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Monitoring of steel-concrete bond using pull-out test with the acoustic emission technique

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ABSTRACT. Cracking in reinforced concrete structure is of major concern since it may impact their durability and their structural integrity. Cracking is mainly influenced by the stress distribution along the interface between steel and concrete which is responsible of transferring load from steel bar to the surrounding matrix. Thus, quantitative evaluation of the influence of steel-concrete bond on the fracture properties is important. An experimental investigation on pull-out and tensile tests on reinforced concrete ties is reported in this study. Pull-out and tensile tests are conducted on cubic specimens with different reinforcement diameters of high adhesion in parallel with a continuous monitoring using the Acoustic Emission (AE) technique and the Digital Image Correlation (DIC). The AE technique allows real time monitoring of the fracturing stages and can provide useful information about the location of defects and damage characteristics. Two failure modes are observed according to the steel bar section: concrete cover splitting and pull out with damage concentrated near the concrete rebar interface. The results show a good correlation between the loading force and the AE activity with AE signal of different characteristics indicating different active fracture mechanisms. The order of apparition of cracks, their width and their spacing was also measured in correlation with the loading level for short ties with different lengths and bar diameters. In addition, the location of AE events is consistent with the actual crack development.

KEYWORDS. Damage, reinforced concrete, pull out tests, Acoustic Emission, Digital Image Correlation

INTRODUCTION

The structural behavior of reinforced concrete (RC) is highly affected to bond between reinforcement and concrete. A wide range of factors affect the bond-slip response between bars and concrete, as bar diameter, concrete properties, bond length, and reinforcing material [1, 2, 3]. Bond-slip interaction between reinforcement and concrete is characterized by three main components: chemical adhesion, mechanical interaction, and friction. Two mode of bond failure are possible based on the cover and the confinement: pull-out failure and splitting of concrete cover failure [4]. The chemical adhesion breaks down first for low bond stress values where no slip between the reinforcement and the concrete is observed. Then, for higher bond stress values, the limited wedging action of the lugs cause transverse microcracks which allow the bar to slip. In a bar pull-out failure, the wedging action is enhanced and hoop stresses appear at the surrounding concrete, which at the same time exerts a confinement action on the bar. Thus, the force transfer mechanism changes from rib bearing to friction and shearing of the concrete keys cast between each pair of lugs. In a concrete cover splitting failure, bond failure is mostly due longitudinal splitting of the concrete surrounding the bar. A recent study conducted by Mezhoud & al. [5] proposed new relations for the characteristic values of the first curvilinear bond slip law based on the same pull-out tests and the behavior of short tie rods was deduced. However, few studies analyzed the acoustic emission (AE) response corresponding to the degradation mechanisms for a better monitoring of the fracturing stage of RC structures [6]. In fact, the AE technique allows real time monitoring of propagating cracks and can provide useful information about the location of defects and damage characteristics [7].

The aim of the present research work is to investigate the influence of bar diameters on the steel-concrete bond strength and splitting cracks and to give insight on the active fracture mechanisms in correlation with the AE activity. An experimental investigation on the pull-out test proposed by the RILEM [8] is reported due to its simplicity. Pull-out and tensile tests are conducted on cubic specimens ($10 \times 10 \times 10 \text{ cm}^3$) with different steel sections in parallel with a continuous monitoring using AE resonant sensors and DIC.

First, the materials and test conditions are presented. Then, a detailed analysis of AE signal parameters with respect to bond stress is proposed in order to characterize the different phases of failure. Finally, the cracking response of reinforced concrete and the influence of the reinforcement ratio are investigated.

EXPERIMENTAL PROGRAM

Materials properties

The concrete was cast using ordinary Portland cement, water, river sand and coarse aggregate with a maximum grain size of 15 mm. The mix proportion of concrete is shown in table 1 with a water to cement ratio of 0.5.

Table 1. Concrete mixture proportions

Constituents	Dosage (kg/m^3)
Gravel 5/15	1148.07
Sand 0/5	629.34
Cement	400
Water	202.17

Compression and tensile tests are conducted on prismatic ($15 \times 15 \times 15 \text{ cm}^3$) and cylindrical ($11 \times 22.5 \text{ cm}^3$) concrete specimens respectively. Hot rolled ribbed commercial bars were used with a nominal diameter of 8, 12, 14 and 16 mm. Table 2 presents the mechanical properties of concrete and steel bar.

Table 2: Properties of concrete and steel bar

Concrete	Mean value	Steel bar	Mean value
f_t (MPa)	2.6	E_s	200 GPa
f_c (MPa)	33.7	f_y	500 MPa

Note here that the adhesion between steel and concrete depends on the geometrical characteristics of the ribs considering the height h_1 , the spacing e_1 , the angle of the ribs α_1 (45 to 50°) and their inclination α_2 (45 to 50°) (figure 1).

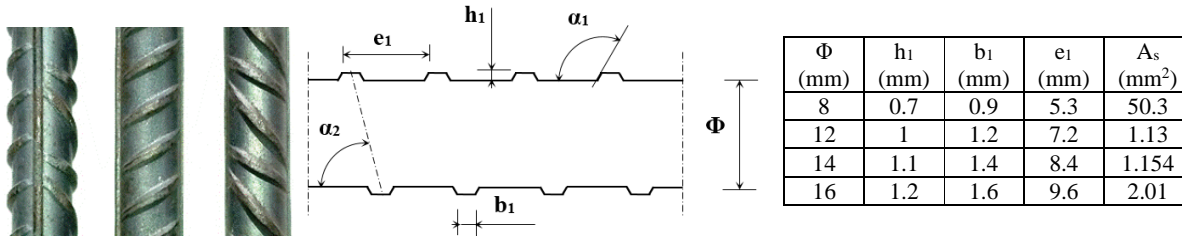


Figure 1. a) Ribbed steel bar used b) Geometric characteristics of the ribs c) Geometric characteristic values of the ribs

Pull out tests

RC pull out specimens were designed based on the RILEM with a length varying based on bar diameter Φ . The samples had the shape of cubes with an edge length of 10 cm. Reinforcing steel rods were placed prior to casting of concrete with a protective layer on the bottom and upper side of embedded steel over a length of 5Φ using a PVC hose covering as shown in figure 2 (a) in order to avoid inaccurate stresses in the specimens and friction in the sample. Bars are embedded into a 15Φ concrete cube and where the bond length of the steel bar and concrete is equal to 5Φ .

After casting, specimens were covered with a thin sheet of plastic to prevent water loss. 24 hours after casting, specimens were stripped off from the moulds and kept for curing in lime water at 20°C for 28 days.

Tests were performed in the axial tensile mode using a testing machine with a special metal framework. The free top part of the rod was clamped by a testing machine for pulling out and withdrawal of the reinforcing element from concrete. The sample was placed in a holder with a stopper fixed at the lower (immobile) clamp of the testing machine (figure 2 b). The sample was loaded by pulling out the rod at a constant velocity in the vertical direction. The loading force and displacement of the mobile clamp were continuously monitored. In addition, two LVDT sensors were placed in order to measure the slip between the rod and concrete on the bottom and the upper side of the sample. The maximal bond stress τ is considered constant along the anchorage and is calculated as:

$$\tau = F / \Pi \Phi l \quad (1)$$

Where F is the maximum applied load, Φ the bar diameter and l the anchorage length

As the section of specimens is kept constant, the percentage of steel is varied $\rho = A_s / A_t$; where A_s and A_t represent respectively the section of the steel and the section of the specimen.

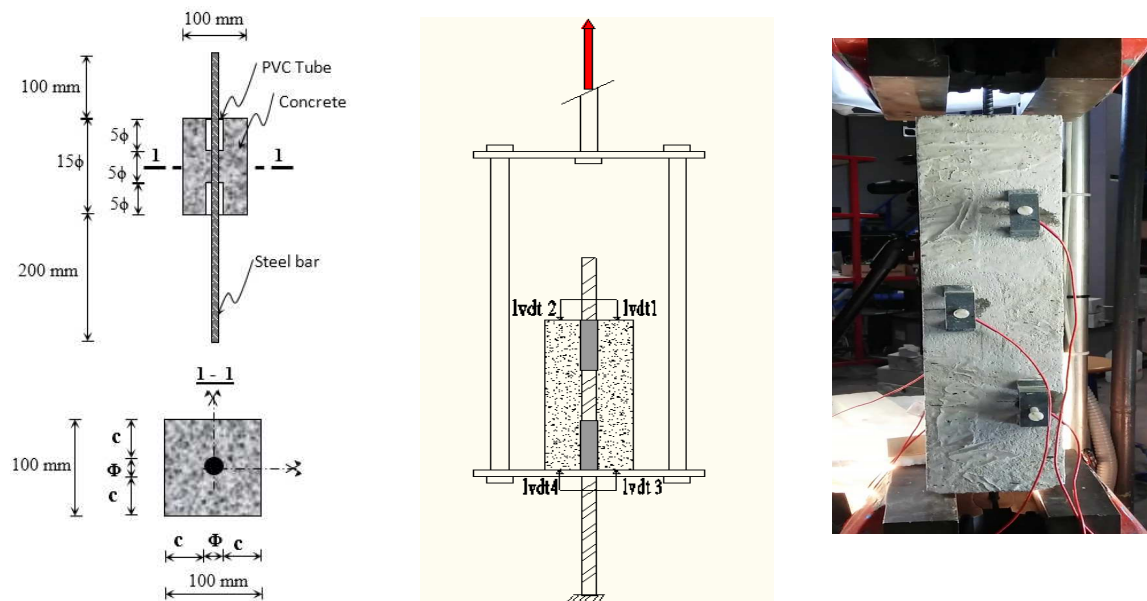


Figure 2. a) Specimen's dimension and section, b) Schematic diagram of the experimental arrangement of pull out test, c) AE sensor arrangement

Tensile tests on reinforced concrete ties

Tests on reinforced concrete ties are also carried out on samples with different length and considering the same concrete cross section $10 \times 10 \text{ cm}^2$ in order to study the effect of bar diameter on the state of maximum mobilization of the adhesion between steel and concrete and beyond the mode of decrease of this connection. For each bar diameter, three lengths were considered: 250, 450 and 650 mm. Tests are conducted up to the yielding of the bars at a concrete age of 28 days. The DIC and AE technique were also performed during the loading of reinforced concrete ties.

Acoustic emission technique

The AE system comprised of an eight channel AE Win system, a general-purpose interface bus (PCI-DISP4) and a PC for data storage analysis. Six piezoelectric transducers (resonant frequency of 150 kHz) were used to convert the mechanical waves to electrical signals. The pull out tests were monitored by a three dimensional positioning. The sensors were placed in a 3D parallelepiped position on both free frontal surfaces of the sample with silicon grease as the coupling agent (figure 2 c). The recorded AE amplitudes range from 0 to 100 dB. The detected signals were amplified with a 40 dB gain differential amplifier. In order to overcome the background noise, the signal detection threshold was set at a value of about 35 dB (value adjusted before every test) slightly above the measured background noise [7]. The acquisition system was calibrated before each test using a pencil lead break procedure HSU-NIELSEN (Norme NF EN 1330). The effective velocity and the attenuation of acoustic waves were also calculated. For this analysis, the effective velocity was assumed to be constant for the analysis of AE source locations even though there may be some variability depending on the wave propagation path. The effective velocity was assumed to be 3800 m/s. In order to eliminate mechanical and electromagnetic disturbances, a high pass filter with a cut-off frequency of 20 kHz, and a low-pass filter with a cut-off frequency of 400 kHz were used. Signal descriptors such as rise time, counts, energy, duration, amplitude, average frequency and counts to peak were captured and calculated by AEwin system. Each waveform was digitized and stored.

TEST RESULTS AND DISCUSSIONS

Bond stress versus slip curves

Figure 3 shows the bond stress versus the slip obtained for specimens with $\Phi 8$, $\Phi 12$, $\Phi 14$ and $\Phi 16$ bars. Two failure modes were observed: concrete cover splitting with $\Phi 14$ and $\Phi 16$ and pull out with damage concentrated near the concrete bar interface for $\Phi 8$ and $\Phi 12$. This is due to the different confinement thickness [9] and to the interface resistance [10]. In the case of concrete cover splitting, Torre-Casanova & al. [9] established a linear relation between the ratio τ_{\max}/f_t and the ratio c/Φ where c represents the thickness of the confinement. From a certain critical ratio c/Φ , the ratio τ_{\max}/f_t remains constant indicating a rupture by pull out.

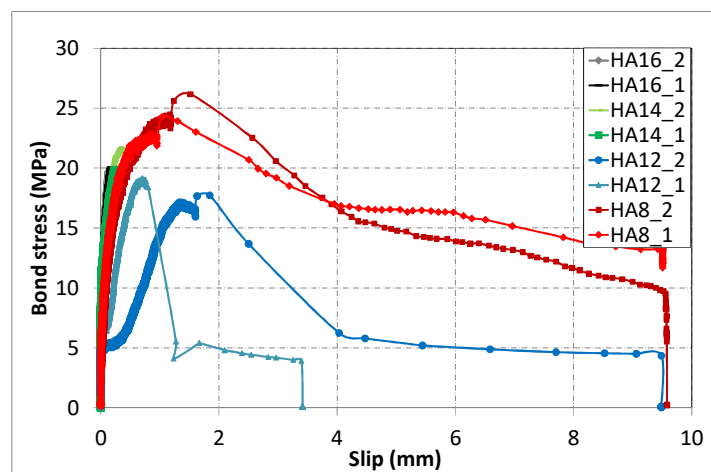


Figure 3: Equivalent uniaxial behavior law of plastic sliding interface for $\Phi 8$, $\Phi 12$, $\Phi 14$ and $\Phi 16$ bars.

In order to have a better understanding of the differences between those two modes of rupture in term of AE activity response, the pull-out tests with $\Phi 8$ and $\Phi 16$ were considered. Figure 4 (a) shows a typical curve of the bond stress in correlation with the cumulative number of AE hits and the duration of AE hits matched on a common time scale for reinforced concrete specimen with $\Phi 8$. Three phases can be distinguished. The load increases at the beginning according to a linear law with a very low slip value (assimilated to the elastic deformation of concrete) indicating a perfect bond at the interface between concrete and steel. During this phase few AE hits were detected. Those hits can be attributed to the rupture of the chemical adhesion between concrete and steel. Then, the AE activity begins to increase at 20 % of the maximal strength with more energetic AE hits indicating the nucleation of microcracks in localized zones along the interface between steel and concrete. This is due to the coalescence of microcracks in the zones of stress concentration related to the morphology of steel bars, the presence of the ribs and the spatial variability of the mechanical properties. In parallel, a decrease in the rigidity was observed until the maximal value of shear stress which correspond to the resistance of the interface.

For $\Phi 8$ specimen, shortly prior to the loss of stability, the rate of AE hits increases quickly indicating the development of defects and the slip of the rod (figure 4 a). Thus, the stress at the interface between concrete and rod reached the critical stress due to the accumulation of damage at the interface. The AE activity increases quickly after the peak with more energetic AE hits and a larger duration indicating the slipping of the bar and the development of friction at the concrete-concrete and concrete-steel interface. This is accompanied with the decrease of stress indicating that the concrete is crushed between the ribs of the bar. The load decreases until the bar is displaced of a distance equal to that between the ribs.

For $\Phi 16$ specimen, a brittle rupture was observed due to the splitting of concrete accompanied with the emission of very energetic hits (figure 4 b). A rapid decrease of the stress is observed indicating the loss of stability and the macroscopic rupture of concrete. The surface of the specimens after the rupture show the traces of the ribs and the crushed concrete. In fact the ribs can apply a pressure and a shear stress on the surrounding concrete; when radial cracks are extended to the surface, the splitting failure of concrete appears.

Note here that the number of AE hits is largely superior in the case of pull – out failure.

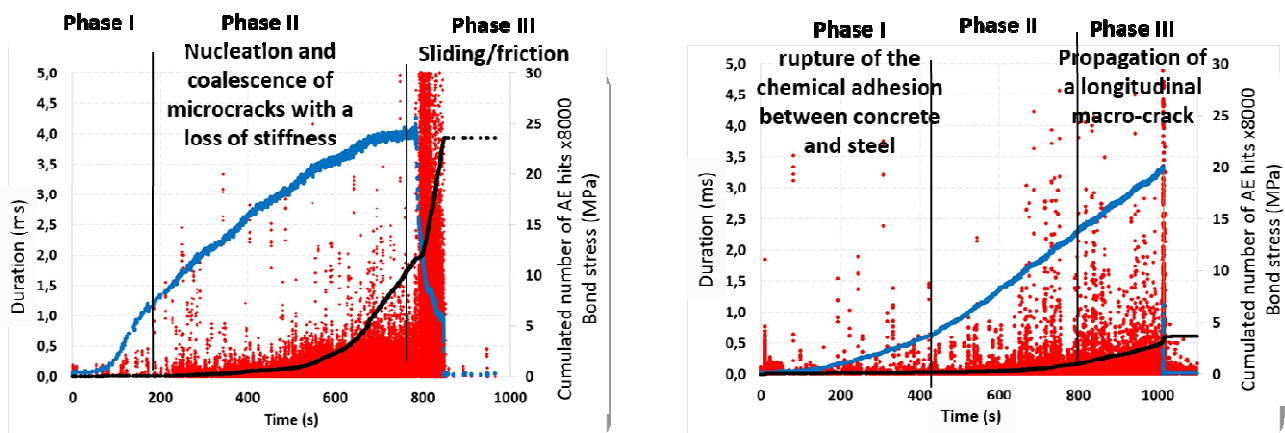


Figure 4. Correlation between the bond stress and the cumulated number of AE hits and the duration of the AE hits for reinforced concrete specimens with $\Phi 8$ (a) and $\Phi 16$ (b).

In function of the bar diameter and the length of the short tie rods, ties without or with one or two main cracks were observed during tensile tests. As the specimen is subjected to tension, the effects of the steel-concrete bond, such as stress distribution, tension stiffening reduction and concentration of forces at some local points can be observed. Once the normal stress in concrete reaches the concrete tensile strength, a macro crack appears. AE signals with parameters similar to those generated during pull-out tests were also observed at different loading levels indicating similar damage mechanisms. Figure 5 show the AE events localization maps in correlation with the digital image correlation at different loading level for the RC concrete tie with a length of 650 mm and a $\Phi 16$ steel bar. Based on those images, the order of apparition of transverse cracks, their width and their spacing can be measured. In addition, the location of AE events is consistent with actual crack development obtained with DIC.

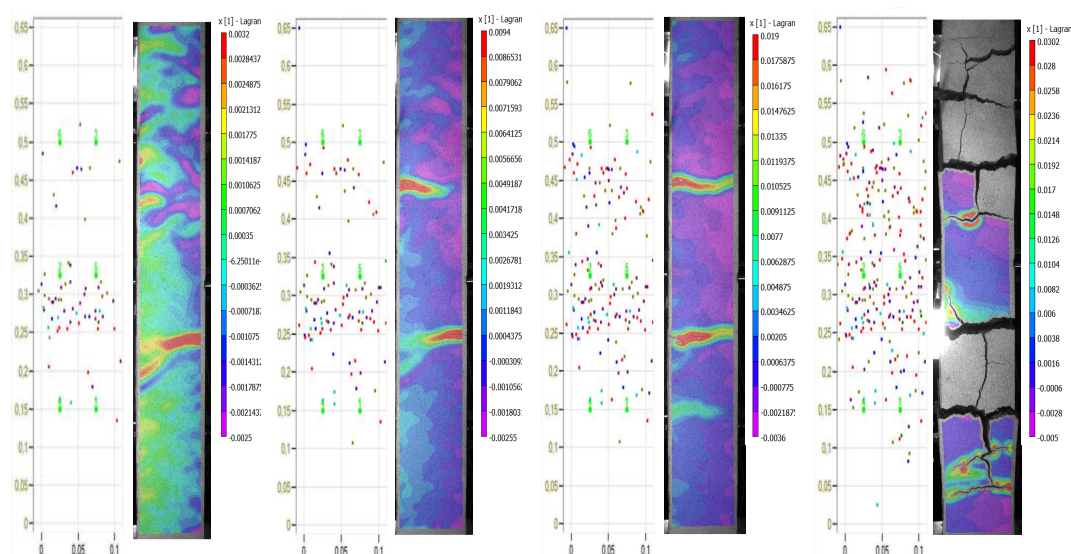


Figure 5: AE events localization maps in correlation with the vertical displacement obtained with DIC at different loading levels

CONCLUSIONS

This study allows to analyze the characteristics of AE hits generated during pull-out test. Two modes of failure were observed in function of bar diameter: pull-out and splitting of concrete failure. The AE activity is highly correlated to different degradation phases of the steel-concrete bond. The pull-out failure generate a high number of AE signals characterized with important duration due to friction in comparison to the brittle fracture of RC specimens with a macroscopic longitudinal crack. Tensile tests are also conducted in order to investigate the cracking response of reinforced concrete and the influence of the reinforcement ratio. The order of apparition of transverse cracks, their width and their spacing were measured with DIC and the AE activity response was analyzed. Numerical simulation will also be realized in complements to the experimental research for a better understanding of the influence of different properties and parameters and to reduce the amount of experimentation.

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