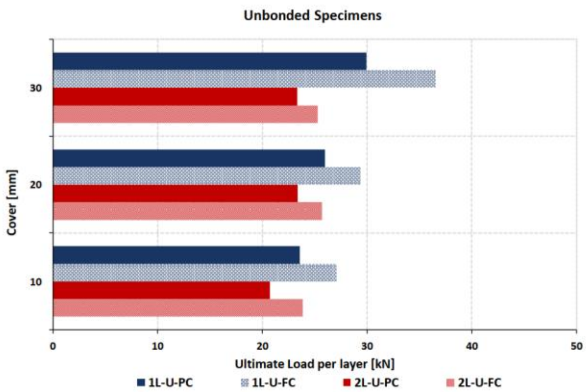

Figure 16. Ultimate load per layer in unbonded specimens

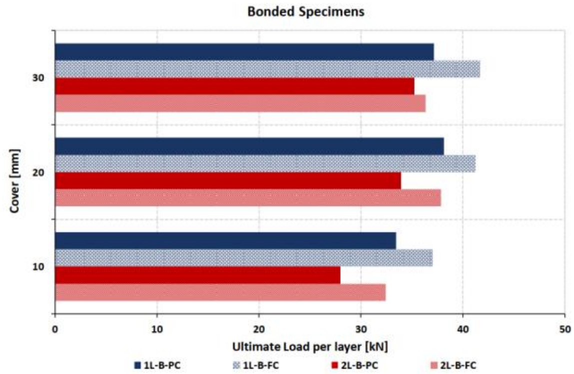

Figure 17. Ultimate load per layer in bonded specimens

With respect to behaviour of the prediction models, this is given in Table 3. It is clear that the behaviour of the models, as interpreted in this paper is not ideal. The EN 1992-1-1:2023 models, seems to overestimate the contribution of bond and underestimates the resistance of the specimens with two layers and no bond. This last observation could be due to the fact that the confinement effect on the side of applied load is neglected, since it is unclear how to consider it. Note that the specimens with two layers of reinforcement had larger ultimate load per layer than the ones with a single layer. However, they were penalized in the determination of a_d accounting for the group effect, whereas the bars in the specimens with a single layer were considered as either corner or edge, both of which provide higher resistances.

The Model of EN 1992-4 on the other hand is conservative throughout, but it may be argued that it is overconservative.

Table 3. Comparison of standard models and experimental results.

		$P_{u,exp}/P_{u,model}$	
Specimen_ID	**$P_{u,exp}$ Ultimate load [kN]**	**EN 1992-1-1: 2023 [kN]**	**EN 1992-4:2018 [kN]**
ϕ20-c10-U-1L-a	71	1.45	1.73
ϕ20-c20-U-1L-a	78	1.21	1.65
ϕ20-c30-U-1L-a	90	0.92	1.39
ϕ20-c10-B-1L-a	114	0.86	2.15
ϕ20-c20-B-1L-a	111	0.73	1.84

ϕ20-c30-B-1L-a	124	0.76	1.96
ϕ20-c10-U-1L-b	81	1.08	2.04
ϕ20-c20-U-1L-b	88	0.95	1.95
ϕ20-c30-U-1L-b	110	0.81	1.73
ϕ20-c10-B-1L-b	124	0.85	2.53
ϕ20-c20-B-1L-b	125	0.64	1.95
ϕ20-c30-B-1L-b	143	0.62	1.89
ϕ20-c10-U-2L-a	124	1.38	1.49
ϕ20-c20-U-2L-a	140	1.54	1.55
ϕ20-c30-U-2L-a	140	1.42	1.39
ϕ20-c10-B-2L-a	168	0.79	1.86
ϕ20-c20-B-2L-a	204	0.68	1.52
ϕ20-c30-B-2L-a	211	0.69	1.50
ϕ20-c10-U-2L-b	143	1.87	1.71
ϕ20-c20-U-2L-b	154	2.10	1.81
ϕ20-c30-U-2L-b	152	2.07	1.71
ϕ20-c10-B-2L-b	195	1.16	2.32
ϕ20-c20-B-2L-b	227	1.02	1.95
ϕ20-c30-B-2L-b	218	1.00	1.83

9. Conclusions

A significant experimental campaign has been carried to study the Ultimate Limit State behaviour of headed anchor bars, including 24 specimens. The parameters studied were the effect of cover, the effect of bond and the effect of confinement. The experimental results showed the expected tendencies: an increase of strength with concrete cover , bond contributes to the resistance, and confinement also enhances the resistance. The only unexpected measurement was a larger resistance per layer in the case of two layers. This may be related to the large number of bars that have a large cover (2nd layer).

Regarding the performance of the EN 1992-1-1:2023 model, it would seem than the factor 1.1, which divides the contribution of bond when adding it to the contribution of the head, may too low. Also, there seems to be a need to provide a less conservative formulation for a_d for the case of two layers of reinforcement. On the other hand, the model of EN 1992-4:2018 provides overly conservative results throughout the tests.

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