Acoustic Emission Monitoring of Chemically Bonded Anchors

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Abstract This paper presents a study on the use of acoustic emission (AE) to assess the structural soundness of concrete reinforced with chemically bonded anchors. The results of an experimental work based on six pullout tests monitored using an AE instrumentation suite are reported below. In every test one rebar was embedded in the hardened concrete by means of polyester resin. The AE was adopted to monitor the onset and progression of any structural damage. The parametric analysis, the intensity analysis and the moment tensor analysis of AE data were used to discriminate among different sources of damage. The technique shows promise for field application and may contribute to fully understand the structural mechanism in the rebar/adhesive/concrete systems.

Keywords Anchor rods · Pullout tests · Acoustic emission · Parameter analysis · Moment tensor · Intensity analysis

1 Introduction

Epoxy adhesive anchor systems are widely used in civil engineering to anchor both threaded rods and reinforcing bars into hardened concrete. Common applications include bridge widening, structure-mounted signs, luminaries and light poles, concrete repair and rehabilitation, and tunneling finishing. The recent collapse of a section of a suspended concrete ceiling of the Interstate 90 connector tunnel in Boston due to a poor creep resistance of the epoxy resin and a general lack of understanding the effects of creep in epoxy adhesive anchor systems [1] has demonstrated the importance of develop an in-situ nondestructive method to monitor such structural systems.

Anchors can be divided into two general groups: cast-in-place and post-installed. A typical cast-in-place anchor consists of a rebar in concrete with or without protective coating. Instead a post-installed anchor is made of a rebar installed in a hole and then bonded with a chemical or a nonchemical agent. Bonded anchors utilizing nonchemical agents are often called “grouted anchors”. To evaluate the structural strength of anchor systems the destructive method of “pullout test” is commonly used. Using this test, the force needed to pull out an anchor is estimated.

To perform in-situ evaluation of epoxy bonded anchors, nondestructive evaluation (NDE) methods are necessary. To the best of the authors’ knowledge, no literature is available about NDE of epoxy bonded anchor systems. Typically, previous works focused on rebar/concrete systems. Cheng and Chiou [2] and Lin et al. [3] used pullout tests and impact-echo method to estimate the bond-loss at the interface between steel bars and concrete. Ghandehari and co-authors [4] used speckle laser interferometry to monitor the displacements at the concrete/rebar interface and to measure crack length and crack opening during a pullout test.

Video
microscopy was used by Söylev and François [5] during the pullout test of bars from concrete column elements. X-rays are used to visualize the failure in a pullout test of cable bolts and rock bolts [6]. Raman spectroscopy was applied by Pisanova et al. [7] to monitor the crack length during the pullout of glass fibers or aramid fibers from epoxy. The active method of guided ultrasonic waves was numerically and experimentally investigated by Beard et al. [8] and Beard and Lowe [9] to detect the presence of damage in rebars embedded in concrete. The passive method of acoustic emission (AE) was applied to pullout tests in the bar/concrete systems [10–13]. For instance, Balázs et al. [10] discussed AE results obtained in monotonic loading, cyclic loading and long-term loading of rebars embedded in concrete cubes and also subjected to a pullout load.

In this paper, the results of experimental pullout tests conducted on post-installed, chemically bonded anchors are presented. Each anchor consisted of a rebar chemically bonded to a hardened concrete cylinder by means of polyester resin. The specimens were monitored using an AE suite instrumentation. In the light of the previous researches, the main objective of the present paper is to demonstrate the use of AE for failure monitoring of adhesively bonded anchor rods. By attributing each emission to a particular source type or failure mode, the resulting different sources of damage can be discriminated.

Six pullout tests were performed. The AE data were analyzed using the parameter analysis [14–16], the intensity analysis [16, 17], and the moment tensor analysis [18–22].

It is demonstrated that by combining a few different AE approaches, it is possible to discriminate between different sources of damage in adhesively bonded anchor systems.

2 The Pullout Test: Generalities and Failure Modes

The pullout test measures the force required to pull an embedded bar from a concrete specimen or a given structure [23].

While in the cast-in-place anchors the load is transferred into the concrete at the anchor head, in adhesive anchors, the load is transferred from the steel through the adhesive layer along the bonded surface. The bond at the interface consists of three mechanisms: adhesion, friction, and mechanical interlocks.

In pristine conditions, the bond between steel and the adhesive medium or concrete is due to the chemical adhesion. Once the chemical connections fail and relative displacements occur between the two surfaces the friction forces would dominate. If debonding takes place around the rebar surface, the ribs govern the stress-deformation behavior. When the resin between the ribs is subjected to a shear force, its deformation creates a bar-resin mechanical interlock dependent on the ribs’ geometry. The inclined shape of the ribs is therefore subjected to a force orthogonal to the ribs’ surface which turns into a reaction acting on the resin or concrete.

When the rebar is cast-in-place without coating, at the early stages of a pullout test, inclined cracks (theoretically at 45°) start to appear due to pure shear stress in the concrete which yields to tensile and compressive stresses along the principal directions. When the load increases, the horizontal component of the reaction force represents an increasing radial force that, for large slip values, promotes the development of longitudinal cracks. This mode of failure is usually referred to as a splitting failure.

Rebars chemically bonded offer higher limit stress with respect to the cast-in-place systems. Such systems are prone to one of the following failure modes [24, 25]:

1) an anchor steel failure characterized by yielding or fracture of the steel;
2) a concrete cone failure occurring when the embedment’s depth is less than 50 mm and the concrete is unconfined;
3) a bond failure at the bar/resin or resin/concrete interface;
4) a combined cone-bond failure usually in unconfined concrete and an embedment depth greater than 50–100 mm.

These failures are schematized in Fig. 1. The occurrence is dependent upon boundary and anchoring conditions, the bonding agent and the materials involved, the surface roughness, the temperature, and the loading gradient [24, 25].

3 Acoustic Emission

AE method exploits the propagation of transient elastic waves generated by the rapid release of energy from a localized source or sources within a specific material. The elastic energy propagates as a stress wave (AE event) in the structure and is detected by one or more AE sensors. AE events may be generated by moving dislocations, crack onset growth and propagation, fiber breaks, disbands, plastic deformations, etc.

Fig. 1 Failure modes during a pullout test for unconfined concrete: (a) steel failure; (b) concrete cone failure; (c) bond failure; (d) combined cone-bond failure