Hindawi
Mathematical Problems in Engineering
Volume 2020, Article ID 1901073, 12 pages
https://doi.org/10.1155/2020/1901073

Research Article

Investigation of Residual Bearing Capacity of Corroded Reinforced Concrete Short Columns under Impact Load Based on Nondestructive Testing

Guorui Sun,[1] Yi Zhang,[2] Yubin Tian ,[1] Lizhuang Bo,[3] Jiyang Shen ,[1] and Jun Shi [4]

[1] *Key Lab of Structures Dynamic Behavior and Control of the Ministry of Education, Harbin Institute of Technology, Harbin 150090, China*
[2] *Academy of Combat Support, Rocket Force University of Engineering, Xi'an 710025, China*
[3] *CCTEB Infrastructure Construction Investment Co., Ltd., Wuhan 430000, China*
[4] *School of Transportation Science and Engineering, Harbin Institute of Technology, Harbin 150090, China*

Correspondence should be addressed to Yubin Tian; tianyubin@hit.edu.cn

Received 2 January 2020; Revised 25 February 2020; Accepted 6 April 2020; Published 11 May 2020

Academic Editor: Mohamed Shaat

This paper investigates the damage and residual bearing capacity of corroded reinforced concrete (RC) short columns after impact and presents a method for evaluating the residual bearing capacity of RC short columns by nondestructive testing. Firstly, accelerated corrosion test and drop hammer impact test were carried out to obtain specimens under different impact loads and corrosion rates. Then, the damage caused by corrosion and impact loads was evaluated by supersonic wave aided nondestructive test. Through the damage factor, the influence of corrosion rate and impact loads on the specimen was revealed, and the calculation method of corrosion rate and impact velocity was proposed. Finally, according to the bearing capacity test results, the influence factors of reinforcement, concrete, and impact were introduced into the bearing capacity calculation equation. Considering the relationship between the residual bearing capacity of RC short columns and the damage factor, an improved formula for calculating the residual bearing capacity of corroded RC short columns under impact loads was proposed. This work lays the foundation for further research on mechanical properties of corroded RC structures under impact loads.

1. Introduction

With the development of economic and technology, the building environment may be more complex, the problem of reinforcement corrosion becomes emergent, and the impact loads on buildings may occur more frequently. The damage caused by corrosion and impact load could bring huge irreparable losses to the society.

Reinforcement corrosion could cause grave damages to concrete and ultimately weaken the bearing capacity and durability of RC structures [1, 2]. Hence, with the development of society, researchers have paid more attention to the research on the mechanical behavior of reinforced concrete structures after corrosion. On the basis of bearing capacity test, Du et al. [3] reported that the effect of different types of corroded steel bars on the residual bearing capacity was comparable and proposed the prediction formula of residual bearing capacity. Dang and François [4] proposed that the service life of corroded structures was limited by the ductility reduction of bending properties, and the reduction of bending properties was more obvious to the reduction of bearing capacity. By assessing the effect of corrosion on the residual bearing capacity of RC structures, Nepal and Chen [5] proposed an approach for determining risk-cost balanced repair strategy of corrosion damaged RC structures with consideration of uncertainty in structural resistance deterioration. Chen and Xiao [6] presented an approach for reliability analyses of corrosion RC structures affected by reinforcement corrosion based on the representative symptoms identified during the deterioration process. In addition, to evaluate the damage of RC structures caused by corrosion, different detection methods have been used to study the damage detection caused by corrosion. Liang and Su [7] proposed a method to evaluate the corrosion damage of steel reinforcement by impact echo method. This method converts the displacement spectrum into acceleration spectrum to predict the corrosion damage of RC specimens. Zhang et al. [8] proposed a nondestructive test method for steel corrosion in RC structures by using a 3-dimensional digital micromagnetic sensor to detect and analyze the self-magnetic field leakage from corroded RC structures, which can be used to detect and evaluate the range of the inner steel corrosion in engineering structures. Based on the analysis of magnetic flux leakage signals, Zhou et al. [9] proposed a nondestructive testing method that can qualitatively determine the location and extent of steel corrosion.

When a structure is subjected to an impact load, since the impact load is transient and usually local, its behavior may differ from that of the structure under static load. In order to evaluate the effects of impact load on the performance of RC structures, many researches have been conducted based on theoretical analysis, experiment, and numerical simulation [10–18]. Based on theoretical analysis and numerical simulation, Sun et al. [19] investigated the failure modes of RC columns under explosion. Based on the impact test, Chen and May [20] provided experimental data to calibrate numerical procedures for the simulation of impact-loaded RC structures. Thilakarathna et al. [21] simulated the dynamic response of RC column under lateral impact by using the finite element software ANSYS/LS-DYNA. Kantar et al. [22] investigated the behavior of two kinds of concrete specimens through drop hammer test and analyzed the mechanical performance under impact loads. By conducting dynamic impact loading tests on 12 RC specimens with different materials and sizes, Anil et al. [23] investigated the mechanical properties with different concrete types under dynamic impact load. Through LS-DYNA finite element analysis, Yu et al. [24] reported that the mechanical properties of RC structure are related to the combination form of mass and impact velocity, and the combination of mass and impact velocity should be considered in the design of concrete structures subjected to impact load.

When both corrosion and impact loads act simultaneously, the effects on the mechanical properties of RC structures would change with the change of corrosion rate and impact velocity. Dai et al. [25] conducted a drop hammer impact test on RC specimens with different corrosion rates to investigate the impact of the specimens on the midspan and found the influence of longitudinal steel corrosion on the impact performance of RC specimens. Yang et al. [26] simulated the whole process of lateral impact resistance of corroded RC columns based on LS-DYNA software and verified the reliability of the simulation through experiments. Based on the test and numerical simulation, Fang et al. [27] investigated the lateral impact resistance of corroded RC columns by simulating the corrosion of reinforcement through the degradation of reinforcement mechanical properties.

In conclusion, many researches on impact and corrosion of RC structures have been carried out in terms of mechanical properties, damage conditions, and detection methods. However, there are still some problems in calculating the residual capacity of RC structures under the combined action of corrosion and impact loads:

(1) Most research studies only consider the influence of a single factor on the structure of RC. There are few studies on damage degree and residual bearing capacity of corroded RC structures after impact.

(2) Due to the complex environment of buildings, it is difficult to determine the numerical value of impact velocity and corrosion rate in construction projects. Researchers mainly study the effect of corrosion and impact on reinforced concrete structures through corrosion rate and impact velocity, so it is difficult to apply in practical engineering.

In view of the above problems, this paper investigated the relationship between damage and residual bearing capacity through nondestructive testing and bearing capacity tests of corroded RC short columns under impact load. The electric accelerated corrosion and drop hammer impact test were carried out to obtain the specimens with different corrosion rates and impact energy. Ultrasonic nondestructive testing of RC short columns was carried out to obtain the damage information of the specimens. Then damage factors were introduced to describe the damage degree of RC short columns. Based on corrosion damage factor and impact damage factor, the calculation formulas of corrosion rate and impact velocity were presented, respectively. Finally, the bearing capacity test was carried out to find out the influence of corrosion rate and impact energy on the residual bearing capacity of specimens. By establishing the relationship between concrete, reinforcement, impact factors, and damage factors, a fast, effective, and simple method for calculating the residual bearing capacity of RC structures was provided.

2. Experimental Programme

2.1. Design and Fabrication of Specimens. In this experiment, the corrosion rate and impact energy are taken as experimental variables. Seven RC short columns, numbered C0X0-C2X10, are prepared, as shown in Table 1, where "*C*" and "*X*" denoted the impact energy and corrosion rate, respectively. As shown in Figure 1, the RC short column used in the experiment is a square solid section, with a size of 300 mm × 300 mm × 1200 mm. The diameter of longitudinal reinforcement is 18 mm, and the diameter of stirrup is 8 mm. In order to study the impact resistance and residual bearing capacity of corroded RC columns, material performance tests were performed on the concrete, longitudinal bars, and stirrups, and relevant mechanical parameters were obtained. The designed strength of longitudinal reinforcement used in specimen is 360 MPa, and the elastic modulus is 196 GPa. The designed strength of stirrup is 270 MPa, and the elastic modulus is 197 GPa. The compressive strength of the concrete specimen is 40.6 MPa and the elastic modulus is

26.3 GPa. The protective layer thickness of the concrete is 30 mm.

2.2. Corrosion Method. There are two main types of corrosion of RC structures: electrochemical corrosion and stray current corrosion. Electrochemical corrosion of steel bar is ubiquitous in nature and the main cause of steel bar corrosion. Due to the heterogeneous characteristics of steel bar and concrete, the potential of steel bar at different positions is different, which results in galvanic effect and electrochemical corrosion. When the structure is eroded by chloride ions or acted by oxygen, the passive film on the surface of steel bar is decomposed and the steel bar begins to be corroded. The volume of steel products after corrosion is several times larger than the original, after corrosion of steel surface volume expansion and so the protective layer of concrete tensile stress. When the tensile stress increases to a certain extent, cracks appear in the concrete protective layer, which would accelerate the corrosion of steel reinforcement.

There are three types of techniques that can be used to corrode reinforcement, namely, natural corrosion, accelerated corrosion, and simulated corrosion. Natural corrosion may take many years for corrosion to have any significant influences on its mechanical properties, which is unrealistic for laboratory test. Therefore, an electrochemical technique was adopted to accelerate the corrosion process of reinforcement in order to achieve a significant amount of corrosion of reinforcement within a reasonable time. Based on Faraday's law of electrolysis, the magnitude of current and conduction time can be determined by

$$\Delta m = \frac{M \cdot It}{96500 \times n}, \tag{1}$$

where Δm is the weight of steel bar involved in chemical reactions; M is the molar mass of material; I is the magnitude of current; t is the conduction time; n is the number of electrons in electrode reaction measurement equation. The product of current and time required for corrosion of steel bar with a corrosion rate of 5% is $It = 115$ Ah, and the product of current and time required for corrosion of steel bar with corrosion rate of 10% is $It = 230$ Ah. When the magnitude of current is 0.4 A, it takes 287.5 h and 575 h to corrode the reinforcement, respectively. Due to the current instability during the test, the time required to reach the corresponding corrosion rate is different from the theoretical time. Hence, the actual conduction time is 30% more than the theoretical time to achieve the designed corrosion rate. Therefore, the actual corrosion time is 373.75 h and 747.5 h, respectively. In order to carry out the corrosion test of reinforcement, NaCl solution with a mass concentration of 5% was injected into a pool. There were four layers of plastic sheets in the pool to prevent leakage of chlorine ions from the solution during the test. The RC short columns were immersed in the pool for 48 hours to eliminate passive film on the steel bar. The steel bars to be corroded were connected to the positive pole of the power supply, and the copper sheets were connected to the negative pole of the power supply. After the equipment is connected, the current is adjusted to the design value to corrode the steel bar, and the corrosion test is completed after the corrosion time is reached. In order to determine the actual corrosion rate of reinforcing bars, corrosion tests were carried out on four steel bars at the same time. The corrosion process and the steel bar after corrosion are shown in Figure 2. After corrosion test, the steel specimens used for comparison were washed in HCl solution, then dried, and weighed; the measuring corrosion rate (ω) of the steel is obtained shown in Table 2. The average corrosion rate of specimens designed to have corrosion rates of 5% and 10% was actually 17% and 30%, respectively.

Table 1: Specimen parameters.

Number	C0X0	C0X5	C0X10	C1X5	C1X10	C2X5	C2X10
Corrosion rate	0	5%	10%	5%	10%	5%	10%
Impact energy (kJ)	0	0	0	1	1	2	2

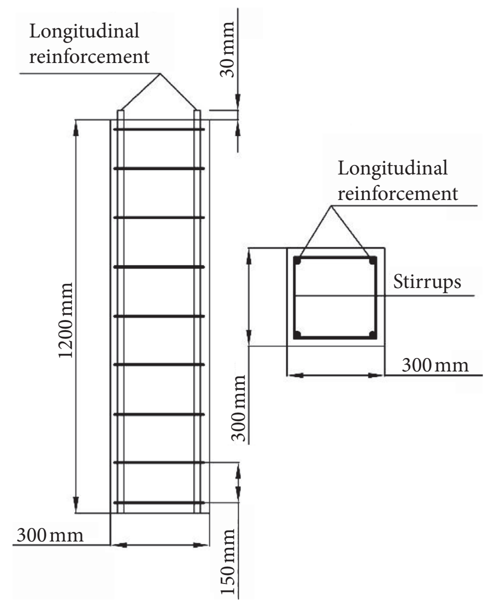

Figure 1: Geometric configuration of the specimen.

2.3. Drop Hammer Impact Test. In order to study the impact resistance of components and achieve the impact phenomenon that often occurs in civil engineering practice, an impact test was performed on RC columns. As shown in Figure 3, drop hammer impact test is used to simulate the impact load on RC short columns. In order to ensure the stability of the supports during the impact process, the rigid mount used in this experiment is rectangular solid sections with a size of 300 mm × 400 mm and a height of 1000 mm. The rigid mount was connected with the lower steel plate of the testing machine with high-strength bolts. The upper part of the rigid mount was the hinge support, which was also connected with the rigid support by high-strength bolts. The specimen is placed on the upper part of the hinge bracket, fixed by carbon fiber clamps on both sides, and connected to

(a)

(b)

Figure 2: Corrosion test. (a) Layout of corrosion test. (b) Corrosion of steel bar.

Table 2: The measuring corrosion rate of steel bar.

Time (h)	Initial weight (g)	Corroded weight (g)	Calculated corrosion rate	Measuring corrosion rate
374	700	580	5%	17.1%
374	708	575	5%	18.8%
748	792	550	10%	30.6%
748	803	565	10%	29.6%

the rigid bracket with a wire rope to prevent the specimen from moving out of position. The RC short columns were impacted by drop hammer, which was dropped from a specific height. The impact load level is determined by adjusting the weight and falling height of the drop hammer. The hammer head used in this test was flat hammer head, the weight of the drop hammer was 400 kg, and the falling height of the drop hammer was 0.25 m and 0.5 m. The test surface *A* of RC short column was the impacted surface.

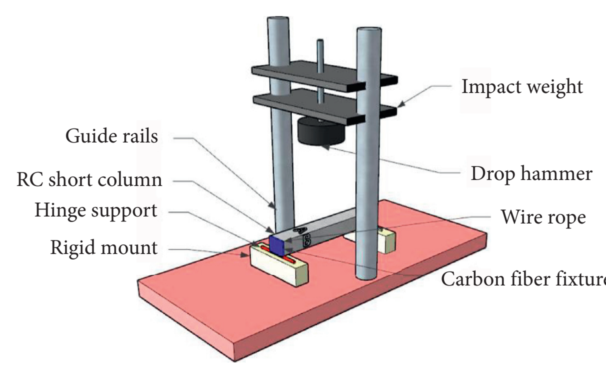

Figure 3: Apparatus used for impact experiment.

2.4. Supersonic Wave Aided Nondestructive Test. Supersonic wave aided nondestructive testing, which is easy to operate, widely applicable, and reliable in testing results, is used to detect the internal damage of concrete caused by corrosion and impact. This method used the ultrasonic transmitter to continuously transmit the pulse signal. After the signal passes through the concrete and returns to the receiver, the acoustic parameters such as wave velocity can be obtained. By establishing the relationship between these acoustic parameters and the damage degree of RC short columns, the purpose of detection could be achieved. The layout of ultrasonic testing area is directly related to the results of damage detection. In order to understand the damage situation of RC short columns more comprehensively and carefully, 48 measuring points were evenly arranged on the four facades of the columns. The specific layout of measuring points is shown in Figure 4.

2.5. Bearing Capacity Test. Bearing capacity test of the RC short column was performed on a Precision Testing Machine, which was equipped with a data-processing computer, a 5000 kN pressure testing machine, and a static acquisition system. The computer was programmed to control the test under force and to record the applied load, strain, and displacement of the specimens. The preliminary loading rate was controlled at 4–6 kN/s, and when the ultimate bearing capacity was approached, the loading rate was reduced to 0.5–1 kN/s. The static acquisition system with 16 acquisition channels could simultaneously collect displacement meter signal, strain gauge signal, and force sensor signal and transmit the data to the computer. In addition, a force sensor was placed at the top of the column, and four high precision

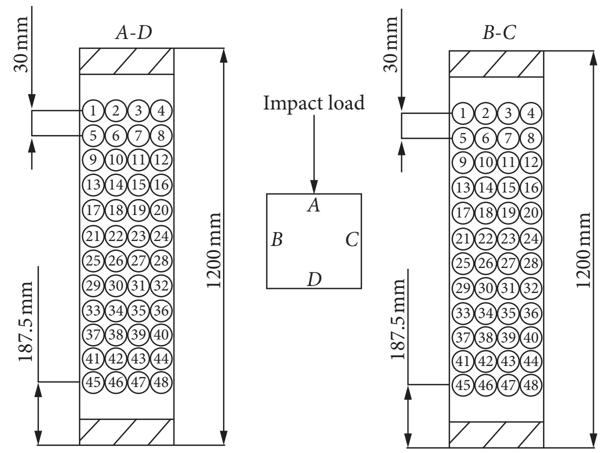

Figure 4: Layout of damage detection points (units: mm).

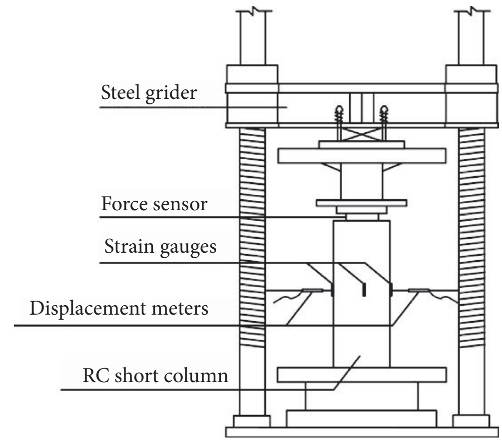

Figure 5: Layout of specific measuring points.

displacement meters were set at the four corners of the column. Concrete strain gauges were placed in the middle of the four sides of the concrete. The layout of specific measuring points is shown in Figure 5.

3. Damage Detection of RC Short Columns

Concrete damage refers to the mechanical properties of concrete changed, resulting in the reduction of the bearing capacity of structures. Damage detection of RC short columns was carried out by using wave velocity-based damage detection method. For RC short columns, some damage information could be found by analyzing the mean and variance of wave velocity before and after corrosion, but it could not be used as a basis for judgment. Hence, introduce the damage factor (D) to infer the damage degree of concrete.

Assuming that E is the modulus of elasticity of materials before damage and E^* is the modulus of elasticity of materials after damage, the damage factor (D) is defined as $D = 1 - E^*/E$ [28]. When the concrete density (ρ) and Poisson's ratio (γ) are constant, the quadratic of ultrasonic wave velocity is proportional to the elastic modulus of concrete. Therefore, the damage factor expressed by wave velocity can be calculated through

$$D = 1 - \frac{{\nu_1}^2}{\nu_0^2}, \quad (2)$$

where ν_0 is the initial wave velocity and ν_1 is the postdamage wave velocity.

3.1. Damage Detection of Corroded RC Short Columns before Impact Test. Before the impact test, the damage information of corroded RC short columns was detected. The wave velocity data before and after corrosion damages are processed by (2), and the distribution of damage factors at each measuring point is obtained, as shown in Figure 6. It can be seen that the damage distribution of C1X5 short column from the bottom to the top is relatively uniform, indicating that the corrosion of reinforcement is roughly uniform. Due to the volume expansion caused by the corrosion of steel bars, the concrete near the steel bars was pulled up, resulting in serious damage to the concrete near the steel bars. Therefore, the closer the concrete is to the steel bar, the more serious the corrosion effects are and the greater the damage degree is. For C1X5, the damage levels of B and C test surfaces are greater than those of A and D, and for other short columns, the damage levels of B and C test surfaces are less than those of A and D test surfaces. It shows that the damage caused by corrosion is different in the two directions of the same concrete, which may cause the mechanical properties of the RC column to change. The damage factors of other specimens are relatively uniform in distribution, which is similar to the distribution rule of C1X5 short column, except that the damage factors of individual test points are relatively large.

To acquire the relationship between corrosion rate and concrete damage degree, the concept of corrosion damage factor ($\overline{D}$) is introduced. The corrosion damage factor ($\overline{D}$) is defined as the average value of damage factors under different corrosion rates. As shown in Table 3, the corrosion damage factor is 0.07024 when the corrosion rate of steel reaches 17%, which is 7% higher than that before corrosion. When the corrosion rate increases from 17% to 30%, the corrosion damage factor of concrete is 0.07437, which increases by 5.88%. After the corrosion rate is higher than 17%, the increase of corrosion damage factor is very small. It can be seen that when the corrosion rate reaches a certain level, the damage caused by corrosion to concrete decreases with the increase of the corrosion rate. The reason may be that when the steel bar corrosion rate reaches 17%, cracks appear on the concrete surface, the concrete protective layer no longer can bear the tension, and the tensile stress caused by the volume expansion of the corroded steel bar in the concrete is released.

From the distribution of damage factors, it is known that the damage of concrete caused by corrosion is generally uniform. Therefore, corrosion damage factor can be used to indicate the damage degree of RC short columns. According to the experiment, there is a certain relationship between the damage factor and the corrosion rates. In combination with the experimental law, the linear curve fitting was carried out to investigate the influence between different corrosion rates

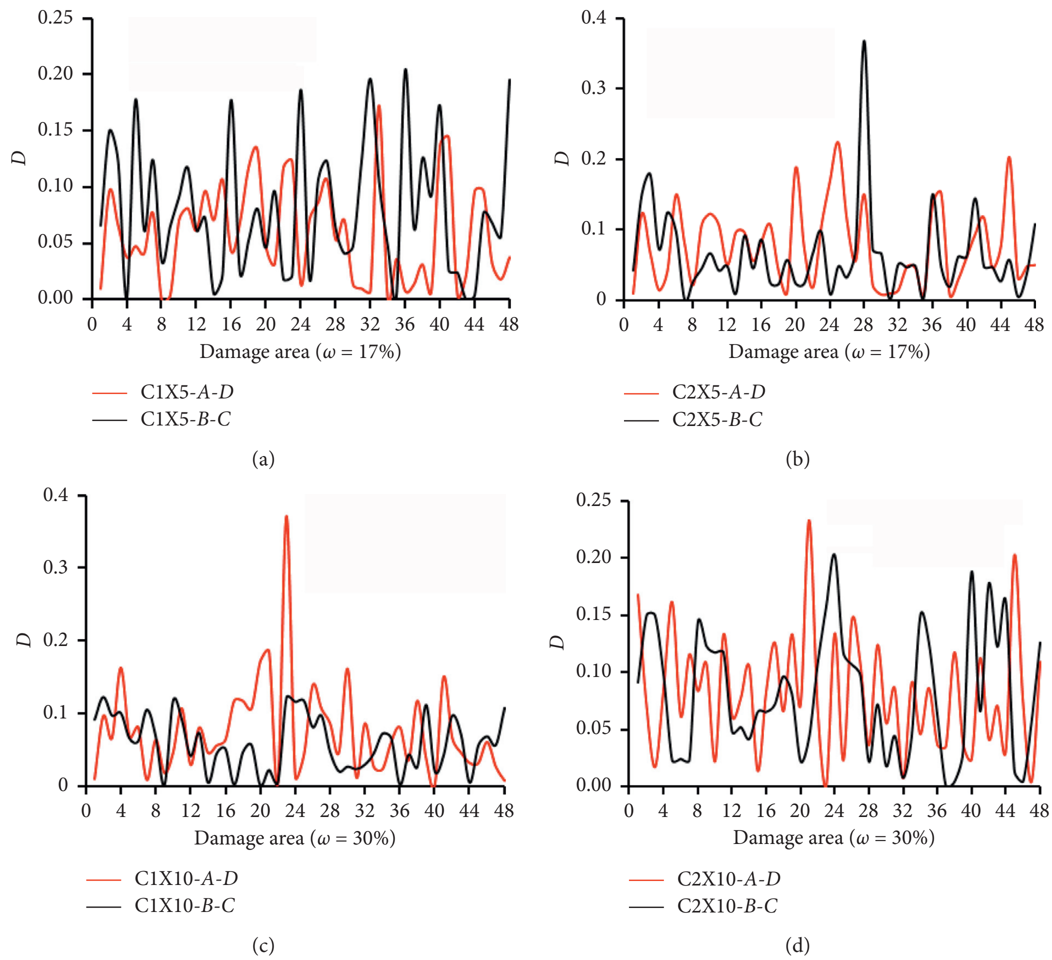

Figure 6: Distribution of damage factors caused by corrosion. (a) C1X5 *A-D* and *B-C* test surfaces. (b) C2X5 *A-D* and *B-C* test surfaces. (c) C1X10 *A-D* and *B-C* test surfaces. (d) C2X10 *A-D* and *B-C* test surfaces.

Table 3: Damage factor of test surfaces under corrosion.

Corrosion rate	Test surfaces	Average value	Variance	Maximum	Minimum	Corrosion damage factor
17%	C1X5-*B-C*	0.08066	0.00344	0.2044	0.00025	0.07024
	C1X5-*A-D*	0.05937	0.00201	0.1726	0.00025	
	C2X5-*B-C*	0.06370	0.00371	0.3682	0.00078	
	C2X5-*A-D*	0.07721	0.00313	0.2232	0.00806	
30%	C1X10-*B-C*	0.05909	0.00144	0.1228	0.00078	0.07437
	C1X10-*A-D*	0.07469	0.00425	0.3718	0.00182	
	C2X10-*B-C*	0.08209	0.00300	0.2029	0.00025	
	C2X10-*A-D*	0.08161	0.00269	0.2333	0.00078	

and corrosion damage factor. When the corrosion rate is between 0 and 0.4, the corrosion damage factor ($\overline{D}$) can be calculated through

$$\overline{D} = 0.25618w + 0.00807. \quad (3)$$

3.2. Damage Detection of Corroded RC Short Columns Caused by Impact Load. After the impact test, the damage information of corroded RC short columns caused by impact was detected. The wave velocity data before and after impact are processed by equation (2), and the distribution of damage factors at each measuring point is obtained, as shown in Figure 7. When calculating the damage factor caused by impact, the wave velocity after corrosion damaged is taken as the wave velocity before impact damaged. The effect of corrosion is not considered, so the damage factor of Figure 7 can be larger than that of Figure 6. As nonimpact test surfaces *B* and *C*, the closer to the impact area of the short column, the greater the value of damage factor. It shows that the impact energy diffuses to both sides and decreases gradually, resulting in greater damage in the middle than on both sides. As impact test surfaces *A* and *D*, there is no large damage factor in the impact area, and the larger damage factor mainly occurs near the reinforcement. By comparing the damage factors of each test surface, it is found that the damage area of the impact surface is mainly concentrated in the position of column being impacted. For the nonimpact surface, the impact damage area is also concentrated near the impact area of the column, but the damage in the tension area is particularly serious.

For impact surfaces *A* and *D*, under the same impact energy, the peak value of damage factor of specimens with high corrosion rate is larger and the damage is more serious, which indicates that the impact resistance of RC short columns under impact direction is reduced due to corrosion. For *B* and *C* test surfaces without impact, the peak and average damage factors of specimens with different corrosion rates are close at the same impact height, indicating that the corrosion rate has few effects on the impact damage in this direction. At the same corrosion rate, the higher the impact height is, the higher the peak value of damage factor is, which indicates that the greater the impact energy is, the more serious the damage to the column would be. The damage of *A* and *D* test surfaces is more serious than that of *B* and *C* test surface at 30% corrosion rate, but there is no such phenomenon at 17% corrosion rate, which indicates that the situation is related to the corrosion rate. When the corrosion rate reaches a certain level, the test surface under direct impact is more vulnerable to damage.

As shown in Table 4 and Figure 7, the damage caused by impact on RC short columns is concentrated and large. There is a linear relationship between impact and damage level, so the concept of impact damage factor ($D\prime$) is introduced to determine the relationship between impact energy and concrete damage. The impact damage factor ($D\prime$) is defined as the maximum damage factor of RC short columns. When the impact height increases from 0.25 m to 0.5 m, the impact velocity (v) changes from 2.21 m/s to 3.16 m/s. Considering the influence of different impact surfaces and corrosion rate on impact damage, the linear curve fitting is carried out to investigate the influence between different impact velocity and impact damage factor, as shown in Table 5.

4. Experimental Analysis of Residual Bearing Capacity of RC Short Columns

4.1. Analysis of Bearing Capacity Test of Corroded RC Short Columns without Bearing Impact Load. Before impact test, the residual bearing capacity of RC short columns with different corrosion rates was tested. The failure forms of columns under different corrosion rates are consistent, which could be divided into three stages:

(1) The force-displacement curve of the RC column presents a straight upward state, of which the concrete and steel bars are in the elastic stage.

(2) As the force continues to rise, the force-displacement curve bends and the force begins to decline shortly after the plastic zone appear.

(3) As the test continues, the force decreases rapidly and the displacement increases rapidly. At this time, the short column enters the stage of destruction, and the concrete protective layer begins to fall off. Finally, the short column was destroyed and the experiment was over.

From Table 6, it can be seen that the corrosion of steel bar could reduce the residual bearing capacity (F) and peak displacement of RC short columns. Compared with the C0X0 short column, the bearing capacity of C0X5 short column decreases by 11.33%, and that of C0X10 short column decreases by 15.93%. With the increase of corrosion rate, the residual bearing capacity of RC short column decreases, and the rate of decline decreases. When the corrosion rate tends to 1, the residual bearing capacity of RC short column would not approach zero due to the residual bearing capacity of concrete in the core area.

The equation for bearing capacity of RC short columns given in GB 50010-2010 [29] is as follows:

$$F = 0.9\varphi\left(f_c A + f_y' A_s'\right), \quad (4)$$

where F is the bearing capacity; 0.9 is reliability coefficient; φ is the stability coefficient of RC short column; f_c and f_y' are the strength design value of concrete and steel bar; A is the area of concrete section; A_s' is the area of steel bar section. The calculated bearing capacity of C0X0 short column is 4155 kN, which is basically consistent with the actual bearing capacity of C0X0 short column.

Due to corrosion, cracks appear along the ribs of the protective layer, and the cross section of the concrete and steel bars is reduced, which results in a reduction in bearing capacity. Considering the influence of corrosion on the equivalent section and yield strength of reinforcement and concrete, the influence factors of reinforcement (ζ) and concrete (ξ) are introduced into (4). The improved equation for calculating F is obtained as follows:

$$F = 0.9\varphi\left(\xi f_c A + \zeta f_y' A_s'\right). \quad (5)$$

In order to determine the influence factor of reinforcement, the relationship between the influence factor of reinforcement and the corrosion rate is established by linear curve fitting. The equation for calculating ζ is obtained as follows:

$$\zeta = -1.3476\omega + 0.9958, \quad 0 < \omega < 0.4. \quad (6)$$

Similarly, through linear curve fitting, the relationship between concrete influence factor and steel corrosion rate is established. The equation for calculating ξ is obtained as follows:

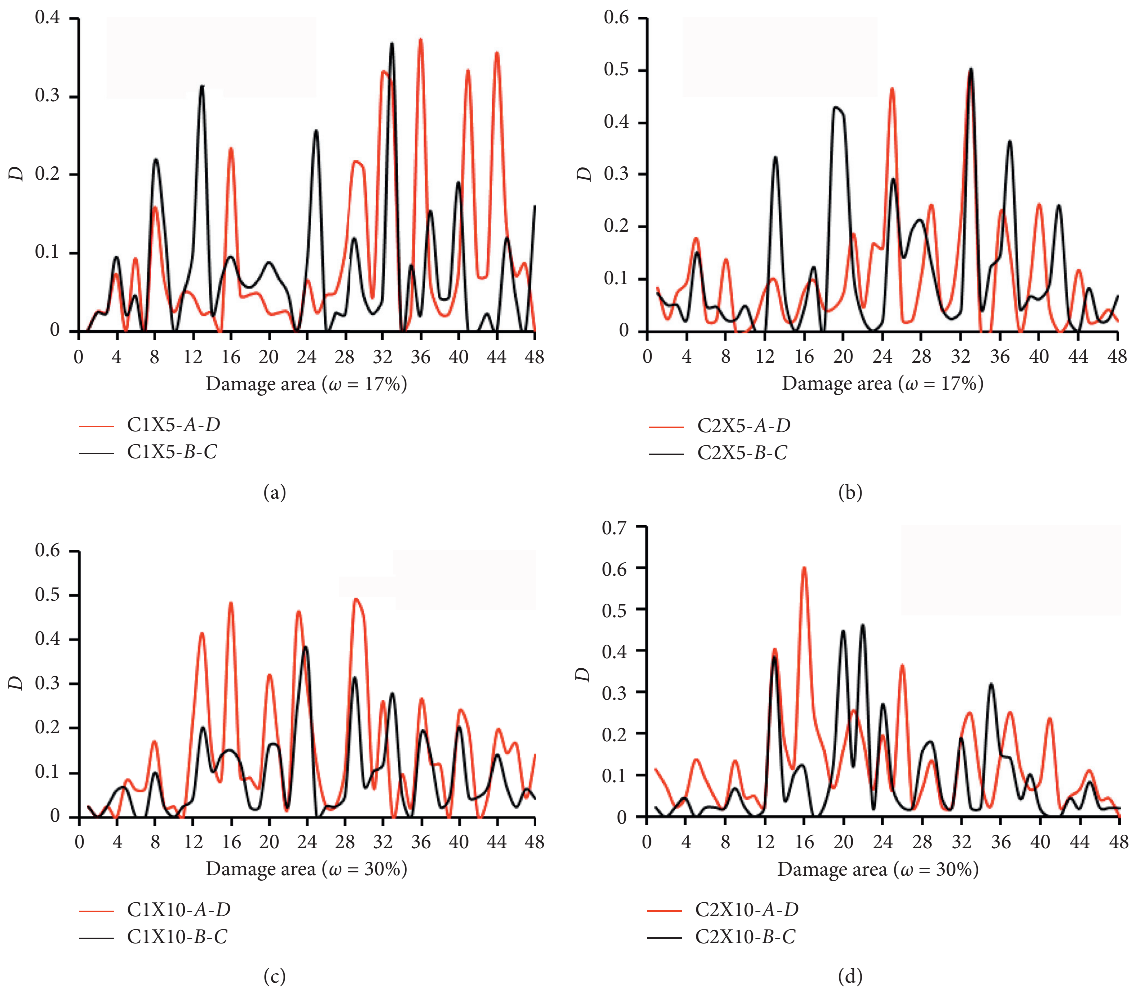

FIGURE 7: Distribution of damage factors caused by impact. (a) C1X5 *A-D* and *B-C* test surfaces. (b) C2X5 *A-D* and *B-C* test surfaces. (c) C1X10 *A-D* and *B-C* test surfaces. (d) C2X10 *A-D* and *B-C* test surfaces.

$$\xi = -0.3537\omega + 0.996, \quad 0 < \omega < 0.4. \tag{7}$$

Therefore, the calculation equation of the bearing capacity of the corroded RC short columns is as follows:

$$F = \begin{cases} 0.9\varphi\left(f_cA + f_y'A_s'\right), & 0 < \omega < 0.4, \\ 0.9\varphi\left(-0.3537\omega f_cA + 0.996 f_cA - 1.3476\omega f_y'A_s' + 0.9958 f_y'A'\right), & \omega \neq 0. \end{cases} \tag{8}$$

According to (8), the bearing capacity of C0X5 short column is 3863.8 kN, and the error between the calculated result and the measured value is 1%, while the bearing capacity of C0X10 short column is 3548.1 kN, and the error is 0.01%. The calculation error is less than 5%, which indicates the rationality of the equation.

As it is difficult to determine the corrosion rate of reinforcement in reality, (8) is difficult to be applied in engineering buildings. Corrosion damage factors of RC short columns could be obtained through ultrasonic testing. Hence, to calculate the residual bearing capacity of RC short columns more conveniently, corrosion damage factors are used to replace the corrosion rate.

Based on the linear curve fitting, the relationship between the influence factor of reinforcement and the corrosion damage factor is established. The equation for calculating ζ is obtained as follows:

$$\zeta = -4.5583\overline{D} + 1.0041. \tag{9}$$

Similarly, the relationship between the influence factor of concrete and the corrosion damage factor is established

Table 4: Damage factor of test surfaces under impact load.

Test surfaces	Average value	Variance	Maximum	Minimum
C1X5-*B-C*	0.07186	0.00681	0.3680	0
C1X5-*A-D*	0.08629	0.01076	0.3743	0
C2X5-*B-C*	0.10540	0.01147	0.4944	0
C2X5-*A-D*	0.09397	0.01533	0.5029	0
C1X10-*B-C*	0.08760	0.00786	0.3759	0
C1X10-*A-D*	0.13810	0.01909	0.4862	0
C2X10-*B-C*	0.08620	0.01307	0.4605	0
C2X10-*A-D*	0.12389	0.01338	0.5996	0

Table 5: The relationship between impact damage factor and impact velocity.

Test surfaces	w	$D' = a \times v + b$	
		a	b
A-D	17%	0.1610	0.0043
A-D	30%	0.1951	0.0127
B-C	17%	0.1582	0.0042
B-C	30%	0.1500	0.0103

Table 6: Test results of bearing capacity of corroded RC short columns.

	Number	C0X0	C0X5	C0X10
Peak	Bearing capacity (kN)	4246.3	3765.4	3569.9
	Displacement (mm)	1.334	1.215	1.218
	Concrete strain ($\mu\varepsilon$)	2110	1757	1757
	Strain of reinforcing steel ($\mu\varepsilon$)	225t5	—	1512
Destructive	Force (kN)	3991.9	2828.1	1563.5
	Displacement (mm)	1.486	4.860	5.290
	Concrete strain ($\mu\varepsilon$)	2343	—	—
	Strain of reinforcing steel ($\mu\varepsilon$)	2399	—	—

through linear curve fitting. The equation for calculating ξ is obtained as follows:

$$\xi = -1.2479\overline{D} + 1.0008. \quad (10)$$

The improved equation for calculating the bearing capacity of RC short columns through corrosion damage factor is as follows:

$$F = \begin{cases} 0.9\varphi\left(f_c A + f_y' A_s'\right), & \overline{D} = 0, \\ 0.9\varphi\left(-1.2479\overline{D} f_c A + 1.0008 f_c A - 4.5583\overline{D} f_y' A_s' + 1.0041 f_y' A\prime\right), & \overline{D} \neq 0. \end{cases} \quad (11)$$

According to (11), the bearing capacity of C0X5 short column is 3679 kN, and that of C0X10 short column is 3651 kN. The error between the calculated results and the measured values is less than 5%, which shows the rationality of the equation.

4.2. Test Results Analysis of Residual Bearing Capacity of Corroded RC Short Columns after Impact Load. After impact test, the residual bearing capacity of RC short columns with different corrosion rates was tested. As shown in Table 7, the residual bearing capacity of corroded RC columns decreases with the increase of impact height. When the corrosion rate reaches 17%, if the impact height increases from 0 to 0.25 m, the bearing capacity decreases by 14.9%, and if the impact height increases from 0.25 m to 0.5 m, it decreases by 3.2%. When the corrosion rate reaches 30%, if the impact height increases from 0 to 0.25 m, the bearing capacity decreases by 15.4%, and if the impact height increases from 0.25 m to 0.5 m, it decreases by 6%. The larger the corrosion rate of steel bars is, the faster the bearing capacity decreases.

In order to investigate the effect of impact velocity on the residual bearing capacity of RC short columns, the experimental results of specimens are used to make linear curve

Table 7: Statistics of bearing capacity test results of corroded RC short columns after impact load.

	Number	C1X5	C2X5	C1X10	C2X10
Peak	Bearing capacity (kN)	3205.6	3104.6	3018.4	2837.2
	Displacement (mm)	1.29	1.77	1.30	2.03
	Concrete strain ($\mu\varepsilon$)	1113	1015	1325.3	1599
	Strain of reinforcing steel ($\mu\varepsilon$)	1960	—	2634	—
Destructive	Force (kN)	2873.7	2814.3	1650.8	1726.7
	Displacement (mm)	1.88	2.02	3.45	3.38
	Concrete strain ($\mu\varepsilon$)	—	2240	1839	1560
	Strain of reinforcing steel ($\mu\varepsilon$)	—	—	—	—

Table 8: Comparisons of calculated value and test value of equation.

Number	Bearing capacity (kN)		Calculation error
	Experimental data	Calculated value	
C1X10	2871.4	2835.9	1.2%
C2X10	2256.4	2201.7	2.4%

fitting. The relationship between residual bearing capacity and impact velocity of corroded RC short columns is as follows:

$$F = \begin{cases} 3746.81 - 216.92v, & w = 17\%, \\ 3562.46 - 234.99v, & w = 30\%. \end{cases} \quad (12)$$

Considering the influence of impact loads on corroded RC structures, the impact factor (γ) is introduced into 5. The improved bearing capacity equation is as follows:

$$F = 0.9\varphi\left(\gamma\xi f_c A + \zeta f_y' A_s'\right). \quad (13)$$

The relationship between the impact factors and the impact damage factors is established through linear curve fitting. The equation for calculating γ is obtained as follows:

$$\gamma = -0.6155D' + 1.0097. \quad (14)$$

The calculation equation for RC short columns considering corrosion and impact damage of steel is as follows:

$$F = \begin{cases} 0.9\varphi\left(f_c A + f_y' A_s'\right), & \overline{D} = 0, \\ 0.9\varphi f_c A\left(1.0097 - 0.6155D'\right)\left(1.0008 - 1.2479\overline{D}\right) + 0.9\varphi f_y' A_s'\left(1.0041 - 4.5583\overline{D}\right), & \overline{D} \neq 0. \end{cases} \quad (15)$$

According to (15), the bearing capacity of C1X10 short column is 2835.9 kN and that of C2X10 short column is 2201.7 kN. As shown in Table 8, the error between the calculated results and the measured values is less than 3%, which shows the rationality of the bearing capacity equation. It should be noted that, through nondestructive testing, it can be known that the corrosion of the steel bar in this experiment has a more uniform effect on the RC column, so the parameter D could be used to express the damage of the column.

5. Conclusions

In this paper, the effects of impact energy and corrosion rate on the damage and residual bearing capacity of RC short columns were discussed through the supersonic wave aided nondestructive test and bearing capacity test. A method for calculating the residual bearing capacity of corroded RC column under impact loads is presented by supersonic wave aided nondestructive testing. The following conclusions can be drawn:

(1) When the damage of RC short column is caused by corrosion of longitudinal reinforcement, the damage along the direction of reinforcement is uniform. The closer the concrete is to the longitudinal reinforcement, the higher the damage degree would be. Before the reinforcement corrosion reaches a certain degree, there are no cracks on the surface of concrete, and the damage of concrete aggravates with the increase of reinforcement corrosion. After cracks appear on the concrete surface, the increasing speed of concrete damage gradually decreases with the increase of steel corrosion rate. The damage degree of RC columns is related to the corrosion rate, and the corrosion rate of RC short columns could be determined by damage detection.

(2) The impact resistance of RC short columns subjected to direct impact test surface decreases due to corrosion of steel reinforcement. When the corrosion rate reaches a certain level, the test surface under direct impact is more vulnerable to damage. The greater the impact energy is, the more serious the damage to the column is and the damage is mainly concentrated near the impact area. The damage degree of RC columns is related to the impact load, and the impact load of RC short columns could be determined by damage detection.

(3) In order to determine the effect of impact and corrosion on the residual bearing capacity of RC short columns, the equation of bearing capacity of RC columns under axial compression in China's current codes was introduced. According to the

results of bearing capacity test, corrosion damage factor and impact damage factor were introduced into the bearing capacity calculation formula, and a reliable and simple calculation formula for the residual bearing capacity of corroded RC structures under impact load was presented.

In general, this paper investigated the influence of corrosion and impact load on the damage and residual bearing capacity of RC short columns through ultrasonic test and residual bearing capacity test. By establishing the relationship between the damage degree and the residual bearing capacity of RC structures, a new method for calculating the residual bearing capacity of corroded RC structures under impact load by damage detection is proposed. In addition, this study provides a new research direction for determining the residual bearing capacity of the structure. However, due to the complexity of the corrosion and impact problems, there are still many problems that need further study. This article only considers two impact heights and two corrosion rates, so more experimental data are needed to improve the bearing capacity formula in the future.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

Authors' Contributions

Guorui Sun and Yi Zhang equally contributed to this manuscript as co-first authors.

Acknowledgments

This work was financially supported by the National Natural Science Foundation of China (Grants nos. 51608069 and 51778198). The authors would like to thank the members of the HIT 504 office for their selfless help and useful suggestions. This research was funded by National Natural Science Foundation of China(Grant no. 51608069).

References

[1] I. S. Yoon, "Comprehensive approach to calculate oxygen diffusivity of cementitious materials considering carbonation," *International Journal of Concrete Structures and Materials*, vol. 12, no. 1, p. 16, 2018.

[2] M. Davis, N. A. Hoult, and A. Scott, "Distributed strain sensing to assess corroded RC beams," *Engineering Structures*, vol. 140, pp. 473–482, 2017.

[3] Y. G. Du, L. A. Clark, and A. H. C. Chan, "Residual capacity of corroded reinforcing bars," *Magazine of Concrete Research*, vol. 57, no. 3, pp. 135–147, 2005.

[4] V. H. Dang and R. François, "Prediction of ductility factor of corroded reinforced concrete beams exposed to long term aging in chloride environment," *Cement and Concrete Composites*, vol. 53, pp. 136–147, 2014.

[5] J. Nepal and H.-P. Chen, "Risk-based optimum repair planning of corroded reinforced concrete structures," *Structural Monitoring and Maintenance*, vol. 2, no. 2, pp. 133–143, 2015.

[6] H.-P. Chen and N. Xiao, "Symptom-based reliability analyses and performance assessment of corroded reinforced concrete structures," *Structural Engineering and Mechanics*, vol. 53, no. 6, pp. 1183–1200, 2015.

[7] M.-T. Liang and P.-J. Su, "Detection of the corrosion damage of rebar in concrete using impact-echo method," *Cement and Concrete Research*, vol. 31, no. 10, pp. 1427–1436, 2001.

[8] H. Zhang, L. Liao, R. Zhao, J. Zhou, M. Yang, and R. Xia, "The non-destructive test of steel corrosion in reinforced concrete bridges using a micro-magnetic sensor," *Sensors*, vol. 16, no. 9, p. 1439, 2016.

[9] J. T. Zhou, J. L. Qiu, Y. X. Zhou, Y. Zhou, and R. Xia, "Experimental study on residual bending strength of corroded reinforced concrete beam based on micromagnetic sensor," *Sensors*, vol. 18, p. 2635, 2017.

[10] F. G. Zhang and L. Z. Li, "A method to determine the parameters of the model for concrete impact and damage," *Journal of Ballistics*, vol. 13, pp. 12–16, 2001, In Chinese.

[11] Q. M. Li and H. Meng, "About the dynamic strength enhancement of concrete-like materials in a split Hopkinson pressure bar test," *International Journal of Solids and Structures*, vol. 40, no. 2, pp. 343–360, 2003.

[12] L. Shang and J. G. Ning, "Dynamic constitutive relationship of concrete subjected to shock loading," *Engineering Mechanics*, vol. 22, pp. 116–119, 2005, In Chinese.

[13] K. Fujikake, B. Li, and S. Soeun, "Impact response of reinforced concrete beam and its analytical evaluation," *Journal of Structural Engineering*, vol. 135, no. 8, pp. 938–950, 2009.

[14] Y. B. Lu and Q. M. Li, "About the dynamic uniaxial tensile strength of concrete-like materials," *International Journal of Impact Engineering*, vol. 38, no. 4, pp. 171–180, 2011.

[15] G. Ulzurrun and C. Zanuy, "Flexural response of SFRC under impact loading," *Construction and Building Materials*, vol. 134, no. 1, pp. 397–411, 2017.

[16] H. J. Hwang, L. Zang, and G. Ma, "Effect of impact loading on bar development length in CCT node," *Journal of Structural Integrity and Maintenance*, vol. 4, no. 1, pp. 26–36, 2019.

[17] H. J. Hwang, T. H. K. Kang, and C. S. Kim, "Numerical model for flexural behavior of reinforced concrete members subjected to low-velocity impact loads," *ACI Structural Journal*, vol. 116, no. 2, pp. 65–76, 2019.

[18] G. Ma, H. Li, and H.-J. Hwang, "Seismic behavior of low-corroded reinforced concrete short columns in an over 20-year building structure," *Soil Dynamics and Earthquake Engineering*, vol. 106, pp. 90–100, 2018.

[19] J. Y. Sun, G. Q. Li, and Y. Lu, "Equivalent single degree of freedom model of SRC columns under blast loading," *Journal of Vibration and Shock*, vol. 26, pp. 82–89, 2007, In Chinese.

[20] Y. Chen and I. M. May, "Reinforced concrete members under drop-weight impacts," *Proceedings of the Institution of Civil Engineers - Structures and Buildings*, vol. 162, no. 1, pp. 45–56, 2009.

[21] H. M. I. Thilakarathna, D. P. Thambiratnam, M. Dhanasekar, and N. Perera, "Numerical simulation of axially loaded concrete columns under transverse impact and vulnerability

assessment," *International Journal of Impact Engineering*, vol. 37, no. 11, pp. 110–112, 2010.

[22] E. Kantar, R. Erdem, and Ö. Anıl, "Nonlinear finite element analysis of impact behavior of concrete beam," *Mathematical and Computational Applications*, vol. 16, no. 1, pp. 183–193, 2011.

[23] Ö. Anil, C. Durucan, R. T. Erdem, and M. A. Yorgancilar, "Experimental and numerical investigation of reinforced concrete beams with variable material properties under impact loading," *Construction and Building Materials*, vol. 125, pp. 94–104, 2016.

[24] Y. J. Yu, C.-H. Kim, and J.-Y. Cho, "Investigation of behavior of RC beams subjected to impact loading considering combination of mass and impact velocity," *Procedia Engineering*, vol. 210, pp. 353–359, 2017.

[25] M. J. Dai, O. Yang, Y. Xiao, and F. C. Li, "Influence of longitudinal bar corrosion on impact behavior of RC beams," *Materials and Structures*, vol. 49, no. 9, pp. 3579–3589, 2016.

[26] X. S. Yang, X. Z. Xia, and C. Q. Fang, "Numerical analysis of lateral anti-impact on the corroded reinforced concrete pier," *China Harbour Engineering*, vol. 37, pp. 25–29, 2017, In Chinese.

[27] C. Q. Fang, H. Y. Sun, S. Yang, C. J. Qiu, and R. Hu, "Concrete piers resistance to lateral impact properties of marine environment," *Concrete*, vol. 4, pp. 69–77, 2017, In Chinese.

[28] Y. B. Tian, T. Huang, J. Liu, R. X. Jin, and C. W. Zhang, "Damage detection and compressive behavior of concrete after impacting," *Journal of Building Structures*, vol. 35, pp. 58–64, 2014, In Chinese.

[29] G. B. Mohurd, *50010-2010: Code for Design of Concrete Structures*, China Architecture & Building Press, Beijing, China, 2011, In Chinese.