Bond Strength between Corroded Steel Rebar and Concrete

Marco Valente

***Abstract*—Experimental tests of push-pull type using reinforcement bars embedded in concrete specimens and finite element analyses were carried out in order to investigate the effects of natural corrosion, confinement and repeated cyclic loading on bond between steel rebar and concrete. The results obtained in the experimental tests under monotonic and repeated loading history were affected by the conditions of the concrete cover and by the different corrosion levels of the longitudinal and transverse reinforcement. Bond strength degradation was observed due to repeated cyclic loadings. Three-dimensional finite element models were developed on the basis of the laboratory tests and parametric analyses were conducted to provide a better understanding of the experimental results. The analyses showed fairly agreement with the experimental results as regards the evaluation of the effects of reinforcing bar corrosion on bond strength reduction. Numerical results pointed out that high confinement levels provided by steel reinforcement enhanced bond strength and delayed the onset of bond deterioration.**

***Index Terms*—Bond strength, corrosion, experimental tests, finite element analyses, steel-concrete bond.**

I. Introduction

This study is part of a long-term research program started in 1992 at the Politecnico di Milano and focused on bond of corroded bars in concrete, [1]-[4]. Experimental tests of push-pull type were carried out on concrete specimens with reinforcing bars in order to study the effects of natural corrosion, reinforcement confinement and repeated cyclic loading on bond between steel rebar and concrete. Three-dimensional axi-symmetric finite element analyses of the test specimens were performed to provide better understanding of the experimental results. Parametric analyses comprised numerical models with different confinement, concrete strength and corrosion levels subjected to both monotonic and repeated cyclic loading. Experimental and numerical results showed that bond deterioration was influenced by the corrosion level, the loading history and the amount of confinement reinforcement.

II. Experimental Tests

The specimen geometry, shown in Fig. 1, was arranged according to the Italian specification for bond tests on deformed steel bars. The confinement reinforcement consisted of both four longitudinal bars (8 mm diameter) and four transverse stirrups (6 mm diameter). The concrete cover amounted to 28 mm. A longitudinal FeB44K ribbed bar (14 mm diameter) was embedded in concrete in a central position. The steel bar was in contact with the concrete only in the central portion for a length of ten times the bar diameter (14 cm) by means of plastic sheaths placed around the two extremities of the bar in order to deactivate bond. The test specimens were exposed for over ten years in an aerated and moderately aggressive environment in presence of chlorides, which produced corrosion of both the longitudinal bar and the confining reinforcement, being next to the external surface of the specimen.

The bond tests carried out in the experimental campaign were of push-pull type, [5]. The bar ends were blocked and the load was applied to the upper side of the specimen: thus one part of the bar was in tension and the other part was in compression. The tests were performed using a Schenk press and a specially designed and fabricated frame was used and fixed to the base of the machine during the loading. The experimental set-up is schematically shown in Fig. 2.

III. Experimental Results

The main results of the experimental tests carried out on the test specimens under monotonic and repeated loading history were reported. Fig. 3 shows the curves of the average bond stress and the bar slip measured in the lower part of the specimen. The different results obtained in the experimental tests can be mainly explained considering: 1) the corrosion level of both the transverse reinforcement and the longitudinal bar; 2) the conditions of the concrete cover; 3) the type of the loading history. The conditions of the concrete cover and the corrosion state of the stirrups influenced the confinement, whereas the corrosion level of the longitudinal bar directly affected bond. In some cases the presence of an effective confinement prevented the formation of splitting cracks and high peak values of bond stress were achieved. The steel yielding anticipated the bond failure, influencing the obtained results. In other cases a marked deterioration was observed at the outer surface of the concrete and considerable levels of corrosion were detected on the longitudinal bar. The premature bond failure prevented the attainment of the bar yielding and therefore smaller values of the bar slip corresponding to the peak stress were registered. The application of repeated cyclic loads caused appreciable bond deterioration.

The presence of corrosion products on the longitudinal bar slightly increased the steel-concrete bond for low corrosion levels, whereas significant bond deterioration was observed

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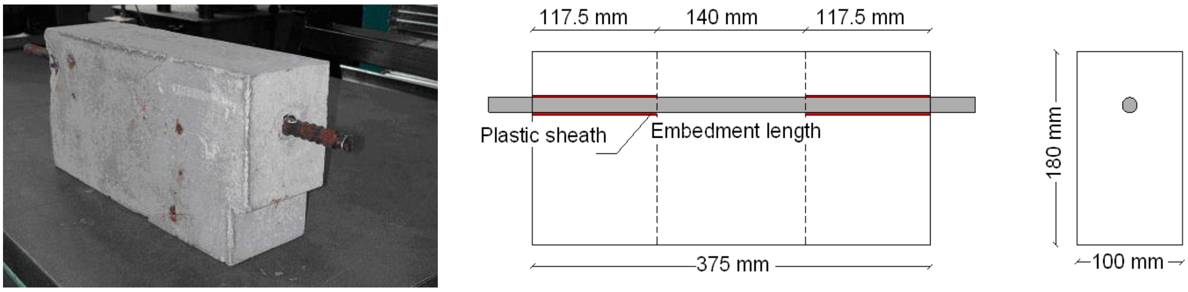

Fig. 1. General view and details of the test specimens.

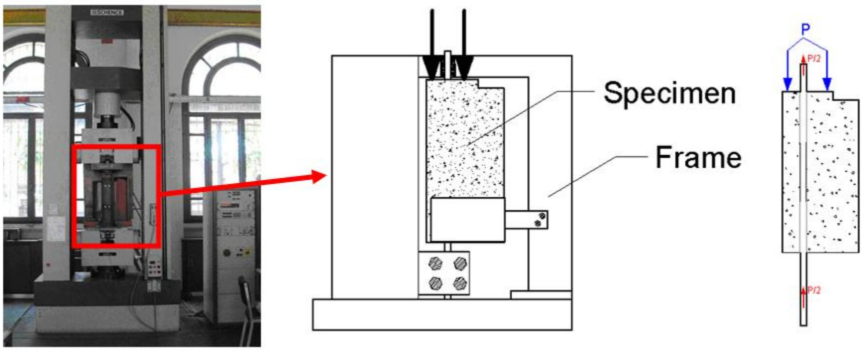

Fig. 2. Experimental set-up and scheme of the push-pull test.

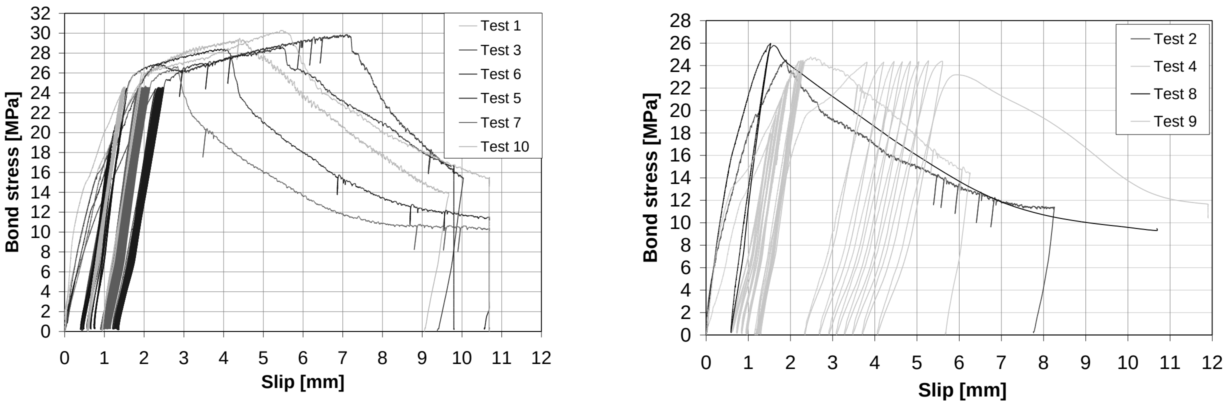

Fig. 3. Experimental tests: average bond stress-bar slip curves.

for high corrosion values. Such results can explain the different load peak values registered in the experimental tests with the same loading history. The residual bond strength was not significantly affected by the corrosion levels. The stress values at the end of the post-peak descending branch were similar regardless of the bond stress peak value achieved in the tests. The initial slope of the curve was not correlated to the bond strength, as shown by the specimens with similar ascending branches but with different bond stress peak values.

IV. Numerical Models

Numerical models of the test specimens were created by using the finite element code Abaqus [6] on the basis of the experimental results. Three-dimensional axi-symmetric elements were adopted to model the steel bar with ribs of annular shape and the surrounding concrete. The finite element mesh used for the analyses of the test specimens is shown in Fig. 4. The concrete model provided by the code and based on a smeared crack approach was used. An elastic-plastic model, obeying the von Mises yield criterion, the associated flow rule and isotropic strain hardening, was used to describe the constitutive behavior of the steel. The stress-strain relationship obtained from uniaxial tension tests carried out during the experimental campaign was used in the finite element analysis. In order to model the confinement provided by the stirrups, springs were arranged in the radial direction at the boundary of the concrete volume. The interface between the steel rebar and the concrete was simulated by using a surface-based interaction. The steel rebar and concrete surfaces were allowed to move relative to each other. When concrete and reinforcing steel are in contact, a normal pressure acts on the two contact surfaces; the contact pressure is reduced to zero if the surfaces separate. In addition, friction acts on the surfaces, which resists the sliding of the surfaces. A master-slave contact algorithm is used; nodes on one surface (the slave) cannot penetrate the segments of the other surface (the master). The contact pressure increases with an increase of the

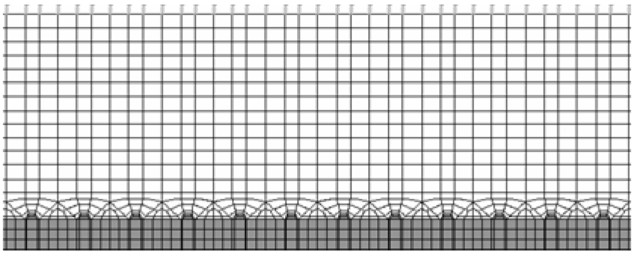

Fig. 4. Finite element mesh: steel rebar, surrounding concrete and springs representing transverse steel confinement.

confinement and decreases with corrosion. The volume increase of the corrosion products compared with the virgin steel was taken into account by means of thermal strains imposed for the steel bar. An orthotropic thermal expansion was specified in order to obtain radial expansion, causing a radial and circumferential stress state in the concrete and radial cracking.

V. Numerical Results

Three-dimensional finite element analyses were performed in order to simulate the experimental tests. The experimental and numerical bond stress-slip curves for a specimen under monotonic loading history in displacement control are shown in Fig. 5. A reasonable good agreement between test results and analyses was obtained. However, some discrepancies in stiffness were observed and the numerical model slightly overestimated bond strength and slip corresponding to the peak stress.

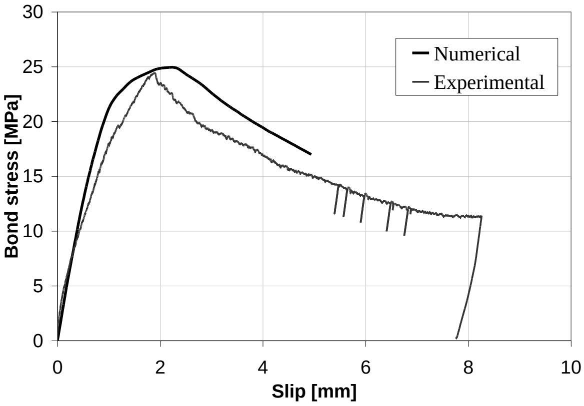

Fig. 5. Experimental and numerical bond stress – bar slip curves.

The effects of repeated loads on bond strength are shown in Fig. 6. The loading history consisted of the application of ten cycles with constant load magnitude followed by a conclusive cycle in displacement control. The applied loading history caused a significant bond deterioration. The bar slip values corresponding to the peak stresses were different, reproducing the experimental results. The post-peak descending branch showed a similar slope in the two analyses.

The effects of bar corrosion levels on normalized bond strength for different confinement are shown in Fig. 7. Corrosion levels up to 300 μm were imposed by means of thermal strains. The different confinement levels were indicated in terms of stirrup diameter and spacing. A small initial bond increase for corrosion levels of 10-20 μm was observed due to the bar expansion. Then, a sharp bond loss was registered. A residual bond strength level was reached between 100 and 200 μm due to the effect of stirrup confinement in case of Φ6/100. This trend confirms the effective role of stirrups in the post-cracking stage. A further loss of confinement due to cover cracking and hence bond deterioration took place beyond 200 μm corrosion.

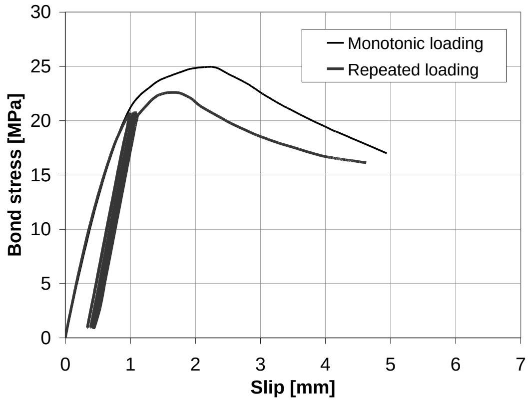

Fig. 6. Effects of repeated loads on bond stress – bar slip curve.

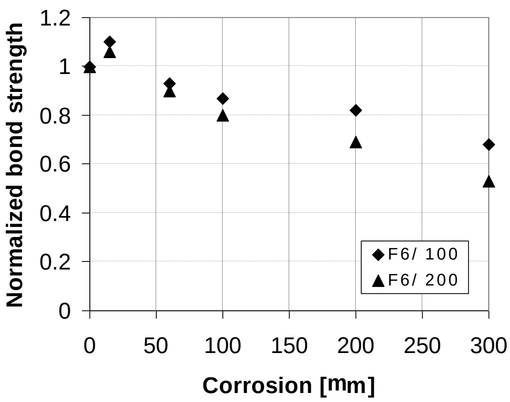

Fig. 7. Effects of bar corrosion on normalized bond strength for different confinement levels (stirrup diameter/spacing [mm]).

Bond deterioration was limited by confinement and was influenced by the percentage of transverse reinforcement, confining the bar and opposing the expansion of the corrosion products. Fig. 8 shows the results for different steel confinement, indicated by the stirrup diameter and the spacing. Numerical analyses showed the considerable contribution of transverse reinforcement confinement to the bond strength. An increase in the stirrup confinement delayed the onset of bond deterioration and enhanced the bond strength, as observed in the experimental tests. The effects of the confinement were progressively lost with cover cracking, as the confining action of the stirrups couldn't be transferred to the bar.

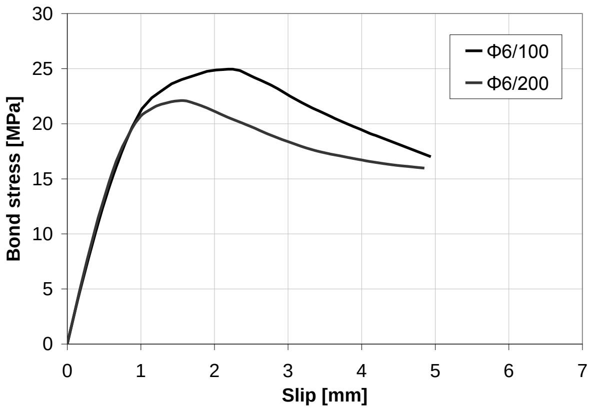

Fig. 8. Effects of stirrup confinement (stirrup diameter/spacing [mm]) on bond stress-bar slip curve.

The influence of concrete compressive strength on bond stress-bar slip curve was reported in Fig. 9 for the models subjected to repeated loadings. The different behavior for two different concrete strength values was captured. The bond strength increased and the slip decreased with increasing concrete strength and bond deterioration was limited in case of higher compressive strength of concrete.

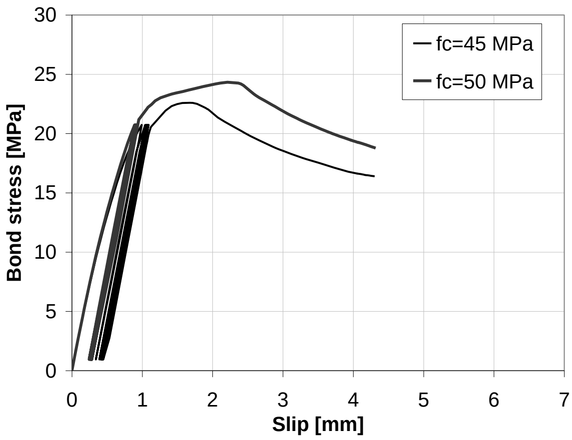

Fig. 9. Effects of concrete strength on bond stress-bar slip curve in case of repeated loading.

VI. Conclusion

Experimental tests and finite element analyses conducted in this research program highlighted the effects of natural corrosion, confinement and repeated loading on bond strength between steel rebar and concrete. Different bond stress-bar slip curves were observed from experimental tests. In some cases the presence of an effective confinement prevented the formation of splitting cracks and high peak values of bond stress were achieved. In other cases a marked deterioration of the concrete cover and considerable levels of longitudinal bar corrosion caused a sudden loss of bond strength and premature bond failure. The steel bar yielding was prevented and lower values of the slip corresponding to the peak bond stress were registered. Finite element models were developed on the basis of the results of the laboratory tests and parametric analyses were carried out to provide a better understanding of the experimental findings. The numerical results, compared with the experimental data, pointed out the important role of confinement as a parameter influencing the bond strength of corroded bars. The bond strength decreased and the slip enhanced with increasing corrosion. A small initial increase of bond strength was observed for low corrosion levels. Then, it was followed by an appreciable bond strength reduction, mainly if low levels of confinement reinforcement were used. Bond deterioration was limited by confinement for a certain range of increasing corrosion levels. The application of repeated loads caused an appreciable bond deterioration. The models with higher concrete strength levels showed higher peak values of bond strength.

References

[1] M. Berra, A. Castellani, D. Coronelli, S. Zanni, and G. Zhang, "Steel-concrete bond deterioration due to corrosion: finite element analysis for different confinement levels," *Magazine of Concrete Research*, vol. 55, no. 3, pp. 237-247, 2003.

[2] D. Coronelli, "Corrosion cracking and bond strength modeling for corroded bars in reinforced concrete," *ACI Structural Journal*, vol. 99, no. 3, pp. 267-276, 2002.

[3] M. Valente, "Bond between concrete and corroded steel rebar under cyclic loading: experimental tests," *First European Conference on Earthquake Engineering and Seismology*, Geneve, Switzerland, 2006.

[4] M. Valente, "Steel-concrete bond deterioration under repeated loading for different confinement levels," *Applied Mechanics and Materials*, vol. 217-219, pp. 188-191, 2012.

[5] H. H. Abrishami and D. Mitchell, "Analysis of Bond Stress Distributions in Pullout Specimens," *Journal of Structural Engeenering*, vol. 122, no. 3, pp. 255-261, 1996.

[6] Hibbit, Karlsson and Sorensen. *Abaqus User Manual*, vol. 6, no. 5, 2005.