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Development of a Method to Make Existing Reinforced Concrete Structures Fragile, using Theprinciple of Induction Heating

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Abstract

In existing buildings, demolitions and new constructions are performed to respond to the rapidly changing needs of society regardless of the structure's performance. In terms of the demolition ability of the construction materials, for the demolition ability at the early stages of design when remodeling is considered, technologies that reduce the energy required for the recycling process and have minimal environmental impact are necessary. Currently, in each industrial sector in the 3R (Reduce, Reuse, Recycle), considering the materials designed for this degradation is an important issue. These material designs are introduced in many industry sectors (especially in the electronics sector) for easy maintenance, upgrade, and recycling after the demolition work. Moreover, demolition ability is considered to be an important issue in the facilities field. In this study, the feasibility of the induction heating method as a demolition method was investigated. First, using an induction heating device, the temperature changes in the rebar were measured according to the power rate. Then, the heated rebar was used to weaken the concrete structure. In the process, the demolition ability of induction heating method was evaluated.

Keywords: deconstruction, heat induction, ease to scrap, heat transfer, weakening

INTRODUCTION

High-frequency induction heating is a method of heating a material by using eddy current loss or hysteresis loss occurring in a dielectric material placed inside an alternating magnetic field.

When an alternating current flows through the coil, a magnetic field is generated according to the principle of electromagnetic induction, which changes for the current is an alternating current. Therefore, as shown in Fig. 1, an induced eddy current (overcurrent) is generated in the metallic body in the coil without conducting wires, thereby generating heat due to resistance loss. Further, when an alternating current flows through the coil, a magnetic flux is generated inside the metal body surrounded by the coil. If the metal body is a magnetic body such as iron, the magnetic flux draws a hysteresis loop for the alternating current. Every time the loop is drawn once, the energy corresponding to the area enclosed by the loop is supplied from the external magnetic field to the magnetic body, whose magnetic energy is then converted into heat energy. In general, however, induction heating does not produce a closed magnetic path like a transformer, and the magnetic flux density is extremely large at 1 T (tesla=1Wb/m2)), so the effective permeability and the hysteresis coefficient are also small. Moreover, as the frequency used increases above 10 KHz, the hysteresis loss becomes negligible because the eddy current loss increases proportionally with the square of the frequency.

Metals such as iron and stainless steel with adequate electric resistance are suitable as the heated material, while copper or aluminum with high electric conductivity are not as not enough heat is generated. Table. 1 shows the infiltration depth δ of various materials. If a high-frequency current flows through the conductor, a larger amount of current flows through the surface than the exterior. This is called a surface effect, and it reduces current by 1/e (36.8%) compared to the surface.

Table 1: Electric conductivity and infiltration depth of materials

Material	Permittivity ($\times 10^7$S/m)	Resistivity ($\times 10^{-8}\Omega$ - m)	Infiltration depth (㎛)
Silver	6.17	1.62	1.30
Copper	5.92	1.69	1.32
Gold	4.66	2.15	1.49
Aluminum	3.82	2.62	1.65
Nichrome wire	0.10	100	1.65
Brass	2.6	3.85	2.00
Nickel	1.5	6.67	2.63
Steel	1.0	10.00	3.22
SUS304	0.14	71.43	8.60
Titanium	0.18	55.0	7.58

$$\delta = \sqrt{\frac{\sigma}{\pi f \mu_r \mu_0}} \tag{1}$$

where δ = infiltration depth

σ = resistivity

f = frequency

μ_0 = vacuum permeability

μ_r = relative permeability of the heated object

As shown in Table 1, the infiltration depth is shallow in materials having high conductivity, such as gold, silver, copper, and aluminum, and the infiltration depth is deep in materials having low conductivity, such as stainless steel, titanium, and steel. In terms of heat generation, it is also confirmed that the heat generation is small in the former because of a small loss and is large in the later because of a large loss.

Using the aforementioned principle, the purpose of this study is to establish a technique to easily dismantle buildings for energy conservation. By using the induction heating method, which can heat the reinforcing steel without directly contacting it inside the reinforcing concrete, the feasibility of the technology is verified by devising a demolition technique, a concrete member, and by evaluating the demolition performance of the concrete member.

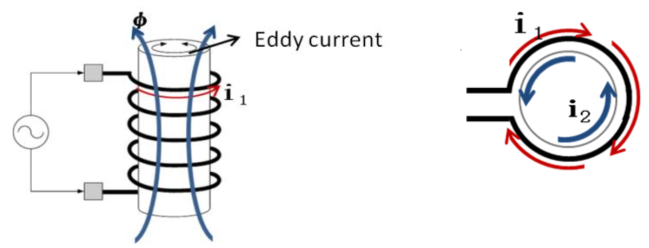


Figure 1: Flux of magnetic induction Ø by AC i_1 and Eddy current i_2

MATERIALS AND METHOD

Temperature Characteristics of Reinforcing steel from Induction Heating

Experimental variables and levels

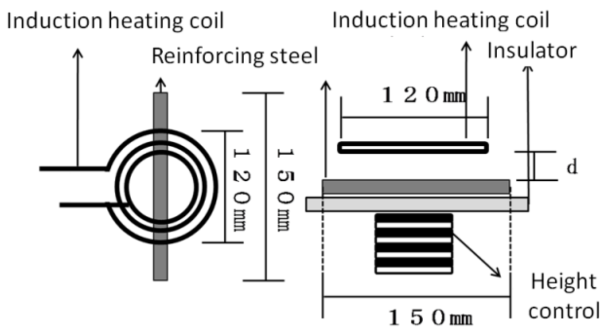
In this experiment, as shown in Table 2, the type of reinforcing steel, the distance to the heating coil, and the power output were used as experimental parameters. The length of the reinforcing bar was 150 mm, and five types—D6, D10, D19, D25 and D32—were used. The distance from the heating coil to the surface of the reinforcing bar was set to 10 mm, 20 mm, 30 mm, and 50 mm, and the output to 5 kW and 6 kW.

Reinforcement Heating by Induction Heating

For induction heating, a basic frequency of 120 kHz (operating frequency 60–120 kHz) with the maximum output of 6 kW was utilized. A pancake type heating coil with a size of Ø120, a diameter of Ø10, and three revolutions was implemented. Five kinds of reinforcing steel each cut to a length of 150 mm were arranged to be parallel to the center of the heating coil surface, and the distance from the bottom surface of the heating coil to the surface of the reinforcing bar was adjusted to measure the highest contact temperature at the middle area of the reinforcing bar surface. The change in temperature, which ranged from 0°C to 800°C, was measured by thermography. The heating method of the reinforcing steel using induction heating is shown in Fig. 2.

Table 2: Experiment factor and level

Experiment factor	Level
Reinforcing steel kind (Length 150mm)	D6, D10, D19, D25, D32
Distance to coil (d)	10mm, 20mm, 30mm, 50mm
Output	5kW, 6kW



(a) Ground plan (b) Section

Figure 2: Method for investigating the induced heating of the reinforcing steel

RESULT AND DISCUSSION

Temperature Characteristics of Reinforcing steel

Figure 3 shows the experimental images and thermal image data measured by thermography. Figures 4 and 5 shows the results of the temperature rise characteristics of the reinforcing bars using induction heating of 5 kW and 6 kW, respectively. As shown, the results of 5 kW and 6 kW exhibit no significant difference.

In regards to time and temperature, when the distance from the heating coil to the surface of the reinforcing bar is 10 mm, 20 mm, and 30 mm, the target temperature reaches 300°C (concrete embrittlement temperature specified in this study) within 60 s. The temperature increases rapidly as the distance from the heating coil becomes smaller, with a sharp increase up to 600 °C or higher. For distances of 10 mm and 20 mm, the thermal equilibrium state was observed between 600 and 800°C, and for the distance of 30 mm, thermal equilibrium was observed between 500 and 700°C. However, the distance of 50 mm required a time of 300 s or longer to reach the target temperature of 300° C.

As a result, it was found that the temperature near the surface of the reinforcing steel suddenly increased in a short time immediately after heating, and that the temperature remained almost constant thereafter. Therefore, considering the demolition performance and the energy effect, a distance of less than 30 mm, which exhibits a sharp gradient of temperature rise, is suitable for heating up to 6 kW.

D6, D10, D19, and D25 exhibited sudden temperature rises; however, the temperature rise characteristics of D32 were lower than those of other types of reinforcing steel. Because induction heating rapidly heats the surface of the reinforcing bar, for a thick reinforcing bar with a large diameter, a longer time is required for the molecular movement inside the reinforcing bar until the temperature difference of the entire reinforcing bar is constant owing to the surface heating effect.

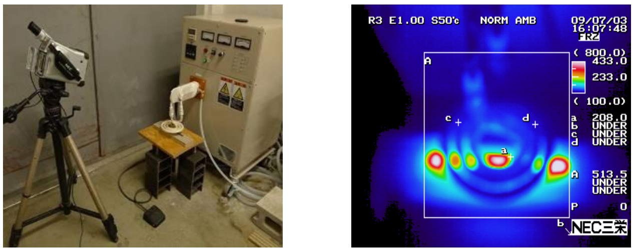
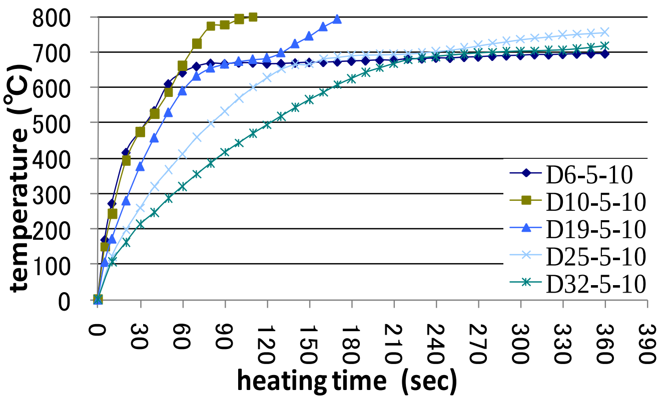
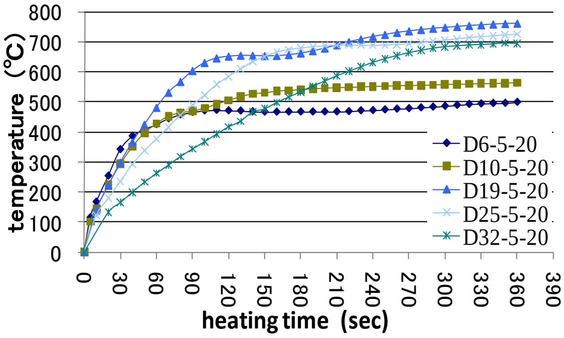


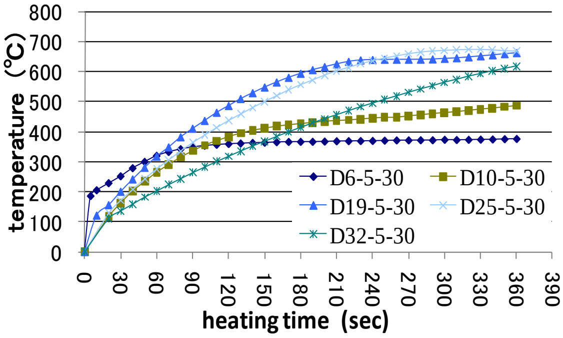
Figure 3: Thermography and measured heat image screen



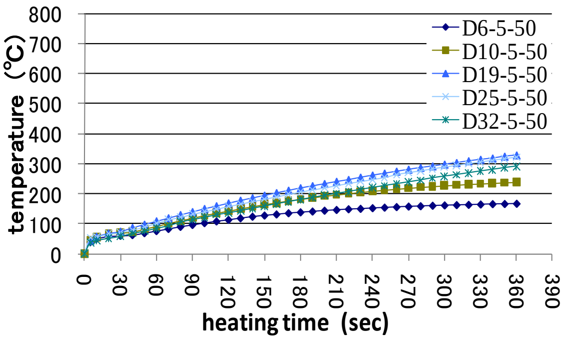
(a) Heating distance - 10mm



(b) Heating distance - 20mm



(c) Heating distance - 30mm



(d) Heating distance - 50mm

Figure 4: Temperature property of Reinforcing steel (5kW) (D00－0－0 : D Reinforcing steel kind-Output kW-Distance mm)

Temperature distribution property of Reinforcing steel

Overheating, lack of heating, or irregular temperature gradients during the process of heating reinforcing steel by using the induction heating method may result in weakening of the concrete due to the temperature rise.

Analysis of the temperature distribution characteristics of reinforcing steel based on the induction heating method of 5 kW and 6 kW using the infrared radiation temperature measurement method, which are illustrated in Fig. 6, shows that the heating distance 10mm has the highest temperature rise rate. The horizontal axis of the graph represents the length of the 150 mm-long specimen, yet there may be some errors in the infrared temperature measurement. The horizontal axis is in the range of 160 ± 5 mm on average, and an error of 10 ± 5 mm due to radiant heat is considered to have no significant influence on the heat measurement at the center or the ends.

In most specimens, the center area was intensively heated compared to the end portion. The portion of the reinforcing steel outside the heating coil range of 120 mm in diameter exhibited a temperature range of 150-450°C as compared with the central portion, thus calling for further considerations of the temperature deviation.

DEMOLITION EXPERIMENT OF THE REINFORCING CONCRETE

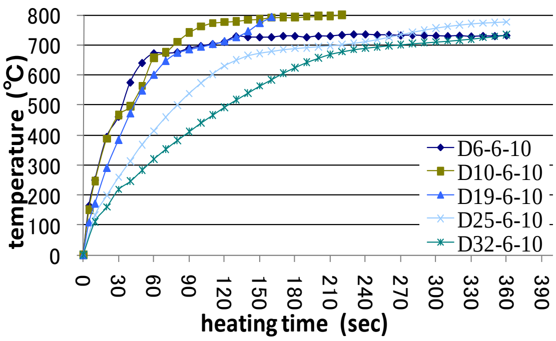
Experimental variables and levels

In this experiment, the type of reinforced concrete inside the concrete, the distance to the heating coil, and the output were used as experimental parameters. D10, D19, and D25 (type) were used for the reinforcing steel, and the heating distances of the reinforcing bar were 20 mm, 30 mm, and 40 mm (Fig. 7), with the output fixed at 6 kW. Table 3 shows the experimental parameters and levels.

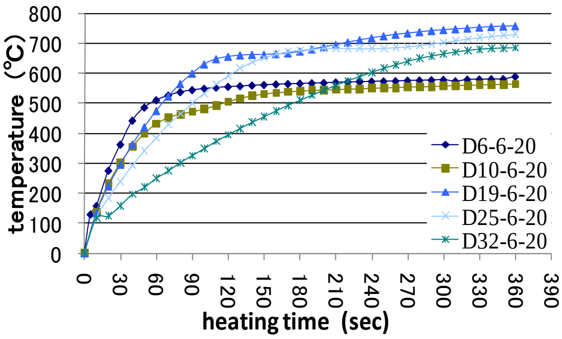
Method

For the induction heating, the test specimens were heated with a basic frequency of 120 kHz (operating frequency 60–120 kHz) and a maximum high frequency output of 6 kW, and the characteristics of temperature rise and the change in bonding strength between reinforcing steel and the concrete were measured.

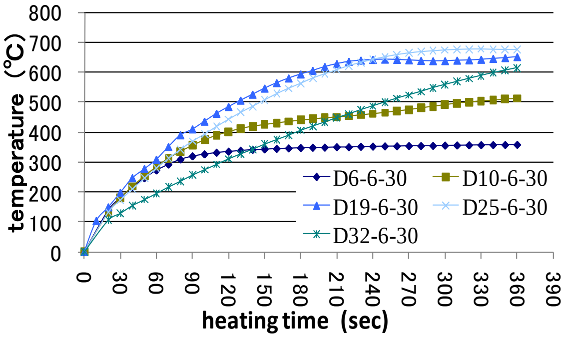
A 100 × 100 × 150 mm specimen made of concrete (W/C = 50%) reinforced with a 180-mm long deformed bar was made to evaluate the induction-heating heat transfer characteristics of the reinforced concrete using a thermocouple. The bonding strength test was performed to evaluate the residual bond strength before and after heating. Figures 7 and 8, and Table 4 show the method of making the reinforced concrete specimen and the strength test method of the reinforcing steel.



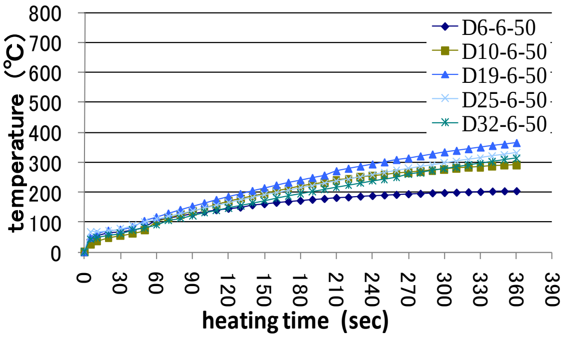
(a) Heating distance - 10mm



(b) Heating distance - 20mm



(c) Heating distance - 30mm



(d) Heating distance - 50mm

Figure 5: Temperature properties of reinforcing steel (6 kW) (D00－0－0 : D Reinforcing steel kind-Output kW-Distance mm)

Table 3 Experiment factor and level

Experiment factor	Level
Reinforcing steel kind (Length 150mm)	D10, D19, D32
Distance to coil (d)	20mm, 30mm, 0mm
Output	5kW, 6kW

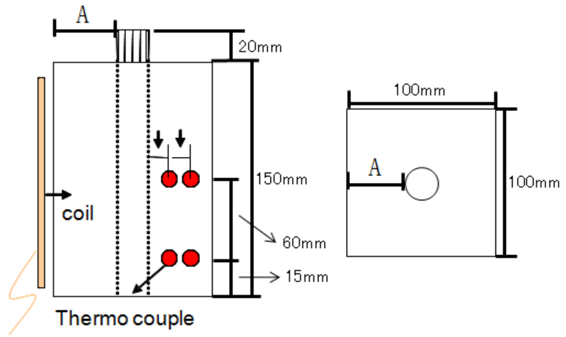


Figure 7: Position of reinforced concrete test body and thermo couple

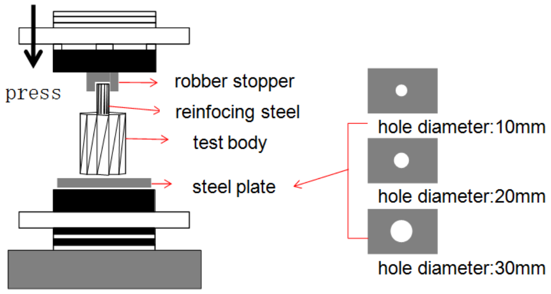
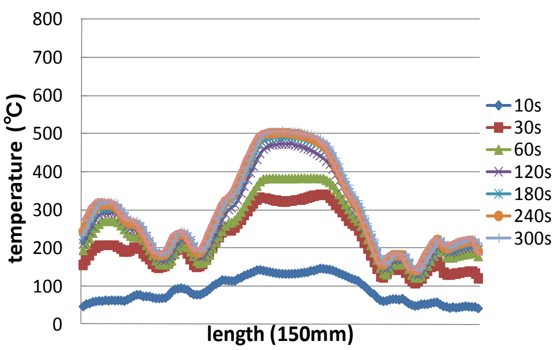


Figure 8: Method of investigating bond strength of reinforced concrete

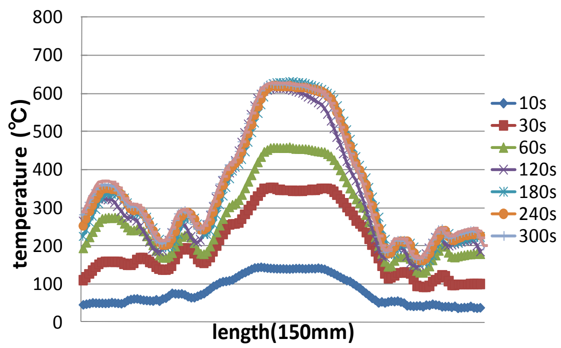
Table 4 Concrete mixture

Mixture strength (N/mm^2)	Slump (cm)	Air (%)	W/C (%)	s/a (%)
24	12	3	50	45

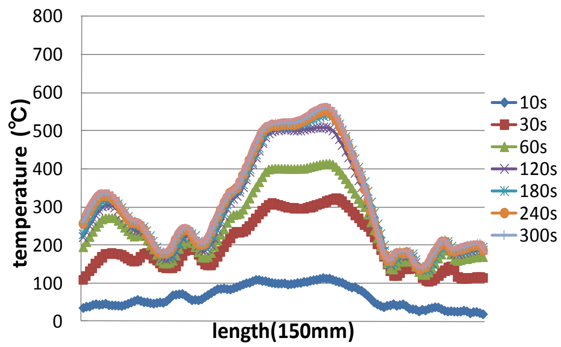
Wunit (kg/m^3)	Mass			a compound
	C	S	G	
180	360	799	1003	(0.3%)



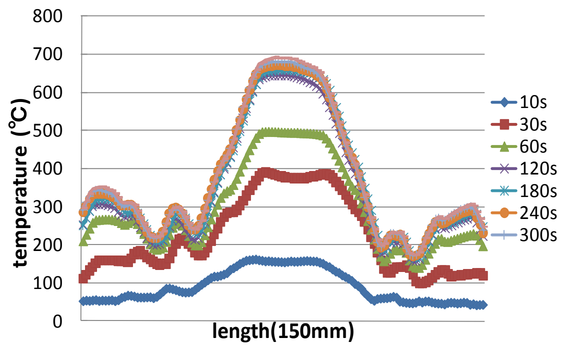
(a) D6-5kW



(b) D10-5kW



(c) D6-6kW



(d) D10-6kW

Figure 6: Temperature distribution of reinforcing steel concrete by induction heating

RESULT AND DISCUSSION

Temperature Measurement and Characteristics of Reinforced Concrete

The results of the increasing temperature characteristics around the reinforced concrete measured by the thermocouple are shown in Fig. 9.

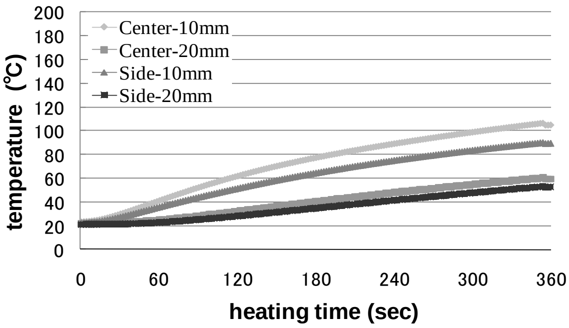
In the legend, the center represents the position at 75 mm, in the middle of the 150 mm-long concrete specimen, and the side at 15 mm. Furthermore, 10 mm and 20 mm represent the distance from the surface of the reinforcing bar inside the test body to the thermocouple.

When the heating was carried out at 6 kW for 360 s, the temperature change in the concrete was measured with a thermocouple at 10 mm and 20 mm away from the center of the steel bar.

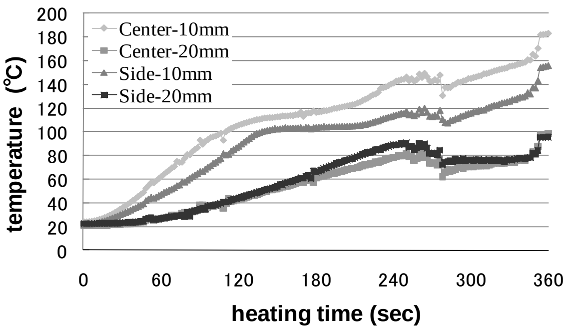
As a result of induction heating, the temperature increased first at the center of the reinforcing steel apart by 10 mm, followed by the end by 10 mm, the center by 20 mm, and the end by 20 mm; the temperature difference at 10 mm and 20 mm away from the core of the steel was 46–90°C.

As shown in Fig. 9, in which the distance from the heating coil was 40 mm in the specimen using D19, the temperature difference at 10 mm and 20 mm away from the center of the reinforcing steel was not large. A temperature difference of 74–83°C was generated at the ends, unlike at the center. However, the difference between the maximum and the minimum temperature was 30°C or less, which had no significant effect on the concrete heat conduction.

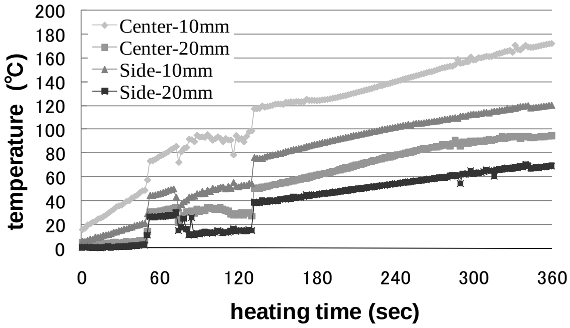
When a single reinforcing bar D10 was heated at a distance of 30 mm for 360 sec, the maximum temperature at the center of the reinforcing bar was 510°C. However, when the reinforcing bars inserted into the concrete were heated as in Fig. 9, the maximum temperature of the concrete 10 mm away from the center of the reinforcing surface was 106°C. In addition, the maximum temperatures in D19 and D25 at which only the reinforcing bars were heated were 651°C and 613 °C, respectively; however, when the reinforcing steel inserted in the concrete were heated as shown in Figs. 9 (a) and (b), the maximum temperature at the point 10 mm away from the center of the concrete was 171°C and 139°C, respectively, indicating that time is required for the heat to be transferred from the surface of the reinforcing steel to the outside of the concrete.



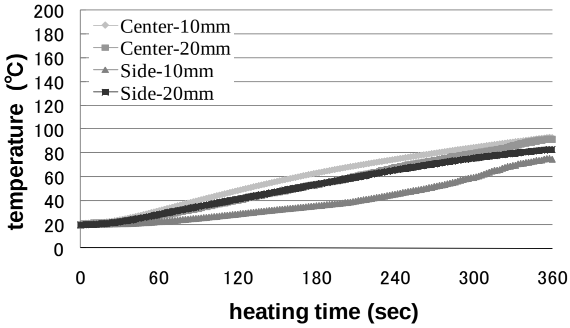
(a) D10-30mm



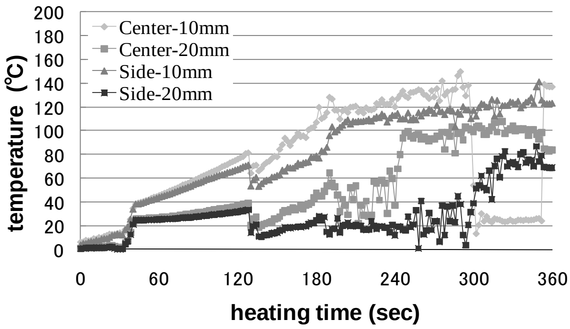
(b) D19-20mm



(c) D19-30mm



(d) D19-40mm



(e) D25-30mm

Figure 9: Reinforced concrete temperature rise characteristic by induction heating

Cracking of reinforced concrete and strength test of reinforcing steel

The generated cracks after heating the concrete member using the induction heating method are shown in Fig. 10, and the measured results of the steel bond strength test are shown in Fig. 11 and Table. 5.

For the 20 mm of reinforced concrete specimen inserted with D19, cracks occurred up to the surface of the concrete within about 50 s following heating. The shorter the distance from the heating coil, the shorter the time of crack generation, and the larger the size and width of cracks.

Comparing the results of the bonding strength test of the specimens before and after heating, the residual strength of the rebars was calculated to evaluate the weakness properties of the concrete after heating the reinforcing steel.

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D32 exhibited the lowest residual strength after heating, while D10 showed the highest residual strength. D19 did not show significant difference for distances of 20, 30, and 40 mm.

The sizes of the test specimens were unified in this experiment and only the positions of the reinforcing steel were moved. Therefore, it is considered that the error due to the thickness of the concrete and the heating distance caused by the diameter of the reinforcing steel affected the residual strength of the reinforcing bar strength.

However, as the reinforcement inside the original reinforced concrete is heated, cracks appear in a short time from the surface of the inner reinforcing bar to the surface of the concrete due to the expansion pressure of the reinforcing bar. In the case of D19-40 mm, where the reinforcing steel were placed at the center of the specimen, the attachment rate was reduced by 31%. When the reinforcing bar is locally heated by using the induction heating method, the expansion pressure of the bar increases due to the temperature rise that forms a sharp gradient, generating cracks. Later, the concrete is weakened as a high temperature is delivered to the concrete close to the reinforcing bar from the reinforcement surface.

As shown from the reinforcing bar sample separated after the strength test in Fig. 12, the concrete around the reinforcing steel is weakened, and the reinforcing steel and concrete are cleanly separated. Therefore, the heating method using the induction heating can be applied as a basic technique for separating and dissembling the reinforcing bar and concrete.

Figure 10: Sample of a test body after it is heated and cracks are induced

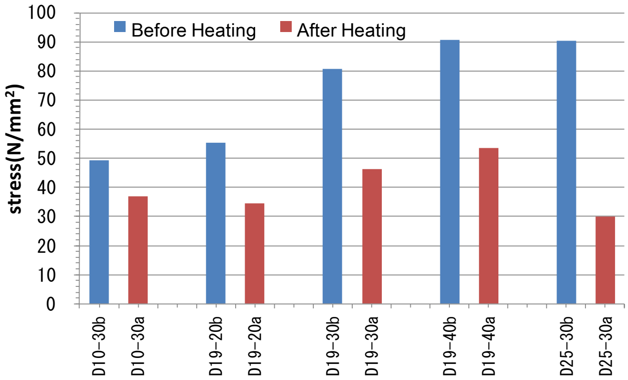

Figure 11: Reinforced concrete bond strength before and after inducement heating

CONCLUSIONS

In this study, experiments were performed to investigate the temperature rise characteristics of a single reinforcing bar and a reinforcing concrete, and the demolition characteristics of the members made of reinforced concrete using the induction heating method. The following conclusions were drawn.

Table 5: Change in reinforced concrete adhesion by induction heating

	Induction Heating (Before)	Induction Heating (After)	Strength remaining ratio
D10-30mm	49.25kN	36.79kN	0.75
D10-30mm	55.42kN	34.41kN	0.62
D10-30mm	80.75kN	46.15kN	0.57
D10-30mm	90.75kN	53.46kN	0.59
D10-30mm	90.35kN	30.10kN	0.33

1) Unlike the conventional dielectric heating method, the induction heating method only heats the surface rapidly, which makes it possible to raise the surface temperature of a single reinforcing steel by 600° in 60 s using a small power of 5 kW and 6 kW.
2) If the induction heating method is used as a decomposing mechanism, it is possible to apply the basic technique of demolishing the member by weakening the strength of the reinforcing bar by 30% or more for a concrete member with an output of 6 kW, a rebar diameter of 20 mm or less, and a coating thickness of 30 mm or less. Furthermore, by separating the reinforcing steel from concrete, it can be reused as a single material without the secondary process.
3) In weakening the concrete using induction heating, it is considered that the selection of the type of reinforcing steel and the heating distance would be important factors in the demolition efficiency. In addition, a careful examination is necessary afterward.

Based on the result of this experiment, the method proposed can be applied to actual existing members if the output amount of induction heating is increased. However, it is necessary to investigate the behavior of vapor pressure inside the concrete member by heating and the heat conduction characteristics from the inside of the concrete to the surface layer. Furthermore, a method for completely separating reinforcing steel from concrete after cracking should be investigated.

ACKNOWLEDGMENTS

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