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Test Method Applied on One Surface to Corner Defect of Reinforcing Bar in Concrete Pier with Permanent Magnet

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ABSTRACT

Many cases of deterioration of concrete structures caused by alkali-silica reaction (ASR) have been reported. ASR causes cracks on surface and, in severe condition, ruptures of reinforcing bar inside of concrete. In previous studies, these rupture can be detected with magnetic flux density method. This method is one of non-destructive tests using a permanent magnet and a device to measure magnetic flux density on surface of concrete. In this study, a more efficient test for corner rupture of reinforcing bar by magnetic flux density method was proposed in which only single surface is needed. By conducting experiment and FE analysis, and also by compering obtained results and another results from applying the method on-site to an actual concrete pier, the efficiency was evaluated. As a result, the possibility of detecting the rupture of reinforcing bar with this method was shown.

Keywords. Non-destructive test, ASR, Rupture of reinforcing bar, Magnetic flux density, On-site test

INTRODUCTION

In recent years, early deterioration of concrete structures has been reported and ASR is one of the deterioration mechanisms. ASR can occur when the three factors are gathered: alkali in cement, silica in aggregate and water supply. First, alkali in cement reacts with silica in aggregate, and then alkali-silica gel is produced. This gel expands in the presence of moisture and results in cracking in concrete. Furthermore, shocking cases were reported that the ASR expansion caused the rupture of reinforcing bar in badly deteriorated concrete structures mainly at bent corners (Figure 1). To know the condition of reinforcing bar is important from the perspective of maintenance of RC structures. By partial chipping, it can be checked whether the re-bar is ruptured or not visually, but it is a time-consuming work. Therefore, an effective non-destructive test for rupture of reinforcing bar is required. Magnetic flux density method (hereinafter, magnetic method) is one of these non-destructive tests. This method needs a permanent magnet to magnetize re-bar and a sensor unit to measure magnetic flux density on surface of concrete. In case of testing the bent corner, the rupture can be detected by magnetizing and measuring from two surfaces (Figure 2).

However, applying the magnetic method to an on-site bridge pier, for example, is sometimes difficult because of existence of superstructure which disturbs approach to the upper surface of the corner. Hence in such case, the magnetic method applied just from one surface is required where further studies are needed. In this paper, a laboratory experiment and FE analysis on the magnetic method for single surface were conducted to know the applicability of this method with considering the effect of damage level in reinforcing bar and cover thickness. Furthermore, the applicability of the proposed test method was evaluated by making a comparison between the experimental results and on-site investigation result.

Figure 1. Rupture of reinforcing in a concrete structure

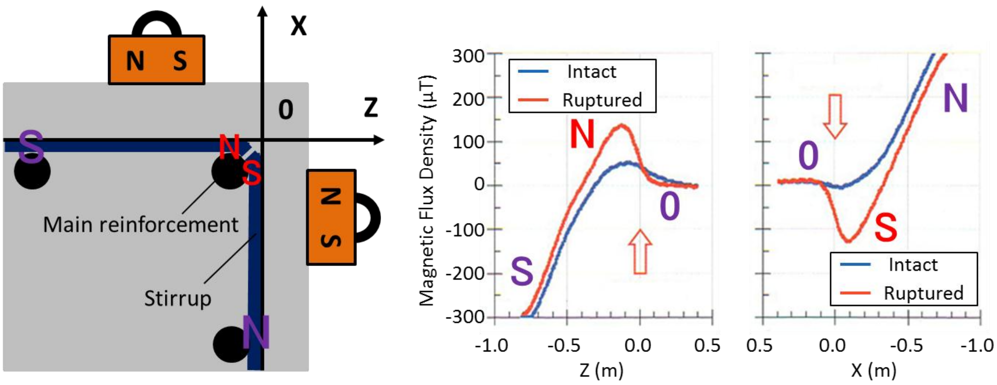

Figure 2. Basic magnetic method using two surfaces

OUTLINE OF THE RESEARCH

Experiment. Assumed situation of concrete cross section and re-bar arrangement is shown in Figure 3: A superstructure is placed on a T-shaped RC pier and rupture of a stirrup in the pier is to be detected. In general, concrete is not magnetic body, so the experimental apparatus was made of wood, instead of concrete and re-bars were fasten on it with plastic ties. Re-bars used in this study are as follows: stirrup (D16, 1800mm, bent at the corner), longitudinal reinforcement (D32, 1500mm). Three damage condition models were adopted for the stirrup: “intact” without any artificial damage, “cracked” (the cross section were cut with a band saw up to 25, 50 and 75% of the diameter from inside of the bent point) and "ruptured" (gaps were 0 or 2mm after full cut). The cover thickness was varied from 50 to 150mm. Experiments were done for 5 times (N = 5) in each case. The testing devices consist of a permanent magnet to magnetize the stirrup and a sensor unit to measure the magnetic flux density normal to the concrete surface. Figure 4 shows the process of the test method. The start position of magnetization was varied from 0 to 100mm.

Step 1: magnetization of the stirrup to test from the surface vertically above the stirrup (X = start position to -500, Y = 0)

Step 2: supplemental magnetization on the parallel line 300mm away from the stirrup (X = start position to -500, Y = 300)

Step 3: measurement of the magnetic flux density and position (X = -500 to 100, Y = 0)

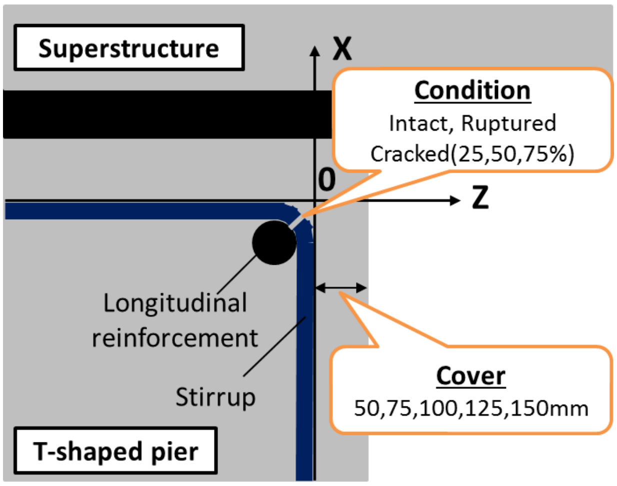

Figure 3. Assumed situation of concrete cross section

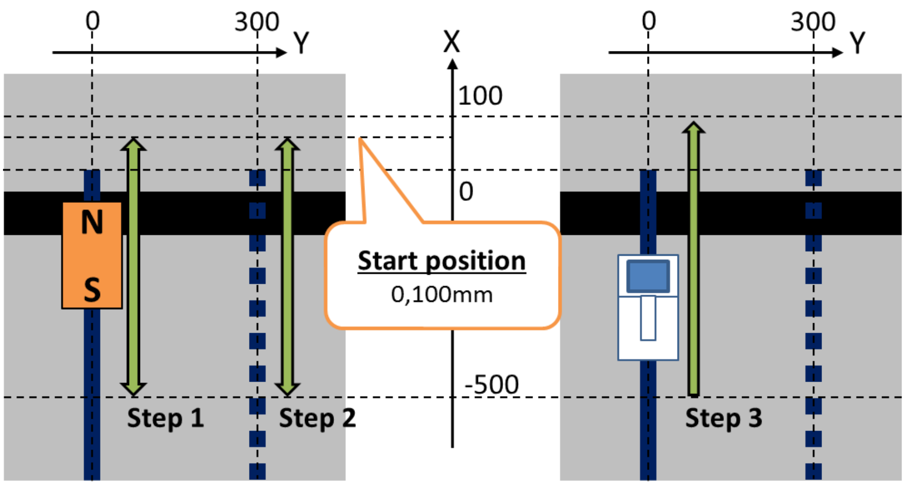

Figure 4. Process of the magnetic method (front view, Unit: mm)

FE analysis. The three-dimensional static magnetic field analysis by the Finite Element Method was also carried out. Purpose of the analysis is to clarify distribution of magnetization in stirrup. Figure 5 shows outline of FE model. The number of elements was 393,768 and the number of nodes was 400,926. Reinforcing bars had hysteresis characteristics, and two stirrups of the three in Figure 5 were regarded as concrete, which was not magnetic body and equivalent to air (relative magnetic permeability = 1). Rupture was expressed by taking corner elements of stirrup for air. Process of magnetization was similar to the experiments. Cover thickness was 75mm, and start position of magnetization was 100mm.

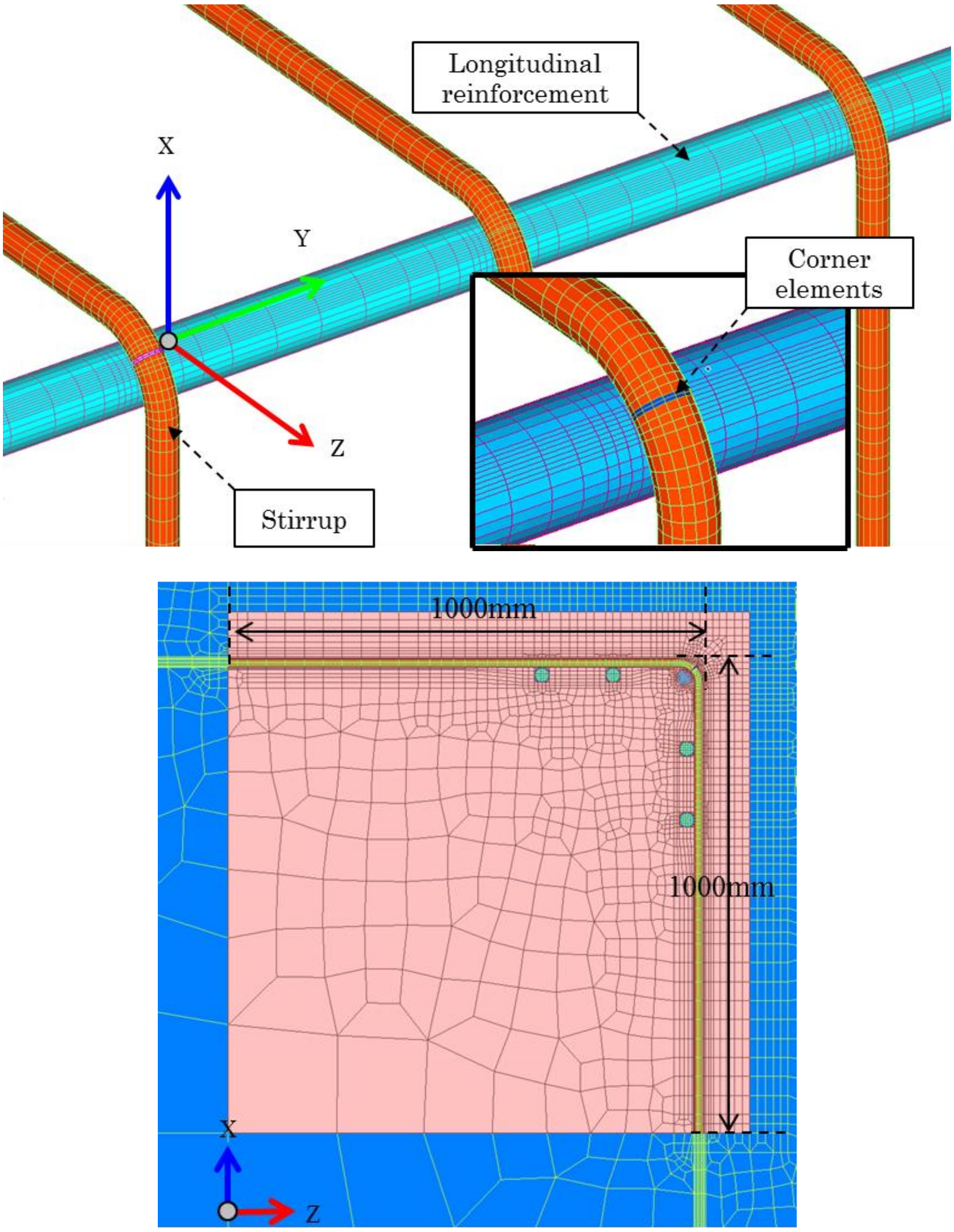

Figure 5. Outline of analytical model

RESULTS AND DISCUSSIONS

Mechanism of detecting the rupture. Figure 6 shows the result of FE analysis in contour diagrams of magnetic flux density around the bending point on X-Z cross section after the magnetization. On the stirrup, there are points recognized where magnetic flux flows in (S pole) and out (N pole). With Figure 6, the magnetized condition of stirrup is expressed as Figure 7. If the stirrup is ruptured, S pole is generated near the point of bending. From Figure 7, it is clear that adequate difference in magnetized condition between intact and ruptured is generated after the magnetization from only single surface.

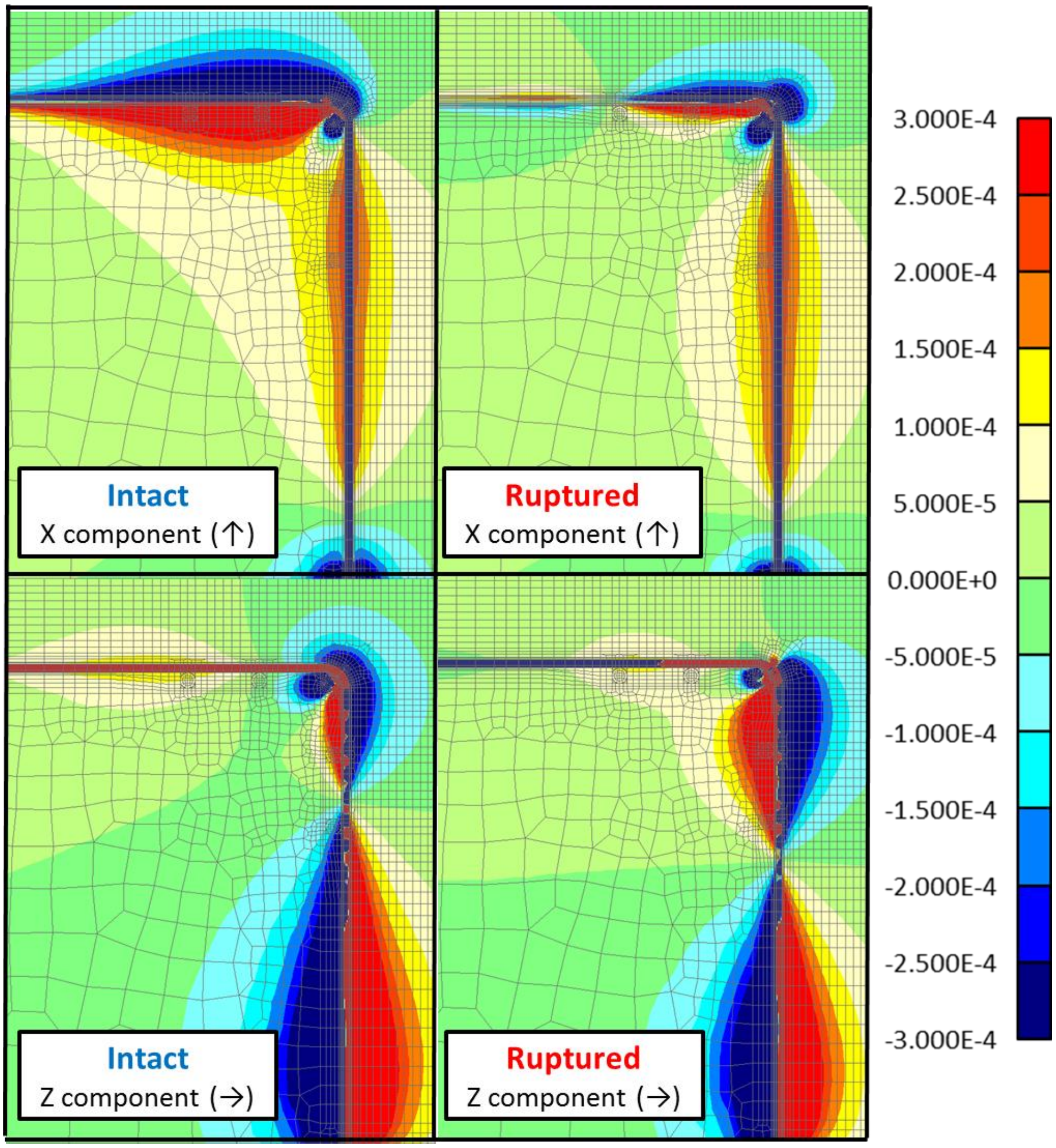

Figure 6. Magnetic flux density after magnetization (Unit: T)

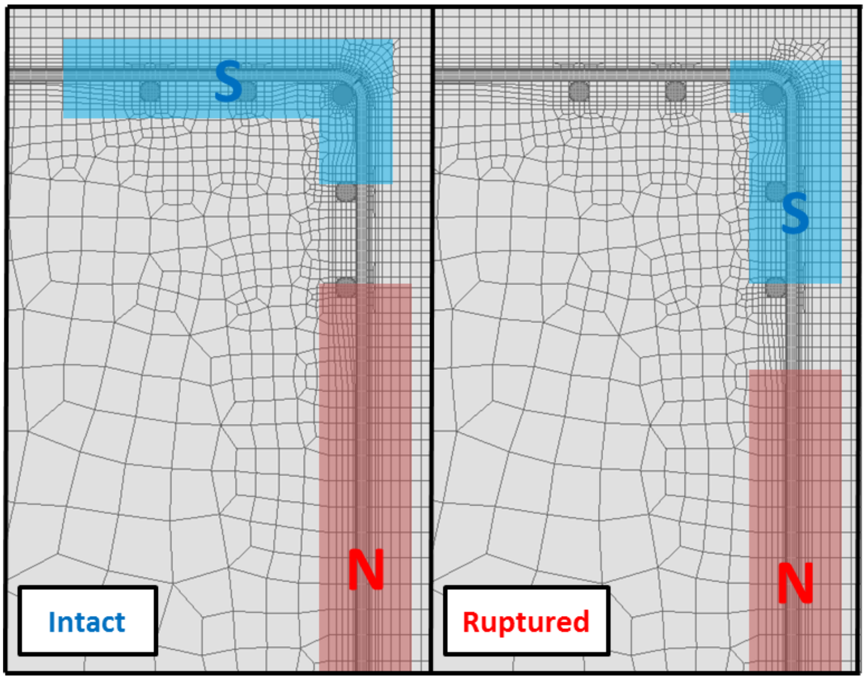

Figure 7. Schematic difference in magnetized conditions

Experimental indicators. Figure 8 shows an example of measurement result of magnetic flux density. If a reinforcing bar is ruptured, the graph curve becomes absolutely higher and steeper than intact one. To evaluate the shape of the curves, two indicators were adopted: peak value and gradient. Peak value represents height of the curve which is defined as the difference between the peak and the value at the point of bending (X = 0). Gradient evaluates the steepness of a curve which is defined as the maximum value of the gradient of the magnetic flux density curve.

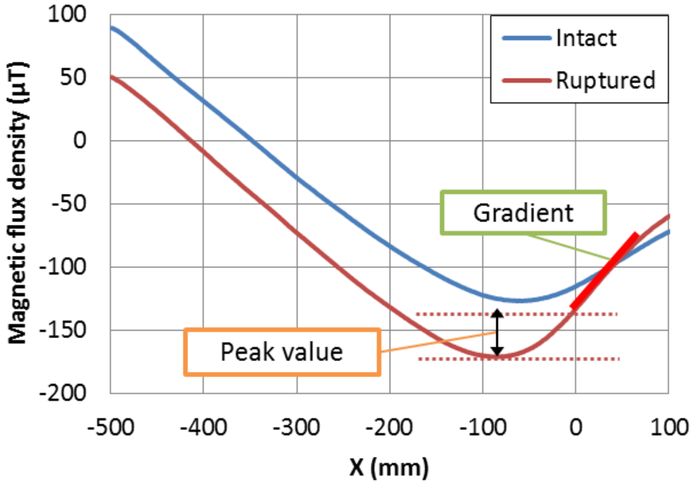

Figure 8. Experimental indicators

Conditions of the reinforcing bar. The relationship between conditions of the stirrup and values of experimental indicators are shown in Figure 9. The start position of magnetization is X = 100. With each indicator, value of "ruptured" is large enough to distinguish from "intact" ones. As the crack extends, peak value becomes larger and close to value of "ruptured". Therefore, it may be possible to detect the conditions of "cracked" in a certain desirable measurement conditions. On the other hand, it is difficult to distinguish the value of "cracked" from "intact" with gradient.

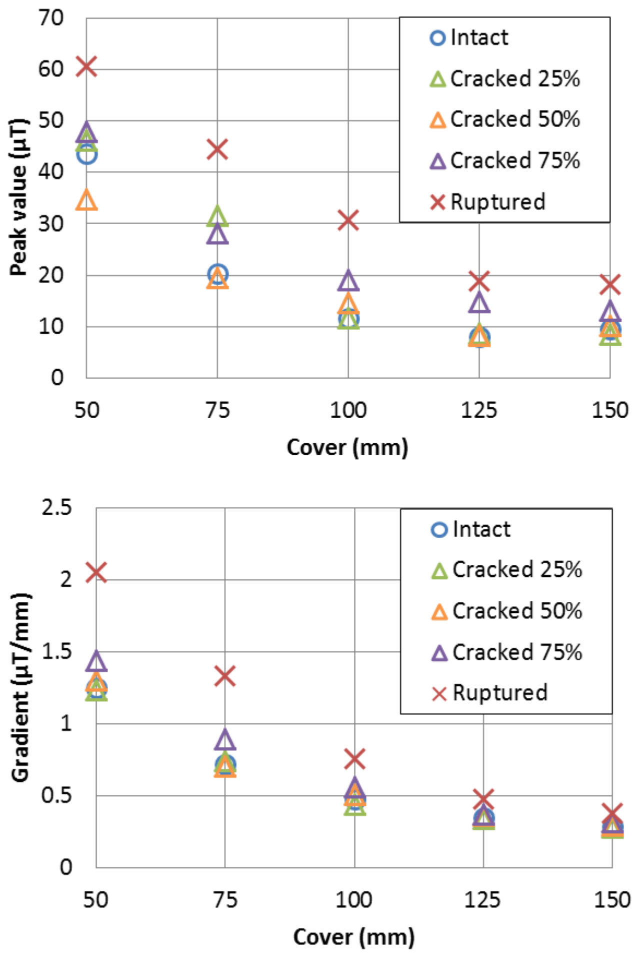

Figure 9. Relationship between conditions of the stirrup and indicators

Start position of magnetization. Figure 10 shows the relationship between start position of magnetization and values of indicators. Conditions of stirrup in Figure 10 are, "intact" and "ruptured". In each condition, the value of indicators with start position being 0mm is larger than the value of 100mm. Therefore, it is necessary to take the influence of start position into consideration. According to Figure 10, the approximate line can be expressed as below.

$$y = ax^2 + bx + c \quad (1)$$

Where, x is cover (Unit: mm), y is value of indicator, and a, b, c are functions of start position. In this study, judgemental criteria are defined as the median between intact and ruptured. Supposing the influence of start position is linear, median of a, b and c for peak value and gradient can be obtained as shown in Table 1, where z is start position (Unit: mm). Using Equation (1) and Table 1, judgemental criteria are expressed quantitatively.

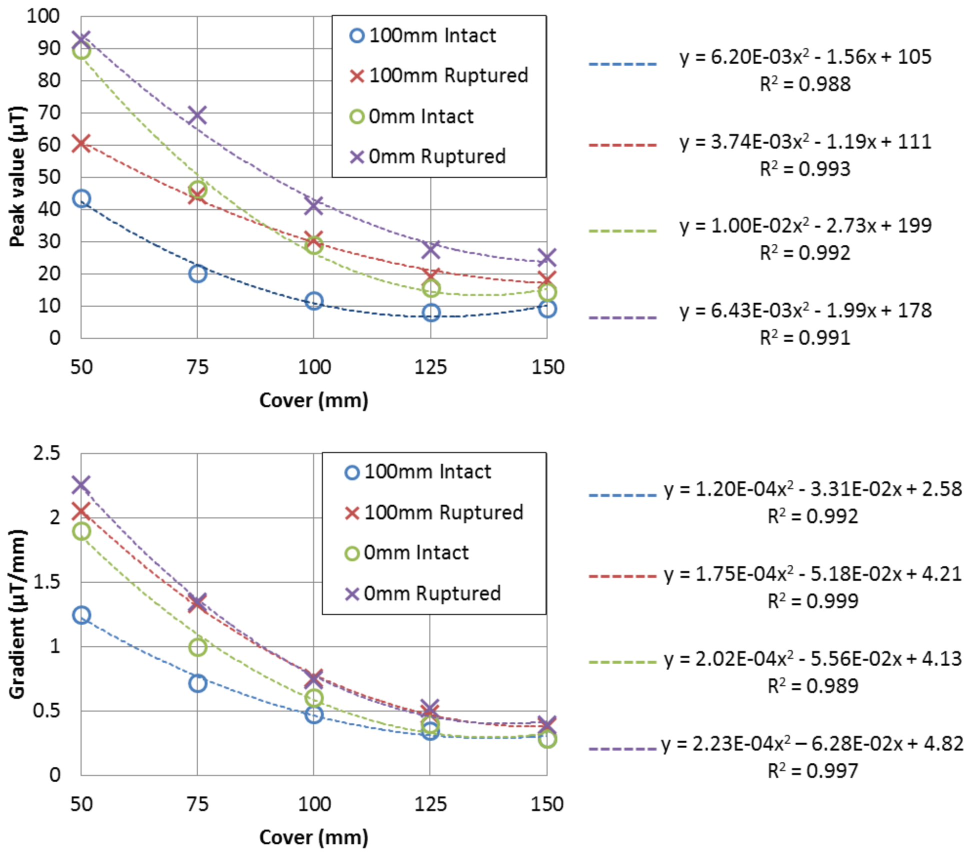

Figure 10. Relationship between start position of magnetization and indicators

Table 1. Median variables a, b and c for judgemental criteria

	Peak value	Gradient
a	$-3.25\times10^{-5}z+8.22\times10^{-3}$	$-6.50\times10^{-7}z+2.13\times10^{-4}$
b	$9.85\times10^{-3}z-2.36$	$1.68\times10^{-4}z-5.92\times10^{-2}$
c	$-0.805z+189$	$-1.08\times10^{-2}z+4.48$

Outline of on-site test. The magnetic method from single surface was applied to eight (① to ⑧)stirrups in an existing bridge pier in Hokuriku region, Japan. After the test from under surface, the magnetic method from two surface and chipping investigation were also carried out (Figure 11). Figure 12 shows the result of on-site measurement. The diameter of the stirrup was 16mm, and other factors are listed in Table 2. The shapes of the curves were more complicated than experiments; possibly because separators or edges of unknown reinforcing bars had some effect on measurement results. Due to these effects, there were some gradient peaks at certain distances from bent point (X = 0). Therefore, the gradient were derived from the range near the corner (X = -100 to 100).

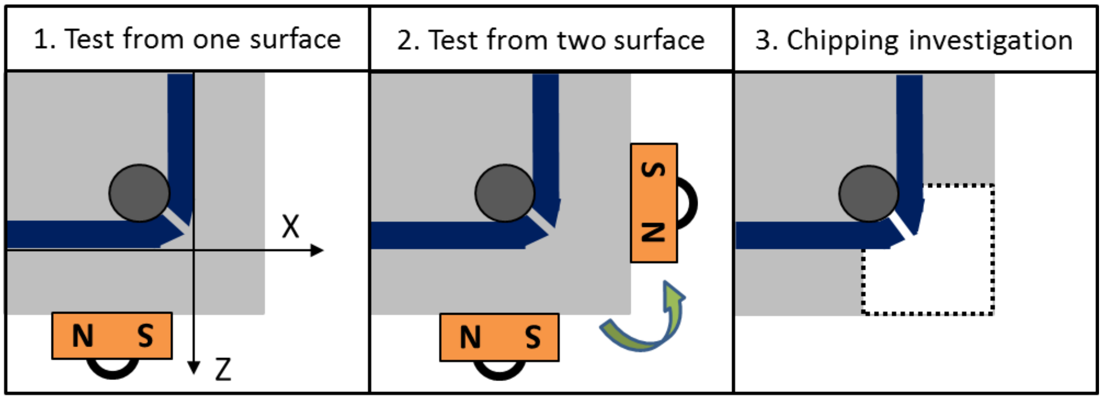

Figure 11. Process of on-site test

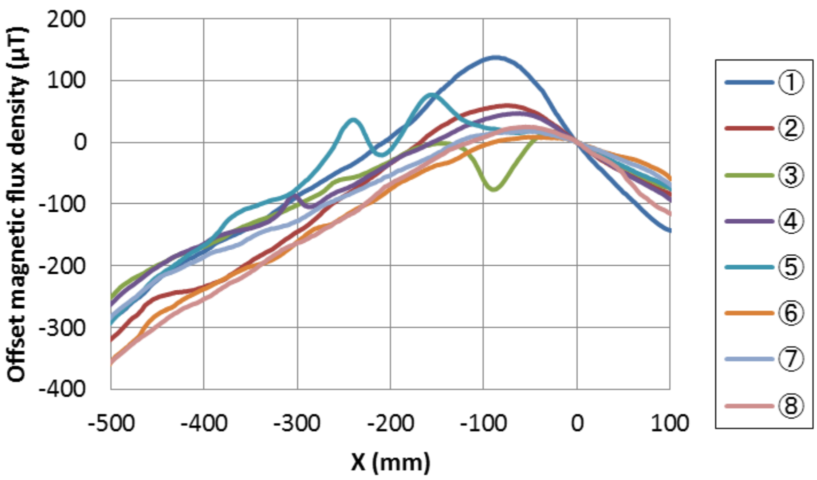

Figure 12. On-site measurement result of magnetic flux density

Table 2. Obtained data about the eight stirrups

	①	②	③	④	⑤	⑥	⑦	⑧
Cover (mm)	58	54	51	56	56	67	77	73
Start position (mm)	81	73	65	50	48	34	38	4
Peak value (µT)	137	59.5	17.6	46.9	76.9	8.31	18.4	24.8
Gradient (µT/mm)	2.35	1.15	1.74	1.06	0.89	1.23	1.00	1.63

Comparison between experiment and on-site test. Table 3 shows the judgement whether the stirrups are ruptured or not by using Equation (1), Table 1 and Table 2, with the judgement by the magnetic method from two surfaces and by the chipping investigation. According to Table 3, a ruptured stirrup ① is exactly judged as ruptured with both the peak value and the gradient. On the other hand, the judgement for not-ruptured stirrups may be different between the two indicators. Therefore, by considering comprehensively with the two indicators, it can be possible to identify the condition of reinforcing bar as precisely as the magnetic method from two surfaces.

Table 3. Applicability of magnetic method from one surface

	①	②	③	④	⑤	⑥	⑦	⑧
Peak value	×	×	○	○	×	○	○	○
Gradient	×	○	○	○	○	○	○	×
Chipping investigation	×	○	−	−	−	−	−	−
Magnetic method from two surface	×	○	○	○	○	○	○	○

○: Not-ruptured, ×: Ruptured

CONCLUSIONS

In this study, a non-destructive test method to detect the corner rupture of reinforcing bar by magnetic flux density method applied from single surface was proposed. Major results are summarized as follows:

1. Condition of reinforcing bar can be evaluated with the peak value and the gradient extracted from the measurement curve of magnetic flux density.

2. The values of two indicators are expressed as the function of cover thickness and start position of magnetization.

3. With the proposed method, it is possible to detect the rupture of reinforcing bar as almost same as the magnetic method from two surfaces.

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