Construction and Building Materials 67 (2014) 197–201

Contents lists available at ScienceDirect

Construction and Building Materials

journal homepage: www.elsevier.com/locate/conbuildmat

Evaluation of corrosion-induced crack and rebar corrosion by ultrasonic testing

Takeshi Watanabe [a,*], Huynh Thi Huyen Trang [b], Kazuki Harada [c], Chikanori Hashimoto [a]

[a] University of Tokushima, Department of Civil and Environmental Engineering, 2-1, Minami-Josanjima, Tokushima 770-8506, Japan
[b] Sumitomo Mitsui Construction Co., Ltd., 2-1-6, Tsukuda, Chuo-ku, Tokyo 104-0051, Japan
[c] Tokushima City Office, 2-5, Saiwaicho, Tokushima 770-8571, Japan

HIGHLIGHTS

- In order to detect rebar corrosion at early stage, ultrasonic testing is applied.
- The damage of concrete and cracking under an electrolytic corrosion test is estimated.
- Energy of waveform could recognize the attenuation of ultrasonic wave due to corrosion-induced cracking.
- Ratio of the propagation distance is characterized by the attenuation, which is correlated with damage of rebar corrosion.

ARTICLE INFO

Article history:
Received 21 January 2014
Received in revised form 18 March 2014
Accepted 9 May 2014
Available online 30 June 2014

Keywords:
Ultrasonic testing
Corrosion-induced crack
Rebar corrosion
Electrolytic corrosion test

ABSTRACT

Recently, the maintenance of concrete structures has become important for the sustainability of infrastructure. Steel-bar (rebar) corrosion is one of typical deteriorations to reduce the service life of concrete structures. Corrosion products of rebar cause cracking in concrete. When these cracks reach to the concrete surface, the damage of rebar corrosion is readily recognized by visual inspection. In this case, however the damage is referred to as the acceleration stage. In order to evaluate the performance of concrete members and structures, it is important to evaluate the corrosion of rebar as early as possible. Thus, the corrosion of rebar is often detected directly to remove cover concrete. In this concern, nondestructive evaluation is important to detect the corrosion and corrosion-induced cracking inside concrete at the dormant and the initiation stage prior to the acceleration stage. In the acceleration stage, it is important to detect the corrosion precisely and to evaluate the cracking of concrete.

In order to detect rebar corrosion at early stage, ultrasonic testing is applied. The damage of concrete and cracking under an electrolytic corrosion test is estimated.

1. Introduction

The corrosion of reinforcing steel-bar (rebar) is one of the typical deteriorations to reduce the service life of concrete structures. Half-cell potential method is, so far, one of popular non-destructive evaluation (NDE) to detect the corrosion [1]. This method can evaluate the possibility of rebar corrosion, while it cannot detect the corrosion rate and cracking in concrete directly. Recently, several NDE methods using elastic-waves have been studied to evaluate the corrosion damage of reinforced concrete. Acoustic Emission (AE) method is introduced to detect corrosion-induced cracking in concrete [2,3]. Impact-echo method is also employed to detect corrosion damage [4,5].

The ultrasonic method is one of elastic-wave methods. It is applicable to determine the uniformity of concrete, the depth of a surface crack, and so forth [6]. In Japan, the ultrasonic method is standardized as a test method for compressive strength and estimation surface-crack depth [7,8]. The method was extensively employed to detect defect in concrete [9], to recognize performance of self-healing of fly ash concrete [10], and to evaluate corrosion damage [11].

In this study, the ultrasonic test method is employed to evaluation the corrosion in rebar and corrosion-induced cracking, because the method has the advantage to be able to detect a minute change, by applying high-frequency elastic waves.

2. Experiment

2.1. Concrete prism for the dormant stage

Two specimens, which are labelled as C40-1 and C40-2, are prepared. These are concrete prisms of dimensions $150 \times 150 \times 300$ mm as shown in Fig. 1. A deformed steel-bar of nominal 13 mm diameter is embedded at 40 mm depth.

* Corresponding author. Tel.: +81 88 656 7320; fax: +81 88 656 7351.
E-mail address: watanabe@ce.tokushima-u.ac.jp (T. Watanabe).

http://dx.doi.org/10.1016/j.conbuildmat.2014.05.013
0950-0618/

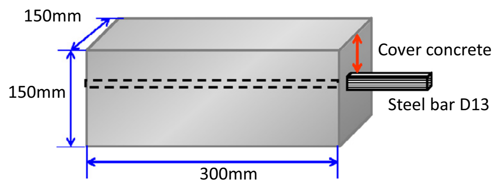

Fig. 1. Sketch of concrete prisms with steel bar.

Mixture proportion of concrete specimen is given in Table 1. The water-to-cement ratio is 50%. Ordinary Portland cement, crushed sand and coarse aggregate are used. Specimens were moisture-cured for 28 days. After curing, five faces except the bottom surface were insulated with epoxy resin coating. An electrolytic corrosion test was applied after curing. Specimens were soaked in water solution with 5% sodium chloride solution and electric current density charged was controlled at 50 mA/m^2. The surface crack appeared in 91 days after the onset of the test.

Ultrasonic tests were conducted once in every three days by using the ultrasonic measurement system. Two sensors are attached on the surface of the specimen with contact medium as shown in Fig. 2. In this case, the receiver mainly detects reflected waves from rebar as well as boundary of specimen. A driving frequency is 200 kHz and pulse voltage is 300 V.

2.2. Concrete beam at the acceleration stage

Five concrete beams of dimensions 100 × 200 × 900 mm were tested as shown in Fig. 3. A rebar of 13 mm diameter is embedded with 30 mm cover-thickness. Mixture proportion of concrete is given in Table 2. The water-to-cement ratio is 55%. Ordinary Portland cement, crushed sand and coarse aggregate are used. Specimens were moisture-cured for 28 days.

An electrolytic corrosion test was also applied after curing. Specimens were soaked to electrolyte solution water of 100 mm in depth. Water solution was 5% sodium chloride. Electric current density controlled was 1 A/m^2. Focussing on the acceleration stage, five specimens were made. Names of these specimens, elapsed periods of the electrolytic corrosion test and times to conduct the ultrasonic test are summarized in Table 3. After evaluation by the ultrasonic test, rebars were taken out and the decrease rate in the mass of rebar was evaluated by using 10% aqueous solution of ammonium hydrogen citrate. The rates of rebar were calculated with 50 mm pitch.

Two sensors were arranged as shown in Fig. 4. Input sensor is located just above rebar and Ch.2 is moved between 200 mm and 700 mm each by 50 mm apart from the attenuation sensor. All sensors are attached with contact medium of water-soluble grease. P-wave velocity is defined, as follows,

$$V = \frac{L_2 - L_1}{T_2 - T_1} \tag{1}$$

V velocity, L_1: distance of ch.1 from attenuation sensor, L_2: distance of ch.2 from attenuation sensor, T_1 arrival time of ch.1, T_2: arrival time of ch.2,

Eq. (1) shows P-wave velocity of medium between Ch.2 and Ch.1. Arrival time was read from the detected waveform by visual confirmation.

Table 1
Mixture proportion of concrete prism.

Gmax (mm)	Slump (cm)	Air (%)	W/C (%)	s/a (%)	Unit weight (kg/m^3)				
					W	C	S	G	AE admixture
20	8	5	50	45	175	350	768	933	0.84

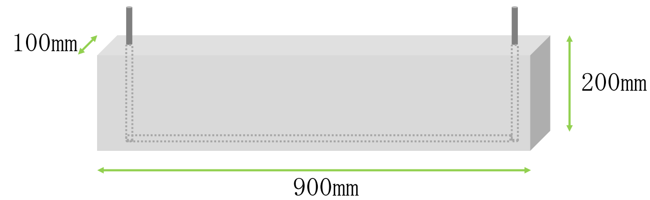

Fig. 3. Sketch of concrete beam.

Table 2
Mixture proportion of concrete beam.

Gmax (mm)	Slump (cm)	Air (%)	W/C (%)	s/a (%)	Unit weight (kg/m^3)					
					W	C	S	G	AE admixture	SP
20	8	5	55	45	175	318	779	949	7A	0.24

In order to evaluate the attenuation of ultrasonic waves due to cracking and rebar corrosion, the ratio of propagation distance is defined in this study. The propagation distance is defined as the length between the attenuation sensor and Ch.2, when waveforms are detected by CH.2 as just lower than the threshold level. The threshold is referred to as 0.15 V of amplitude. Then, the ratio of propagation distance is calculated as a ratio of the propagation distance after corrosion to that of no corrosion. When the ratio of propagation distance of specimen B0 becomes 1, in B10, B20 B30 and B33, the ratios of the propagation distance become smaller than 1, because of attenuation due to corrosion-induced cracks and rebar corrosion.

3. Results and discussion

3.1. Dormant stage

Cracks at the concrete surface were observed about 90 days after starting the electrolytic corrosion test. At 98 days elapsed, the crack width became about 1.4 mm as shown in Fig. 5. After removing cover-concrete, the corrosion of rebar is clearly observed as shown in Fig. 6. In this case, a mass-decrease rate of rebar was about 5.9%.

Results of hall-cell potentials are shown in Fig. 7, which readily indicate that the potentials are lower than ASTM criterion (−350 mV).

Typical ultrasonic waveforms of specimen C40-1 detected at the surface are shown in Fig. 8. Comparing these waveforms, it is observed that the amplitude at 24 days elapsed becomes smaller than that of no corrosion. These phenomena are similarly observed from 24 days to 90 days elapsed. These imply that reflection scattering due to corrosion-induced cracking could occur.

In order to clarify the deference of waveforms, energies of waveforms were calculated as an area between 15 μs and 110 μs. This area was selected to capture reflection waves from rebar and the bottom of the specimen. Since P-wave velocity of concrete is 4022 m/s measured by UT, the arrival time of rebar reflection is

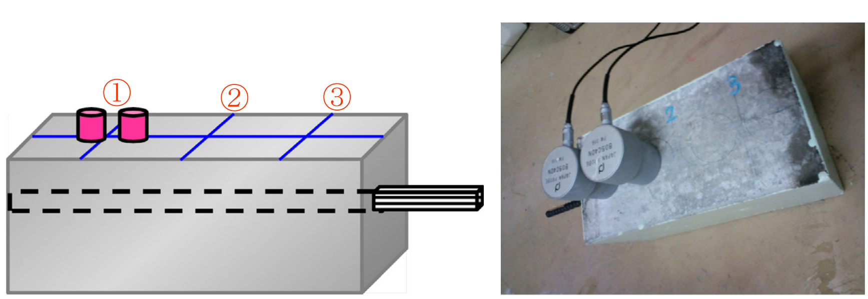

Fig. 2. Sketch and photo of concrete prism tested.