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Simplification of Magnetic Flux Density Method from One Surface to Corner Rupture of Continuously Arranged Steel Bars in Concrete

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ABSTRACT

Some cases of rupture of reinforcing bars in concrete structures have been reported because of deterioration of concrete due to ASR (alkali silica reaction). In previous studies, the rupture can be detected with one of non-destructive testing methods called magnetic flux density method (hereinafter, magnetic method). The process of the method is, firstly, to magnetize steel bars to test with a permanent magnet, and secondly, to measure magnetic flux density over the cover concrete. However, to detect the corner rupture of a steel bar, this method needs a premise: two surfaces should be accessible. Concrete structures often include superstructures near the corner in which reinforcing bars are arranged. In such cases, it is necessary to conduct the test from one surface. In this study, the magnetic method to single surface was examined with a view point of suitable indices to judge the corner rupture of multiple and continuously arranged steel bars by experiments and FE analyses. It was also focused to simplify the magnetization process in the magnetic method applied to single surface. As a result, a proper and simple method for detecting the corner rupture of multiple steel bars was proposed.

Keywords. Magnetic method, ASR, Rupture of re-bars, Non-destructive test, Simplification

INTRODUCTION

In recent years, early deterioration of concrete structures has been reported and ASR is one of the deterioration mechanisms. ASR brings up cracks in concrete and it sometimes causes the rupture of reinforcing bars in badly deteriorated concrete structures mainly at bent corners.

To know the condition of reinforcing bars is important in maintenance of RC structures. By partial chipping, it can be checked whether the re-bar is ruptured or not visually, but it requires a lot of time and labor. Therefore, an effective non-destructive test for rupture of a reinforcing bar is required. Magnetic flux density method (hereinafter, magnetic method) is one of those non-destructive tests. This method needs a permanent magnet to magnetize a re-bar and a sensor unit to measure the magnetic flux density over the cover concrete. In case of testing the bent corner, the rupture can be detected by magnetizing and measuring from two surfaces (Figure 1).

However, applying the magnetic method to an on-site bridge pier, for example, is sometimes difficult because of existence of superstructure which disturbs testing from the upper surface of the corner (Figure 2). Hence in such case, the magnetic method applied just from one surface is required where further studies are needed. In addition, it should be taken into account that object steel bars are generally continuously arranged and multiple in actual sites. Moreover the times and efforts should be reduced in applying this method since the permanent magnet is not necessarily easy to handle with its weight. In this study, the magnetic method to single surface was examined with a view point of suitable indices to judge the corner rupture of multiple and continuously arranged steel bars by experiments and FE analyses. It was also focused to simplify the magnetization process in the magnetic method applied to single surface by shortening length of magnetization.

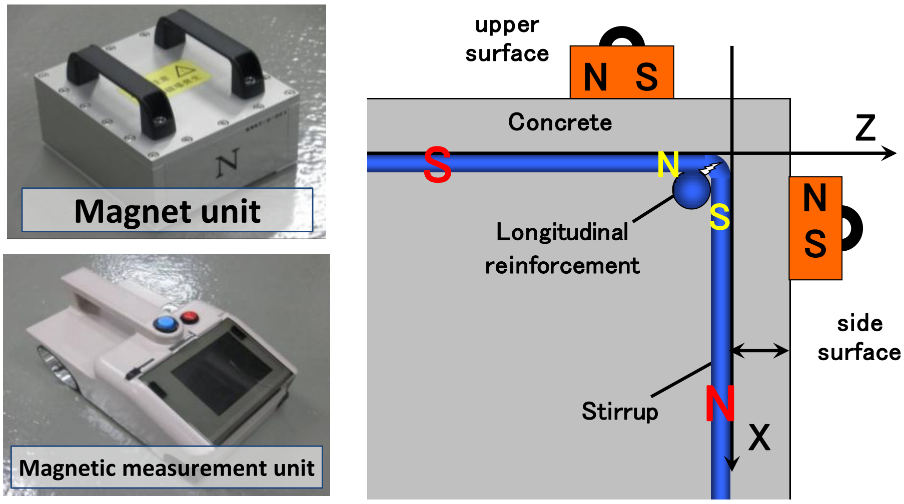


Figure 1. Testing devices and process of magnetization

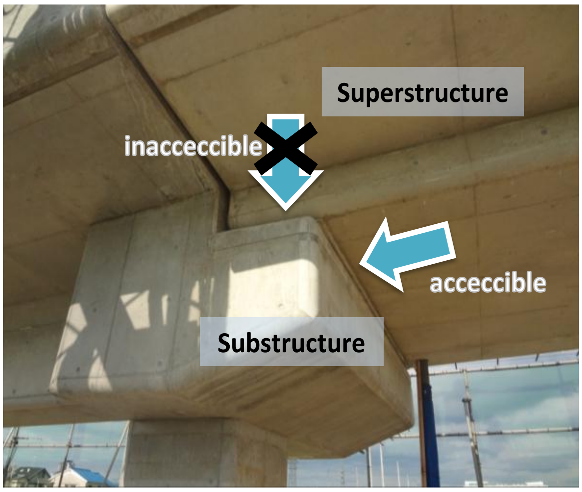


Figure 2. Existence of a superstructure on a substructure

OUTLINE OF EXPERIMENT

Experimental specimen. 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. Number of arranged stirrups were three. In general, concrete is not magnetic body, so the experimental specimen was a frame 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 center), longitudinal reinforcement (D32, 1500mm). The rupture gap of stirrups were 2mm. The stirrups were cut after bent with a band saw at the bent point.

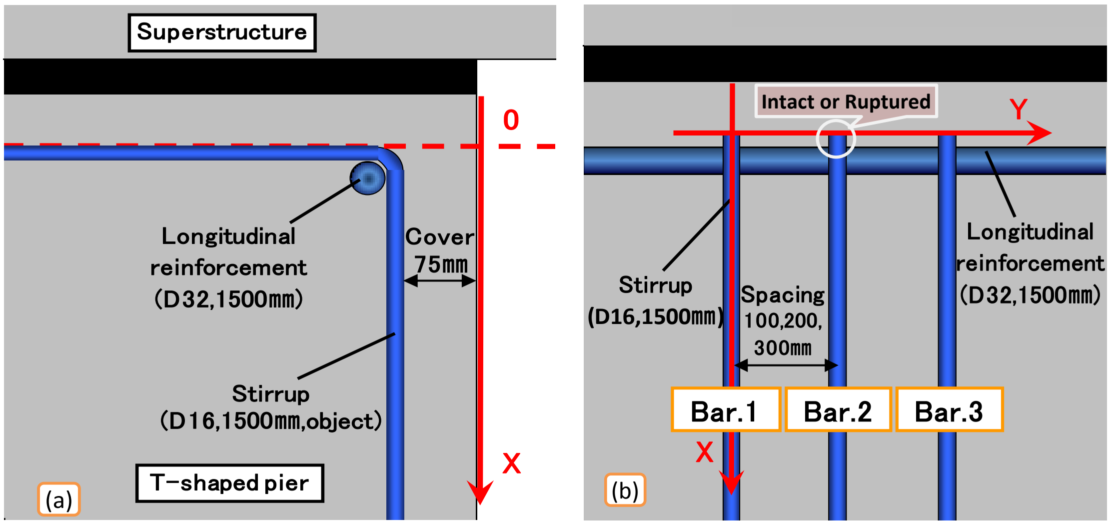


Figure 3. Experimental re-bar arrangement: (a) Side view (b) Front view

Experimental factors. In this study, major factors were set as below and shown in Table 1.

Condition of Bar.2 (Intact or Ruptured)

Center to center spacing between steel bars (S = 100, 200 or 300mm)

Stop position of magnetization (x = 500, 300, 100 and -100mm)

Magnetic method. The testing devices consist of a permanent magnet to magnetize the stirrups and a sensor unit to measure the magnetic flux density normal to the concrete surface. The process of the test method is as follows:

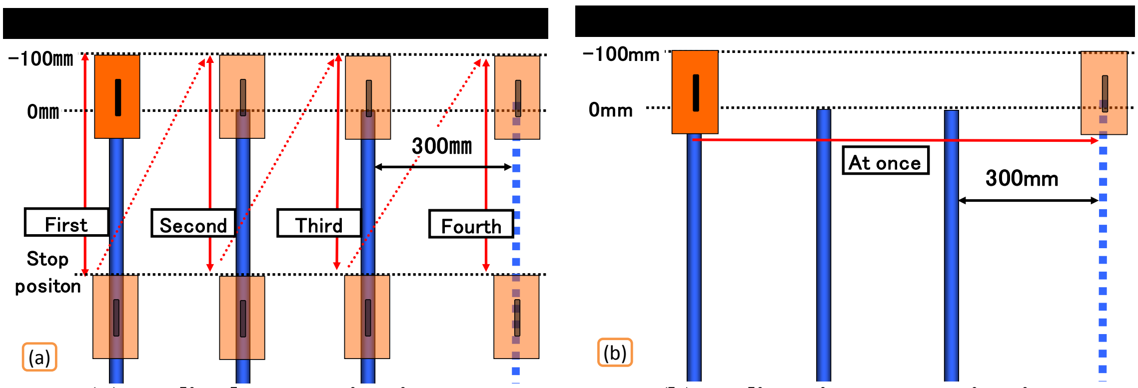
Step 1: magnetization of the Bar.1, Bar.2 and Bar.3 to test from on the cover right above each stirrup in turn (x= -100 to the stop position, y = 0, S, 2S)

Step 2: final supplemental magnetization on the parallel line 300mm away from the Bar.3 (x = -100 to the stop position, y = 2S + 300)

Step 3: measurement of the magnetic flux density and position (x = -100 to 500, y = 0, S, 2S)

The step 2 magnetization is done with assuming to apply to an actual bridge pier in which more stirrups to test are arranged. Hereinafter, this magnetization method is called the ordinal magnetization (Figure 4(a)).

When the stop position of magnetization is x=-100, Bar.1 through Bar.3 were magnetized at once by sliding the permanent magnet in y-direction (x = -100, y = 0 to 2S + 300) Hereinafter, this magnetization method is called y-direction magnetization (Figure 4(b)).



(a) Ordinal magnetization **(b) Y-direction magnetization**

Figure 4. Processes of the magnetization

Table 1. Experimental factors

Spacing (㎜)	Longitudinal reinforcement	Stop position of Magnetization x(㎜)	Re-bar Condition Bar.1	Bar.2	Bar.3
200	Nothing	500	Intact	Intact	Intact
			Intact	Ruptured	Intact
		300	Intact	Intact	Intact
			Intact	Ruptured	Intact
		100	Intact	Intact	Intact
			Intact	Ruptured	Intact
		-100	Intact	Intact	Intact
			Intact	Ruptured	Intact
	Present	500	Intact	Intact	Intact
			Intact	Ruptured	Intact
		300	Intact	Intact	Intact
			Intact	Ruptured	Intact
		100	Intact	Intact	Intact
			Intact	Ruptured	Intact
		-100	Intact	Intact	Intact
			Intact	Ruptured	Intact
		500		Nothing	
		300			
		100			
		-100			
100		500	Intact	Intact	Intact
			Intact	Ruptured	Intact
		300	Intact	Intact	Intact
			Intact	Ruptured	Intact
300		100	Intact	Intact	Intact
			Intact	Ruptured	Intact
		-100	Intact	Intact	Intact
			Intact	Ruptured	Intact

OUTLINE OF ANALISYS

It is important to know the magnetization state of particular points in steel bars which can not be obtained in experiments to understand the measured magnetic flux density. So, three-dimensional static magnetic field analysis by the finite element method was carried out.

An analytical model was provided as shown in Figure 5 to simulate the experiment. It was composed by stirrups and a longitudinal reinforcement. Table 2 shows analytical factors adopted corresponding to the experimental factors previously shown in Table 1. A general purpose 3D FEA software for the static magnetic field was used. The hysteresis characteristics were considered in magnetization of steel bars. Concrete was regarded as air in which relative magnetic permeability, μ was assumed to be 1. The rupture was expressed by making an aerial gap (width: 2mm) in the bent point of a stirrup. When a stirrup was in intact condition, steel elements were filled into the gap. The number of elements was 393,768 and the number of nodes was 400,926.

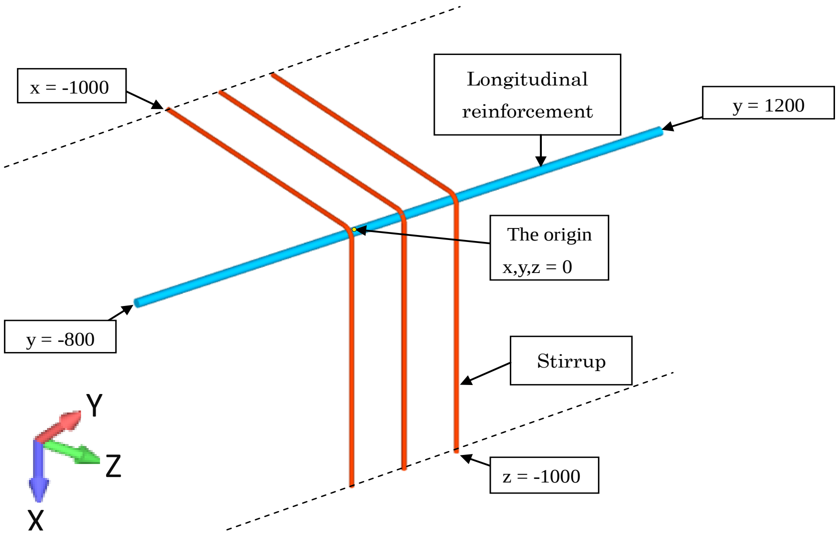


Figure 5. Outline of the analytical model

Table 2. Analytical factors

Spacing (㎜)	Longitudinal reinforcement	Stop position of Magnetization x(㎜)	Re-bar Condition		
			Bar.1	Bar.2	Bar.3
200	Present	500	Intact	Nothing	Nothing
			Ruptured		
	Nothing		Intact		
			Ruptured		
	Present	500	Intact	Intact	Intact
				Ruptured	
	Nothing			Intact	
				Ruptured	
	Present	-100		Intact	
				Ruptured	
100	Present	500	Intact	Intact	Intact
				Ruptured	
300				Intact	
				Ruptured	

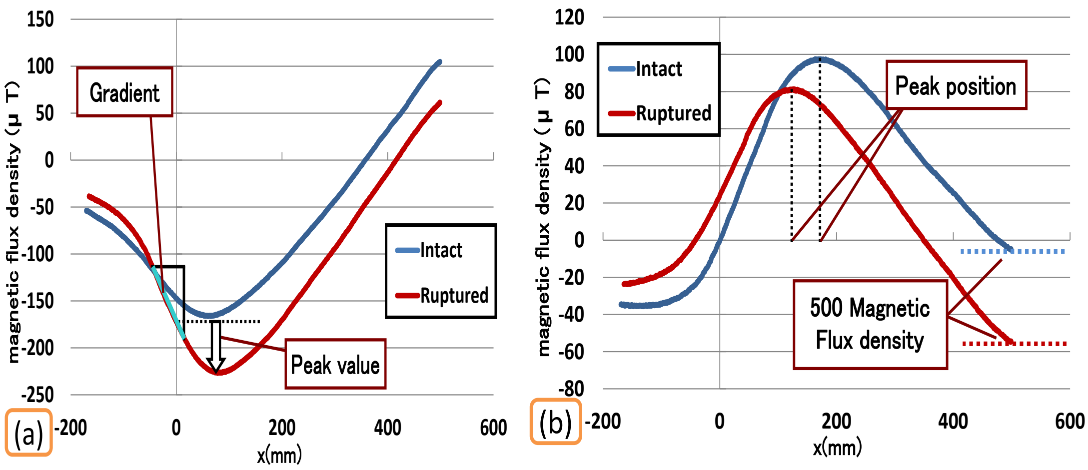
RESULTS AND DISCUSSIONS

Experimental indicators. Figure 6(a) shows an example of measurement result of the magnetic flux density and proposed experimental indicators used in the ordinal magnetization. After the magnetization, the magnetic pole is generated near the bent point. So if a reinforcing bar is ruptured, the graph curve becomes absolutely higher and steeper than intact one. Therefore, two indicators, they were peak value and gradient, were adopted.

The peak value is an index of height of the curve which is defined as the difference between the minimum value and the value at the point of bending (x = 0). The peak value has also been used in evaluation of the magnetic method from two surfaces. The gradient evaluates the steepness which is defined as the minimum absolute value of the gradient of the magnetic flux density curve.

Figure 6(b) shows an example of measurement result of the magnetic flux density and the proposed experimental indicators used in the y-direction magnetization. The direction of the magnetic pole and characteristic of distribution of magnetic flux density are different from the ordinal magnetization. If a reinforcing bar is ruptured, the pole position near the bent point moves from intact one. Moreover, the father it is from the bent point, the bigger the difference between intact one and ruptured one is. Therefore, another two indicators, they were peak position and 500 Magnetic Flux Density were adopted.

The peak position is an index of position of the maximum pole in x axis. The 500 Magnetic Flux Density is defined as the magnetic flux density at end of measurement range (x = 500).



(a) Ordinal magnetization **(b) Y-direction magnetization**

Figure 6. Experimental indicators

The stop position of magnetization and applicability of the indicators. Applicability of the experimental indicators was evaluated by normalized distance. The normalized distance is a ratio of difference between the indicator value in a ruptured steel bar and the average indicator value in intact steel bars, to their standard deviation. Since the normalized distance is dimensionless and quantified, it can evaluate applicability of each indicator similarly. The larger it is, the easier it is to detect a rupture.

The relationship between applicability of each indicator and the stop position of magnetization are shown in Figure 7, with classifying the normalized distance into four grades.

The gradient was gradually not able to detect the rupture with decrease in length of magnetization, until it was very hard to use when the stop position is x = 100mm. However, the peak value was able to detect the rupture even if the stop position is x = 100mm.

The spacing between steel bars and applicability of the indicators. The relationship between applicability of each indicator and the center to center spacing between steel bars are shown in Figure 8 and Figure 9 for the ordinally and y-direction magnetization, respectively.

The gradient was effective when spacing was 200mm, but it was not applicable when the spacing was 100mm and 300mm. This result might be caused by influence of magnetism of neighbouring stirrups on both sides and the longitudinal reinforcement, respectively. However, the peak value was superior and less influenced by the spacing.

Using y-direction magnetization, the peak position and the 500 Magnetic Flux Density had high possibility for detection of ruptures. Especially the 500 Magnetic Flux Density was hardly be affected by the spacing.

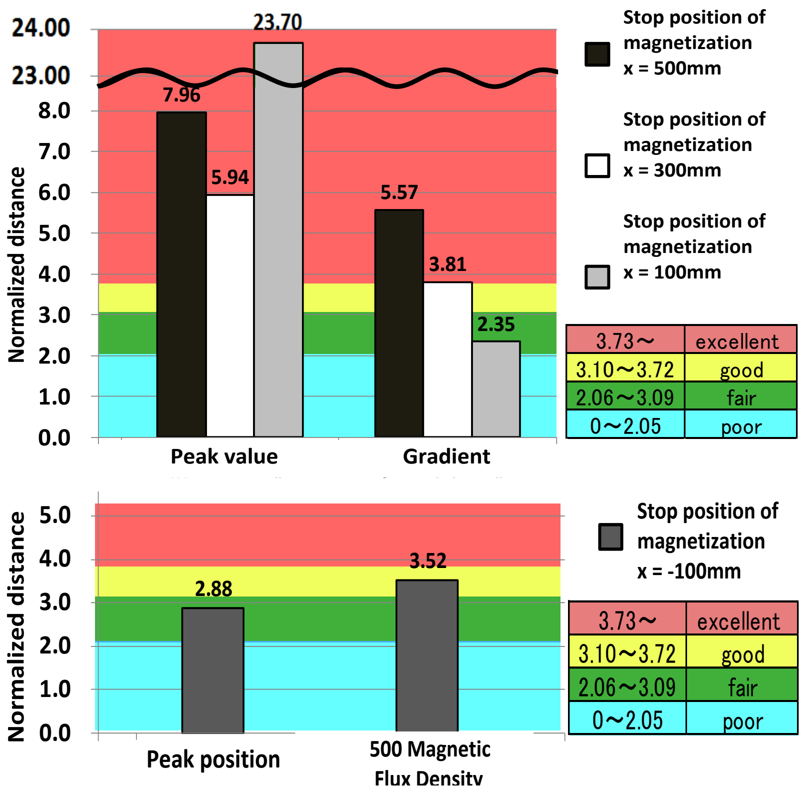


Figure 7. The stop position of magnification and applicability of the indicators (Spacing between steel bars: 200mm)

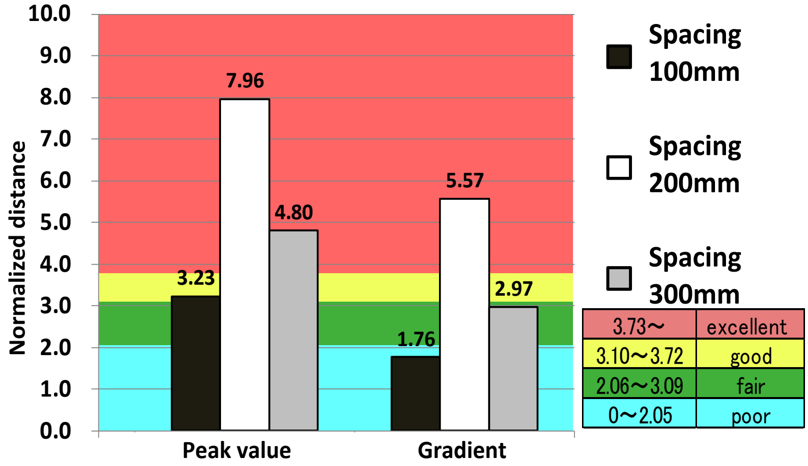


Figure 8. The spacing between steel bars and applicability of the indicators (Stop position of magnification: x = 500mm, the ordinarily magnetization)

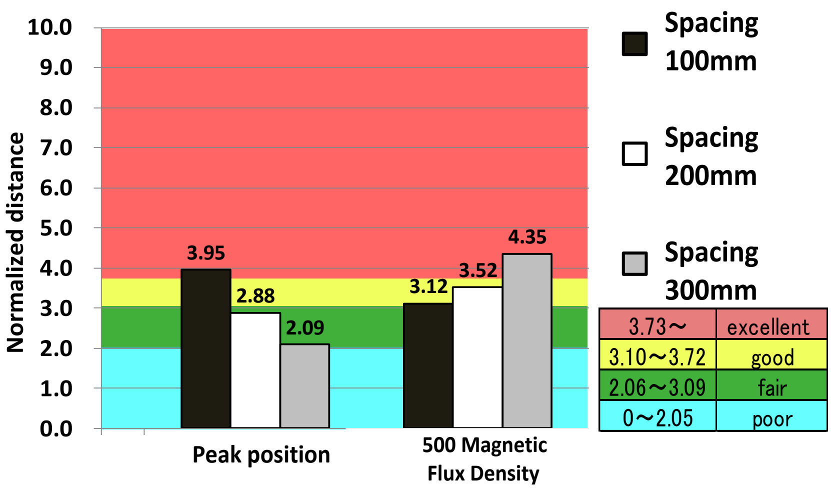


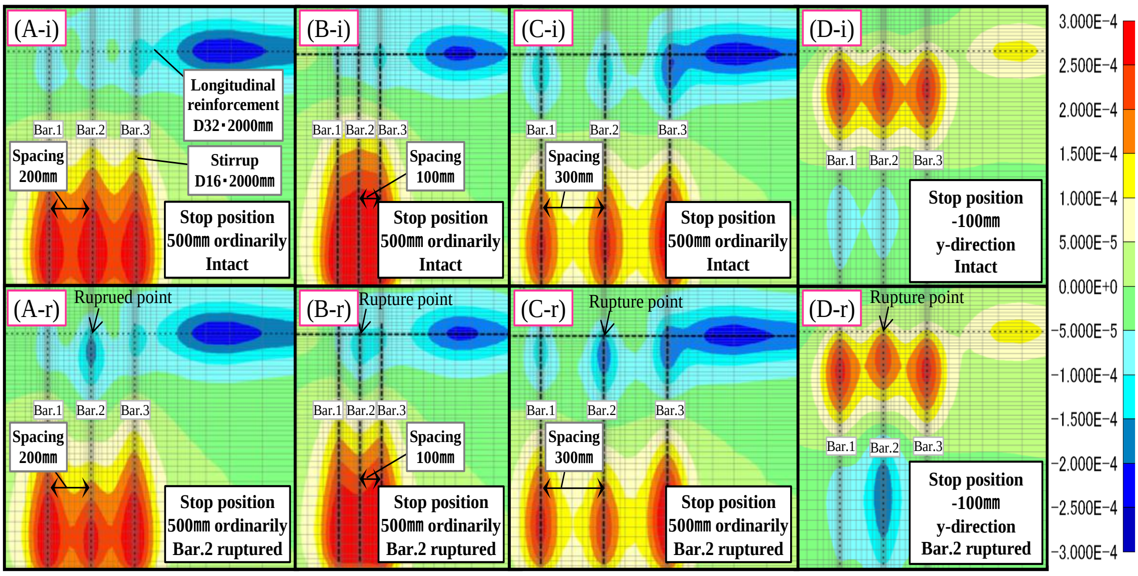
Figure 9. The spacing between steel bars and applicability of the indicators (Stop position of magnification: x = -100mm, the y-direction magnetization)

Analytical results. Figure 10 shows a part of the results in contour diagrams of z-direction magnetic flux density on the front surface (just like the front view in Figure 3). As the first step here, the validity of the indicators used in the experience was evaluated by comparing tendencies of the indicators subjected to the factors in between the analyses and the experiments.

From Figure 10 (A), the ruptured steel bar had lower and steeper magnetic flux density peak than intact ones. From (B), when a pitch was as small as 100mm, reinforcing bars next to each other interacted with each other, which lead to weaken the characteristic of the ruptured steel bars. From (C), when the pitch was 300mm, Bar.3 was similar to ruptured Bar.2. This may be caused by a negative pole generated in the end of the longitudinal reinforcement.

From (D), when using y-direction magnetization, the peak point of the ruptured steel bar was closer to the bent point than intact ones. In addition, the ruptured one had remarkable negative magnetic flux density at the point around 500 ~ 700mm far from the bent point.

These analytical results are wholely similar to the experimental results and demonstrate applicability of experimental indicators as well as validity of the experiment and analysis in this study.



S=200mm S=100mm S=300mm S=200mm (y-direction)

Figure 10. Magnetic flux density on the front surface from FE analysis (Longitudinal reinforcement: present)

CONCLUTIONS

In this study, the magnetic method to single surface were focused to obtain suitable indicators to judge the corner rupture of multiple steel bars in concrete with experiments and FE analysis. Simplification of the magnetization process was also examined. Major results are summarized as follows:

1. Possible reduction in magnetization length was found in applying the magnetic method to multiple steel bars. In addition, another simplified method using y-direction magnetization with the 500 Magnetic Flux Density as an indicator was proposed.

2. The peak value generally had good applicability in the ordinal magnetization process although it was influenced by the magnetization length and the spacing between steel bars. The 500 Magnetic Flux Density could also clearly detect the rupture in y-direction magnetization.

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