

ACOUSTICAL LETTER

Non-contact alignment-free soundness evaluation of adhesive anchors by exciting/detecting longitudinal bolt vibrations using electromagnetic acoustic waves

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(*Received 15 December 2016, Accepted for publication 8 February 2017*)

Keywords: Non-contact evaluation, Electromagnetic acoustic waves, Adhesive anchors, Longitudinal bolt vibrations

PACS number: 43.35.Zc [doi:10.1250/ast.38.225]

1. Introduction

Adhesive anchors are widely used in civil engineering applications, particularly to anchor the bolts of illuminators and ventilators in tunnels. The evaluation of the soundness of these anchors is essential to structural safety. Conventionally, their soundness has been evaluated based on visual inspection and hammering tests performed by skilled workers. Meanwhile, certain non-destructive methods of testing adhesive anchors have also been developed. In one method, flexural and longitudinal vibrations of bolts are excited with the use of an electromagnetic acoustic transducer (EMAT) and then measured with a laser Doppler vibrometer (LDV) [1]. In another method, the leakage vibrations at the concrete surface are measured by means of an acoustic emission (AE) sensor [2]. The AE induced by damage progression has also been detected by AE sensors [3]. Furthermore, echoes of the guided waves directed to bolts excited with a piezoelectric transducer have been shown to be useful in evaluating the anchor soundness [4–6]. However, in all these previous methods, either contact with the target under test or precise position alignment of the evaluation system is indispensable.

The use of an EMAT [7,8] enables not only non-contact excitation but also non-contact detection of vibrations [9,10]. When a dynamic magnetic field is applied to a conductive material placed under a static magnetic field, the material undergoes vibrations due to the Lorentzian force experienced by eddy currents induced on the material surface. Therefore, the application of a periodical dynamic magnetic field can be utilized to excite the vibration of the material. The detection of vibrations can be performed through the reverse process, namely, when a vibrating material is placed under a static magnetic field, eddy currents are generated on its surface, thereby inducing a detectable dynamic magnetic field.

To date, various configurations of EMAT-based non-contact ultrasonic inspection systems have been implemented [1,9–14], because they do not require coupling agents (which lead to contamination) or smoothing fabrication; further, such systems can operate at high temperatures. A major drawback of EMAT-based systems is their low signal intensity. The signal-to-noise ratio in such systems has been improved by sweeping the exciting frequency and thus exploiting acoustic resonance [15].

In this work, based on this resonance-based technique, we implement a new EMAT-based system for non-contact evaluation of the soundness of adhesive anchors, wherein we use the EMAT to both excite and detect longitudinal vibrations of bolts. This configuration does not require precise position alignment of the EMAT system, which will be of great use in practical applications. We investigate the influence of the amount and degradation of adhesive on the resonance frequency and the quality factor.

2. Experimental setup

Figure 1(a) schematically shows the cross-sectional view of the EMAT used in the experiment. The EMAT (diameter: 40 mm, length: 17 mm) consists of three ring-shaped neodymium magnets, a steel yoke, an exciting coil (30 turns, self-inductance: 12 μH), a receiving coil (30 turns, self-inductance: 11 μH), and an acrylic bobbin. The self-resonant frequencies of both the coils are over 4 MHz, below which no impedance peaks or dips exist. The interval between the bolt and the coils is approximately 0.5 mm. The steel stud bolt touches neither the yoke nor the coils; it touches the acrylic bobbin, which appears to have almost no influence on the measurement results. As the EMAT is fixed to the bolt using a magnetic force, precise alignment is not required. When an alternating current is applied to the exciting coil, an alternating magnetic field is generated, thereby inducing an eddy current on the surface of the bolt. Due to the Lorentzian force arising from the interaction between the static magnetic field and the eddy current, longitudinal vibrations of the bolt are excited, and as regards detection, an eddy current is generated on the surface of the bolt as it vibrates under the static field. The resulting change in the magnetic field caused by the eddy current is detected with the use of the receiving coil.

Four M8 steel stud bolts (length: 100 mm) were fixed using adhesive (solidified; employed at the bottoms of the holes; EA-500S, Asahi Kasei) in the holes (diameter: 9 mm, depth: 70 mm) of four concrete blocks (diameter: 100 mm, height: 250 mm). The amount of the adhesive utilized for the four samples was varied as 1.15, 2.30, 4.50, and 4.50 g (4.50 g corresponds to completely filled holes). The adhesion of one

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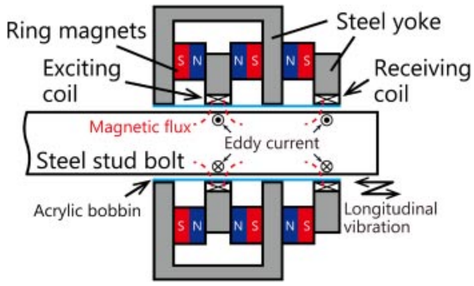
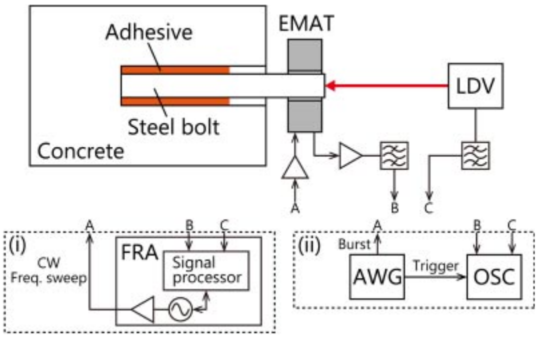
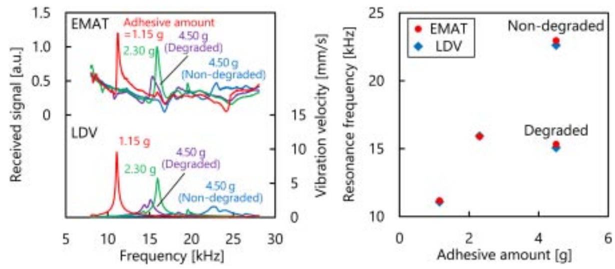


(a)



(b)

Fig. 1 (a) Schematic cross-sectional view of EMAT utilized for exciting and detecting the longitudinal vibrations of a steel stud bolt. (b) Experimental setup for measuring (i) frequency dependences and (ii) damping characteristics of the bolt vibrations. AWG, arbitrary waveform generator; EMAT, electromagnetic acoustic transducer; FRA, frequency response analyzer; LDV, laser Doppler vibrometer.



(a) (b)

Fig. 2 (a) Frequency dependences of the received electromagnetic acoustic transducer (EMAT) signal amplitude and the laser Doppler vibrometer (LDV)-measured vibration velocity. (b) Resonance frequencies of the EMAT-based and LDV-based results plotted as functions of the amount of adhesive.

of the 4.50-g samples was artificially degraded by means of the following procedure: 1) after the bolt was fixed, it was inductively heated and maintained at 220°C for 2 h, 2) the bolt was cooled by air to room temperature, and 3) processes 1) and 2) were repeated again (See Appendix for details) [16–19].

The measurement setup is depicted in Fig. 1(b). First, with the use of configuration (i), we measured the frequency characteristics of the longitudinal vibrations of the bolt and determined the first-order resonance frequency. Continuous waves output from a frequency response analyzer (FRA; FRA5097, NF) were amplified by 26 dB (peak-to-peak voltage: 8 V) and input to the EMAT. The received signal from the EMAT was amplified by ~70 dB, filtered with a bandpass filter (BPF, 1–100 kHz), and observed with the same FRA. The frequency of the continuous waves was swept from 8 kHz to 28 kHz with a step of 32 Hz over a ~20-s period (which can be set to values less than even 1 s in practical applications). To confirm the validity of this measurement, we also directly measured the vibrations of the bolt using an LDV and a BPF (1–100 kHz). Subsequently, using configuration (ii), we derived the damped oscillations of the longitudinal vibrations of the bolt at the first-order resonance frequency and calculated the quality factor. The burst waves output from an arbitrary waveform generator (AWG) were amplified by 26 dB (peak-to-peak voltage: 8 V) and input to the EMAT. The received signal was amplified by ~70 dB, filtered using a BPF (10–100 kHz), and observed with an oscilloscope (OSC). An LDV-based measurement was also performed for verification.

3. Experimental results

The frequency dependences of the received EMAT signal amplitude and the LDV-measured vibration velocity are shown in Fig. 2(a). The EMAT signal was divided by the frequency-dependent gain of the amplifier to "flatten" the data. With increasing adhesive amount, the signal amplitude of the resonance peak in the EMAT decreased, which was the same trend as the vibration velocity of the LDV-measured resonance peak. The obtained resonance frequencies are valid because the first-order resonance frequency of a 100-mm-long steel bar (longitudinal sound velocity: 5,120 m/s [20]) under a fixed-free boundary condition is calculated to be approximately 10.3 kHz. Figure 2(b) shows the resonance frequencies of the EMAT-based and LDV-based results (calculated as the frequencies at which maximal peaks were observed in Fig. 2(a)) plotted as functions of the amount of adhesive. With increasing amount of adhesive, the resonance frequency increased. Further, heat-induced degradation was found to reduce the resonance frequency. The measurement error between the EMAT-based and LDV-based results was 1.68% at maximum, which indicates that the EMAT-based measurement is highly reliable.

Figure 3(a) shows an example (for an adhesive amount of 1.15 g) of the temporal variations in the received EMAT signal amplitude s and the LDV-measured vibration velocity v when the excitation of the vibration was abruptly stopped. The vibration was stopped by setting the voltage applied to the exciting coil to 0 V, and the corresponding instant of time was defined as 0 s. After 0 s, the amplitude of the EMAT signal decayed exponentially, which agreed with the behavior of the vibration velocity. The received EMAT signal was found to be influenced by the current that continues flowing in the exciting coil shortly after stopping the vibration. In order to remove this influence, we calculated the exponential fits of the

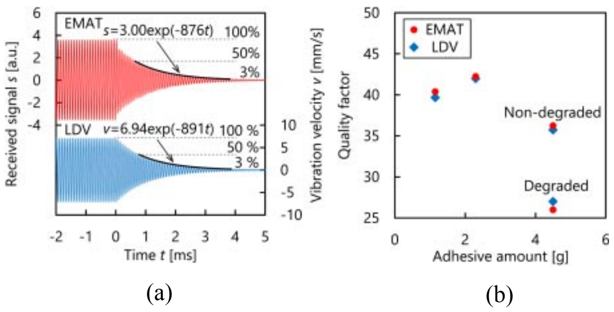


Fig. 3 (a) Temporal variations in the received EMAT signal amplitude and the LDV-measured vibration velocity when the excitation of the vibration was abruptly stopped. The adhesive amount was 1.15 g. (b) Quality factors of the received EMAT signal amplitude and the LDV-measured vibration velocity plotted as functions of the amount of adhesive.

maximal points of the measured results (while the amplitude became 50% to 3% of that during excitation). Subsequently, the quality factor Q was calculated as [21,22]

$$Q = -\frac{\omega_0}{2a}, \tag{1}$$

where a represents the coefficient of t (time) in the exponential fits (-876 for the EMAT and -891 for the LDV in Fig. 3(a)) and ω_0 the angular resonance frequency. Figure 3(b) shows the quality factors of the received EMAT signal amplitude and the LDV-measured vibration velocity plotted as functions of the amount of adhesive; the quality factor is nearly constant irrespective of the amount of the adhesive, but the heat-induced degradation lowers the quality factor. The EMAT-based and LDV-based results were in good agreement with each other with an error of $<3.72\%$. Our results suggest that the shortage of adhesive arising from shoddy workmanship and the aging degradation of adhesive can be potentially evaluated using the resonance frequency and the quality factor, and that these parameters can be detected by a non-contact electromagnetic method without using an LDV. Note that some other samples with similar structures were also tested, and the measured results exhibited almost the same trends, which supports the reliability of the conclusion.

4. Conclusion

We developed a new non-contact method for evaluating the soundness of adhesive anchors. The longitudinal vibrations of bolts were both excited and detected with the use of an EMAT. As the amount of adhesive increased, the resonance frequency also increased, but the quality factor remained nearly unchanged. Meanwhile, heat-induced degradation of the adhesive lowered both the resonance frequency and the quality factor. As our configuration does not require precise position alignment, we believe that this method will be of great potential use in evaluating shoddy construction and the aging degradation of adhesive anchors in the near future.

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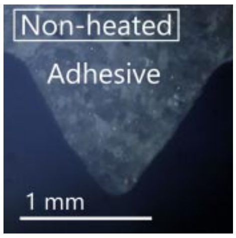
Appendix

The heat-induced degradation of the adhesive appears to originate from the degradation of the material itself [16–18] as well as from cracks/chips caused by the mismatch between the thermal expansion coefficients of the adhesive and the steel [19]. Here, we examine how the adhesive used in experiment was degraded by heating after bolt fixation. We prepared two 48-mm-long hexagon bolt (M12) samples. Adhesive (EA-500S) was attached to each sample on its end side to a "depth" of 30 mm. One of the two samples was heated at approximately 200°C for 1 h and then air-cooled to room temperature. Subsequently, the adhesives of the two samples were broken in half (Fig. A.1(a)), and the boundaries between the adhesives and the bolts were examined with a microscope. Unlike the case of the non-heated sample (Fig. A.1(b)), a number of chips were observed in the heated sample (Fig. A.1(c)), which can be interpreted as heat-induced degradation.

(a)



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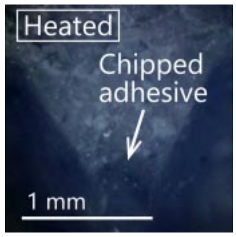

(c)

Fig. A.1 (a) Photograph of the bolt and adhesives. (b, c) Micrographs of the boundaries between the adhesives and bolts of the non-heated and heated samples, respectively.