INVESTIGATION OF DETECTABILITY OF CRACKS IN ANCHOR BOLTS FOR APPLICATION OF PHASED ARRAY ULTRASONIC TESTING

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ABSTRACT

It is necessary to assess the integrity of anchor bolts used in nuclear power plants after a massive earthquake to check for any cracks that may be present in the bolts. Reliable detection of fatigue cracks in anchor bolts in aging nuclear and thermal power plants is a major concern. Phased array ultrasonic testing (PAUT) is an effective technology for the detection of such cracks and determining their size. However, it is necessary to first determine if the cracks are actually detectable by PAUT when this technology is applied to anchor bolts. We prepared different types of bolt specimens with different fatigue cracks introduced. Linear array probes with frequencies of 5 and 10 MHz were used to test the bolt specimens. The test results show the following: (1) it is difficult to detect a crack that has a depth of less than 2 mm at 5 MHz, but 1-mm-deep cracks are detectable when a 10-MHz linear array probe is used; and (2) the concrete surrounding a bolt and the mark engraved on the bolt end scarcely affect the detectability of cracks.

KEYWORDS: Ultrasonic testing, Anchor bolts, Crack, Phased array technique, Detectability

INTRODUCTION

Massive earthquakes may result in cracks in anchor bolts that are used to fix components to foundations in nuclear power plants. Moreover, numerous fatigue cracks have previously been found in aging nuclear and thermal power plants [1-2]. To assess the integrity of anchor bolts, we need to reliably detect cracks and determine their size. Presently, hammering and visual testing are used to detect cracks in bolts. It is impossible for a visual test to detect underground defects. Meanwhile, the results of hammering testing are strongly influenced by environmental and human factors. However, in contrast with hammering and visual tests, ultrasonic tests offer an effective technique for detecting cracks in bolts [3]. Because the tip echo from a crack is overwhelmed by the reflection echo, it is difficult to determine the crack size by the conventional tip echo technique. Phased array ultrasonic testing (PAUT) is a promising candidate for determining crack size because it provides a measurement result corresponding to different propagation directions at the same time. However, before applying PAUT to anchor bolts, it is necessary to check the detectability of the cracks in the anchor bolts.

In this study, four types of bolt specimens with different size fatigue cracks were prepared to investigate the detectability of cracks. Three linear array probes were used, whose respective frequencies were 2 MHz, 5 MHz, and 10 MHz. Variation in the crack echo intensity due to the concrete surrounding the anchor bolts and the engraved marks on bolt ends were also studied.
SPECIMEN and PAUT for anchor bolts

Specimens

For convenience, parameters related to the definition of a crack are shown in Figure 1. The geometry of bolt specimens made of SS400 carbon steel is shown in Figure 2. Bolt specimens were 300-mm long and their thread lengths were 120 mm. Taking the dimensions of a base plate and nut into consideration, the axial position of a crack was determined to be 90 mm. Fatigue cracks were introduced to M30 or M24 bolts with the bending fatigue test. The targeted crack depths were 1 mm, 2 mm, 4 mm, and 6 mm. Specimens shown in Figure 1 are called bare specimens.

To investigate how the concrete surrounding bolts influence the detectability of cracks in bolts, concrete specimens were prepared as shown in Figure 3. The length of the concrete segment was 260 mm so that the cracks could be embedded in the concrete.

Sometimes, identification numbers are engraved on bolt ends in manufacture processes. To clarify the influence of engraving on the detectability of cracks, concrete specimens with engravings of numbers on the bolt ends were prepared as shown in Figure 4. The depths of the engraved marks ranged from 0.35 mm to 0.83 mm.

With the reduction in axial position, a crack echo superimposed the thread echoes, which caused some difficulty in differentiating the crack echo from thread echoes. Figure 5 shows the geometry of short specimens whose axial positions were 50 mm after cutting a part of the thread off the bare specimens.
In our experiment, symbols such as M30-4 were introduced to differentiate bolt specimens from each other. M30-4 indicates a bolt with a diameter of 30 mm and a 4-mm-deep crack. Figure 6 shows fracture surfaces of fatigue cracks corresponding to M24-1, M24-2, M30-1, and M30-2 whose true depths were 1.03 mm, 1.70 mm, 1.35 mm, and 2.13 mm, respectively.

**PAUT for anchor bolts**

Before applying PAUT to bolt specimens, the detectability of cracks by longitudinal normal beam techniques was investigated. The frequency and diameter of the probe used here were 5 MHz and 10 mm, respectively. Figure 7 shows the measurement result for M30 where TP, TE, BW, FE, and DE represent the transmission pulse, thread echo, backwall echo, crack echo, and delayed echo, respectively. As shown in this figure, it is easy to detect a crack with a depth larger than 4 mm, but it is difficult for a crack with a depth smaller than 2 mm because its crack echo is overwhelmed by thread echoes. For M24, the result is the same.
Obviously, the detectability by the longitudinal beam techniques is not adequate for guaranteeing the integrity of anchor bolts. PAUT is a promising solution to this problem because it can potentially obtain information regarding various propagation directions and focusing positions in one measurement. Figure 8 shows the system used to detect cracks in bolt specimens, which consisted of a jig, a probe, a controller, a phased array instrument, and a computer. Different adapters are used for bolts with different diameters. In this study, two 64-ch probes were used that had respective frequencies of 5 MHz and 10 MHz. The active aperture was set to be 32 and the refraction angle was set to be in \(-20\text{–}20^\circ\) range. The focusing depth for transmission was 60 mm, but it ranged from 10 to 150 mm for reception in the dynamic depth focusing mode.
Figure 9 shows the measurement results for the M30-1 bare specimen at 5 MHz and 10 MHz. At 5 MHz, the thread, backwall, and delayed echoes were observed, but no echo from the 1-mm-deep crack was detected. In contrast, the 1-mm-deep crack was easily detected at 10 MHz. It was also verified that the echo from a crack with a depth greater than 2 mm can be easily detected at 5 MHz and 10 MHz. The same results were obtained for the M24 sample. These results suggest that a probe with a frequency of at least 10 MHz should be used if we want to detect a crack with a depth smaller than 1 mm.

Concrete specimen
Measurements were performed for bare specimens and concrete specimens at 5 MHz under same conditions for both specimens. From the measurement results, we easily obtained the intensities of thread echoes corresponding to different refraction angles for the M30 and M24 bolts. The average thread echo intensities for the M24 and M30 bolts are shown in Figure 10. Compared to bare specimens, the thread echo intensities for concrete specimens are lower.
This decrease is dependent on the refraction angle and bolt diameter. The maximum decrease in the M24 bolts was 3.1 dB, and for the M30 bolts, it was 0.9 dB. From this result, we can also conclude that the crack echo intensities for concrete specimens are slightly lower than those of bare specimens.

However, it was confirmed that cracks in the M24-2 and M30-2 concrete specimens could easily be detected at 5 MHz and 10 MHz, and even 1-mm-deep cracks were detected at 10 MHz. This means that a small reduction in the intensity of a crack echo does not greatly affect the detectability of cracks in bolts.

**Engraved mark specimen**

The thread echo intensity comparison between engraved mark specimens and bare specimens is shown in Figure 10. On account of the engraved marks, the thread echo intensity of the M24 bolts was 2.2 dB to 3.2 dB lower compared to the bare bolts. For M30 bolts, the reduction ranged from 0.0 dB to 2.4 dB.

Measurements were performed for the engraved mark specimens with 5 and 10 MHz probes. Cracks with a depth of 2 mm were easily detected at 5 MHz and 10 MHz; specifically, at 5 MHz, the intensity of the 2-mm-deep crack echo was approximately 3 dB lower than that of the bare specimens. It was also verified that it is not difficult to detect 1-mm-deep cracks at 10 MHz.
Short specimen
Figure 12 illustrates measurement results corresponding to M30-1 at 10 MHz and results corresponding to M30-2 at 5 MHz for short specimens. As predicted, crack echoes are superimposed with thread echoes in the results. However, it is possible to differentiate a crack echo from thread echoes. Therefore, there is no issue with detecting a crack whose depth is larger than 1 mm if the axial position of the crack is between 50 mm to 90 mm.

CONCLUSIONS
Because the detectability of cracks must be determined before utilizing PAUT, the detectability of cracks in anchor bolts was investigated. Two linear phased array probes with respective frequencies of 5 MHz and 10 MHz were used to detect cracks in bare specimens, concrete specimens, engraved mark specimens, and short specimens. Measurement results show the following: (1) 1-mm-deep cracks are detectable at 10 MHz, but are undetectable at 5 MHz; (2) the concrete surrounding anchor bolts and the engraved number mark on bolt ends cause the intensity of crack echoes to decrease slightly, but they scarcely affect the detectability of cracks in anchor bolts; and (3) no difference was observed in detectability of cracks when the axial position varies from 50 mm to 90 mm.

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REFERENCES