An Approach for Remote Nondestructive Testing Method for Concrete Structure Using Laser-generated Ultrasonic

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Abstract

The aim of this work is to demonstrate the potential for the testing method of the reinforced concrete structure of the laser generated ultrasonic propagating along the rebar. Four kinds of reinforce concrete test pieces having different adhesiveness between rebar and outer concrete are prepared. Irradiating the bottom of the rebar with Nano second pulse-laser generates the ultrasonic propagating along the rebar, receiving the ultrasonic at the opposite bottom of the rebar with ultrasonic receiver. The measured ultrasonic signals are analyzed in time and frequency domain. It is found that the change of adhesiveness between the rebar and outer concrete has effects on the ultrasonic propagating along the rebar and that is applicable to reinforced concrete structure testing.

1. Introduction

Decommissioning of Fukushima Daiichi Nuclear Power Plants (NPPs) is one of the most important missions for JAEA since the Great East Japan Earthquake. The decommissioning will be carried out for several decades to come. Testing and monitoring of concrete structures in NPPs is needed in order to guarantee hereafter workability of decommissioning.

Recent work[1] says that Core Concrete Reaction (CCR) advances erosion of the concrete structures of Fukushima Daiichi NPPs and it is difficult to estimate the correct depth of CCR because of undefined shape of the nuclear fuel debris and CCR's complex process. In addition, it is clear that sea water intrusion makes the rebar in the concrete structures corroded gradually. Thus, advanced remote evaluation methods for the deterioration of the concrete should be considered.

Classical concrete testing methods are unsuitable for remote operation. For example, half-cell potential method[2] needs to uncover the concrete to exposure the rebar. Ultrasonic or Impact wave method[2] is necessary to use couplant and ultrasonic transducer or impact hammer. These classical concrete testing methods are fundamentally oriented for in-situ point-by-point operation by inspectors not for remote operation.

Recently, new approaches are being reported by some researchers that are rapid, safe and suitable for remote operation. Kurahashi et al.[3] reported laser-hammering method. This method irradiates the concrete surface with pulse laser, exciting ultrasonic, measuring it with Laser Doppler Vibrometer (LDV) and analyzing its frequency characteristic. Sugimoto et al. [4] proposed another approach using Long Range Acoustic Device (LRAD) and LDV. These two methods are based on laser technology and oriented for remote operation, however, they are interested in the crack or void near the surface and do not focus on the inner corrosion or deterioration. In this work, we demonstrate another approach for concrete testing method oriented for remote operation and inner deterioration.

2. Our Viewpoints

Deterioration process of the reinforced concrete is shown in Fig.1. External force or other kinds of reason causes the cracks. After the cracks reach the rebar, water comes into around the rebar. The rebar will rust and push the outer concrete apart to cause more cracks. Reinforced concrete finally comes away by repetition of the process decreasing the adhesiveness between rebar and outer concrete.

The decrease of the adhesiveness appears in the deterioration process mentioned above. We had a sense of possibility introducing another concrete testing method based on that. Ultrasonic propagating along the rebar will be absorbed by outer concrete in the case of the sound condition which the rebar gets close to outer concrete in. In the deteriorated condition where the adhesiveness between the rebar and outer concrete decreases, the ultrasonic is not absorbed enough by the outer concrete. It is clear that the decrease of the adhesiveness has effects on the amount, frequency and vibration mode of the ultrasonic to be absorbed. The wave profile observed varies depending on the degree of the adhesiveness, which is applicable to the testing method by extracting the information from the wave profile.

The procedure of the testing method is follows: digging a hole to exposure the rebar embedded in the concrete, irradiating the uncovered the rebar with pulse laser to excite ultrasonic wave propagating along it, measuring the ultrasonic wave at the other uncovered position. The propagated ultrasonic wave gathers the information about the defect, corrosion and deterioration around the rebar. Schematic illustration of the testing method is shown in Fig.2.

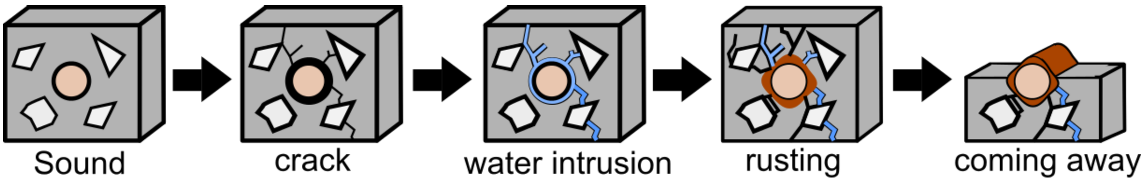


Fig.1: The deterioration process of reinforced concrete

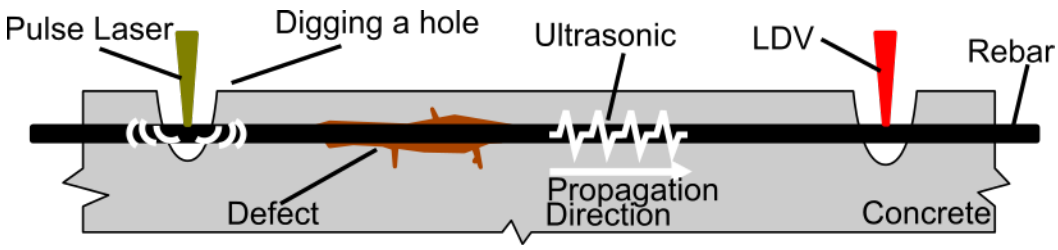


Fig.2: Concept of the remote testing method for reinforced concrete structure

3. Experimental Setup

3.1 Test pieces

In current experiment, we investigate how the decreased adhesiveness has effects on propagating ultrasonic along the rebar. In order to confirm that, four kinds of test piece having different adhesiveness between the rebar and outer concrete are prepared: bare rod, sound, heated and corroded reinforced concrete. Fig.3 shows schematic illustration of the each test piece and the actual photos.

Bare rod is carbon steel cylindrical rod. In order to make it easy to analyze propagated ultrasonic wave profiles, there are no ribs on the rod. Diameter of the rod is 15 mm and length is 500 mm. Sound test piece is made of the bare rod and cylindrically pored mortar around the rod. Diameter of the cylindrical mortar is 60 mm and the length is 200 mm. Heated test piece is made by burning the rebar of the sound test piece with gas burner torch. Thermal expanding rebar pushes the outer concrete apart and the adhesiveness decreases. Corroded test piece is made by electric corrosion method. Dipping sound test piece to sodium chloride water solution, it is electrified with stabilized power supply. Carbon steel rebar is connected to anode side and copper plate attached on the mortar is connected to cathode side. The current of 2 A is passed for up to 60 h.

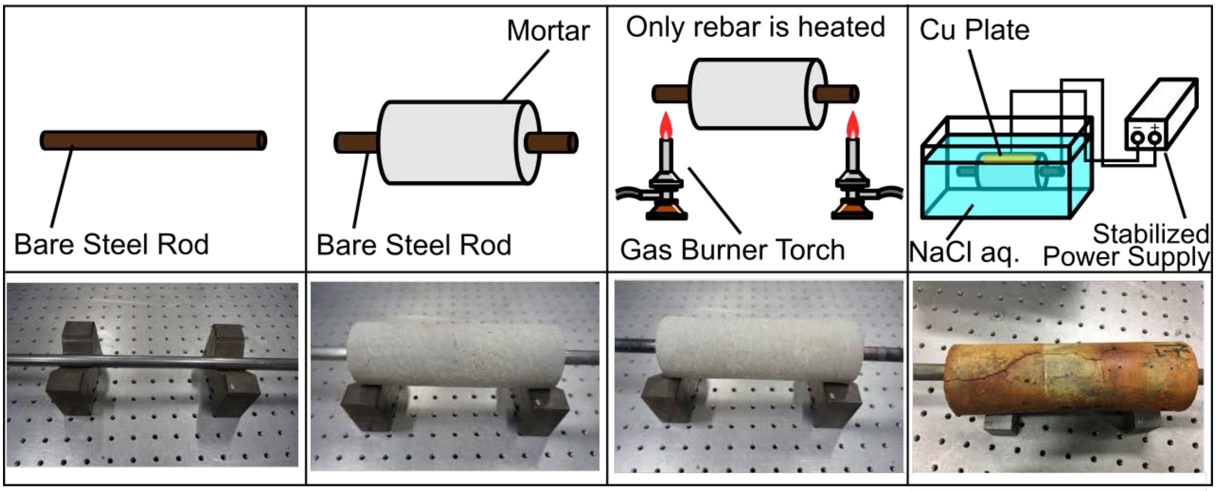


Fig.3 Schematic illustrations of each test piece and the actual photos: (a) bare steel rod, (b) sound reinforced concrete, (c) heated reinforced concrete and (d) electrically corroded reinforced concrete, respectively.

3.2 Experimental Method

Experimental setup is shown in Fig.4. The system is composed of oscilloscope, ultrasonic receiver (B10C5N W-335, Gnes Co., Ltd) , Nano sec pulse laser source (Surelite:SL-2-10, Continuum Co., Ltd) and test pieces. Irradiating bottom of the rebar with Nano second pulse-laser to excite ultrasonic wave propagating along it, the ultrasonic wave is received with ultrasonic receiver at the opposite bottom. The laser spot diameter, the pulse width, and the wavelength and the beam profile is 5 mm, 10 ns, 1064 nm and Gaussian profile, respectively. The bottom of the rebar where ultrasonic receiver put on is applied with couplant to measure the ultrasonic.

In current experiment, bottom of the rebar is irradiated with pulse-laser contrary to our concept shown in Fig. 2 to simplify the waveform analysis. It seems that excited and propagated ultrasonic in this way is a kind of the guided wave. Guided wave on cylindrical rod has many kind of vibration mode and velocity dispersion characteristic, which possibly make it difficult to analyze waveform. Irradiating center of the bottom is intended to minimize the ultrasonic vibration mode as possible. Ultrasonic waveforms obtained from the experiment are analyzed in time and frequency domain.

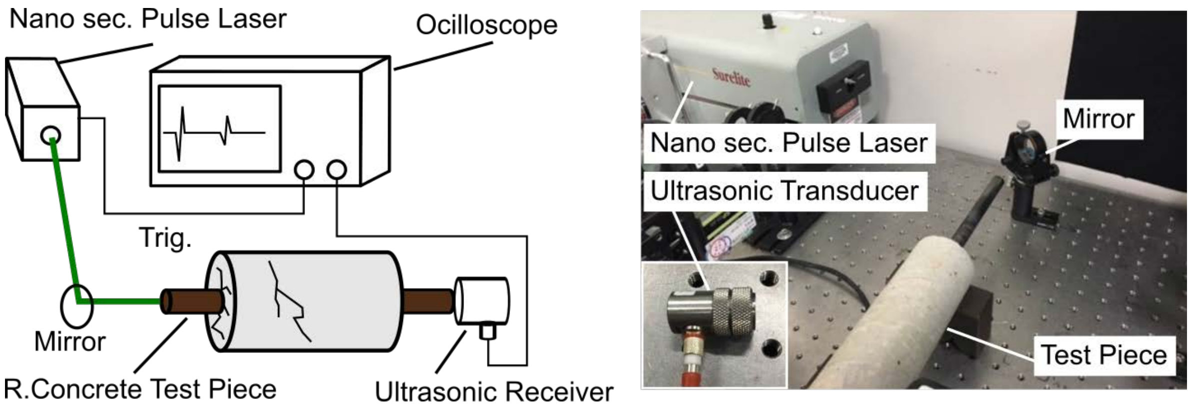
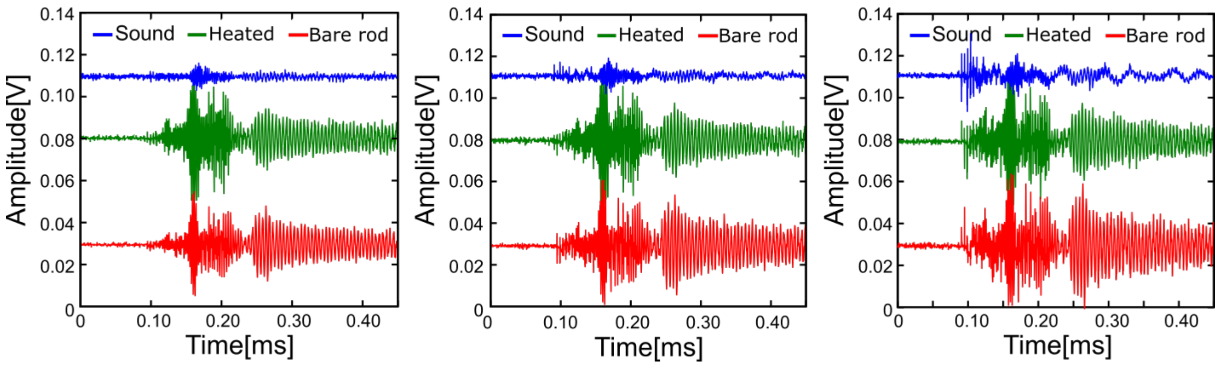


Fig.4 Schematic illustration of experimental method (Left) and the actual system (Right).

4. Experimental results

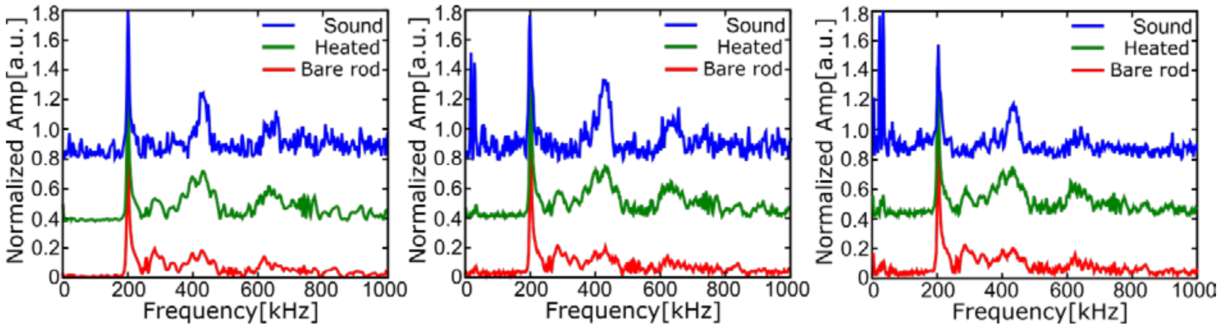
4.1 Ultrasonic waveforms of bare rod, sound test piece and heated test piece

It is investigated how the ultrasonic waveforms change with laser irradiation power on each test piece; bare rod, sound test piece and heated test piece and the adhesiveness. Fig. 5 shows collection of the ultrasonic waveform. Blue, green and red solid lines represent the signals of sound test piece, heated test piece and bare rod, respectively. The remarkable features seen in Fig.5 are ultrasonic wave profile of the bare rod and heated test piece are good agreement and low frequency components seen in signal of the sound test piece are noticeably increase in Fig.5(c) of 140 mJ laser irradiation power. Normalized frequency spectrums corresponding to the signal in Fig.5 are shown in Fig.6. Ultrasonic signals of the sound test piece irradiated with over 100 mJ have strong peak in lower frequency region and all of the signals have strong peak about 200 kHz.



(a) (b) (c)

Fig.5 Ultrasonic waveforms: (a) is 60 mJ of laser irradiation power, (b) is 100 mJ and (c) is 140 mJ, respectively. Blue, green and red solid lines represent sound test piece, heated test piece and bare rod, respectively.



(A) (B) (C)

Fig.6 Normalized frequency spectrum of the ultrasonic signals: (A) is corresponding to the Fig.5 (a) signals, (B) is Fig.5(b) and (C) is Fig.5 (c), respectively. Blue, green and red solid lines represent sound test piece, heated test piece and bare rod, respectively.

4.2 Ultrasonic waveforms of corroded test piece

Here it is investigated how ultrasonic wave profile of the reinforced concrete test piece changes with the progress of the corrosion of the rebar. Laser irradiation power is 140 mJ. Fig.7 shows the collection of the ultrasonic signals measured with each 2 A current and 8 hours energization time. Fig.7(a) shows the signals of 0 hour energization time to 16 hours, Fig7(b) is from 24 hours to 40 hours and Fig.7(c) is 48 hours to 60 hours. Fig.8 shows corresponding frequency spectrums. It is easily seen that ultrasonic signal profiles get close to the profile of the bare rod with duration of the energization time. In particular, low-frequency components are seen in the signal of the test piece up to 8 hours energization but it is hard to see them in the signals of the test piece after 16 hours energization. Up to 40 hours energization time, there seems no remarkable change in the profiles. Remarkable tail-like wave bullet begins to appear after 48 hours energization. In frequency domain shown in Fig.8, strong peak around 200 kHz is seen in the signals after 48 hours energization as well as in the signals of the bare rod.

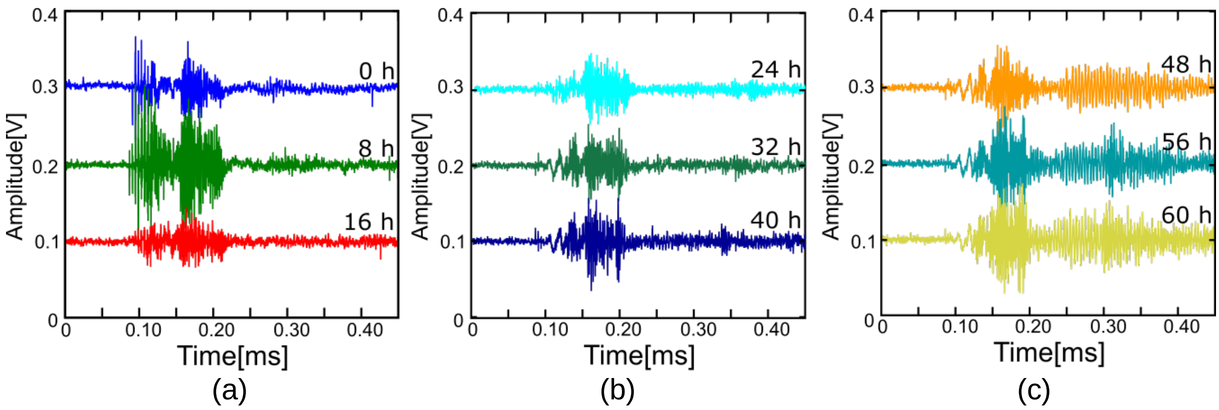


Fig.7 Ultrasonic waveforms of the corroded test piece with each 8 hours energization time.(a) is from 0 hour to 16 hours, (b) is from 24 hours to 40 hours and (c) is from 48 hours to 60 hours.

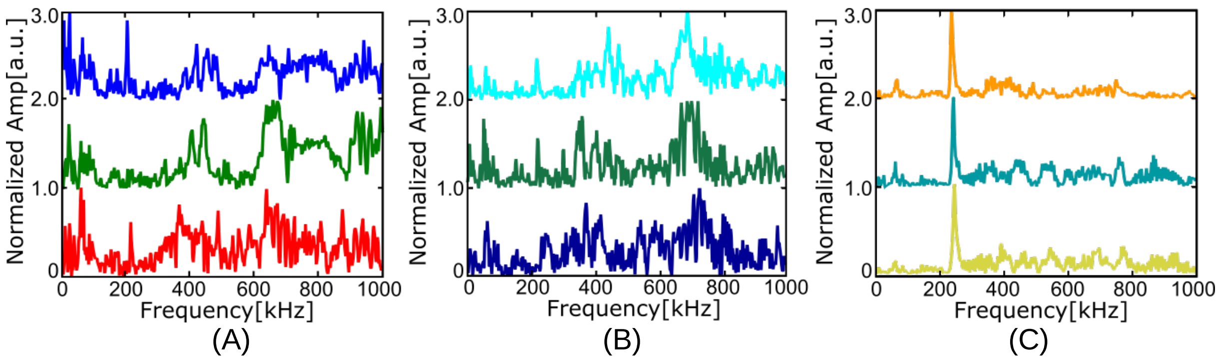


Fig.8 Normalized frequency spectrum of the ultrasonic signals: (A) is corresponding to the Fig.7 (a) signals, (B) is Fig.7(b) and (C) is Fig.7 (c), respectively.

4.3 Discussions

As it is seen in Fig.5 and Fig.6, there appear low frequency components of the ultrasonic signal when it is irradiated with 100 mJ or more laser power. There are two ultrasonic excitation mode of the laser ultrasonic technique; thermal mode and ablation mode. In former one, ultrasonic is excited by thermal expansion and in the latter it is excited by the reaction force of the ablated surface. It indicates that ultrasonic vibration mode which is easy to be absorbed by outer concrete is possibly excited by the ablation mode.

Another remarkable feature is seen in Fig.5 and Fig.6. Ultrasonic waveform of the heated test piece is agreed with the one of the bare rod. The heated rebar expands and pushes outer concrete apart to decrease the adhesiveness. The decreased adhesiveness constitutes a limiting factor for the ultrasonic to be absorbed by the concrete. That is the reason why the ultrasonic propagate on the heated rebar as well as on bare rod to show strong peak frequency around 200 kHz. The strong peaks around 200 kHz are corresponding to the tail-like wave bullet seen in the latter part of the signals in Fig.5 (b) and Fig.5 (c).

Ultrasonic waveform of the corroded test piece changes as well as the heated test piece. In the condition that is not enough corroded, for example in 0 hour energization time, the signal profiles has the low frequency components as the sound test piece has. It is seen in Fig.7 (a) and Fig.8(A). With progress of the degree of the corrosion, the low frequency components decrease. The degree reaching a enough corroded state, the remarkable tail-like wave bullet appears which is seen in bare rod and heated test piece signals as well. The corresponding strong frequency peak is seen around 200 kHz, but it slides to higher frequency region than bare rod and heated test piece. We are positive that the difference of the peak frequency is caused by the changing of the diameter of the rebar.

Ultrasonic wave profile propagating on the rebar of the reinforced concrete gets close to the one of the bare rod with the decrease of the adhesiveness between the rebar and outer concrete. The ultrasonic signals have remarkable tail-like wave bullet which has specific frequency depending on the diameter of the rebar. It is found that the presence or absence of the specific signals is able to apply the structural health monitoring or testing of the reinforced concrete structure.

5. Summary and Future work

In this work, we demonstrated that ultrasonic propagating along the rebar has the potential for the testing method of the reinforced concrete structure. 4 kinds of the test piece; bare rod, sound test piece, heated test piece and corroded test piece, which have different adhesiveness between the rebar and outer concrete was made to investigate how the different adhesiveness has the effects on the ultrasonic wave profiles. The ultrasonic was excited by irradiating the bottom of the rebar of the test pieces with pulse laser and was measured by the ultrasonic transducer to be analyzed in time domain and frequency domain. Through the experiment above, it was shown that the decrease of the adhesiveness has enough effects on the propagated ultrasonic wave profiles.

Future work is to develop a portable in-situ testing device based on this method and continue to investigate the mechanism of the ultrasonic propagation on the rebar and ultrasonic absorption by outer concrete.

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