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# Bond behaviour of twisted stainless steel bars in mortar joints

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**ABSTRACT:** The use of twisted stainless steel bars has proven to be effective in scenarios where lateral loads (e. g. earthquakes and winds storms) can cause partial or complete out-of-plane collapse of masonry wall's outer leaves or separation of wood diaphragms from masonry walls. The particular application of these bars as a dry system in mortar joints, without any binder, brings additional advantages in terms of cost, installation time and weather restrictions. An experimental campaign composed by 60 pull-out tests aimed at characterizing the bond behaviour of twisted stainless steel bars in mortar joints. The influence on bond behaviour of two diameters of the helibar ($\phi$8 mm and $\phi$10 mm), three different anchorage lengths ($8\phi_{hb}$, $12\phi_{hb}$, and $20\phi_{hb}$), and two diameters of the pre-drilled holes ($\phi_{hb}$–2 mm and $\phi_{hb}$–4 mm) was studied. Bond strength increased for the tighter pre-drilled hole but decreased for the higher twisted steel bar diameter. Good correlations between bond strength and anchorage length were found for the less tight pre-drilled holes.

*Keywords: twisted steel bar, pull-out, bond, mortar joint*

## NOTATION

| | |
|---|---|
| $\phi_{hb}$ | diameter of the helibar; |
| $\phi_h$ | diameter of the pre-drilled hole; |
| $l_b$ | anchorage length; |
| $F$ | applied force; |
| $\tau_b$ | bond stress. |

## 1 INTRODUCTION

In recent years mechanical anchors (ties) and strengthening rods made of twisted steel bars have been widely use to improve the structural performance of masonry constructions. Starting with historical constructions, their use have been concentrated on the improvement of connections between different structural elements (e.g. timber beams and walls) [1], [2] or even to increase the bearing capacity to vertical and out-of-plane loadings of multi-leaves masonry walls [3], [4]. For "new" constructions, the anchoring systems have been used to build veneer and cavity walls, as well as to re-anchor different walls or masonry leaves [5], [6]. Steel bars are often used to improve the tensile and shear capacities, either through near surface mounted reinforcements at the mortar joints or crossing the units and knitting the masonry to increase the cohesion of the composite material [6], [7].

To any kind of construction or strengthening technique that uses twisted steel bars, bond by mechanical interlocking, friction, adhesion or their combinations plays an important role to the effectiveness of the connection. Bond behaviour is mainly conditioned by the mechanical properties of

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the substrate (mortar, brick, etc.), the volume of the surrounding substrate, the confinement (reinforcement), the surface condition of the twisted steel bar, and the geometry of the twisted steel bars [8]. Focusing on historical constructions, the first and last point mentioned before have critical importance. A poor mortar like the one present in most historical constructions presents lower values for the mechanical properties, and consequently the bond strength is lower than for other materials. On the other hand, being a softer material facilitates the execution of the strengthening. The twisted shape of the steel bars is another variable that causes great impact on the distribution of compression and tensile stresses on the interface bar/mortar, and consequently formation of cracks and damage. Therefore, it is important to characterize the bond behaviour between twisted steel bar and mortar joints.

The technique applied in this study is based on the DryFix system of the company Helifix® [9]. The technique does not require any resin, grout or mechanical expansion, relying only on mechanical interlocking and friction to tie different elements together. Since no binder is needed, installation costs and difficulty, time of execution, and weather restrictions decrease considerably. The basic requirement is the execution of a small diameter pilot hole, for the installation of the twisted stainless steel bar (referred as helibar).

This specific technique usually addresses application of wall ties on masonry veneer walls or cavity walls of unreinforced masonry buildings (URM), but it can be used as well for crack stitching [10]. Damage on these construction systems is usually associated with high tensile demand on the wall ties, due to strong wind storms or moderate to severe earthquakes, which lead to out-of-plane failure. There are three common type of failures of the wall ties: (a) tie yielding; (b) tie pull-out from the mortar joint; and (c) tie fastener (nail) pull-out from the wood backup, being the last two more common in recent construction [11]. Therefore, this paper aims at studying the pull-out behaviour of the helibars in mortar joints and analysing the influence of different variables, such as the diameter of the helibars, the diameter of the pre-drilled pilot hole and the anchorage length. With these objectives, pull-out tests of helibars from unconfined mortar cylinders were performed. A low strength mortar was chosen for the cylinders to study the applicability and the bond behaviour of the helibars in mortar joints of historical constructions.

## 2 PULL-OUT TESTS

### 2.1. Test set-up

Altogether, 60 specimens were tested combining two diameters of the helibar, three different anchorage lengths, and two diameters of the pre-drilled holes. The diameters of the helibar, $\phi_{hb}$, chosen are ϕ8 mm and ϕ10 mm, considering common mortar joint thicknesses. The anchorage lengths were defined considering walls' thicknesses and result from multipliers of the diameter of the rod: $8\phi_{hb}$, $12\phi_{hb}$, and $20\phi_{hb}$. The two diameters of the pre-drilled holes were determined by extracting 2 and 4 mm to the diameter of the helibar. An overview of the combinations is given in Table 1.

The mortar cylinders were made with Weber Tradition® ready-mixed lime based mortar. The amount of water was kept precisely following the instructions in order to limit imperfection factors. Four mortar cylinders with the average dimensions of ϕ72 mm × 149 mm were tested at 28 days, to determine the compressive strength. The mean compressive strength was equal to 4.7 MPa with a CoV of 9.2%, and the stress-strain curves of the specimens are presented in Figure 1.

The preparation of the specimens has two main steps: first the execution of the pre-drilled pilot holes with different diameters and lengths (see Figure 2a), and second gently hammering the helibars into the mortar cylinders (see Figure 2b). Due to the helical shape, the helibars easily rotated into the pre-drilled pilot hole, without power drilling. Before inserting the helibars in the mortar, they were equipped on the free end with an aluminium cylindrical case filled with epoxy resin, to improve the contact with the grip and prevent sliding. In Figure 2c one can see the final configuration of the specimen.

**Table 1.** Different specimens' combinations

| Helibar diameter $\phi_{hb}$ (mm) | Pre-drilled hole diameter $\phi_h$ (mm) | Anchorage length $l_b = n\phi_{hb}$ (mm) | Mortar cylinder: diameter × height (mm × mm) | Number of specimens |
|---|---|---|---|---|
| 8 | 4 ($\phi_h$ – 4mm) | $8\phi_{hb} = 64$ | Φ75 × 150 | 5 |
| | | $12\phi_{hb} = 96$ | Φ75 × 150 | 5 |
| | | $20\phi_{hb} = 160$ | Φ100 × 200 | 5 |
| | 6 ($\phi_h$ – 2mm) | $8\phi_{hb} = 64$ | Φ75 × 150 | 5 |
| | | $12\phi_{hb} = 96$ | Φ75 × 150 | 5 |
| | | $20\phi_{hb} = 160$ | Φ100 × 200 | 5 |
| 10 | 6 ($\phi_h$ – 4mm) | $8\phi_{hb} = 80$ | Φ75 × 150 | 5 |
| | | $12\phi_{hb} = 120$ | Φ100 × 200 | 5 |
| | | $20\phi_{hb} = 200$ | Φ150 × 300 | 5 |
| | 8 ($\phi_h$ – 2mm) | $8\phi_{hb} = 80$ | Φ75 × 150 | 5 |
| | | $12\phi_{hb} = 120$ | Φ100 × 200 | 5 |
| | | $20\phi_{hb} = 200$ | Φ150 × 300 | 5 |

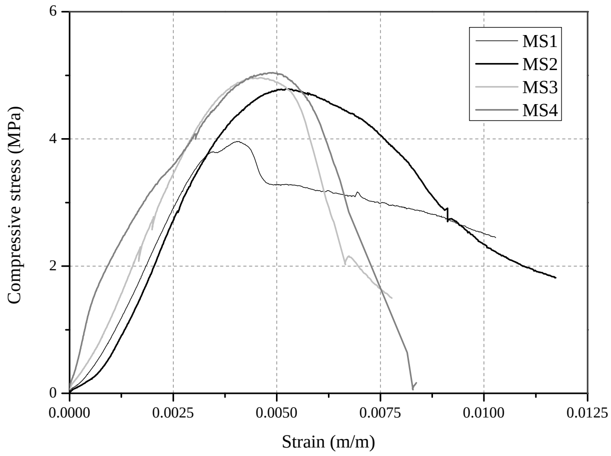


**Figure 1.** Stress-strain curves of the mortar samples

(a) (b) (c)

**Figure 2.** Preparation of the specimen: (a) pre-drilled hole; (b) insertion of the helibar; (c) final configuration

A steel plate with a circled shaped opening of 50 mm diameter was placed on top of the specimens, to provide reaction to the pull-out load and to induce pull-out failure only. Two Linear Variable Differential Transformers (LVDT) were attached to the helibars to measure the loaded end slip relatively to the mortar cylinder surface, as shown in Figure 3. Due to the shape of the helibars, rotation had to be prevented during the pull-out tests. Allowing rotation, would change the shear contact area and wouldn't be representative of the real behaviour.

The tests were performed under displacement control and the procedure was monotonic. The displacement rates were chosen to obtain maximum force between 1 and 3 minutes, as it is recommended by ASTM standard for pull-out tests on concrete cylinders [13].

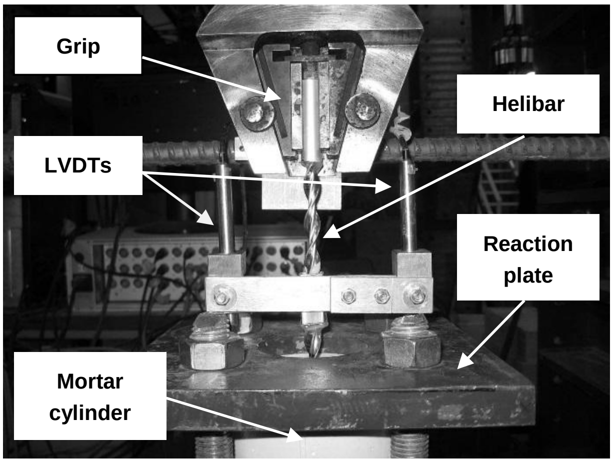


**Figure 3.** Test apparatus

## 2.2. Results

Of the 60 pull-out tests, 15 were considered outliers or were not admissible due to sliding of the grip. Maximum pull-out forces and bond strengths are presented in Table 2. Assuming a constant bond stress distribution along the embedment length, this value can be calculated with Equation (1).

$$\tau_b = \frac{F}{\pi \times \varphi_{hb} \times l_b} \tag{1}$$

where $F$ is the applied force, $\phi_{hb}$ is the diameter of the helibar and $l_b$ is the anchorage length.

As shown in Table 2 and Figure 5, bond strength was higher for the 8 mm helibars than for the 10 mm ones, showing that the increase in strength isn't directly proportional to the increase in diameter. This difference was smaller for the less tight pre-drilled holes.

As expected, tighter pre-drilled holes performed better than less tight ones. The difference in behaviour appears to decrease with the increase in anchorage length (see Figure 5). Especially for the tighter pre-drilled holes there was an increase on the Coefficient of Variation (CoV), but the highest one is observed for the anchorage length of 12ϕ8 mm with a less tight pre-drilled hole (approximately 51%).

**Table 2.** Maximum pull-out force, bond strength, and respective CoV, for each combination.

| $l_b$ (mm) | | "$\phi_{hb}$-2" | | | "$\phi_{hb}$-4" | | |
|---|---|---|---|---|---|---|---|
| | | F (kN) | τ (MPa) | CoV (%) | F (kN) | τ (MPa) | CoV (%) |
| 64 | 8φ8 mm | 0.20 | 0.13 | 21.4 | 1.00 | 0.62 | 17.2 |
| 96 | 12φ8 mm | 0.53 | 0.22 | 50.7 | 1.56 | 0.65 | 18.5 |
| 160 | 20φ8 mm | 1.28 | 0.32 | 4.9 | 2.40$^{(1)}$ | 0.60 | - |
| 80 | 8φ10 mm | 0.27 | 0.11 | 5.9 | 0.96 | 0.38 | 25.8 |
| 120 | 12φ10 mm | 0.85 | 0.22 | 7.1 | 1.47 | 0.39 | 14.1 |
| 200 | 20φ10 mm | 1.80 | 0.29 | 19.8 | 2.58 | 0.41 | 13.6 |

(1) Single value.

For higher forces, the bond stress-slip curve is clearly constituted by three branches, which are commonly observed in pull-out tests [13]. A first linear branch related with the adhesive contribution of bond develops, then cracking starts and mechanical interlocking between deformations of the bar and surrounding mortar controls the behaviour. The final end of the softening branch is governed by friction, keeping a residual bond stress.

Figure 4a shows the specimen pull-out failure at the middle and end of the test, when the slip is already very visible. No splitting cracks were observed, only shearing of the surface around the end of the ribs of the helibar. Mortar powder is lifted out by the ribs, because the pre-drilled hole diameter is smaller than the one of the helibars.

(a)

(b)

**Figure 4.** Pull-out failure: (a) beginning of test; (b) end of test.

For the anchorage lengths of 12ϕ8 mm, 20ϕ8 mm and 20ϕ10 mm, with a tighter pre-drilled hole, deformations of the helibar due to torsion were observed. Deformations observed for 12ϕ8 mm and 20ϕ10 mm anchorage lengths were mainly elastic, while for the 20ϕ8 mm length, the helibars yield completely. For this last one, in only one test was observed the pull-out failure mode (see Figure 5e).

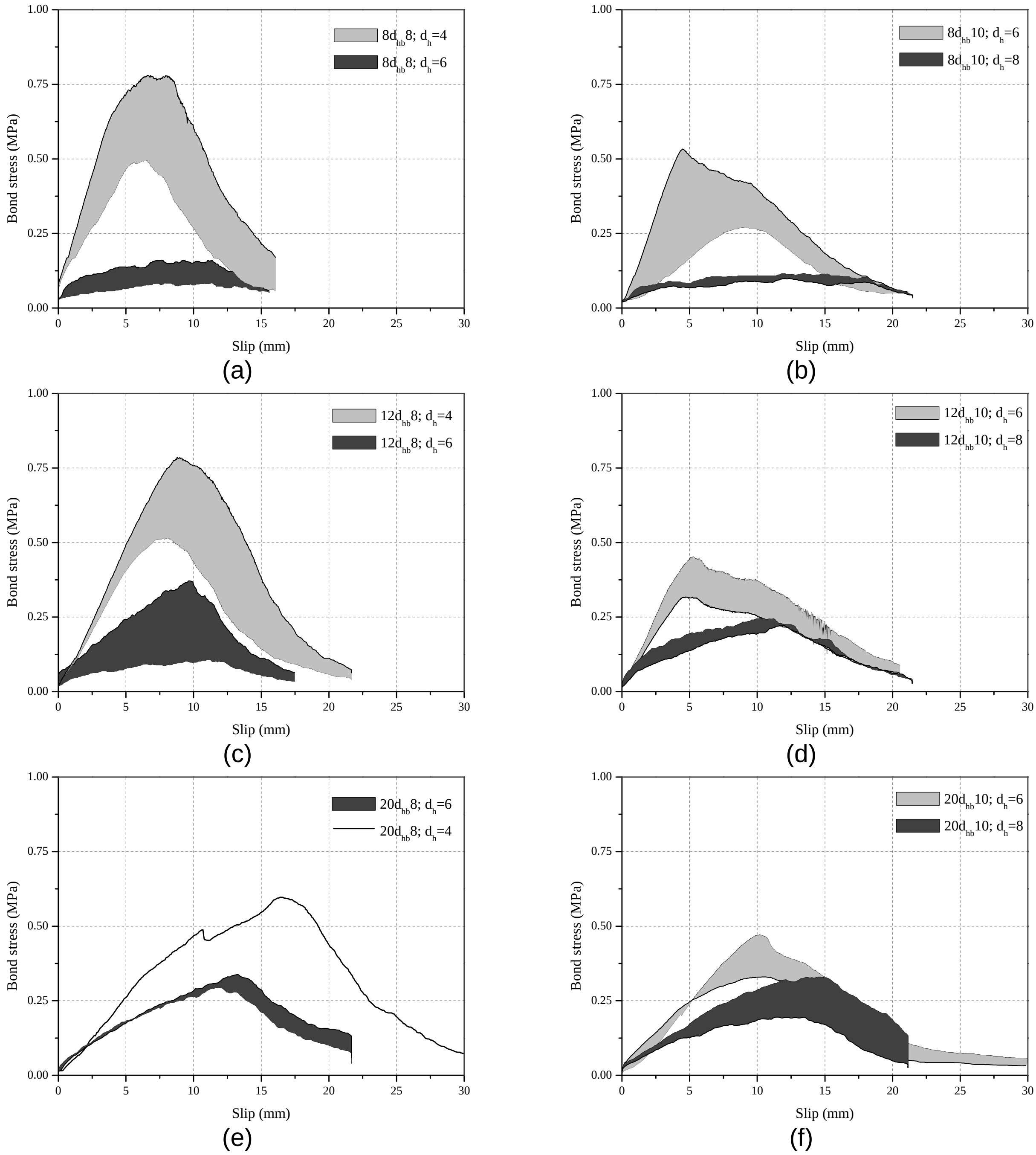


**Figure 5.** Bond stress-slip envelopes for all combinations according to anchorage length: (a) 8ϕ8 mm; (b) 8ϕ10 mm; (c) 12ϕ8 mm; (d) 12ϕ10 mm; (e) 20ϕ8 mm; and (f) 20ϕ10 mm.

## 2.3. Discussion of results

Pull-out failure occurred for all specimens except for four (of five) of the specimens with 20$\phi$8 mm anchorage length and a pre-drilled hole of $\phi_{hb}$ – 4 mm. These last ones failed by yielding of the helibar, which was not within the scope of this study.

In spite of the increase in the pullout load with the diameter of the helibar, the positive difference was not sufficient to increase the bond strength of the 10 mm bars relatively to the 8 mm ones. Therefore, the increase in force is not directly proportional to the increase in diameter of the helibar.

The bond strength increased for tighter pre-drilled holes ($\phi_{hb}$ – 4 mm), as a result of higher mechanical interlocking at the interface. For tighter pre-drilled holes, was also observed deformation of the helibars caused by torsion. So, one must have into consideration, which failure mode is preferable to occur when calculating the diameter of the tie, in a real case scenario.

For both helibars' diameters with a tighter pre-drilled hole, at the anchorage length of $20\phi_{hb}$, there was a decrease in bond strength, possible due to damage caused by the pre-drilling process. Longer anchorage lengths make the drill bit vibrate more, accidentally increasing the diameter of the pilot hole.

The less tight pre-drilled holes ($\phi_{hb}$ – 2 mm) combinations showed good linear correlations between bond strength and anchorage length ($R^2$ above 0.95), as presented in Figure 6. Only combinations with a CoV below to 25% were consider for the correlations. For the combination $\phi_{hb}$ = 8 mm and $\phi_h = \phi_{hb} - 4$ mm (6 mm), bond strength can be estimated with the expression $\tau_b = 0.002 l_b$, and for the combination $\phi_{hb}$ = 10 mm and $\phi_h = \phi_{hb} - 2$ mm (8 mm), the relationship is described by $\tau_b = 0.0015 l_b + 0.005$. The correlations for the tighter ($\phi_{hb}$ – 4 mm) pre-drilled holes combinations aren't represented, because the linear correlation was not good, probably due to the high dispersion of test results.

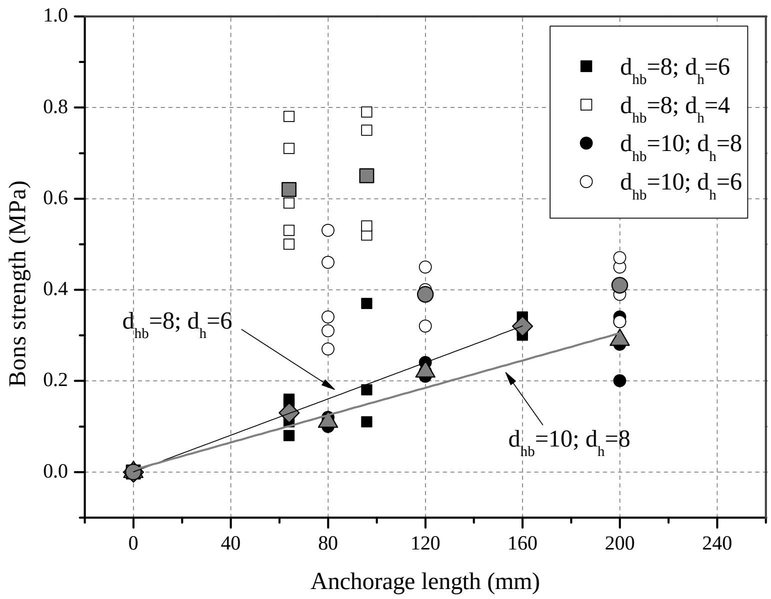


**Figure 6.** Correlation between anchorage length and bond strength ($d_{hb}$ stands for $\phi_{hb}$ and $d_h$ for $\phi_h$).

## 3 CONCLUSIONS

From the experimental campaign, it was possible to prove the feasibility of the technique and to better understand the pull-out behaviour of twisted stainless steel bars in mortar joints.

Two failure modes were observed: pull-out failure and yielding of the steel helibar. Bond stress-slip curves were obtained for twelve combinations of two helibar diameters, two pre-drilled hole diameters and three anchorage lengths, considering only the pull-out failure. For higher forces, the curves clearly demonstrate the three typical stages observed in pull-out failures. Higher bond strengths developed for the 8 mm diameter helibars and for the tighter pre-drilled hole. Good correlations between bond strength and anchorage length were found for the less tight pre-drilled holes.

For future work, pull-out tests should be carried out on different kinds of mortars and on mortar joints loaded vertically. This way it would be possible to study the influence of the mechanical properties of the mortar and the confining effect of the vertical compression existent on walls.

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