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Guided ultrasonic waves for detection of debonding in bars partially embedded in grout

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HIGHLIGHTS

- Guided wave propagation in ground anchors with pre-existing debonding is considered.
- The influence of debonding length and its position on wave propagation is analysed.
- The average velocity of wave propagation in the whole anchor can be used to determine the damage length.
- Debonding with relatively small size can be efficiently detected by guided waves.

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ABSTRACT

This paper deals with theoretical, numerical and experimental investigations of guided wave propagation in multilayered cylindrical bars with pre-existing debonding. The research focuses on a complex description of the nature of the wave phenomena occurring in a debonded specimen with a special emphasis on the influence of the location of damage on the wave conversion and diffraction. Experimental non-destructive and destructive tests are conducted on the laboratory models of ground anchors with a variable debonding length and location. Debonding is simulated by wrapping the bar in the cellophane film with very small thickness, providing indirect contact between steel and grout but reducing grout adhesion to steel. Guided waves are excited and measured at the free end of the bar with the use of piezo actuators. Characteristic reflections are identified in signals registered for anchors with three locations of debonding and five debonding lengths. The obtained results show that despite of such small thickness of debonding (60 μm), guided waves may be used as an effective method for detection of adhesive debonding at an early stage of its development.

1. Introduction

Rebar reinforced concrete is a material commonly and widely used for civil engineering structures. Steel inserts in the form of bars, wires, strings, cables and nets can be used as the reinforcement in complex structures like bridges, dams, silos or buildings. A special case of relatively simple reinforced concrete structures made of a steel bar embedded in concrete is ground anchors or soil nails which are commonly used in geotechnical structures to improve the slope stability and sustain excavation or embankment slopes. Anchors and nails are performed by placing a steel bar or a tendon in a pre-drilled hole in the ground and injecting cement or resin grout which forms an anchor body. Ground anchors can be additionally pre-stressed while soil nails play the role of passive support systems. Both types of structures are adapted to transmit tensile and shear forces from the bar through the bar/grout interface to the surrounding ground. Thus the bond between a tendon and grout is a critical aspect of the anchor load capacity and a proper load transferring. Since interface damage can be a potential threat to proper operation, the analysis of effects of debonding between the bar and grout has been investigated to improve the reliability and safety of ground anchors. Benmokrane et al. [1] presented a study of the behaviour of cement-grouted ground anchors subjected to tensile loading. Strains were measured by vibrating-wire gages welded at certain intervals to the surface of a steel bar. Then, three types of tests including loading and unloading test, creep test and long-term test were conducted and the load distribution along the anchor length was monitored. An analytical model of rock bolts subjected to tensile load was developed by Ma et al. [2]. They presented derivations for the distribution of shear stress at the bolt–resin interface. The model was evaluated

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in laboratory pull-out tests on the example short encapsulation bolts. Ivanović and Neilson [3] proposed a model describing static and dynamic effects of debonding in terms of static load distribution and dynamic response to transient loading. The influence of pre-existing debonding in ground anchors on the load carrying capacity was examined in pull-out tests by Akisanya and Ivanović [4].

In recent years, there has been growing interest in the use of non-destructive testing methods for condition assessment of ground anchors. The two main groups of diagnostic techniques include vibration methods and wave propagation methods. In vibration-based methods, impulse or harmonic excitation responses in the frequency domain can be used for the load monitoring (e.g. [5,6]). Such excitation methods have a potential to be advanced and potentially altered to estimate the total length of an anchor [6]. In the case of wave propagation methods, the evaluation of the condition of anchors can be performed using low and high-frequency modes. The low-frequency modes enable to identify a free length of an anchor or surface defects while the high-frequency modes can be used to identify the total length of an anchor [7]. The previous works indicate a large potential of the use of guided waves in diagnostics of ground anchors, especially in assessing of effects of insufficient rebar and missing grout [8,9], the identification of a free length of an anchor [10], the evaluation of grout quality [11,12] or identification of basic geometric parameters [13]. However, the number of studies on the application of guided waves for detection of debonding between steel and concrete is limited. Na et al. [14] considered a steel bar embedded in a rectangular block of concrete with 0%, 25%, 50% and 75% delaminated interface situated at one end of the bar. Lamb wave measurements were performed by the pitch-catch method using a transmitter and receiver placed at both ends of the bar or the concrete block. Concrete beams with a steel reinforcing bar embedded in the middle of the beam were investigated by Wu and Chang [15,16]. Debonding of different lengths was introduced at the centre part of the beam. Eight PZT actuators and sensors were mounted on the bar surface, then the changes in the signal amplitude and time of arrival were monitored. It was observed in experiments, that the amplitude of wave propagation signals increases with the increased debond length, however, there were no significant changes in the time of signal arrival [15], which was then confirmed by FEM simulations [16]. Zima and Rucka [17] applied guided wave for the assessment of adhesive bonding in double-layer cylindrical specimens consisted of a steel bar embedded in concrete. They investigated numerically the influence of a bonding length on the excitation of multiple modes of longitudinal guided waves.

This paper deals with guided wave propagation in a steel bar partially embedded in grout. The first part of the study is devoted to theoretical and numerical investigations of longitudinal guided modes in multilayered cylindrical bars with pre-existing debonding, including the influence of debonding location and its length on the separation of modes, their conversions and diffractions as well as the average wave velocity. The second part of the paper presents experimental results of both non-destructive testing using guided waves and destructive pull-out tests conducted on laboratory models of ground anchors with variable debonding length and location. Three locations of debonding and five debonding lengths are considered. In previous experimental research debonding between the core and cladding was simulated by the use of a section of a PVC pipe around a bar what completely separated the bar and concrete (e.g. [13,15]). However, real debonding can have significantly smaller size, especially in the case of the progressive deterioration of bond. Therefore, in this study debonding is performed by wrapping the bar in the cellophane film with very small thickness. The presented approach provides indirect contact between steel and grout but significantly reduces grout adhesion to steel and consequently, there is no continuity of stresses and displacements on the contact layer which is the basic assumption in the model of wave propagation in multilayered specimens. Despite such small thickness of debonding, guided waves appeared to be extremely sensitive in detection of defects in adhesive bonding. The high sensitivity of guided waves for detection of debonding was confirmed by results of pull-out tests for a fully debonded specimen. The obtained results revealed that guided waves may be used as an effective method for detection of adhesive debonding in the early stages of its development.

2. Theoretical background of guided wave propagation in cylindrical waveguides

The investigations conducted in this paper are focused on the guided wave propagation in a steel bar partially embedded in the grout (Fig. 1c) with a particular emphasis on the debonding between steel and grout. The wave excited along a free bar results in propagation of the particular number of longitudinal modes in a single waveguide. When the wave reaches the part embedded in grout, the propagation in a multilayered waveguide occurs. The novel element of the paper is a complex description of the nature of the wave phenomena occurring in a debonded element with a special emphasis on the influence of the location of damage on the wave conversion and diffraction. The study includes the derivation of relationships between average velocities of particular modes and the debonding length (Sections 2.2 and 2.3). Moreover, a short background for the longitudinal wave propagation in a single waveguide (Fig. 2a) and a multilayered waveguide (Fig. 2b) is recalled in Section 2.1.

The derivations presented in this section are related to the case of dispersion curves for a 1 cm steel bar embedded in grout with a thickness of 17.5 mm formed in a PVC pipe with a thickness of 2.5 mm, however, in general, they are valid for any case. Similar theoretical investigations for undamaged ground anchors made of different materials and with different geometric parameters can be found in [13]. In this study, the excitation frequency is 60 kHz to induce multimode propagation and to make the observation of the mode conversion possible. For the selected value of frequency, one mode can propagate in the free bar and two modes with different velocities can propagate in the three-layer part of the specimen. Beside considerations based on dispersion curves, results of finite element method (FEM) simulations performed in Abaqus/Explicit programme are presented. The numerical results are given in the form of snapshots illustrating the magnitude of acceleration and the deformation of the specimen at selected time instants.

Due to the fact that the work relates mainly to ground anchors, the anchor body borders only with the surrounding soil which is

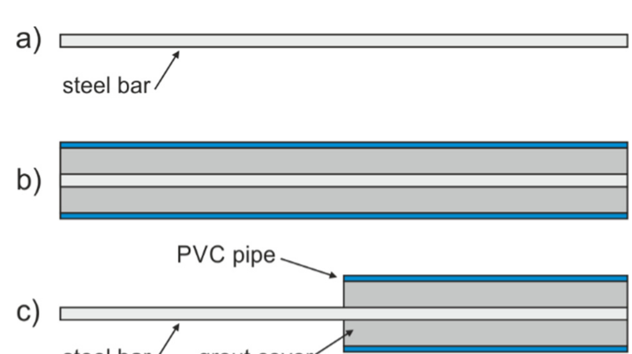

Fig. 1. Schematic diagram of cylindrical waveguides: (a) free bar; (b) fully embedded bar; (c) partially embedded bar.