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Using electric response to mechanical impact for evaluating the durability of the GFRP-concrete bond during the freeze-thaw process

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A B S T R A C T

The paper proposes a contactless method for assessing the durability of the bond between glass fibre-reinforced polymer (GFRP) rebar and concrete under cyclic freeze-thaw conditions. The method is based on measuring the electric response to mechanical impact. Time- and frequency-related features of the measured signals are examined in a series of experiments with an increasing number of freeze-thaw cycles. The results of the theoretical and experimental studies of the electric response parameters under changing conditions of the rebar-concrete interface are presented. The experimental results demonstrate that the proposed method can be used to monitor the behavior of the rebar-concrete bond. The comparison of the proposed method with the acoustic method shows the former's higher sensitivity.

1. Introduction

Constructions of reinforced concrete are typically subjected to static and dynamic mechanical loads and significant seasonal variations in temperature and humidity. Cracks developing in concrete due to these factors may ultimately lead to a structural failure. In colder climates, the damage inflicted upon concrete by the freeze-thaw processes becomes a major problem. Fibre reinforced polymer (FRP) has been increasingly used as an alternative to steel rebar in reinforced concrete elements. The growing popularity of FRP rebar owes itself to FRP's corrosion resistance and high strength-to-weight ratio in comparison to conventional steel reinforcement [1]. However, non-metallic reinforcement has some drawbacks related to the lack of thermal compatibility between concrete and FRP. Due to the difference between the transverse thermal expansion coefficients of FRP rebar and concrete, a temperature increase produces radial pressure at the rebar-concrete interface, which results in tensile stresses within the concrete. These stresses may cause a local degradation of the FRP-concrete bond, a major contributor to the general performance of reinforced structures.

The bond behavior has been extensively examined in a series of short-term pullout tests. The rebar-concrete bonding mechanisms have been investigated [2,3], and the influence of the concrete strength and different rebar surfaces, types, and dimensions upon the parameters of the bond has been studied [3–10]. The GFRP-concrete interface has been also examined during long-term exposure to freeze-thaw action under a constant mechanical load [2,11]. Deformation behavior of concrete beams with different types of reinforcement has been investigated [12,13]. When exposed to natural conditions, GFRP-concrete structures gradually wear out, and currently there is no simple and reliable method for assessing the damage naturally occurring in GFRP-concrete constructions. The development of such a damage identification method would contribute to safer performance and longer life of concrete constructions. Specifically, a method to detect and characterize GFRP-concrete construction damage using nondestructive testing would be of great interest to practicing engineers. Standard methods of damage detection in concrete include acoustic emission [14–17], ultrasonic testing [18–20], nonlinear acoustic methods [21,22], and impact echo methods [23–25]. In recent years, many researchers have been working on the development of contactless ultrasonic methods [26,27]. Other studies [28,29] have been concentrating on registering the characteristics of surface waves in concrete using a laser. However, the methods based on measuring surface waves are not sensitive to deeper cracks. In addition, rough surfaces tend to scatter surface waves, which

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lowers the quality of observation when monitoring and detecting cracks in concrete.

We propose a damage detection method based on the characteristics of the electric response that occurs in concrete as a result of mechanical impact [30,31]. This article is a continuation of the previous studies and examines possible criteria of evaluating the rebar-concrete bond strength.

2. Materials and methods

2.1. The method of mechanoelectric transduction

The mechanoelectric transduction method consists of subjecting the object of the study to an elastic impact, which produces an acoustic wave propagating through the object's material. The wave causes deformation and displacement of electric double layers at the boundaries of the concrete components as well as polarization of piezoelectric quartz contained in sand and gravel. The electric response to mechanical impact is the sum of these effects. Previous studies have established that piezoelectric inclusions play a decisive role in mechanoelectric transductions within concrete [32]. The X-ray diffractometer ARL X'TRA has been used for determining the phase composition of sand and gravel. According to the results of structural X-ray testing, the content of piezoelectric quartz in the concrete's sand reaches 90–95%. The phase composition analysis of the gravel used for manufacturing heavy concrete has not found any grains without quartz [33]. The proportion of grains made up completely of quartz reaches about 20%. During the development of control methods, we have used the diagnostic parameters invariant to the differences in the samples' quartz content [30]. Piezoelectric inclusions are deformed by mechanical stresses created by the acoustic wave near their location. As a result, their polarization occurs, creating an electric field, which becomes the source of a signal detected by an external electric sensor. On the surface of a receiving electrode, free charge carriers appear, induced by the electric field, and a current begins to flow through the input impedance of the measuring circuit (Fig. 1).

The value of the registered voltage from a single piezoelectric source is determined by:

$$U(t) = \varepsilon_0 \varepsilon \frac{\partial E(t)}{\partial t} \mathrm{RS}_d \quad (1)$$

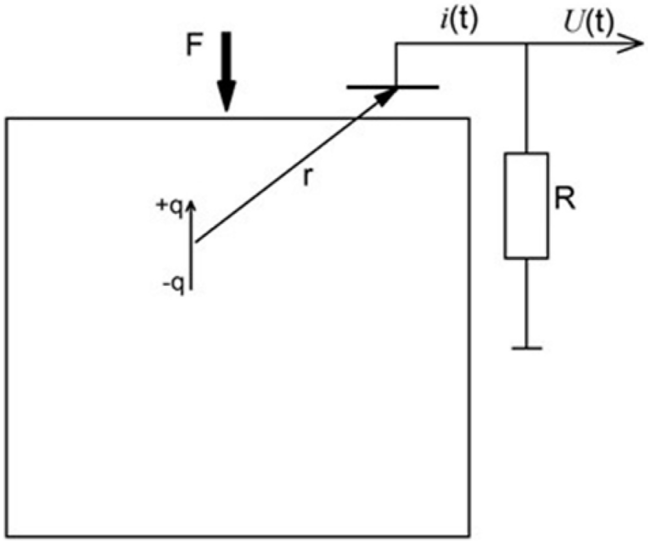

Fig. 1. Measuring circuit.

where R is the input impedance and S_d is the surface area of the receiving electrode. Using classical electrodynamics and mechanics relations, a model of mechanoelectric transductions in heterogeneous materials containing piezoelectric inclusions has been developed [34]. The rate of change of the electric field due to an acoustic excitation of piezoelectric sources has been calculated as follows:

$$\frac{\partial E(t)}{\partial t} = \frac{\mathrm{dSMl}_P}{4\pi\varepsilon_0 \varepsilon L} \frac{V_y(t)}{r^3(t)} \left(\frac{3h^2}{r^2} - 1 \right) \quad (2)$$

where M is the elasticity modulus; L is the model size in the direction of excitation; $V_y(t)$ is the displacement rate in the direction of excitation; h is the depth of the piezoelectric source position; r is the distance from the source to the receiving electrode; l is the thickness of the piezoelectric quartz crystals; d is the piezoelectric modulus of quartz; and S is the sample cross-sectional area.

A simple substitution gives the value of the measured voltage from a single source as follows:

$$U(t) = \frac{\mathrm{dSMl}_P}{4\pi L} \frac{V_y(t)}{r^3(t)} \left(\frac{3h^2}{r^2} - 1 \right) \cdot \mathrm{RS}_d \quad (3)$$

Thus, the voltage is proportional to the displacement rate of the piezoelectric source affected by elastic waves.

Mechanical stresses that occur at the rebar-concrete interface subjected to cyclic freeze-thaw action lead to development of radial cracks within a limited area around the rebar. The increasing number of freeze-thaw cycles results in an increase in the size and concentration of the cracks within the zone of damage as compared with the undamaged zone of the sample. Passing through these different zones, the acoustic wavefront gets distorted, which should affect the characteristics of the electric response according to the formula (3).

At the moment of mechanical impact, the pressure is applied to a small impact area on the surface of the sample. Then it spreads further in, passing into the structure in the form of hemispherical wavefronts, which are also reflected back from the external boundaries of the sample. The waves reflected from the free surfaces spread back into the sample and are reflected from the external boundaries again. As a result, a vibration process develops in the sample. Reflected from the lateral surfaces, the initial spherical wave causes the formation of secondary and subsequent waves in the sample, transmitted at different angles, resulting in a complex wave pattern within the sample.

Objects made of concrete contain a large amount of quartz inclusions with varying directions of piezoelectric axes. The total electric field in the observation area is the sum of all vectors of the fields generated by all sources. Therefore, the electric response can reliably reflect the nature of the transformations the acoustic wave undergoes while passing through the defects of various shape and orientation. In conventional acoustic methods, the piezoelectric sensor detects waves propagating in a direction perpendicular to its own front surface. As a result, the acoustic image does not register the cracks which are perpendicular to the front of the sensor. Consequently, the proposed method is more sensitive to cracks of various spatial orientation and/or complex shape. These types of defects frequently occur in concrete during cyclic freeze-thaw processes.

The electric sensor has no physical contact with the sample. As a result, the surface effects play no role in the measurement of the electric response. Conversely, the signals from a standard ultrasonic transducer are strongly influenced by the surface state of the sample and by the acoustic noise generated in the area of contact between the transducer and the sample. Therefore, the proposed