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Bond Strength of RC Elements with Consideration of Corrosion: An Experimental Survey

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Abstract. The researches on the bond behavior of corroded reinforcements are finalized to the assessment of the structural serviceability loss, providing appropriate tools for the evaluation of the structural integrity, i.e. relation between the corrosion rate and the cracks width detected during visual inspection on existing structures. Unfortunately, several contradictions can be found in the literature and a comprehensive interpretation of the influence of both the concrete cover depths and the reinforcement typology on the corrosion process is still missing. The present work describes the research activities planned in the convention "Effect of corrosion on the steel-to-concrete interaction" and finalized to understand the bond-slip decay in presence of corrosion.

INTRODUCTION

Corrosion is the most frequent cause of degradation in reinforced concrete structures and its principal effects regards both the reinforcement cross-section reduction and the concrete cracking because of the oxides expansion. The latter is strictly connected to a variation in the steel-to-concrete interaction that is one of the fundamental principles of the theoretical interpretation of the reinforced concrete structural elements behavior [1-2].

Several studies are carried out to evaluate the consequences of corrosion on the bond-slip relationships, most of them analyzes ordinary deformed steel bar. A first pioneering experimental study on the topic was performed by [3], that individuate the typical trend for the variation law of bond strength with corrosion: (i) an initial pre-cracking stage, in which the bond strength increases due to the confining action related to the expansion of the corrosion products for low value of mass losses; (ii) an intermediate stage, in which the cracking occurs and a return to the initial conditions is detected; (iii) a post-cracking stage, characterized by a significant decay of the bond strength for higher value of mass losses. Subsequently, to evaluate the loss of structural serviceability, a relationship between the bond strength reduction and the corrosion level was proposed in [4]. A comprehensive overview of the existing studies regarding the bond deterioration of corroded steel bar subjected to monotonic and cyclic loading can be found in [5]. Experimental tests on confined and unconfined deformed elements [6-8] highlight the significant effects of confinement due to the pressure of oxide expansion; those improve the bond strengths up to the 65%. The knowledge gained from the previous researches were collected in [9, 10] to develop a simplified local bond stress-slip relationship to employ in the current engineering practice in case of corrosion. The model, consisting of a simple shifting of the sound local bond stress-slip, catches the observed bond-slip behavior only for high corrosion levels; more effective appears on the other proposed approach, i.e. [11], that however still seems not easy to employ.

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As regards the behavior of smooth corroded steel bar, the steel-to-concrete interaction, in presence of corrosion, is similar to that observed for the deformed bar [12]. However, the local bond stress-slip curve is more rigid, even if it is characterized by lower values of strength and slip at the ultimate load; moreover, the "confining effect" due to the oxides expansion seems more relevant than that observed for deformed bar specimens. Only one work explored the corrosion effects on the bond between steel strand and concrete [13]: a particular shape of the local bond stress-slip curve, that becomes sharper by increasing the corrosion level due to the high corrosion localization [14], is found.

The present paper is a first project report that describes the research activities developed in the framework of the convention "Effect of corrosion on the steel-to-concrete interaction" between Niccolò Cusano University and Oslo Metropolitan University and finalizes to reach a deep understanding of the decay in the local bond-slip relationship.

SPECIMENS REALIZATION

The research will assess the influence of the corrosion degradation on the interaction between the concrete and the most typical steel reinforcement typologies: the steel strands, and smooth and ribbed bars. To compare the results, the reinforcements are characterized by the same diameter (equivalent to 12 mm) and bonded length. To prevent any corrosion localization, the un-bonded parts were protected with a proper antirust after removal of any surface impurity (fig. 1). The procedure is also finalized to achieve a better corrosion morphology. Obviously, to measure the effective mass loss after the corrosion process, reinforcements have been weighed before and after the antirust application.

(a) (b)

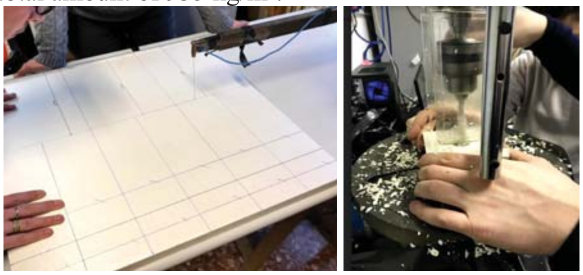
FIGURE 1. Superficial treatment of the bar: (a) ribbed reinforcement after cleaning, (b) steel strand after the antirust application.

A first specimen typology (fig. 2) has been designed according to the RILEM provisions and realized in a precast plant with the same procedures of previous researches [15]. Specifically, the specimens have a cubic shape with 20 cm side, a bonded length of 6Ø is provided at the center of the element, and the remaining reinforcement parts were protected from corrosion and inserted in PVC tubes to inhibit any interaction with the surrounding concrete.

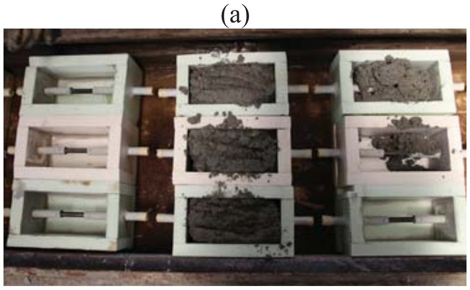
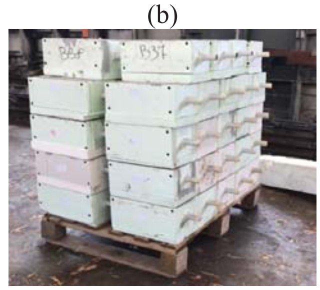
(a) (b) (c)

FIGURE 2. *c/d* = 7.83 bond specimens: realization of the samples in the precast plant. (a) battery of the steel formwork, (b) vibration of the concrete after the casting, (c) specimens after the curing stage.

Due to the large confinement actions performed by the concrete and related to the cover-to-diameter ratio *c/d* = 7.83, a pull-out failure will be expected in the sound specimens (according to [16] this occurs for cover greater than *5Ø*). Then, specimens with lower concrete cover were realized to investigate the influence of the confinement. In this case, samples characterized by a *c/d* = 3.67 are designed obtain a splitting failure in the un-corroded specimens. With this aim, non-standard 10x10x20 cm^3 polypropylene formwork were realized in the UniCusano Lab, while the casting occurred in the precast plant using the same concrete of the standard specimens (fig. 3). The concrete presents a compressive strength of 29 MPa after 28 days; the mix design consisted in a water-to-cement ratio equal to 0.46, a sand content equal to 1000 kg/m^3 and two different typologies of aggregates: 6-12 mm and 10-20 mm graded crushed stone, in a total amount of 935 kg/m^3.




(a) (b)

(c) (d)

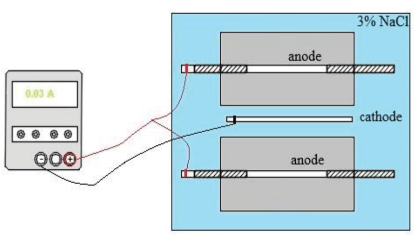
FIGURE 3. *c/d* = 3.67 bond specimens: (a) realization of the non-standard polypropylene formwork, (b) battery of the polypropylene formwork, (c) concrete casting in the precast plant, (d) specimens after the curing stage.

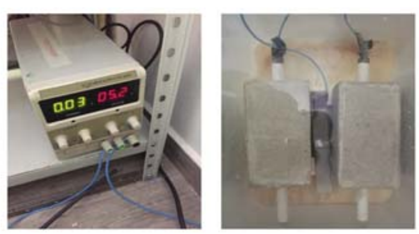
ACCELERATED CORROSION PROCEDURE PLANNING

An accelerated corrosion process will be applied to simulate long-term corrosion: the specimens are immersed into a 3% sodium chloride electrolyte solution and an external power supply allows the development of an electrochemical circuit in which the anode is constituted by the reinforcement and an external steel plate will act as cathode (fig. 4a). The necessary time to reach a certain corrosion level can be estimated by means of the Faraday's 2nd Law of Electrolysis, slightly modified to take account for the possibility that the process doesn't start immediately [17]:

$$time\ [\text{sec}] = \alpha \cdot \frac{M_{loss} \cdot n_{specimen} \cdot C_{Faraday}}{current[A] \cdot M_{specimen}} \quad (1)$$

where M_{loss} is the desired mass loss after the corrosion process, $M_{specimen}$ is the molar mass of the steel reinforcement, $n_{specimen}$ is the steel valence, equal to 2, $C_{Faraday}$ is the Faraday constant, equal to 96480, and α is a constant that takes into account the not instantaneous beginning of the corrosion.






(a) (b) (c)

FIGURE 4. Preliminary corrosion test on *c/d* = 3.67 bond specimens: (a) schematic illustration of the procedure, (b) accelerated corrosion test setup in the laboratory, (c) crack pattern after 12 days.

A preliminary corrosion test has been performed to assess the accelerated procedure (fig. 4a): two *c/d* = 3.67 specimens were subjected to artificial corrosion, applying a constant current density of 500 μA/cm^2 for 12 days. It is worth to underline that before the current application, the specimens were kept immersed into the solution for three days, to have the complete concrete imbibition. The obtained corrosion cracks are characterized by an average width of 0.70 mm, corresponding to a mass loss of about 3% according to [18]. Consequently, for the considered specimens a constant α = 2.40 should be introduced in the Eq. 1 to take into account not instantaneous beginning of the corrosion.

FUTURE ACTIVITIES

After the artificial corrosion process, the specimens will be subjected to conventional pull-out test in order to define complete degradation curves, represented in terms of peak bond strength vs corrosion level. The latter will be expressed as a mass loss, then the weight of the bars will be measured after the complete concrete removal by means of a mechanical cleaning process. For all the six sets of bond specimens, the experimental campaign will consider seven different corrosion levels, including the absence of corrosion.

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