# PULL-OUT TEST FOR STUDYING BOND STRENGTH IN CORROSION AFFECTED REINFORCED CONCRETE STRUCTURES - A REVIEW

# AUSZIEHTEST ZUR UNTERSUCHUNG DER VERBUNDFESTIGKEIT IN KORROSIONSGESCHÄDIGTEN STAHLBETONKONSTRUKTIONEN - EIN REVIEW

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## SUMMARY

Corrosion is one of the most important causes of degradation in reinforced concrete structures. It endangers the serviceability of the structure, requires a vast amount of effort, and consumes considerable financial resources towards repair and retrofitting of the damaged part of structures. Therefore recognizing this phenomenon and its effects on structures are essential. When embedded steel rebar corrodes, it leads to a reduction of its effective cross-section area, while the corrosion products with more volume than the original steel cause cracks in concrete. Furthermore, the corrosion products form a lubricating layer around the reinforcing bar. These effects lead to poor performance of the bond between reinforcement and concrete. Since the composite action of steel and concrete directly depends on the bond strength between them, a poor bond performance has a direct negative influence on the existing state of reinforced concrete structures.

The pull-out test is one of the simplest methods for investigating bond characteristics in concrete and was used in various research works. However, there are a variety of specifications, dimensions, and methods to implement this test. Different sizes of concrete specimens, various lengths, and location of the bonded and de-bonded region, different test set-up, various range of concrete clear cover, and several levels of rebar corrosion have been discussed in the literature. The present paper provides a review of different experimental research that focused on bond performance through the pull-out test on corroded reinforcement in concrete. The advantages and disadvantages/limitations of different test methods are discussed.

## ZUSAMMENFASSUNG

Korrosion ist eine der Hauptursachen für die Verschlechterung von Stahlbetonkonstruktionen. Sie gefährdet sowohl die Standsicherheit als auch die Gebrauchstauglichkeit des Bauwerks. Zudem erfordert die Instandsetzung beschädigter Bauteile einen enormen Aufwand und erhebliche finanzielle Mittel. Daher ist es wichtig, dieses Phänomen und seine Auswirkungen auf das Bauwerk zu erkennen. Die Korrosion von Bewehrungsstäben führt zu einer Verringerung der effektiven Querschnittsfläche. Gleichzeitig weisen die Korrosionsprodukte ein größeres Volumen auf als der Originalstahl was Risse im Beton verursacht, die die Verbindung zwischen Beton und Bewehrungsstäben beeinträchtigen. Dies führt zu einer Verringerung der Verbundfestigkeit. Die Verbundwirkung von Stahlbewehrung und Beton ist direkt abhängig von der Verbundfestigkeit zwischen ihnen. Dies zeigt die Bedeutung der Verbundfestigkeit, wenn es darum geht den Zustand bestehender Stahlbetonkonstruktionen zu beurteilen.

Der Auszugsversuch ist eine der einfachsten Methoden zur Untersuchung der Verbundeigenschaften im Beton und wurde in verschiedenen Forschungsarbeiten eingesetzt. Es gibt jedoch eine Vielzahl von Spezifikationen und Methoden um diesen Test durchzuführen. In der Literatur werden unterschiedliche Abmessungen der Betonprüfkörper, unterschiedliche Längen und Lage des Verbundbereichs und des verbundfreien Bereichs, unterschiedliche Versuchsaufbauten, unterschiedliche Betondeckungen und mehrere Stufen der Betonkorrosion diskutiert. Die vorliegende Arbeit bietet einen Überblick über unterschiedliche experimentelle Untersuchungen, bei denen die Verbundeigenschaften korrodierter Bewehrungsstäbe im Beton anhand von Auszugsversuchen ermittelt wurden. Die Vor- und Nachteile/Einschränkungen der verschiedenen Prüfmethoden werden diskutiert.

KEYWORDS: Corrosion in RC structures, Bond strength, Accelerated corrosion

## 1. INTRODUCTION

Composite performance of reinforced concrete (RC) depends on the force transferring mechanism between concrete and surface of embedded steel rebar. This interaction within the length of rebar is called the bond. Corrosion of embedded rebar in concrete is the most common reason for the degradation of bond performance. After the initiation of corrosion and during the propagation of corrosion products, a reduction in rebar cross-section area occurs. This phenomenon leads to deteriorating the ductility and strength of rebar. Moreover, corrosion products with more volume than the base steel rebar, produce internal tensile stresses in concrete around the rebar that causes cracks in concrete. In severe corrosion state, these cracks can reach to the concrete surface and result in concrete cover to spall [1]. These effects reduce anchorage or bond capacity between rebar and concrete. Eventually, changes in overall stiffness and load-carrying capacity of structure can be observed [2].

The pull-out test is one of the most common techniques for the evaluation of bond strength in various conditions, such as having different deformation patterns of rebar [3], different concrete covers, and different confinement conditions. By using this method, it is also possible to study the effect of rebar corrosion on bond strength. In the literature, researchers considered different specifications for pull-out test specimens and set-up regarding their objectives. The scope of this paper is previous researches that studied the effect of corrosion on bond strength by using the pull-out test.

In the following parts, the basic pull-out test in some codes and references is explained then some different studies for corrosion by the pull-out test is explained. Since the process of corrosion in most of the previous researches are based on accelerated corrosion technique, this method also is discussed.

## 2. PULL-OUT TEST

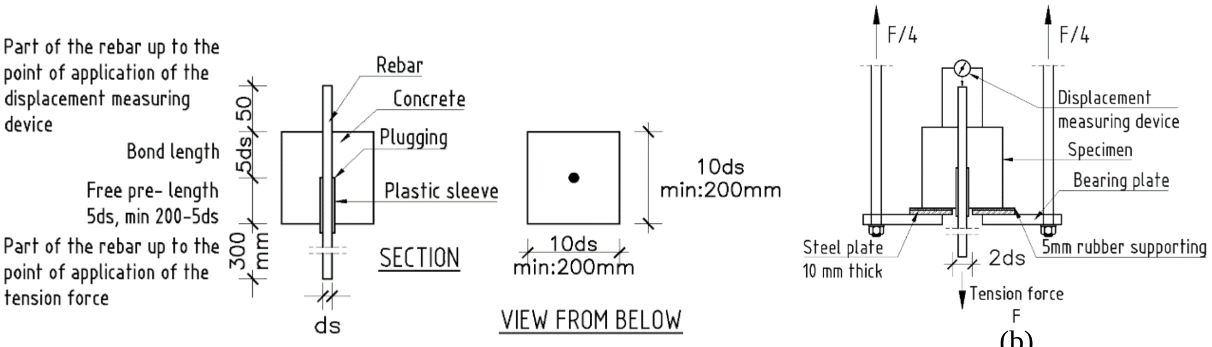
Assessment of the bond between rebar and concrete by the pull-out test can be carried out according to different standards and references. In a pull-out test, rebar is embedded within a concrete prism or cylinder. During the test, rebar is pulled out by applying a tension force in a static loading rate and with a confined test setup (reaction applied directly to the specimen itself). The values of the applied force and corresponding relative displacement between rebar and concrete (i.e. bond-slip) are continuously measured and recorded. References or standards suggest different set-ups, concrete specimen dimensions, bond length, rebar location and loading rate for the pull-out test.

RILEM technical recommendation [3], ASTM 234-91a [4], and DS 2082 [5] are the most commonly followed references that give the recommendations on the pull-out test. In the following, the recommendations of [3] and [4] are explained.

## 2.1 RILEM TECHNICAL RECOMMENDATION METHODS

In this reference, two methods are discussed. One method is related to testing of bond in autoclaved aerated concrete (Section AAC8.1), and the other one provides the test method for the bond in normal concrete (RC 6). Since the scope of this paper includes only normal concrete, in the following, the latter will be discussed.

According to section RC6, one bar is embedded in the middle of a square concrete prism of side length 10 ds (not less than 200 mm in any case) and a bond length of 5 $d_{s,}$ where $d_s$ is the diameter of the bar in mm. In Fig. 1a, geometry, and specifications of the test rig are shown. A Plastic sleeve is used to create a de-bonded zone in the front portion of the bar. The length of the de-bonded zone is such that the bond length of bar in concrete is 5ds. Besides 5 mm rubber supporting plate (Fig. 1b) is used to decrease the effect of friction between the support steel plate and concrete prism. Pull out loading rate ($V_p$) is maintained as $V_p = 0.5 d_s^2\ (\frac{N}{\sec})$. The slip of the rebar is measured through the measurement of relative displacement of the concrete specimen and unloaded end of the reinforcing bar. Thus, this test uses a relatively simple test setup for studying the bond behavior in concrete. However, due to confined test setup, in this test method while loading the bar in tension, the concrete is in compression. This boundary condition does not simulate the real-life situation correctly, and therefore, other techniques such as beam-end specimens in which the boundary conditions regarding the flexural members are more similar than standard pull-out specimens are also often used [3], [6], [7].



(a) (b)

*Fig. 1: (a) Dimensions of cube specimen (b) Testing setup*

### 2.2 ASTM 234-91A

This standard suggests two types of concrete cubes with dimensions of $150 \times 150 \times 150\, mm^3$ with one vertical embedded rebar at the middle and $150 \times 150 \times 300\, mm^3$ with two horizontal embedded rebar. In Fig. 2, formwork dimensions for the two cases are shown. Unlike [3], the use of sleeves to create a de-bonded zone in front of the rebar is not mentioned in this standard. The displacement is measured at the loaded end of the bar. The elongation of the free length of the bar is calculated and deducted from measured displacement to calculate bond-slip. The loading rate is limited to 22 $kN/min$ or 1.27$mm/min$.

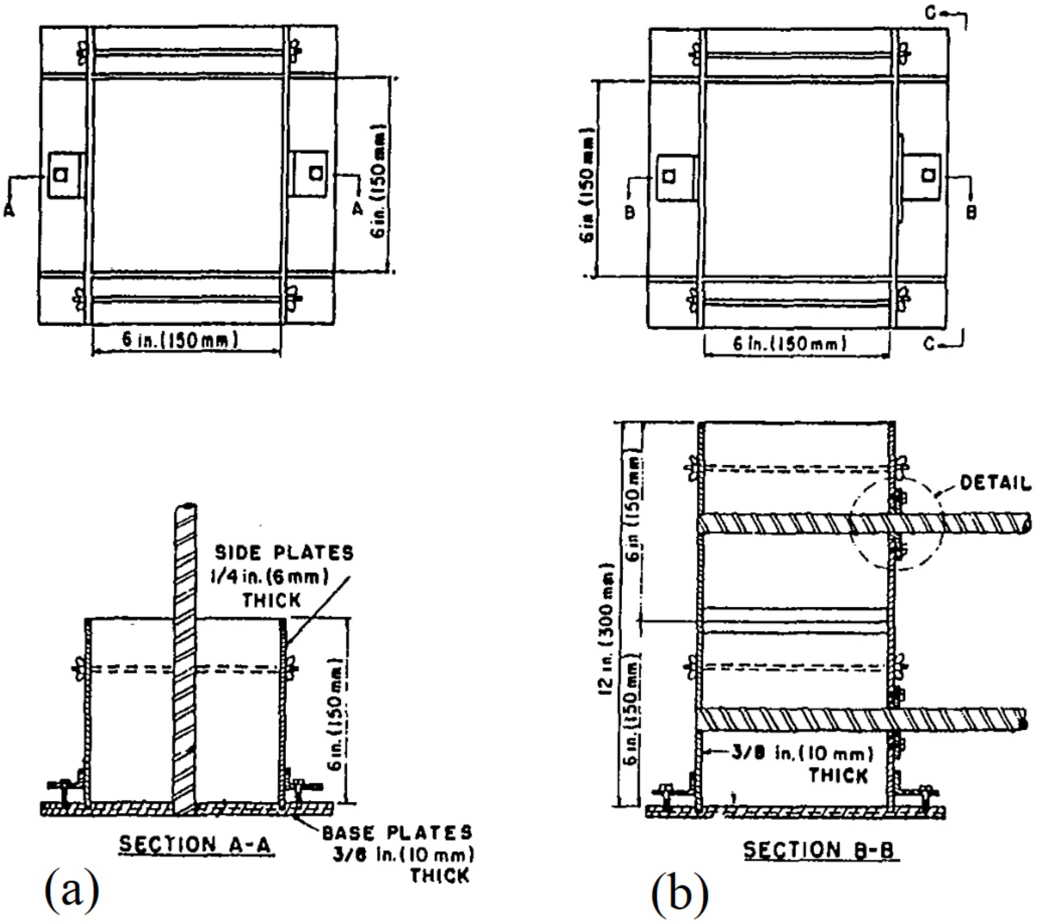


Fig. 2: (a) Molding for vertical rebar, (b) Molding for horizontal rebar

## 3. SPECIMENS' SPECIFICATIONS

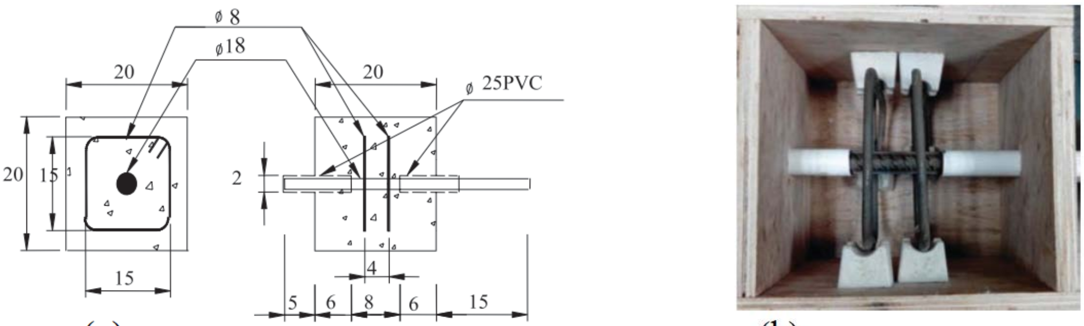
Although standards propose the specifications for concrete specimens, researches used different specimens suitable to achieve their objectives considering the limitations of the test laboratories. Some specifications for pull-out test specimens in previous researches are presented in Table 2. In all cases, the dimensions of the prism are less than 200 mm. Parameters such as rebar location (minimum and maximum cover), bond length, rebar diameter, and confinement were studied in these researches.

Bond length is a key parameter in bond studies. As shown in Table 2, the bond length is typically varied between three to fifteen times of rebar diameter ($d_s$) in these studies. However, this parameter in most of the researches is in the range of 3 to $6d_s$. According to [8], this range of bond length relates to short specimens, in which the bond stress distribution along the rebar is fairly uniform.

*Table 1: Different specifications for pull-out test specimens*

| Researcher | Concrete prism dimensions (mm) | Location of rebar | Minimum cover (mm) | Bond length (mm) | Rebar diameter ($d_s$ in mm) | Transverse reinforcement |
|---|---|---|---|---|---|---|
| Sudki et al. [9] | 150×150×200 | Corner | 15, 30 and 60 | 150 ($15d_s$) | 10 | None |
| Fang et al. [10] | 140×140×180 | Center | - | 80 ($4d_s$) | 20 | 2 stirrups |
| Chung et al. [11] | 150×150×200 | Center | - | 39 ($3d_s$) | 13 | None |
| Yalciner et al. [12] | 150×150×150 | Center | 15, 30 and 45 | 50 ($3.57d_s$) | 14 | None |
| Zhou et al.[13] | 200×200×200 | Center | - | 80 ($5d_s$) | 16 | 2 stirrups |
| Wang et al. [14] | 150×150×150 | Corner | 15, 25 and 35 | 84 ($6d_s$) | 14 | 1 stirrup |
| Tondolo F. [15] | 120×120×120 | Center | - | 60 ($5d_s$) | 12 | 2 stirrups |
| Yang et al. [16] | 150×150×150 | Center | - | 100 ($5d_s$) | 20 | None |
| Lei et al. [17] | 150×150×150 | Center | - | 90 ($4.5d_s$) | 20 | None |
| Ma et al. [18] | 150×150×150 | Edge | 30 | 100 ($5d_s$) | 20 | None |
| Farhan et al. [19] | 160×160×160 | Center | - | 80 ($5d_s$) | 16 | None |
| Sudki et al. [9] | 150×150×200 | Corner | 15,30 and 60 | 150 ($15d_s$) | 10 | CFRP wraps |

Transverse reinforcement is provided to achieve confinement by means of placing one, two, or even three stirrups across the bond length (Fig. 3).



(a) (b)

*Fig. 3: (a) Specimens geometry, (b) Formwork for specimen [20]*

Fang et al. [10] stated that in pull-out specimens without confining reinforcement, bond strength is susceptible to the level of corrosion and generally decreases with the higher corrosion level, while for deformed rebar with confining reinforcement, corrosion has no substantial effect on bond strength. In this research, they considered the rebar only in the middle of the concrete prism and with no electrical connection to the stirrups. Hence the stirrups were not subjected to accelerated corrosion and did not corrode. It leads the stirrups and the concrete around it to be functional even after corroding the main rebar in a high level of corrosion. More specifications on the pull-out test in [10] are presented in Table 1.

Zhou et al. [13] subjected both rebar and stirrups to the accelerated corrosion process. They tested 30 pull-out test prisms with the test rebar at the middle of the concrete prism (bond length of 80 mm) and with two stirrups for providing confinement to different corrosion levels from 0.2 to 16% mass loss. More details for this research can be found in Table 1. The accelerated corrosion process was carried out in two steps. First, the main rebar was corroded to the required corrosion level, and then the stirrups were connected to the constant current for corroding. It was stated that stirrup corrosion has great effects on bond performance and can reduce the confinement of concrete, which leads to degrading bond strength. In this research, corrosion of the main rebar is before stirrups. In real cases, they can be simultaneous or more often because of having less cover, stirrups corrode before the main rebar, and produce some cracks which can affect the corrosion of the main rebar.

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Soudki et al. [9] studied the effect of confinement by carbon fiber reinforced polymer (CFRP) wrapping on bond strength of corroded rebar. They considered 32 pull-out specimens with variables such as three clear covers (15, 30, and 60 mm) and four corrosion levels (1, 5, 7, and 10% mass loss). Fifteen specimens were wrapped with CFRP, as shown in Fig. 3, then subjected to the accelerated corrosion set up (Table 2). Results showed that within corrosion levels from 1 to 5% mass loss, the effect of CFRP wraps on maximum bond strength is not significant. However, in general effect of confinement by CFRP is more pronounced in specimens with a lower clear concrete cover due to their effectiveness in attenuating/preventing bond splitting failure.

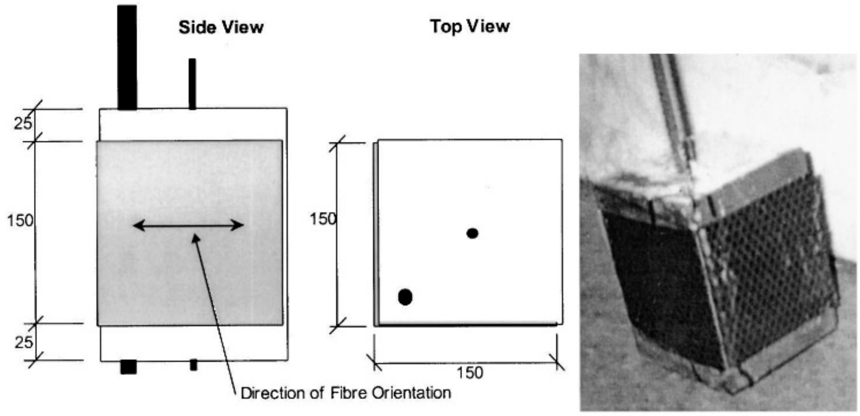

*Fig. 4: CFRP strengthening scheme [9]*

Implementation of the pull-out test to assess the effect of corrosion on bond strength between steel rebar and concrete is a prevalent technique among researchers. In comparing with real scale RC elements such as beams and columns, simulating corrosion in the pull-out test specimens according to the size of specimens, is much easier. In the following part, the process of accelerated corrosion is presented.

## 4. ACCELERATED CORROSION SETUP

Natural corrosion is a slow electrochemical phenomenon. Therefore in the past, many researchers benefitted from accelerated corrosion techniques to expedite and simulate the natural corrosion in different RC elements ([9] and [12]). The impressed current method is one of the most recognized techniques for expediting corrosion in RC elements. In this technique, the RC element and cathode are placed in an electrolyte such as saltwater, then rebar and cathode are connected to the positive and negative terminal of power supply, respectively. Constant direct current through this circuit expedite corrosion of rebar. Therefore, saving time and cost and the ability to control the rate of corrosion are some advantages of this technique [21]. El Maaddawy et al. [22] studied the influence of changing impressed current density (amount of current/anodic surface on the steel rebar) level from 100 to 500 $\mu Acm^{-2}$. They recommended using current densities less than 200 $cm^{-2}$ , since increasing the level of current density more than 200 $\mu Acm^{-2}$ leads to a significant increase in the strain response and crack width due to corrosion of the steel rebar.

In Table 2, specifications of some previous accelerated setups for the pull-out test are presented. As it is shown, the current density in different researches varies from 140 to 17700 $\mu Acm^{-2}$ , but mostly it is less than 2000 $\mu Acm^{-2}$. Moreover, in most cases, the cathodic metal is outside the concrete prism, and the required electrolyte is saltwater.

*Table 2: Details of accelerated corrosion setup for pull-out test*

| Researcher | Applied current ($mA$) | Current density ($\mu Acm^{-2}$) | Cathodic metal | Environment |
|---|---|---|---|---|
| Al-sulaimani et al. [23] | Varies | 2000 | External stainless steel | Salt water |
| Sudki et al. [9] | 7.4 | 140 | Internal stainless steel bar | Constant high humidity |
| Abosrra et al. [24] | 400 | 17700 | External graphite rod | 3% Nacl solution |
| Kearsley et al. [25] | 60 | 1087 | External steel mesh | 5% Nacl solution |
| Tondolo F. [15] | 4.5 | 200 | Stainless steel wool | Wet and dry cycles |
| Kivell et al. [26] | 100 | 2100 | External steel plate | 5% Nacl solution |
| Lei et al. [17] | 11.3 | 200 | Not stated | Not stated |
| Zhou et al. [13] | 13.57 | 150 and 300 | External copper plate | 5% Nacl solution |

A schematic view of accelerated corrosion set-up from [13] is shown in Fig. 5. In this case, each specimen was placed in a separate container with a cathodic metal (copper plate). Therefore, the specimens were connected in series. In this case, controlling of current in each specimen is more comfortable and accurate, since the amount of current in all specimens are similar and is equal to the output current of the power supply but when there is a high number of specimens, this method needs more space and efforts in comparison with a parallel arrangement.

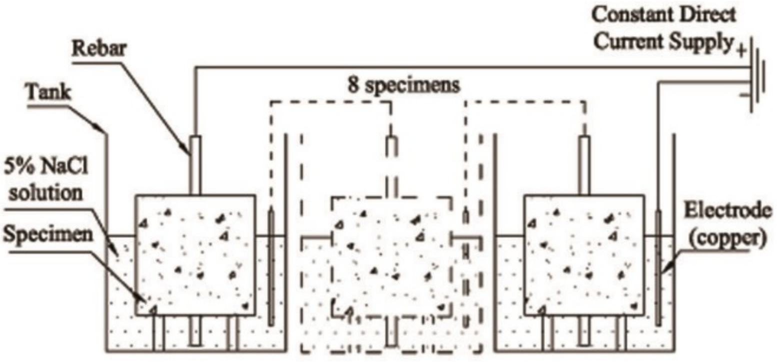

*Fig. 5: Electrochemical corrosion system. [13]*

In Fig. 6, a parallel arrangement of pull-out specimens in a tank is illustrated [16]. In this arrangement, the voltage in all specimens is similar, but total amperage is the summation of amperage in all specimens. Since concrete specimens do not have exact similar electrical resistivity, it is not possible to calculate the current accurately in each rebar without a special electrical instrument. In a parallel arrangement, specimens can be placed in one water tank, and only one cathodic metal is required.

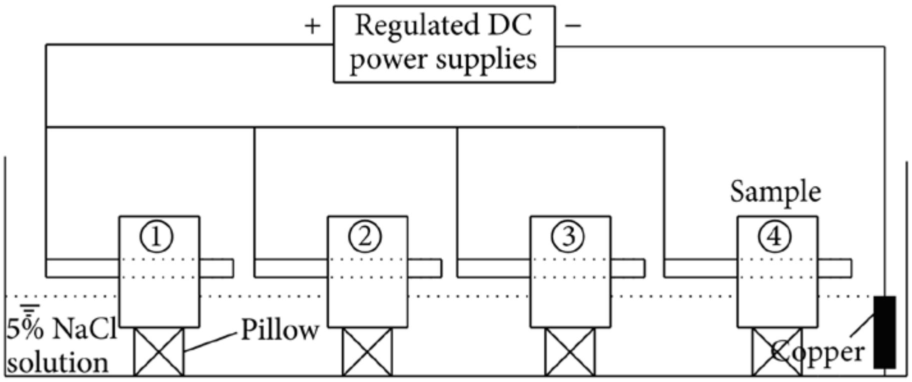

*Fig. 6: Parallel circuits used to accelerate the corrosion of the rebars. [16]*

Corrosion in steel rebar produces corrosion products with the volume more than original steel. The ratio of steel mass after corrosion to the initial mass is mass loss and generally states in percentage. To calculate the theoretical mass loss of rebar, which is subjected to an impressed current, Faraday’s law is used as follows:

$$\Delta m = \frac{Mit}{zF}$$

where $\Delta m$ mass loss in gram is, $M$ is the molar mass of metal (for steel is $55.8 grmol^{-1}$), $i$ is current in amperes, $t$ is corrosion time in second, $z$ is ionic charge (for iron is 2), and $F$ is Faraday's constant ($96500 As^{-1}$). Malumbela et al. [27] asserted that in case of a high level of corrosion or mass loss (> 8%), Faraday's law overestimates the amount of mass loss. Badawi et al. [28] reasoned that overestimated results are because of building up corrosion products around the rebar. In other words, the Accumulation of corrosion products forms a physical barrier against the ingression of water and oxygen that leads to slowing their movement toward the rebar. Researchers usually use Faraday's formula to estimate the required time of subjecting specimens to impressed current, regarding current density and intended corrosion level (mass loss).

## 5. CONCLUSION

In this paper, pull-out tests, modified pull-out tests, and accelerated corrosion process are reviewed. References state simple specifications for concrete specimens and also for the pull-out set-up, but with some modification, there is a possibility of studying more parameters (Such as concrete cover and confinement) about bond strength.

Because of the shape of pull-out test specimens, studying of confinement effect of FRP sheets on bond strength is possible. Although using FRP wraps before corrosion increases the bond strength after corrosion, for studying the retrofitting methods in RC damaged elements by FRPs, it is more desired to add FRP wraps after corrosion process.

A crucial aspect of research on corrosion in RC structures is how to simulate natural corrosion in an acceptable time frame. Impressed current is one of the most common techniques. Controlling of current in specimens is required if the estimation of time for subjecting specimens to impressed current is carried out by Faraday formula. Subsequently, considering a series arrangement for the specimens leads to better estimation of corrosion time, but it requires more space and effort than parallel arrangement.

For implementing an accelerated corrosion process with the maximum similarity to the natural corrosion, it was suggested that current density must be less than 200 $\mu Acm^{-2}$. However, considering low current density leads to prolonging the time of subjecting specimens to the accelerated corrosion set-up.

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