

Effectiveness of Ultrasonic Testing for Detecting Flaws in Long Embedded Bolts

Minako Endou¹, Hideki Yuya¹, Shan Lin², Tatsuya Fujishiro³

¹ Researcher, Chubu Electric Power Co., Inc., Shizuoka, Japan (Endou.Minako@chuden.co.jp)

² Senior Research Scientist, Central Research Institute of Electric Power Industry, Kanagawa, Japan

³ Research Scientist, Chubu Plant Service Co., Nagoya, JAPAN

ABSTRACT

Currently in Japan, one of the items that explains the extension of nuclear power plant operation, the operator must evaluate that internal flaws in the foundation bolts which do not affect safety by Ultrasonic Testing (UT). Conventional UT methods are sometimes difficult to detect depending on the size of the flaw. In this study, we conducted detection tests using a full-scale specimen and the preliminary investigation of UT conditions using ultrasonic propagation simulation for approximately 3 m foundation bolts of the Hamaoka Nuclear Power Plant Unit 3 to clarify the critical dimensions for detecting flaws by UT. We believe that this result leads to assess more confidential detection.

1. INTRODUCTION

When applying for approval to extend the operation period of a nuclear power plant in Japan, it is required to conduct a "special inspection" to ascertain the detailed condition of the facilities and to attach a document describing the results of the inspection. At Chubu Electric Power's Hamaoka Nuclear Power Plant Unit 3, preparations are underway for a special inspection, as the plant will have been in operation for 40 years by 2027. According to the operational guide established by Nuclear Regulation Authority (NRA), the items to be implemented for the special inspection include checking for flaws inside the foundation bolts of the Reactor Pressure Vessel (RPV) and Suppression Chambers (S/C) by Ultrasonic Testing (UT) (NRA, 2020). Such inspections have been conducted at power plants of another electric power company that have conducted the special inspection earlier, but the foundation bolts targeted for Hamaoka Unit 3 have a maximum length of approximately 3 m, which is several tens of percent longer than the those targeted by another electric power company. Therefore, there was a concern that flaws would be difficult to detect using conventional UT methods. In addition, in the U.S., where, like Japan, nuclear power plants are licensed to operate for 40 years, special inspections are not conducted, and there is no confirmed track record of UT for S/C foundation bolts, so it was difficult to use overseas examples as a reference.

In this study, a preliminary study of test conditions was first conducted with ultrasonic propagation simulation to clarify detectable limit of flaw size by UT, then detection test by UT was performed for full-scale specimen for those foundation bolts in the Hamaoka Nuclear Power Plant Unit 3.

2. METHOD

2.1 Detection Test

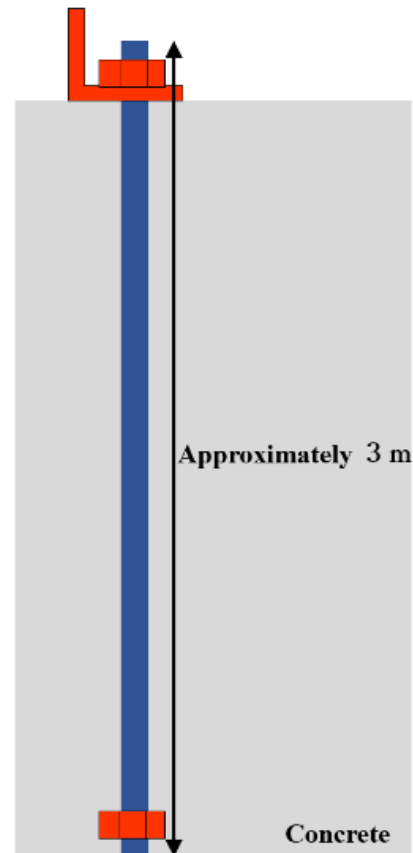
In detection test, UT was conducted by adding a slit-shaped simulated flaw as shown in Figure 2(a), 2(b) to the bolt of the same size as the foundation bolts to be inspected, to confirm the change in detectability due to the radial depths of the simulated flaw. The location of the simulated flaw was set in the threaded valley on the opposite side of the test surface, which is the boundary between the lower nut and the

structure when the bolts is embedded (Figure 3). The UT conditions were in accordance with Japan Electric Association Code (JEAC4207-2008) and the guideline of Japan Nuclear Technology Institute (JANTI-SANE-G2-Edition 1), following another electric power company that had conducted special inspections earlier to ensure accountability. The main test conditions are shown in Table 1.

The radial depths of the simulated flaws were 1.6 mm and 3.2 mm. The 1.6 mm depth was a flaw size that was confirmed to be detectable in the bolts inspected by the electric power company that had conducted special inspections earlier. However, because the bolts inspected at Hamaoka Unit 3 were longer than the bolts inspected by the electric power company, the attenuation of ultrasonic waves inside the bolts was greater, and detection of a simulated flaw with a depth of 1.6 mm was expected to be difficult. Therefore, the first simulated flaw to be added to test pieces was set to the flaw depth that was considered detectable in the inspection by the electric power company, and after confirming its detectability, a test was conducted for a simulated flaw with a depth of 3.2 mm, based on the results of the ultrasonic flaw detection simulation described in next section.

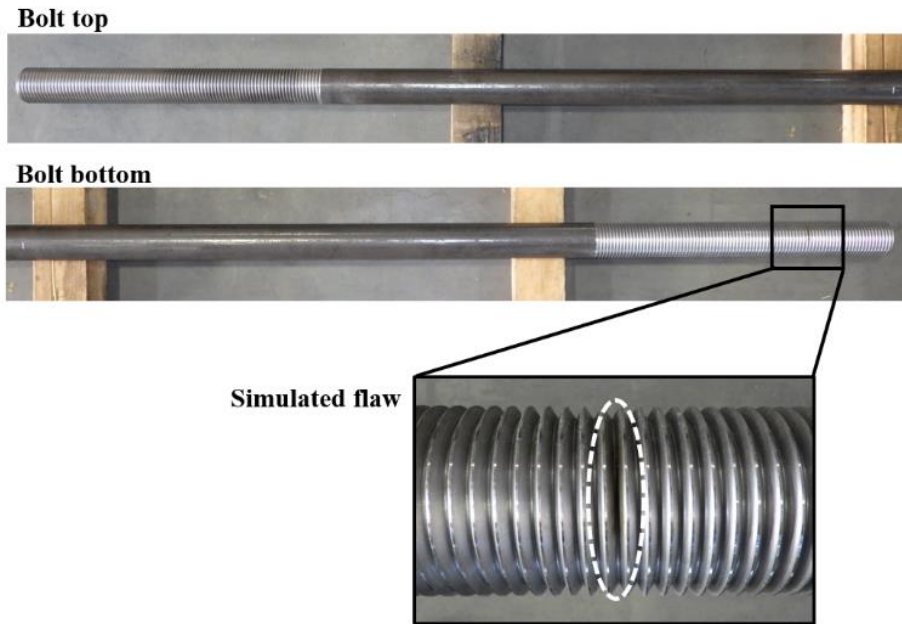


(a) Photo of foundation bolts.

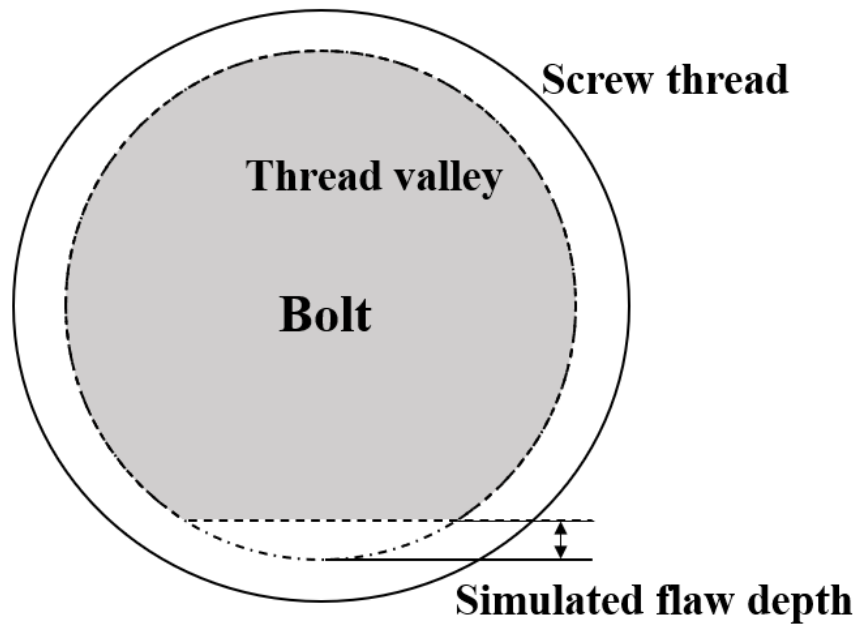


(b) Schematic diagram of foundation bolts embedded.

Figure 1. Foundation bolts for suppression chamber saddle support at Hamaoka Nuclear Power Plant Unit 3.



(a) Simulated flaw introduced in the specimen.



(b) Bolt cross-section view.

Figure 2. Full-scale specimen and simulated flaw.

Table I. Main test conditions described in the guideline of JANTI.

Item	Conditions	
UT technique	Pulse echo	
Probe	Mode	Normal-beam probe
	Frequency	0.4 ~ 15 MHz
	Dimensions	Ultrasonic waves shall be sufficiently transmitted through the test section, which is compatible with the shape and dimensions of the test section.
Reference Sensitivity	The bottom echo of the test bolt is aligned with the range of 80% \pm 5% on the display unit, and the sensitivity is 4 times that of the bottom echo.	
Flaw Judgement criterion	Indicator with an echo of 5% or higher on the indicator scale by reference sensitivity.	

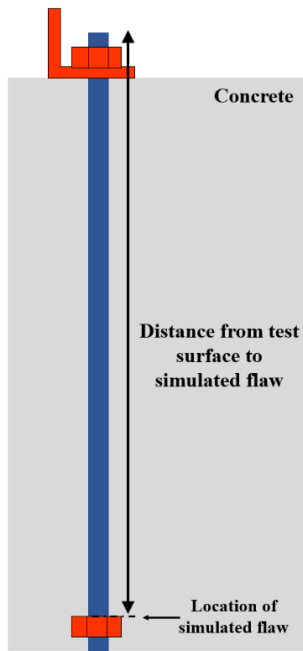


Figure 3. Schematic diagram of location of simulated flaw.

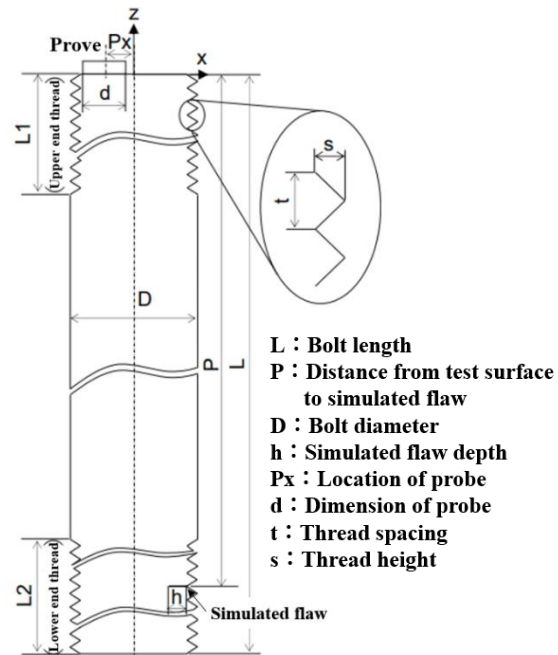


Figure 4. Two-dimensional model of bolt.

2.2 Simulation

Before conducting the detection test again, the ultrasonic propagation simulation was conducted to study the test conditions as a preliminary examination. Once a simulated flaw is placed in the test piece, it can only be processed in the direction to deepen the flaw thereafter. Therefore, to make effective use of the limited test piece, the radial depth of the simulated flaws had to be carefully considered.

In the simulation, the test piece was modeled in two dimensions as shown in Figure 4, and the finite element method was used to reproduce ultrasonic wave propagation in the bolt. The main computational conditions are shown in Table 2. Simulation tests were conducted for flaw depths of 3.2 mm and 4.8 mm, in addition to the flaw depth of 1.6 mm confirmed in the detection test.

In the simulation of ultrasonic propagation, only thicknesses of several 10 cm had been reported so far. Therefore, simulations of propagation at distances of a few meters, such as the one in this study, was required to optimize multiple patterns of element sizes and time increments to avoid the phenomena of ringing (a phenomenon in simulations where waveforms tail off) and divergence of solutions.

Table 2. The main calculation conditions.

Entry	Set value
Courant number	0.6
Mesh size	0.03 mm
Longitudinal wave velocity	5905 m/s
Shear wave velocity	3224 m/s
Material density	7.9×10^3 kg/m ³
Frequency	5 MHz
Propagation time	750 μ s(M68) 1100 μ s(M60)

3. RESULT

3.1 Detection test of simulated flaw 1.6 mm deep

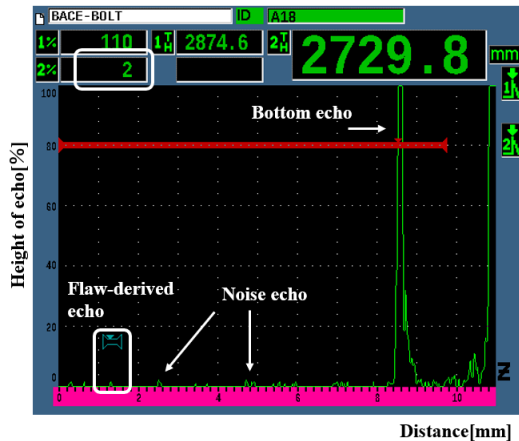
In the first flaw detection test, detectability was checked for a depth of 1.6 mm. As shown in Figures 5(a) and 5(b), the height of the flaw-derived echo was smaller than the judgment criterion of 5 %, and it was difficult to distinguish it from noise echoes, so it was judged to be undetectable.

3.2 Preliminary examination using ultrasonic wave propagation simulation

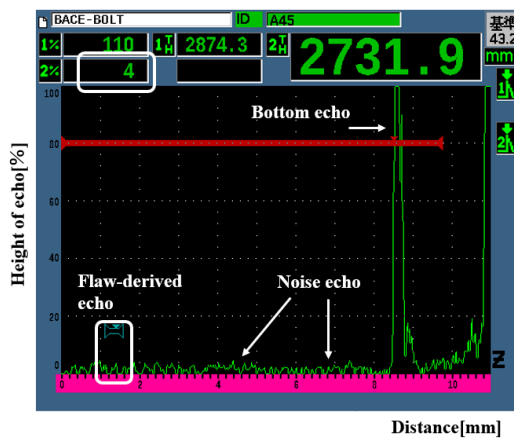
Since the simulated flaw with a depth of 1.6 mm was undetectable in the first test, we modeled the simulated flaw with depths of 3.2 mm and 4.8 mm and performed ultrasonic wave propagation simulation to conduct another test with a larger simulated flaw. As a result, the received waveform shown in Figure 6 has a height ratio of more than 2 to the thread echo, and it was considered sufficiently discriminable from the surrounding noise, and it was predicted that simulated flaws with a depth of 3.2 mm or greater could be detected. It was also confirmed that the echo height varied depending on the diameter of the probe and the position of the probe in relation to the simulated flaw.

3.3 Detection test of simulated flaw 3.2 mm deep

Based on the results of the simulation, a test piece was processed with a simulated flaw of 3.2 mm in depth and the flaw detection test was conducted. As a result, only less than 5% of flaw echoes were observed in the flaw detection test under the same conditions as in the simulation. Therefore, when the testing was conducted within the range satisfying the test conditions shown in Table 1, as shown in Figure 7, flaw-derived echoes with a height satisfying the 5 % criterion were obtained, which were easily discriminated from noise echoes and were detectable.



(a) Waveform when tested with 5C10N(frequency 5MHz, size $\Phi 10$, longitudinal wave) probe.



(b) Waveform when tested with 5C20N (frequency 5MHz, size $\Phi 20$, longitudinal wave) probe.

Figure 5. Waveform obtained during testing of a simulated 1.6-mm-deep flaw.

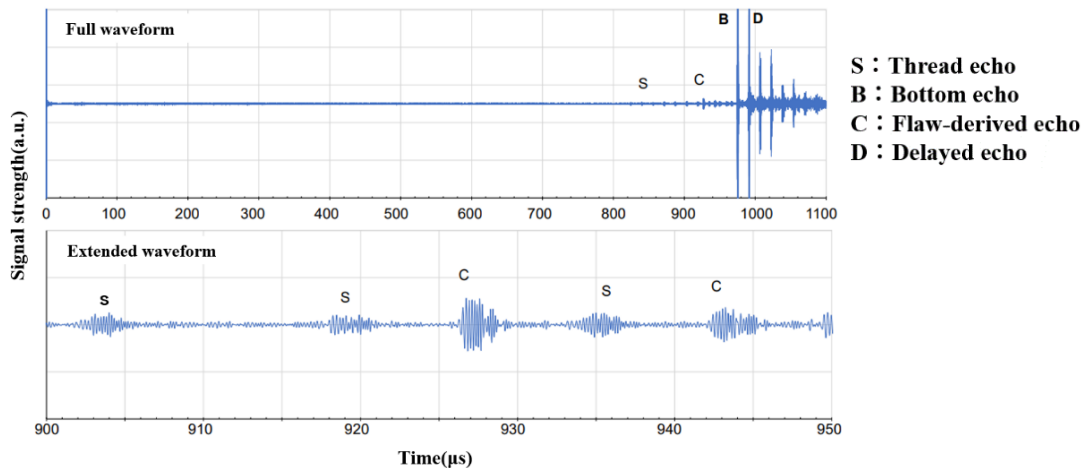


Figure 6. Received waveform for simulated 3.2-mm-deep flaw in simulation.

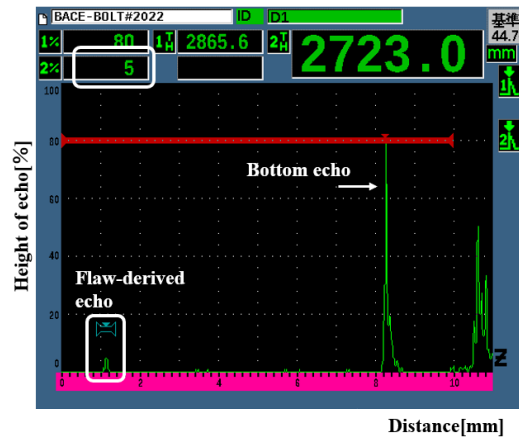


Figure 7. Waveform when tested with 10C10N (frequency 10 MHz, size $\Phi 10$, longitudinal

4. CONCLUSION

To clarify the limit size of detectable flaw by UT for long foundation bolts, which were subject to the special inspection at Hamaoka Nuclear Power Plant Unit 3, we conducted UT and ultrasonic propagation simulation for a full-scale specimen. The main results are summarized as follows:

- (1) The result of UT show that it is difficult to detect a flaw with a depth of 1.6 mm despite it was detected by another electric power company. On the other hand, simulation of wave propagation suggests that a flaw with a depth of 3.2 mm is detectable.
- (2) The ultrasonic wave propagation simulation confirmed that the detectability of a simulated flaw varies with the dimensions of the probe and its position on the test surface. This study also confirmed the possibility to simulate ultrasonic propagation at a frequency of 5 MHz over a propagation distance of several meters.
- (3) Based on the above study, we concluded that the detection limit of the simulated flaw size is 3.2 mm in depth for foundation bolts of approximately 3 m in length. The results obtained here were reflected in the special inspection implementation policy document for Hamaoka Nuclear Power Plant Unit 3.

REFERENCES

- Nuclear Regulation Authority. (2020). *Operation Guide for Application for Approval of Extension of Operation Period of Commercial Power Reactors*.
- Regulations on ultrasonic testing for in-service inspection of light water nuclear power plant equipment, *The Japan Electric Association Code*, JEAC4207-2008
- Japan Nuclear Technology Institute. (2012). *JANTI-SANE-G2-Edition 1 "Guidelines for evaluating the integrity of post-earthquake equipment"*.