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Influence of anti-corrosive coatings on the bond of steel rebars to repair mortars

S. Jorge, D. Dias-da-Costa, E.N.B.S. Júlio

Abstract

Patch repairs are common in the rehabilitation of reinforced concrete structures, mainly bridges but also buildings, exposed to carbonation and chloride ingress. This technique includes the following steps: (i) removal of damaged concrete; (ii) cleansing of corroded steel rebars; (iii) application of anti-corrosive coating; and (iv) application of a repair mortar.

Although the application of an anti-corrosive coating is common practice, part of most manufacturers’ guidelines and, moreover, a mandatory step in some countries’ standards, it is important to assess if it decreases the bond of steel rebars to the repair mortar, in which case the anti-corrosive protection of the rebars should be assured in an alternative way.

The experimental study herein described includes 72 pull-out tests and it was conducted aiming to characterise the bond strength of the rebar-to-mortar interface and, subsequently, to define the most adequate procedure concerning the anti-corrosive protection of the rebars.

In summary, it can be stated that it is advisable to always apply cementitious coatings to plain rebars whereas it should be avoided for ribbed rebars since, in this case, the loss of average bond strength due to coatings can reach 40%.

1. Introduction

Rehabilitation of reinforced concrete structures often includes patch repairs. These are applied to adequately replace concrete in damaged zones, due to carbonation, chloride ingress, among other causes. This method includes [1]: (i) removal of damaged concrete; (ii) cleansing of corroded steel rebars; (iii) application of an anti-corrosive coating; and (iv) application of a repair mortar.

Different types of anti-corrosive coatings are available such as polymer-modified slurry, nonpassivating and passivating epoxy coatings, zinc-rich epoxy coatings, and zinc-rich water-based coatings [1,2]. Since compatibility between coatings and repair mortars must be ensured, most commercial solutions for patch repairs provide both mortar and coating. Nevertheless, the influence of coatings in the bond strength between steel rebars and repair mortars has not been adequately assessed yet. The study herein presented is a contribution to this subject.

Bond strength is usually evaluated by means of pull-out tests [3]. Three main mechanisms provide the bond strength of the connection: (i) chemical adhesion; (ii) friction; and (iii) mechanical interaction, associated with loss of cohesion. For plain bars, chemical adhesion and friction are the most important mechanisms, whereas for ribbed bars, mechanical interaction is most significant. In this case, an important slip is required to mobilise friction, which is accompanied by crushing of concrete placed in front of the ribs [4]. Consequently, the appearance and propagation of both longitudinal and radial cracks is observed [5].

This article is organised in the following sections: in Section 2, the research significance is described; in Section 3, the experimental programme is presented and the pull-out specimens are characterised concerning production, geometry and material properties; in Section 4, the experimental results are provided and discussed; and finally, in Section 5, the most relevant conclusions are summarised.

2. Research significance

Patch repair often includes anti-corrosive coatings. Therefore, the influence of these on the bond strength between steel rebars and repair mortars needs to be adequately addressed. In this article, an experimental study is described in which three commercial solutions were adopted with the following main objectives: (i) to evaluate how bond strength is influenced by coating plain and ribbed rebars; (ii) to evaluate how bond strength is influenced by
corrosion; and (iii) to compare bond strength and bond stress vs. pull-out distance relations for all tested specimens.

3. Experimental programme

The experimental programme was defined taking into account the objectives presented in Section 2. The three most adopted commercial solutions, herein denoted by ‘manufacturer’ A, B and C, have been selected. These include a repair mortar and a compatible coating proposed by each manufacturer. Three pull-out specimens have been prepared for each commercial solution, with: (i) plain and ribbed rebars; (ii) with and without coating; and (iii) with and without corrosion. Therefore, 72 pull-out specimens have been produced, summarised in Table 1, and tested at 28 days of age.

3.1. Experimental set-up

The typical pull-out test setup for characterising the bond strength of steel rebars to concrete is defined in [6]. According to this recommendation the minimum diameter of the pull-out specimen has to be greater or equal to 200 mm. However, when using repair mortars this thickness is significantly reduced and therefore limited by most manufacturers to approximately 50 mm. Consequently, the pull-out test had to be redesigned to meet their specifications.

The defined layout, represented in Fig. 1, was assembled in a 100 kN universal testing machine. The resulting eccentricity is monitored by means of two load cells TML CLC 10A. The perforated steel plate is 40 mm thickness and a 20 mm hole. A displacement transducer TML CDP 25, placed at 137.5 mm from the upper surface of the specimen and connected to a TML TDS 602 data logger, was used to assess the loading curves during tests which were performed using the displacement control of the universal testing machine at a constant rate of 0.025 mm/s.

3.2. Selected materials

Two types of steel rebars with 12 mm diameter were used in pull-out specimens graded by the manufacturer as: (i) S235, for plain rebars; and (ii) S400, for ribbed rebars. The yield stress and the tensile strength were both experimentally assessed using three specimens for each grade [7] (see Table 2).

Corroded steel rebars were obtained by conducting fifteen wetting–drying cycles, using a 2% saturated salt solution during 2 days followed by 2 days drying. The temperature of both water and environment was approximately 20°C, whereas the relative humidity was 70%. The cross section loss was evaluated for each rebar by measuring the diameter at three points (before and after corrosion) with a digital paquimeter (with 0.005 mm precision). The resulting cross section loss was, in average, 5% for plain rebars and 3% for ribbed rebars.

The composition of both repair mortar and coating of each of the selected commercial patch repair systems are presented:

**Repair mortars’ composition:**
- manufacturer A – cementitious grout, sand, synthetic resins, silica fume and polyamide fibres;
- manufacturer B – fibre-reinforced plain cement concrete;
- manufacturer C – hydraulic binder, synthetic resins, siliceous sand, silica fume and synthetic fibres.

**Coatings’ composition:**
- manufacturer A – cement based, modified epoxy resin;

### Table 1
Experimental programme: tested specimens.

<table>
<thead>
<tr>
<th>Type of bar</th>
<th>Coating</th>
<th>Corrosion</th>
<th>Number of specimens</th>
</tr>
</thead>
<tbody>
<tr>
<td>Plain</td>
<td>Uncasted</td>
<td>Non-corroded</td>
<td>3 3 3</td>
</tr>
<tr>
<td></td>
<td></td>
<td>corroded</td>
<td>A B C</td>
</tr>
<tr>
<td>Ribbed</td>
<td>Coated</td>
<td>Non-corroded</td>
<td>3 3 3</td>
</tr>
<tr>
<td></td>
<td></td>
<td>corroded</td>
<td>A B C</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Corroded</td>
<td>3 3 3</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Non-corroded</td>
<td>3 3 3</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Corroded</td>
<td>3 3 3</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Non-corroded</td>
<td>3 3 3</td>
</tr>
</tbody>
</table>

Fig. 1. Pull-out test: (a) photograph of experimental set-up; and (b) scheme of most relevant parts.
Since manufacturers do not provide the standards used to evaluate the mechanical properties of the repair mortars, these have been experimentally assessed in order to establish comparisons. The quasi-static loading Young’s modulus and flexural strength of the repair mortars were assessed using prismatic specimens, with $40 \times 40 \times 160$ mm$^3$, for each manufacturer [8, 9] (see Fig. 2(a) and (b)). Two specimens were used to measure both the Young’s modulus and flexural strength, whereas both halves resulting from the flexural strength were then used to measure the compressive strength. The latter was performed according to [8] (see Fig. 2(c)) using two steel plates of $40 \times 40$ mm$^2$ to apply the load. Table 3 summarises all relevant data. It is pointed out that the experimental values are similar to the manufacturers’ values, concerning both flexural and compressive strengths.

Concerning the selected coatings, it should be mentioned that all three are recommended as corrosion-inhibitors as well as bonding agents. The coatings by manufacturers A and B are cementitious based, containing small aggregates, whereas the other, by manufacturer C, is an aqueous dispersion. Table 4 contains the material properties provided by the manufactures for coatings. It is also important to mention that the coating thickness recommended by each of the manufacturers is different, being the thickest the one by manufacturer A and the thinnest the one by manufacturer C.

### 3.3. Pull-out specimens

Few preliminary pull-out tests were conducted after which the embedment length was settled as 80 mm (approximately 6.7 equivalent diameters) in order to ensure that the failure mechanism is controlled by bond loss and that the tensile stress of the rebar is kept below the yield stress (see Table 2).

All pull-out specimens have been produced at 20 °C and 70% relative humidity following the procedure represented in Fig. 3 and the recommendations of each manufacturer, according to the programme listed in Table 1. First, the surface of the rebar was prepared (see Fig. 3(a)–(c)). The application of rebar coating included two layers with a drying period of 3 h at 20 °C and 70% relative humidity. The average thickness of the coating applied to the rebars was 1.8 mm for manufacturer A, 1.5 mm for manufacturer B, and 0.7 mm for manufacturer C. Then, the mortar was casted using a PVC tube formwork, PN 10 pressure class, with a diameter of 125 mm, 4.8 mm thickness, and a length of 150 mm (see Fig. 3(d)). This ensures a cover of 50 mm, as in the recommendations provided by all manufactures. It is stressed out that the radial confinement of the PVC is insignificant when comparing to the confinement provided by the repair mortar [see 10]. Therefore, the PVC is only be relevant for the post-peak behaviour which is not herein addressed.

### 4. Results and discussion

Table 5 summarises all relevant results, namely: the number of tests considered valid for each situation; the minimum, average

### Table 2

Yield stress and tensile strength of S235 and S400 steel rebars.

<table>
<thead>
<tr>
<th>Steel grade</th>
<th>Measured yield stress (MPa)</th>
<th>Manufacturer's yield stress (MPa)</th>
<th>Measured tensile strength (MPa)</th>
<th>Manufacturer's tensile strength (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>S235</td>
<td>471</td>
<td>15</td>
<td>≥235</td>
<td></td>
</tr>
<tr>
<td>S400</td>
<td>442</td>
<td>11</td>
<td>≥400</td>
<td></td>
</tr>
</tbody>
</table>

### Table 3

Material properties of repair mortars at 28 days.

<table>
<thead>
<tr>
<th>Repair mortar</th>
<th>Measured flexural strength (MPa)</th>
<th>Manufacturer’s flexural strength (MPa)</th>
<th>Measured compressive strength (MPa)</th>
<th>Manufacturer’s compressive strength (MPa)</th>
<th>Measured Young’s modulus (GPa)</th>
<th>Manufacturer’s Young’s modulus (GPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>9.4</td>
<td>0.1</td>
<td>8-9</td>
<td></td>
<td>40.6</td>
<td>0.5</td>
</tr>
<tr>
<td>B</td>
<td>8.5</td>
<td>0.4</td>
<td>8.5</td>
<td></td>
<td>58.2</td>
<td>1.1</td>
</tr>
<tr>
<td>C</td>
<td>9.3</td>
<td>0.4</td>
<td>&gt;9</td>
<td></td>
<td>22.4</td>
<td>3.4</td>
</tr>
</tbody>
</table>

* No static Young’s modulus is provided by the manufacturer.
and maximum values of the average bond strength; and the corresponding pull-out distance are presented. The average bond strength is evaluated by dividing the maximum pull-out force by the area of the rebar in contact with the repair mortar, whereas the pull-out distance is the displacement measured by the LVDT. This pull-out distance includes both the loaded end slip and the elastic deformation along 137.5 mm of rebar, between the upper surface of the specimen and the location of the LVDT (see Fig. 1). It is highlighted that a test is considered valid if: (i) the pull-out load is within 20% of the average value for the series; and (ii) the difference reported by both load cells is smaller than 5% of the total applied load, corresponding to less than 5 mm of eccentricity.

In order to better illustrate the results, some selected average bond stress vs. pull-out distance curves are shown in Figs. 4–10. Additionally, failure mode pictures and summary chart bars are also provided.

From Table 5 it is concluded that the average distance from minimum and maximum average bond strength values to the average bond strength is 6.1%.

### 4.1. Plain rebars

Fig. 4 shows the surface of a typical pull-out failure obtained with plain rebars. In all cases it corresponds to: (i) loss of adhesion; followed by (ii) shear friction.

Average bond stress vs. pull-out distance curves are presented in Figs. 5–7(a). Initially, the average bond stress is almost linearly elastic, increasing at a fast rate. When the average bond strength is reached, a sudden loss of adhesion is observed. Afterwards, the average bond stress gradually decreases. This slow decay is explained by the presence of the shear friction mechanism and the simultaneous decrease of the embedment length of the rebar.

In Fig. 5 the average bond stress vs. pull-out distance curves, for an uncoated non-corroded rebar, are presented. In Fig. 5(a) all three specimens produced with repair mortar A are compared, whereas in Fig. 5(b) the most representative specimen from each repair mortar is represented. In all cases, the average bond stress increases at a fast rate until the average bond strength is reached with a small pull-out distance, near 0.3 mm (see Table 5).

The average bond stress vs. pull-out distance curves for repair mortar A are represented: in Fig. 6(a), for all three coated non-corroded specimens; and in Fig. 6(b), for two uncoated, non-corroded and corroded, specimens. The pull-out distance always increases for coated rebars, non-corroded or corroded (see Table 5). This occurs for both cementitious and aqueous dispersion coatings, although more significant for the latter. In the case of patching A, corroded rebars, coated or uncoated, have a smaller pull-out distance, being concluded the opposite for the two remaining repair mortars.

Fig. 7 summarises the results: Fig. 7(a) shows one representative specimen produced with repair mortar A for each situation; and Fig. 7(b) shows the corresponding average bond strength, for each manufacturer.

By comparing non-corroded and corroded rebars, it is concluded that: (i) although the failure is the same for all tested specimens, the brittleness observed after the peak slightly increases for

### Table 5
Experimental programme: test results.

<table>
<thead>
<tr>
<th>Label</th>
<th>Manufacturer A</th>
<th>Manufacturer B</th>
<th>Manufacturer C</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>#</td>
<td>Average bond strength (MPa)</td>
<td>Pull-out distance (mm)</td>
</tr>
<tr>
<td></td>
<td>Valid</td>
<td>Average</td>
<td>Min</td>
</tr>
<tr>
<td>P-nCt-nCd</td>
<td>3</td>
<td>3.4</td>
<td>3.1</td>
</tr>
<tr>
<td>P-Ct-nCd</td>
<td>3</td>
<td>5.9</td>
<td>5.6</td>
</tr>
<tr>
<td>P-nCt-Cd</td>
<td>3</td>
<td>6.1</td>
<td>5.1</td>
</tr>
<tr>
<td>P-Ct-Cd</td>
<td>2</td>
<td>6.6</td>
<td>7.0</td>
</tr>
<tr>
<td>R-nCt-nCd</td>
<td>2</td>
<td>12.1</td>
<td>11.4</td>
</tr>
<tr>
<td>R-Ct-nCd</td>
<td>2</td>
<td>7.6</td>
<td>6.5</td>
</tr>
<tr>
<td>R-nCt-Cd</td>
<td>2</td>
<td>12.1</td>
<td>11.1</td>
</tr>
<tr>
<td>R-Ct-Cd</td>
<td>2</td>
<td>8.9</td>
<td>8.1</td>
</tr>
</tbody>
</table>

rebars without coating; (ii) without coating, corroded specimens always present an increased average bond strength for all repair mortars; and (iii) with coating, only repair mortar C exhibits a decreased average bond strength for corroded specimens. The former is related to the fact that although corroded rebars present a decreased cross section, the contact surface and dilatancy are increased by the presence of pits [11,12]. Therefore, the average bond strength also increases.

4.2. Ribbed rebars

Fig. 8 shows the surface of a typical pull-out failure obtained with ribbed rebars. This failure is a result of: (i) mechanical

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Fig. 4. Pull-out specimens with plain rebar after failure: uncoated (a) non-corroded (P-nCt-nCd-C2); and (b) corroded (P-nCt-Cd-C1).

Fig. 5. Average bond stress vs. pull-out distance for a plain uncoated non-corroded rebar: (a) repair mortar A; and (b) repair mortar A, B, and C.

Fig. 6. Average bond stress vs. pull-out distance for a plain rebar with repair mortar A: (a) coated non-corroded; and (b) uncoated, non-corroded and corroded.

Fig. 7. Pull-out specimens with plain rebars for all test groups: (a) average bond stress vs. pull-out distance for repair mortar A; and (b) average bond strength and limit values, for all repair mortars.

Fig. 8. Pull-out specimens with ribbed rebar after failure (with highlighted cracks): uncoated (a) non-corroded (R-nCt-nCd-A3); and (b) corroded (R-nCt-Cd-A2).
interaction; followed by (ii) shear friction. The former leads to mortar crushing in front of the ribs and, consequently, to the development of radial splitting cracks (see Fig. 8).

The average bond stress vs. pull-out distance curves are presented in Figs. 9 and 10(a). Initially, the average bond stress is almost linearly elastic, increasing at a fast rate. When the average bond strength is reached, the average bond stress remains practically unchanged, for a pull-out distance of 1–2 mm, whilst radial cracks appear and propagate. With the loss of cohesion, the average bond stress decreases at a fast rate. A final stage is reached when an almost pure shear friction mechanism controls the behaviour of the specimen. During this stage, the average bond stress decay is induced by the decrease of the embedment length.

Fig. 9(a) is related to uncoated non-corroded and corroded pull-out specimens using repair mortar B, whereas Fig. 9(b) shows the result of using coating in non-corroded specimens with the same repair mortar. In this case, it is observed a decrease of average bond strength in relation to uncoated specimens.

The influence of coating in non-corroded rebar is shown in Fig. 10(a), whereas Fig. 10(b) summarises the average bond strength for each situation.

The following observations can be pointed out by analysing Figs. 9 and 10: (i) the average bond strength and pull-out distance between non-corroded or corroded rebars, with or without coating, is similar; (ii) the average bond strength is maintained almost constant during a significant pull-out distance; and (iii) coating decreases the average bond strength for corroded or non-corroded rebars. The latter is related to the importance of the mechanical interaction, induced by the ribs. In fact, this is significantly more important than the presence of pits and the decrease of the cross section induced by corrosion. The average bond strength is always mobilised after an important pull-out distance, typically above 0.7 mm (see Table 5).

4.3. Plain and ribbed rebars

By comparing results from Sections 4.1 and 4.2, the following conclusions can be pointed out:

(i) The failure mechanism in plain rebars is initially controlled by loss of adhesion, whereas for ribbed rebars the response is initially controlled by mechanical interaction.
(ii) After reaching the bond strength, there is a sudden loss of strength in plain rebars due to loss of adhesion.

(iii) For ribbed rebars, instead of loss of adhesion, a slow crushing of the repair mortar in front of the ribs is observed with a simultaneous development of radial cracks (see Figs. 4 and 8). Consequently, the pull-out distance increases and the post-peak behaviour is more soft.

(iv) The residual value obtained with ribbed rebars increases when compared to plain rebars. This results from the confinement provided by the PVC tube, after the bond strength is reached, due to the dilatancy induced by the ribs.

Figs. 7(b) and 10(b) have now been rearranged in order to present the average bond strength for coated and uncoated rebars, respectively Fig. 11(a) and (b). It can be observed that the difference found in the average bond strength of coated rebars between plain and ribbed rebars, corroded or non-corroded, decreases with the increasing thickness of the coating material (see Section 3.3). Therefore, the difference found in manufacturer A is significantly less than the one found with manufactures B and C (see Fig. 11(b)).

5. Conclusions

It can be stressed out that, although bond-stress vs. pull-out distance curves present a similar shape, the failure mechanisms are different [4]: (i) for plain rebars, the loss of chemical adhesion corresponds to the maximum average bond stress. Subsequently, the average bond stress decays at a fast rate towards an almost constant value, related to shear friction; and (ii) for ribbed rebars, the average bond strength is reached with loss of cohesion at the interface. Furthermore, the dilatancy induced by the mechanical interaction with the ribs leads to the development of radial cracks. This process is slow and requires 1–2 mm to stabilise, during which the average bond stress remains approximately constant near the maximum value. Afterwards, the average bond stress gradually decays, together with mortar crushing in front of the ribs, until a shear friction mechanism is reached.

In relation to plain rebars, it can be concluded that coating non-corroded rebars increases the average bond strength for all tested repair mortars. For corroded rebars the conclusion is similar, except for aqueous dispersion paintings (coating C). Furthermore, the average bond strength of corroded rebars is always greater than non-corroded rebars, also with the same exception.

Finally, for ribbed rebars the use of coatings decreases the average bond strength of both non-corroded and corroded rebars, for all tested repair mortars.

In summary, from the experimental programme that has been carried out, it can be stated that it is advisable to always apply cementitious coatings to plain rebars whereas it should be avoided for ribbed rebars since, in this case, the loss of average bond strength due to coatings can reach 40%.

Acknowledgements

The authors acknowledge the partial financial support of the Portuguese Science and Technology Foundation (FCT), Grant No. PEst-C/EEI/UI0308/2011.

References