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An experimental study of damage characteristics at bond of RC after microwave heating

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Research Paper

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An experimental study of damage characteristics at bond of RC after microwave heating

With an increase in urban construction waste, and in order to find an effective method of microwave-assisted mechanical RC regeneration, thermal damage characteristics of the interfacial bond between steel rebar and concrete after different microwave irradiations are analysed in this paper. The results show that, with an increase in microwave power, the overall failure mode of the specimen changes from splitting failure to pull-out failure. Bond slip curves and the corresponding fitting equations were obtained at various levels of microwave irradiation. By analysing characteristic points of the curve, 3500W was determined as a reasonable irradiation power.

Key words:
microwave irradiation, reinforced concrete, damage, failure characteristics, bond slip curve

Prethodno priopćenje

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Eksperimentalno istraživanje svojstava oštećenja na spoju armature i betona nakon mikrovalnog zagrijavanja

Povećanjem urbanog građevnog otpada s ciljem da se nađe učinkovita metoda mehaničke regeneracije armiranog betona uz pomoć mikrovalnog zračenja, u ovom se radu analiziraju svojstva termičkog oštećenja na kontaktu spoja između čelične rebraste armature i betona nakon različitih mikrovalnih zračenja. Rezultati su pokazali da je povećanjem snage mikrovalnog zračenja došlo do promjene sloma uzorka – umjesto sloma cijepanjem, nastao je slom izvlačenjem armature, a krivulja proklizavanja spoja, kao i odgovarajuće jednadžbe prilagodbe odredile su se nakon različitih razina mikrovalnog zračenja. Analizom karakterističnih točaka krivulje, određeno je da je 3500 W prihvatljiva snaga zračenja.

Ključne riječi:
mikrovalno zračenje, armirani beton, oštećenje, svojstva sloma, krivulja proklizavanja spoja

Vorherige Mitteilung

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Verlängerung der Verwendbarkeit von Schienen bei Schäden des Schienenkopfes

Während ihrer Verwendung sind Schienen aufgrund von Biegung den Prozessen von Verschleiß, Korrosion und Kontaktermüdung ausgesetzt. Infolge dieser Prozesse treten verschiedene Schäden und Mängeln an den Schienen auf. Die weitere Verwendbarkeit der Schienen hängt von der Größe, Position und Richtung des Schadens ab. In dieser Arbeit werden die maximal zulässigen Werte der Rissgröße nach der Finite-Elemente-Methode berechnet. Die Richtung der Rissebene wurde in Bezug auf die Ebene der Rad-Schiene-Kontaktfläche analysiert. Die Abhängigkeit des Spannungsgrößenfaktors von der Rissoberfläche wurde bestimmt. Dies ermöglicht die weitere Verwendung beschädigter Schienen und die sichere Fortsetzung des Betriebs auf Eisenbahnschienen mit weniger Aktivität.

Schlüsselwörter:
Eisenbahnschiene, Schienenbeschädigung, Finite-Elemente-Methode, Riss

1. Introduction

With acceleration of China's urbanization process, it is necessary to dismantle a large number of reinforced concrete structures every year to complete the alternate renewal of new and old buildings [1, 2]. Drawbacks of traditional demolition methods, such as high noise, dust, and inefficiency during demolition, have increasingly limited their use in cities [3]. Microwave-assisted mechanical demolition can weaken the bond between steel rebar and concrete in advance [4], thus enabling an efficient and environmentally-friendly demolition of urban buildings. Therefore, it is necessary to study the damage of reinforced concrete adhesion caused by microwave irradiation. A good bond between steel rebar and concrete is the foundation enabling reinforced concrete components to jointly bear the external load [5]. If a reinforced concrete structure is in a high temperature environment, the bond performance between steel rebar and concrete will be greatly affected [6]. Up to now, many scholars have studied properties of bond between steel rebar and concrete by means of experiments, and have proposed in this respect a number of experimental models and bond-slip fitting curves for a variety of load conditions.

An experimental program was used to determine the effect of high temperature on the interfacial bond shear modulus between concrete and reinforcement [7]. Results of the pull-out test were then used, along with an analytical model, to calculate the bond shear modulus. The analytical model was based on physical representation of the pull-out test, assuming linear elastic behaviour of both steel and concrete. Lu [8] made a reinforced concrete specimen measuring 100 mm × 100 mm × 10·d mm (d is the steel bar diameter) and conducted a central pull-out test. The test results showed that the higher the concrete strength, the higher the bond strength. The ultimate tensile strength increased with an increase in steel bar diameter. After the specimen was subjected to high temperature of 300 °C, the bond strength between the steel bar and concrete increased compared to normal temperature. The reason was that the cement inside the specimen had not been completely hydrated, and an appropriate temperature had a certain catalytic effect on hydration of cement inside the concrete, and so the bond strength increased. To investigate the effects of elevated temperatures on bond behaviour between steel bars and concrete confined with stirrups, Liu [9] carried out the pull-out tests and established that all specimens suffered the unplug damage due to confinement of stirrups. Furthermore, there was a trend of decrease in bond strength with an increase in temperature. When the temperature reached 700 °C, the bond strength reduced by about 65 % compared to normal temperature. Finally, a statistical formula on bond-slip curve, considering also the parameter of temperature, was presented. Bonding properties between the reinforcing bar and concrete at 20 °C to -165 °C were analysed by pull-out tests, considering parameters such as temperature, bar diameter, concrete cover thickness, anchoring length, and yield strength of rebars [10]. Experimental studies revealed that bonding properties are significantly dependant on temperature, i.e. the bonding strength increased linearly with a decrease in temperature, and reached the maximum at -80 °C to -120 °C. Furthermore, the enhancing coefficient of bonding strength decreased linearly with the relative cover thickness. Finally, other parameters, such as the anchoring length and yield strength of steel, had little effect. Chiang [11] studied the bond strength between the steel bar and concrete at various temperatures and established a relationship between the bond strength, temperature, and heating time. Hasan [12] made a quantitative analysis of the bond slip relationship between reinforced concrete by taking into account factors such as thickness of protective layer, strength, and temperature of concrete. Haddad [13] determined the influence of different surface forms and reinforcement diameters on the degradation law of bond strength of reinforced concrete at high temperature on the basis of the bidirectional tension test. Katz [14] studied the effect of high temperature on the bond between fibre reinforced polymers (FRP), reinforcing bars (rebars), and concrete. The bond strength exhibited a severe reduction of 80 % to 90 % at relatively low temperature (up to 200 °C), which was accompanied by changes in the pullout load-slip behaviour. A semi-empirical model was developed in order to describe the extent of reduction in bond strength with an increase in temperature. The parameters of rods that were tested for pullout at various temperatures were introduced into the model. The output curves of bond–temperature relationships showed good agreement with test results. Yang [15] conducted the tensile strength test of the steel bar at high temperature, the splitting tensile strength test of the standard cube at high temperature, the temperature field test, and the centre drawing test. The results showed that the strength of rebar at high temperature showed little change below 400 °C, the tensile splitting strength of concrete decreased linearly with temperatures, and the variation trend of bond strength under high temperature was similar to the tensile strength of concrete. The results presented two different relationships between bond stiffness and temperature by the slip of 0.015 mm. With the central pull-out test, the bond strength of reinforced concrete was measured at different temperatures and different cooling methods after high temperature, and the ultimate bond strength and slip of reinforcement and concrete under different conditions were analysed [16]. The results showed that the bond strength decreased gradually with an increase in temperature, while the ultimate slippage also decreased gradually. The effects of material properties on bond strength between reinforcing bar and concrete exposed to high temperatures were investigated extensively using modified pullout tests [17]. Experimental results indicated that the residual bond strength between the reinforcing bar and concrete decreased with an increase in temperature. The first severe bond strength loss was observed for grade S220a in the range from 200 °C to 400 °C and for grade S420a and S500a in the range from 400 °C to 600 °C. The residual compressive strength agreed with the residual bond strength of S420a and S500a, whereas the residual flexural strength agreed with the residual bond strength of S220a.

To sum up, although many research activities are currently conducted on the demolition of reinforced concrete structures, there are still many shortcomings that hinder wider use [18-21]. As a systematic crushing and dismantling method, microwave-assisted machinery is not only applicable to rock breaking [22, 23] but can also be applied to the demolition in narrow urban spaces and to the demolition of special reinforced concrete structures. In the research on bond performance of reinforced concrete at high temperature, most specimens are heated in electric furnace at a slow heating rate and at low temperature gradient, and the corresponding results are mostly applied in fire protection [24]. Therefore, in order to extend the technology of microwave-assisted mechanical demolition of reinforced concrete to engineering applications and to enable wider use of such technology in engineering, it is necessary to conduct an in-depth study on the bond damage and failure characteristics between steel rebar and concrete under microwave irradiation at the initial stage.

In view of the above problems that are based on previous studies, the focus is placed in this paper on reinforced concrete as the research object, on the conduct of microwave irradiation and pull-out tests using standard reinforced concrete specimens, and on the study of bond strength attenuation and failure characteristics of reinforced concrete specimens subjected to microwave irradiation.

2. Basic principles of microwave heating and damage model

Concrete consists of natural aggregate and mortar. As aggregate and mortar differ in electromagnetic properties and microwave induction, the temperature in concrete is uneven after microwave exposure for a time period, and the temperature in mortar rises faster than that of natural aggregate. The difference in temperature will cause temperature stress in concrete, especially at the interface between mortar and natural aggregate. At the extension of microwave irradiation time, temperature stress gradually increases, resulting in the new cracks in concrete, and the bond between mortar and natural aggregate also gradually weakens. In addition, internal water vaporization also occurs and extends the cracks in concrete. The microwave power lost per unit volume in concrete medium P_d can be expressed as follows [25]:

$$P_d = 2\pi f \varepsilon' \varepsilon'' M^2 \quad (1)$$

Where P_d is the dissipation density of microwave power, f is the frequency, ε' is the vacuum nodal coefficient, ε'' is the dielectric loss factor, and is the effective electric field strength.

According to an average power density, the heating rate of minerals in concrete under microwave irradiation can be expressed as follows:

$$C_p \rho_0 \frac{\partial T}{\partial t} = P_d + \nabla \cdot (k \nabla T) \quad (2)$$

Where C_p is the specific heat capacity, ρ_0 is the mineral density, and k is the coefficient of thermal conductivity.

It is assumed that the bond performance parameters at the interface are B in the lossless state and B' in the damaged state [26]. The damage variable D can be expressed as follows:

$$D = \frac{B - B'}{B} \quad (3)$$

When $B = B'$, $D = 0$, there is no damage to the material interface. When $B' = 0$, $D = 1$, the material interface is completely damaged. When $0 < D < 1$, the material interface is damaged to varying extent. The bond stress is expressed as τ, and slip is expressed as S. The following Equation (4) can be obtained:

$$\tau = B'S \quad (4)$$

Combined with the strain equivalence principle, it is assumed that the amount of slip corresponding to the initial Cauchy bond stress at the damaged bond interface of the material, is equal to the amount of slip corresponding to the effective bond stress at the non-destructive interface of the material [27]. The following Equation (5) can be obtained:

$$S = \frac{\tau'}{B} = \frac{\tau}{B'} \quad (5)$$

So, the following Equation (6) can be obtained by combining Equation (3):

$$S = \frac{\tau}{B(1+D)} \quad (6)$$

According to Equations (3), (4), (5) and (6), the bond slip constitutive model considering damage is:

$$\tau = \begin{cases} S \times B & (0 < S < S') \\ S \times B' & (S' < S) \end{cases} \quad (7)$$

In addition, the evolution equation of interfacial bond damage is:

$$D = \begin{cases} 0 & (0 < S < S') \\ 1 - \left(\frac{\tau}{S}\right) / B & (S' < S) \end{cases} \quad (8)$$

The slippage at each point corresponds to the initial slope value B in the bond slip curve of reinforced concrete, and the D value of slip can be obtained at each point. Using regression analysis, the damage evolution equation can be obtained by fitting the relative amount of slip and damage corresponding to each point. The constitutive equation of bond slip considering the damage can also be obtained.

3. Experiment design and preparation

3.1. Experiment design

The centre pull-out test used in this study is based on the Chinese "Standard on Test Method for Concrete Structures" (GB50152-92). The design size of the specimen was 150 mm × 150 mm × 150 mm, the specimen was made of ordinary concrete with the strength grade C30, and hot rolled ribbed bars 16mm in diameter and 400 MPa in yield strength were used. Considering the actual size of microwave oven, the length of hot rolled ribbed steel bars was set to 250 mm. The bond length between the reinforced concrete in the specimen was 2.5d (d is the steel rebar diameter), i.e. 40 mm. In order to eliminate the phenomenon of stress concentration at the ends of the specimen during the pull-out test loading process, two PVC conduit sections were arranged at both ends of the steel rebar and sealed with foam filling to form a 110 mm non-bonding section. The length of each section of PVC conduit was 55 mm and the inner diameter was 25 mm, while the bond between the steel rebar and concrete was located at the middle part of the specimens, so as to obtain better failure of the interface of reinforced concrete at this depth. The specimen size, steel rebar, and PVC conduit layout, are shown in Figure 1.

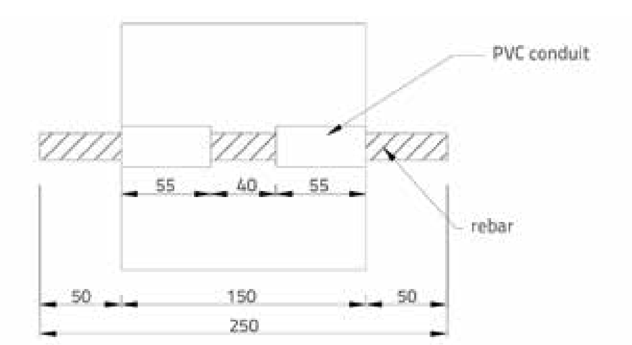

Figure 1. Structural dimension diagram of specimen

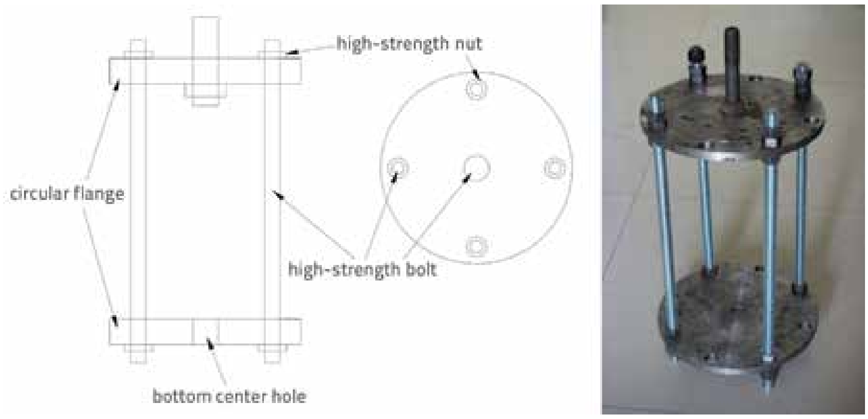

Figure 2. Fixture diagram of pull-out test

3.2. Material and pull-out fixture preparation

The strength grade of concrete designed in this experiment was C30. The cement was the 42.5 grade ordinary Portland cement produced by Tongchuan Shengwei Building Materials co., LTD., Shaanxi province, China. The fine aggregate was made of lime rock crushing sand, with a fineness modulus of 3.82. Coarse aggregate adopted was the 5 mm to 20 mm continuous grading gravel, with a gradation ratio of 4.5 : 3.5 : 2. The bulk density was 1680.4 kg/m^3. Steel rebar is HRB400 type 16 mm in diameter purchased from Daming Palace Steel Market, Xi 'an, China. Cement and steel rebar parameters are shown in Table 1 and Table 2.

The pull-out fixture used in this experiment was customized by Daming Palace Steel Market, the fixture consists of two DN150 high strength firefighting flanges, four long high strength bolts, one short bolt and several nuts. The middle of the round solid flange needed to be punched, as shown in Figure 2.

3.3. Casting and curing of specimens

The strength grade of concrete designed in this experiment was C30. According to Chinese "Specification for mix proportion design of ordinary concrete" (JGJ55-2011), to rule out differences in permeability between specimens, a mix ratio of concrete adopted for adaptation of cement, water, sand and stone was 1:0.46:1.29:1.93 (weight ratio). Steel rebar and PVC

Table 1. Physical and mechanical indexes of cement

Grade	Fineness [%]	Specific surface area [cm^2/g]	Density [kg/m^3]	Final setting time [min]	Compressive strength [MPa]	Flexural strength [MPa]	Ignition loss [%]	Water content [%]
P.O 42.5	4.7	3460	3043	142	229	49.4	2.3	0.38

Table 2. Mechanical properties of steel rebar

Rebar specifications	Nominal diameter [mm]	Nominal cross sectional area [mm^2]	Yield strength [MPa]	Tensile strength [MPa]	Elongation after break [%]	Total elongation at maximum force [%]
HRB400	16	201.06	473.86	639.07	27.9	12.8

conduit were processed in Daming Palace Steel Market, i.e. the steel rebar was processed into 250 mm for each section with a total of 30 sections, and the PVC conduit was processed into 55 mm for each section with a total of 60 sections. It is a 150 mm cube detachable plastic test mould. Due to special requirement for adding steel rebar in the specimen, the centre holes with diameter of 24mm were drilled in the centre of the symmetrical sides of the test mould. Before making the specimen, the separator should be applied to the test mould. Concrete was made in the JG3036-96 single-shaft forced action concrete mixer. under standard curing conditions at the temperature of 20 °C ± 2 °C and at relative humidity of above 95 % according to Chinese "Code for quality acceptance of concrete structure construction" (GB50204-2015). One day after casting, the mould was removed, and under the same conditions the specimens were covered with film, sprayed with water, and cured for 28 days. After curing, specimens were air-dried to constant weight at room temperature before use, to minimize the difference in moisture content between specimens, and to provide conditions for obtaining appropriate microwave irradiation parameters. A total of 30 reinforced concrete specimens were made. The fabrication specimen is shown in Figure 3.

Figure 3. Pull-out test fabrication specimens

4. Determination of experiment heating parameters

The microwave generator used in this experiment, i.e. the ORW10SY-3T high-power microwave oven, is shown in Figure 4. It was produced by Nanjing Aorun Microwave Factory in China. The rated operating voltage and operating frequencies of the microwave oven are 380V and 2450 ± 10 MHz, respectively, and the output power is adjustable and varies from 0 kW to 10kW. The microwave irradiation system consists of a microwave generator and a heating furnace chamber (1050 mm in length, 1050 mm in width, and 1000 mm in height). The two parts are connected by a square aluminium tube. The microwave generated by the microwave generator enters the furnace chamber through the aluminium square tube, and the microwave reflects repeatedly in the furnace chamber made of metal and penetrates the concrete to achieve a uniform and rapid heating effect. The stand off distance is fixed when the specimen is put into the furnace chamber, and so this experiment does not consider the influence of microwave irradiation distance on the results, which provides conditions for obtaining appropriate microwave irradiation parameters.

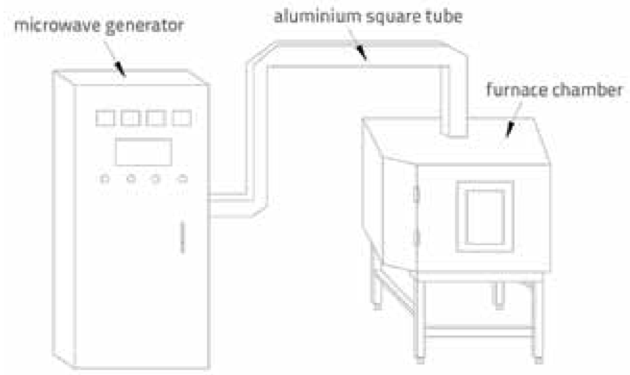

Figure 4. Structure diagram of high power microwave irradiation system

4.1. Preliminary experiment

The specimens of plain concrete used in the preliminary experiment were six cubic blocks with the side length of 100 mm. The concrete used belonged to the same batch as the concrete in the reinforced concrete specimens, and curing was done for 28 days under the same conditions. The moulding specimens are shown in Figure 5.

Figure 5. Concrete moulding specimens used in preliminary experiment

In view of the diversity and complexity of the combination of microwave irradiation power and time, the microwave irradiation time was uniformly limited to 5min in the preliminary experiment and subsequent experiment, and the reasonable power range was determined by microwave irradiation of different power. In the preliminary experiment, microwave with the power of 3000 W, 4000 W, 5000 W and 6000 W was used to randomly irradiate four plain concrete specimens. The result showed that the crack occurred in the plain concrete specimen when the microwave power was 6000 W and the irradiation time was 1 min 16 s. After that, the remaining two concrete specimens were irradiated by microwave with a power of 6000 W, and it was found that the concrete specimens ruptured at 2 min 40 s and 4 min11 s, respectively.

4.2. Parameter determination

Based on the above phenomena, it can be determined that the critical value of irradiation power is 5000 W under the experimental conditions described in this paper, when the microwave irradiation time is constant for 5 min. Therefore, microwave irradiation with a time of 5min and a power of 0 W to 5000 W was determined to heat the specimens in the subsequent experiment.

4.3. Experimental process

The centre pull-out test was conducted using the RFP-09 600kN intelligent dynamometer produced by Tianshui Hongshan Testing Machine Co., Ltd. and the aforementioned pull-out fixture. The testing machine is shown in Figure 6. The force was applied at a rate of 0.2 kN/s by adjusting the control, and the drawing force and displacement were zeroed out before loading and read by the tester sensor. The positions of the specimen and the fixture are shown in Figure 6.

Figure 6. Diagram of testing equipment

According to the range of microwave heating parameters measured in the preliminary experiment, the microwave irradiation time in the pull-out test was determined to be 5min, and the irradiation power was 0 W, 700 W, 1000 W, 1500 W, 2000 W, 2500 W, 3000 W, 3500 W, 4000 W and 5000 W. The specimens were divided into ten groups, with three in each group. The specimens of each group were taken out of the furnace chamber after microwave irradiation and kept at room temperature until the pull-out test. Specimen designations (numbers) are shown in Table 3.

5. Results and discussion

5.1. Failure characteristic analysis

Failure characteristics of the pull-out test for each group after microwave irradiation are shown in Table 4. The external failure photos of representative specimens after reinforced concrete centre pull-out test were sorted out, as shown in Figure 7.

From the external failure images, it can be seen that without irradiation, as the annular tensile stress of the concrete around the steel rebar in the bonding area exceeded the splitting tensile strength of the reinforced concrete, the specimen underwent obvious splitting failure when the steel rebar was pulled out. The main and secondary cracks on the specimen were wide and ran across the whole specimen. The bond strength of reinforced concrete somewhat decreased at 1000 W microwave radiation. After the pull-out test, three cracks appeared on the pull-out surface of the steel rebar, which were roughly 120° around the steel rebar. The cracks were still relatively clear and numerous, but no large crack penetration occurred. The specimen itself was relatively complete and the splitting phenomenon was reduced compared with the specimen after non-irradiated pull-out test. Moreover, a small amount of steel rebar pulling out marks appeared, and specimen underwent a pull-split failure. After 3000 W microwave irradiation, the failure of the specimen was similar to that at 1000 W, i.e. it was also a split-pull failure, except that the width and number of cracks were relatively reduced. After 5000 W microwave irradiation, the bond of reinforced concrete further weakened, and the specimen was only damaged by pulling out without any macroscopic cracks. In order to further study failure of the internal bonding surface of reinforced concrete, the failure specimens of pull-out tests under microwave irradiation conditions of 0 W, 1000 W, 3000 W and 5000 W were cut

Table 3. Specimens numbering table

Power	0 W			700 W		
Number	RC-01	RC-02	RC-03	RC-701	RC-702	RC-703
Power	1000 W			1500 W		
Number	RC-1001	RC-1002	RC-1003	RC-1501	RC-1502	RC-1503
Power	2000 W			2500 W		
Number	RC-2001	RC-2002	RC-2003	RC-2501	RC-2502	RC-2503
Power	3000 W			3500 W		
Number	RC-3001	RC-3002	RC-3003	RC-3501	RC3502	RC-3503
Power	4000 W			5000 W		
Number	RC-4001	RC-4002	RC-4003	RC-5001	RC-5002	RC-5003

Table 4. Statistical table of failure characteristics for each group

Power	0 W			700 W		
Failure characteristic	splitting	splitting	splitting	pull-split	splitting	splitting
power	1000 W			1500 W		
Failure characteristic	pull-split	pull-split	pull-split	pull-split	pull-split	pull-split
power	2000 W			2500 W		
Failure characteristic	pull-split	pull-split	pull-split	pull-out	pull-split	pull-split
power	3000 W			3500 W		
Failure characteristic	pull-out	pull-out	pull-split	pull-split	pull-out	pull-out
power	4000 W			5000 W		
Failure characteristic	pull-out	pull-out	pull-out	pull-out	pull-out	pull-out

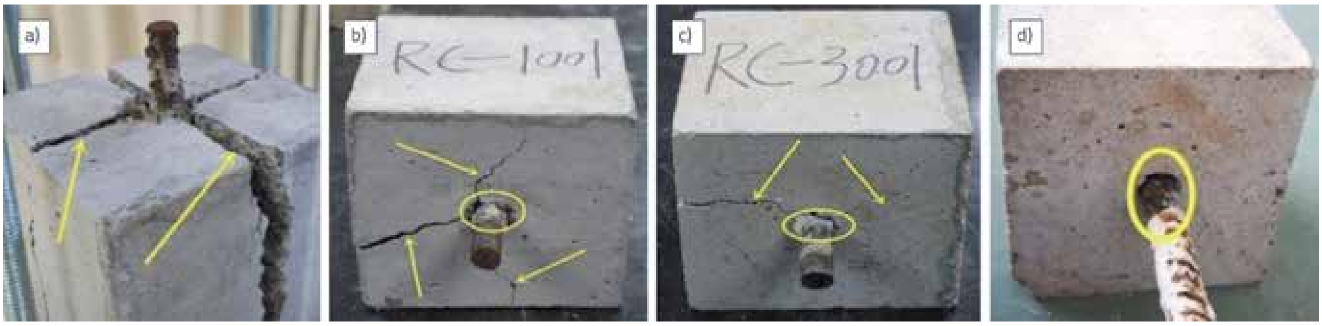

Figure 7. Photos of external damage after microwave irradiation: a) 0 W; b) 1000 W; c) 3000 W; d) 5000 W

open, and the bonding interface of reinforced concrete was observed, as shown in Figure 8.

The image shows failure of the bonding surface between steel rebar and concrete inside the specimen. Without microwave irradiation, fracturing specimen internal rib marks of steel rebar on the surface of the reinforced concrete bonding were still relatively clear; the mechanical bite teeth of concrete did not break. It can be inferred that most of the displacement occurred after the specimen split, and when the displacement occurred, the steel rebar rib and the mechanical bite teeth of concrete separated. Under 1000 W microwave irradiation, the rib marks of steel rebar on the internal bonding surface of concrete with pull-and-split failure were fuzzy; the mechanical bite teeth of concrete broke locally. At the bonding surface, a thin crack appeared along the longitudinal penetration of the steel rebar. Under the condition of 3000 W microwave irradiation, the internal failure of the specimen was similar to that under the condition of 1000 W, except that the rib marks of steel rebar were more blurred, the number of fracture of mechanical bite teeth of concrete increased, and the cracking degree of the crack decreased. Under the condition of 5000 W microwave irradiation, the fracture degree of mechanical bite teeth of concrete inside the specimen was at the maximum, and there were no minute cracks along the longitudinal direction of the steel rebar.

Under the condition of microwave irradiation, the difference of dielectric constant between steel rebar and concrete directly leads to rapid heating of concrete, while the steel rebar itself does not generate any heat. A large temperature gradient and thermal stress are generated at the bonding surface of steel rebar and concrete, so that the shear strength of mechanical bite teeth, which play the main

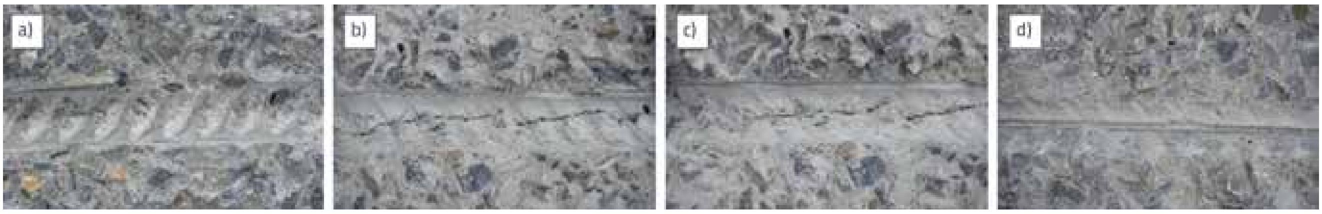

Figure 8. Damage photos of internal bonding surface after microwave irradiation: a) 0 W; b) 1000 W; c) 3000 W; d) 5000 W

bonding role, is attenuated. In addition, as the concrete continues to heat up, internal pore water evaporates, and the bond surface micro-pores and micro-cracks develop significantly. After high temperature, the steel rebar contracts, and the concrete absorbs water and expands, which further reduces the friction force and mechanical bite force between the steel rebar and concrete. When the microwave power reaches 4000 W and 5000 W, the hydration products of concrete rapidly dehydrate and decompose, the aggregate carbonizes and deteriorates, the cracks at the bonding interface between hydration products and aggregate expand rapidly, and the bond strength drops sharply.

5.2. Analysis of bond slip curve

In the pull out test, the bond stress at the loading end of the bond zone is usually greater than that at the free end, and the bond stress distribution is uneven [28]. In this paper, the maximum average bond stress $\tau_{u,\alpha}$, which can be expressed by the following Equation (9) in the bond zone, is taken as the bond strength between the steel rebar and concrete.

$$\tau_{u,\alpha} = \frac{F_{max}}{\pi \cdot d \cdot l_\alpha} \tag{9}$$

Where F_{max} is the load value at the time of specimen failure, d is the nominal diameter of rebar, and l_α is the bond length of reinforced concrete. For the specimen of reinforced concrete given in this paper, when the slip of steel rebar is no more than 105 mm, the length of steel rebar in the bonding zone remains constant at 40 mm, and so l_α can be considered as a fixed value in the experiment.

For the bond slip curve model, the curve is usually simplified as a multi-fold (curved) line. Many simple models are currently available [29, 30]. In order to get close to the constitutive model curve of the whole process of concrete compression, the 4-segment model of European CEB-FIPMC90 specification for concrete is adopted in this paper [31]. Figure 9 is the fitting curve of an average bond strength of reinforced concrete under microwave irradiation of 0 W, 1000 W, 3000 W and 5000 W.

The critical point of the slip amount between the initial slip segment and the slip segment is A, expressed by S_A, and the

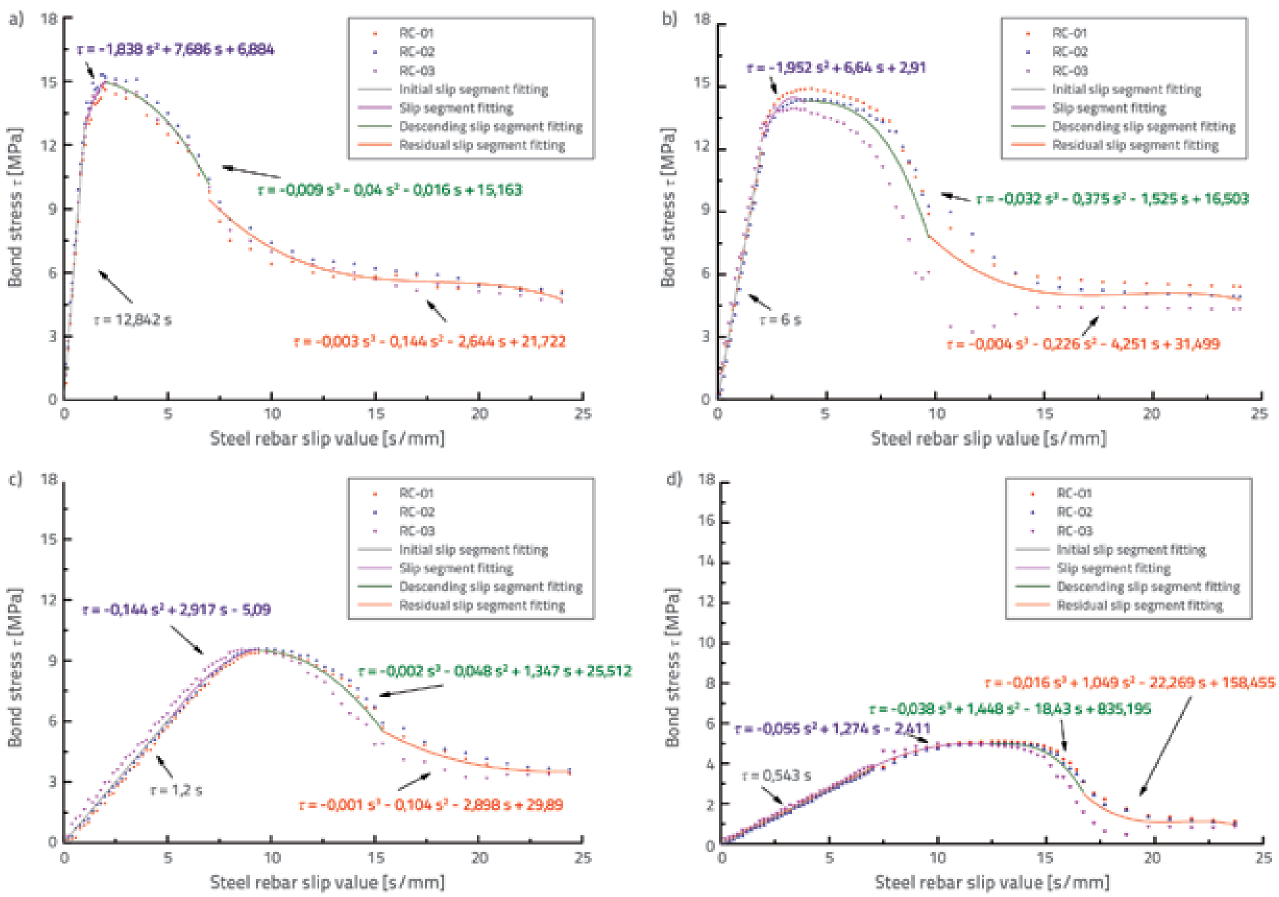

Figure 9. Bonding slip fitting curve of the specimen after microwave irradiation: a) 0 W; b) 1000 W; c) 3000 W; d) 5000 W

Table 5. Statistical table of bond stress of reinforced concrete specimen

Power [W]	τ_A [MPa]	τ_A/τ_{A0}	τ_B [MPa]	τ_B/τ_{B0}	τ_C [MPa]	τ_C/τ_{C0}	τ_D [MPa]	τ_D/τ_{D0}
0	13	1.000	15	1.000	8.5	1.000	4.9	1.000
700	12.2	0.938	14.3	0.953	8.2	0.965	4.8	0.980
1000	12	0.923	14.1	0.940	8.1	0.953	4.7	0.960
1500	10.7	0.823	12.9	0.860	7.6	0.894	4.4	0.898
2000	10	0.769	12.3	0.820	7.3	0.859	4.3	0.878
2500	7.8	0.600	10.7	0.713	6	0.706	3.8	0.776
3000	6.5	0.500	9.5	0.633	5.5	0.647	3.5	0.714
3500	4.5	0.346	7	0.467	3.3	0.388	1.6	0.327
4000	4	0.308	6.5	0.433	3	0.353	1.3	0.265
5000	3.8	0.292	6	0.400	2.6	0.306	1	0.204

ultimate bond strength of the initial slip segment is expressed by τ_A. The critical point of the slip amount between the slip segment and the descending segment is B, expressed by S_B, and the overall ultimate bond strength is expressed by τ_B. The critical point of the slip amount between the descending segment and the residual segment is C, expressed by S_C, and the residual ultimate bond strength is expressed by τ_{BC}. The end point of residual slip is D, expressed by S_D, and the overall residual bond strength is expressed by τ_D.

S_A, S_B and S_C increase gradually with an increase in microwave power (since the maximum value of slip in the experiment is about 24mm, it is considered that S_D remains unchanged), and τ_A, τ_B, τ_C and τ_D all gradually decrease. The bond-slip fitting curve gradually becomes steeper in morphology. It can therefore be speculated that the variation range of bond stress between steel rebar and concrete gradually decreases with an increase in microwave power, and then the force applied to the steel rebar when it is removed from the concrete is more even. This will be beneficial to the control of impact load in the actual application of reinforced concrete structure demolition, and will reduce the uncertainty of structure failure caused by sudden force.

It can be seen in Table 5 that, with an increase in microwave power, the bond stress of reinforced concrete specimen decreased by different degrees at each critical point. The instances of decrease in bond strength at each point under microwave irradiation of 700 W and 1000 W were relatively close, and the decrease was smaller than the baseline value of the non-irradiated group. It indicates that 700 W and 1000 W microwave could not effectively reduce the bond strength between steel rebar and concrete within 5 min. The decrease in bond strength at each point under microwave irradiation of 1500 W to 3000 W is higher than that at 700 W and 1000 W. However, the bond strength of each point decreased greatly under microwave irradiation of 3500 W, and the decline values were 65.4 %, 53.3 %, 61.2 % and 67.3 %, respectively. The values of decrease at each point under 4000 W and 5000 W were very close, and so the values of decrease in bonding stress at each point under 5000 W were 70.8 %, 60 %, 69.4 % and 79.6 %, respectively. Although the bond strength of each point was lower under 5000 W, the decrease in bond strength of each point increased by only 5.4 %, 6.7 %, 8.2 % and 12.3 % compared to that under 3000 W microwave irradiation. Therefore, the application of 3500 W microwave irradiation to the reinforced concrete specimen can not only cause the bond strength to decay greatly, but will also result in a better energy efficiency ratio. The use of the 3500 W microwave irradiation is recommended.

6. Conclusion

The analysis of failure characteristics and bond slip fitting curve of reinforced concrete pull-out test after microwave irradiation shows that the bond between steel rebar and concrete can be attenuated to a great extent by microwave irradiation, which is helpful for the development of the microwave-assisted mechanical demolition technology for abandoned reinforced concrete buildings in cities.

Based on statistical analysis of the forms of failure at the reinforced concrete pull-out test after microwave irradiation of different power, it was established that: specimens would undergo splitting failure under the condition of no microwave irradiation, specimens would undergo pull-out splitting failure and splitting failure under microwave irradiation of 700 W to 3500 W, and specimens would undergo pull-out failure under microwave irradiation of more than 4000 W. In view of the difference of failure forms, it is speculated that the decrease in shear strength caused by temperature stress is the main reason why failure forms tend to pull out with an increase in microwave power in the pull-out test.

The bond slip fitting curve of reinforced concrete pull-out test was analysed after microwave irradiation. The entire fitting curve was composed of the initial slip segment, slip segment, descending segment, and residual segment. With an increase in microwave power, the bond strength corresponding to different critical points decreased to different degrees, but the reduction of bond strength under microwave irradiation of 5000 W was not significant compared with that under microwave irradiation of 3500 W. Therefore, it is believed that the use of microwave irradiation at 3500 W exhibits a better energy efficiency ratio.

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