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Piezomagnetic effect of steel bars in cement composite structures
セメント構造物内の鉄筋の圧磁効果測定

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1. Introduction

Steel bars in reinforced concrete (RC) structures enhance the resistance to the tensile stresses in cement-based composites. The strength, however, is significantly reduced when cracks spread around the steel bars due to the corrosion and expansion. Although the position of steel bars can be detected by ultrasonic inspection or radar tomography,[1)] no direct survey technique for the earlier-stage steel corrosion is established. Usual inspection is currently by visual check or hammer testing. The degradation is thus found only after cracks developped and reached to the surface.

For nondestructive remote inspection of steel corrosion, we focus on the difference in magnetic properties between corrosion products (magnetite, etc.) and host material (steel). Recently, a novel method to measure the magnetic properties of steels via acoustically stimulated electromagnetic (ASEM) response is demonstrated.[2-5)] The principle of this technique is based on the generation of alternating electromagnetic fields induced through the magnetomechanical coupling.

In this work, we propose how to obtain the ASEM signals from steel bars embedded in cement composite structures and demonstrate the magnetic hysteresis measurements in test pieces. Additional ingenuities are required: ultrasonic waves propagate faster with significant attenuation in cement than in the aqueous medium and it makes more difficult to separate the weak signals from tranceducer noises.

2. Experimental techniques

Schematics of test pieces and measurement setup are shown in Fig.1. The test piece consists of mortar (consisting of water, cement and sand) and a round steel bar (16 mm-diameter, SR235). Two test pieces, TP-A and TP-B, are prepared with different covering depths of 120 mm and 50 mm, respectively. Pulsed ultrasonic waves are generated by a transducer (500 kHz, KGK) with a pulsar-receiver (900 V, OLYMPUS 5058PR). The ASEM response is detected by a ferrite rod antenna tuned to the frequency of ultrasonic waves.

One of the key techniques in the ASEM method is to avoid the pulsed electromagnetic noise generated on the transducer. When a target piece is placed at a distance of d from the transducer in an acoustic medium with sound velocity v, the ASEM signal, $I_{\mathrm{sig}}(t)$, will be generated with a time delay of $\tau_{\mathrm{ASEM}} = d/v$ while the noise associated with the ultrasonic excitation and the echo is emitted from the transducer at $\tau = 0$ and $\tau_{\mathrm{echo}} = 2\tau_{\mathrm{ASEM}}$, respectively. To temporally separate the ASEM signals from the transducer noise, we need to carefully tune the distance d.

Figure 1 (a) shows a setup using TP-A, where the distance $d = 120$ mm is long enough to separate the ASEM signals from the noise generated on the transducer, where v is about 4000 m/s in the mortar. In this setup, the steel core of electromagnet is closely connected to both ends of the steel bar.

In the actual infrastructures, the covering depth of steel bars is typically 50 mm. We thus setup another scheme using TP-B as shown in Fig. 1(b). In this scheme, the ultrasonic waves are introduced with a wedge made of mortar. This avoids the direct reflection of ultrasonic waves at the interface between the wedge and the TP-B to the transducer, resulting in the absence of the corresponding transducer noise. Furthermore, considering the realistic situation, the external magnetic fields H are applied from the surface of the test piece in the setup using TP-B (Fig. 1(b)). In magnetic hysteresis measurements, the ASEM intensity $|\bar{I}_{sig}|$ is defined as

$$\left|\bar{I}_{sig}\right| = \int_{\tau_{\mathrm{ASEM}}}^{\tau_{\mathrm{ASEM}}+\Delta\tau} \left|I_{sig}(t)\right| dt \propto |d_{31}(H)| \ ,$$

where $\left|I_{sig}(t)\right|$ is the absolute value of signal current and $\Delta\tau$ is an integral time of 15 μs. The H -dependence of ASEM intensity (ASEM hysteresis curve) corresponds to that of the piezo-magnetic coefficient $|d_{31}(H)|$.[4)]

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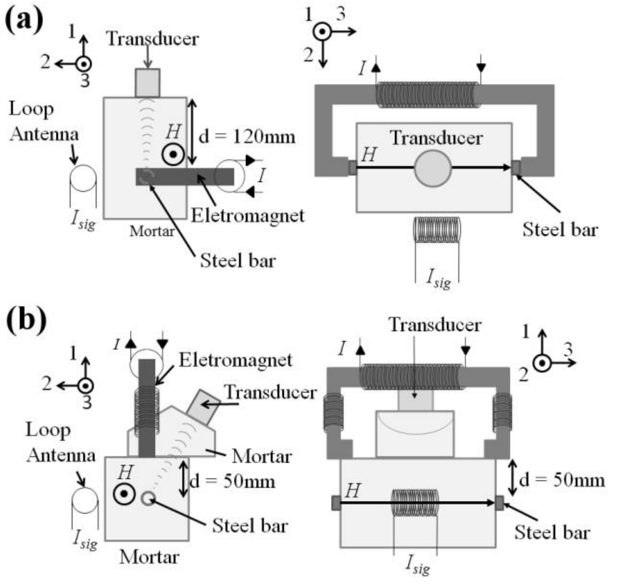

Fig. 1 Schematics of measurement setup using two type of test pieces; (a) TP-A and (b) TP-B.

3. Results and discussion

Figure 2(a) shows the hysteresis curves of ASEM intensity measured by using TP-A. The ASEM hysteresis curve has two minimum values around at $H_{\rm min} = \pm$ 0.4 kA/m, which indicates the de-magnetized condition.4) As shown in Fig. 2(b), the phase inversion of the pulsed waveform is found at $H_{\rm min}$, strongly supporting the above interpretation. As discussed in Ref. [4], the $H_{\rm min}$ observed in the hysteresis curve should correspond to the coercivity H_c in the standard magnetization (M)-field (H) curve. In the hysteresis curve shown in Fig. 2(a), however, the minimum is observed at the field polarities opposite to the conventional definition of H_c. Namely, the $H_{\rm min}$ is positive (negative) for the downward (upward) field direction.

One possible explanation of this unexpected feature is the effect of demagnetizing fields in steel bars with mill scale. At 500 kHz, the skin depth of electromagnetic fields in steel is estimated to be about a few ten micrometers. Because the thickness of mill scale is comparable to the skin depth, the magnetic properties of mill scale as well as those of the host material (steel) will contribute to the ASEM signals. The field on the surface of the steel bar may be largely modified from the external fields due to the demagnetizing fields of the composite ferromagnetic materials.

The similar results are obtained in the more realistic setup for actual applications (Fig. 3). The reduction of signal intensity is attributed to the smaller applied fields in this setup and the ultrasonic reflection at the interface between the wedge and the TP-B.

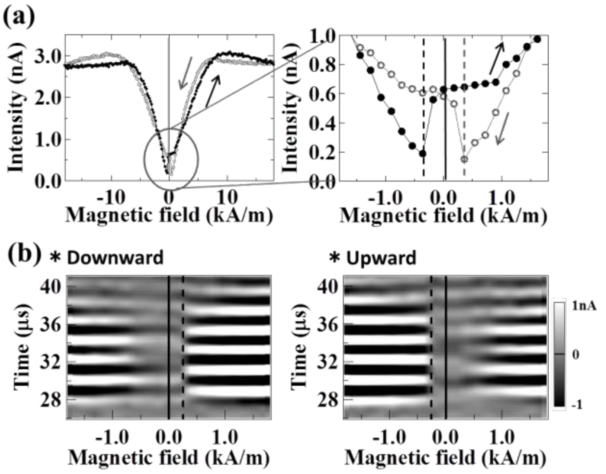

Fig. 2 ASEM response of the steel bar in TP-A. (a) Hysteresis curves of ASEM intensity. The initial magnetization curve is not shown here. The magnetic field is calculated from the current applied to the electromagnet ($H = nI$; the n is the number of turns per unit length). (b) ASEM waveform for the downward (left) and upward (right) field directions. The grayscale corresponds to $I_{sig}(t)$. The dashed lines show $H_{\rm min}$.

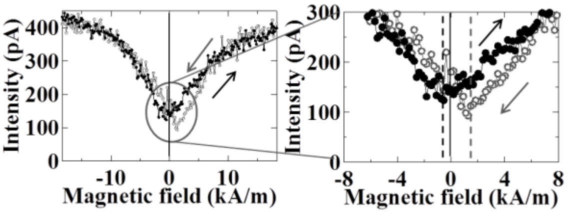

Fig. 3 ASEM hysteresis curve of TP-B measured by the setup in Fig. 1(b). Actual magnetic fields are smaller than horizontal values ($H = nI$). The dashed lines show $H_{\rm min}$.

4. Conclusion

We have demonstrated the measurements of piezo-magnetic effect of steel bars in cement composite structures via ultrasonic stimulation. The hysteresis properties including the demagnetizing states are nondestructively obtained.

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