Desalination and Water Treatment
www.deswater.com

doi: 10.5004/dwt.2021.26779

219 (2021) 24–30
April

Calculation methods of stiffness after strengthening corroded RC beam under marine environment

Shihui Guo[a,*], Xiaozhen Chen[a], Huang Tang[b], Bing Liu[c]

[a]*School of Civil Engineering, Nanyang Institute of Technology, Nanyang 473000, China, email: guoguo91@126.com*
[b]*School of Civil Engineering, Hunan Institute of Technology, Yiyang 413000, China*
[c]*Nanyang Expressway Limited Company, Nanyang 473000, China*

Received 15 August 2020; Accepted 23 November 2020

ABSTRACT

In response to the degradation of mechanical behaviors of concrete structures caused by corrosion of steel bar caused by the permeation of chloride ion in the marine environment, this paper introduces the strain hysteresis coefficient $m(\eta_s)$ of the steel bar to reflect the influence of bond degradation caused by steel corrosion on the stiffness, and the short-term bending stiffness calculation model of corroded RC beam strengthened by steel plate is derived. A corrosive solution tank is designed to simulate the marine environment for electrochemical corrosion of the test beam, and the corroded RC beam is strengthened by a steel plate. Under the condition of keeping the corrosion rate constant, the design changes the thickness parameters of the steel plate and concrete protective layer and makes nine pieces of test beam. The correctness of the calculation method is verified by comparing the static load results with the theoretical calculation results. The results show that: under the condition of similar corrosion rate of steel bar, keeping the concrete protective layer unchanged, increasing the thickness of steel plate can increase the stiffness of members, but with the increase of steel plate thickness, the increasing range of thickness decrease; keeping the thickness of steel plate constant, the influence of changing the thickness of a concrete protective layer on deformation behavior of the beam is not obvious.

Keywords: Marine environment; Corroded RC beam; Steel plate reinforcement; Calculation to stiffness

1. Introduction

Due to the permeation of chloride ions in marine environment, the structures of reinforced concrete in coastal or offshore areas have corrosion on the steel bars. Steel bar corrosion would cause a decrease in stress section of the steel bar and the corrosion cracking of the concrete, lead to the degradation of mechanical behavior of the structure, and influence the durability of the concrete structure. This has been an important problem in actual engineering.

In terms of the problem of the corroded reinforced concrete beam, many scholars have done much experimental research, and theoretical analysis. Sun et al. [1] proposed a formula for calculating the ultimate capacity of corroded RC beam, and did a series of experiments of corroded beam to verify the correctness of the model. Maaddawy et al. [2] and Yang et al. [3] also established the model of degradation of stiffness due to the decrease of cohesion caused by corrosion. Wu et al. [4] studied the deformation behavior and failure modes of beam under fatigue load of corroded reinforced concrete. Brandonisio et al. [5] and Harish et al. [6] investigated the relationship between corrosion rate and crack width, and proposed a model for calculating the crack width.

Steel plate reinforcement is widely used in practical engineering because of its simple construction, low cost, and good effect of reinforcement. Until now, scholars at home and abroad have done a lot of experimental research and

* Corresponding author.

theoretical analysis on non-corroded beam strengthened by steel plate [7–12]. However, there are few theoretical studies on the deformation behavior after strengthening corroded RC beam. This paper makes nine pieces of RC beam, designs a corroded solution tank to simulate marine environment to proceed electrochemical corrosion of reinforced concrete pieces, and affixes steel plates on the bottom of beams to reinforce. Based on the geometric, physical, and mechanical equilibrium conditions of the steel plate reinforcement of corroded RC beam, a formula for calculating the stiffness of steel plate reinforcement of corroded RC beam is derived. The results of the static load test verify the correctness of the calculation formula, and consider the influence of steel plate thickness and concrete protective layer thickness on the stiffness of the corroded beam.

2. Calculation of stiffness of steel plate reinforcement of corroded beam

2.1. Corrosion model of steel bar

After corrosion, the section area and mechanical behaviors of steel bar decrease, and the bonding property α_{sc} between steel bar and concrete changes. After the corrosion of RC structure, the corrosion rate η_s of steel bar section is determined by the depth of steel bar corrosion. Based on the characteristics of pit depth, this paper defines the change rule of bond behavior between steel bar and concrete by using the model (Fig. 1) of reference [13,14]:

$$\alpha_{sc} = \begin{cases} 1, & \eta_s < 1.2\% \\ 1.0168 - 0.014\eta_s, & 1.2\% \le \eta_s < 6\% \\ 0.72 + 0.295e^{-0.0651\eta_s}, & 6\% \le \eta_s < 20\% \\ 0.8, & \eta_s \ge 20\% \end{cases} \quad (1)$$

The residual section area A_{sc} of steel bar in the model can be expressed by the following formula:

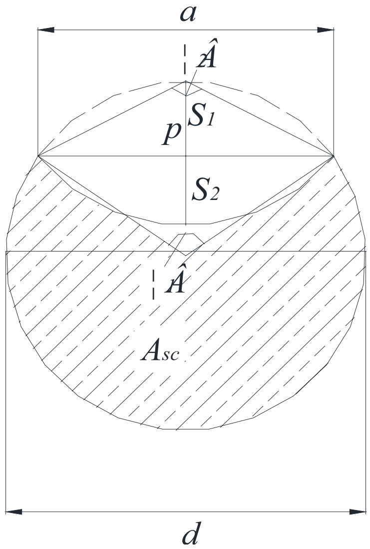

Fig. 1. Model drawing of pitting corroded steel bar.

$$A_{sc} = \begin{cases} \frac{\pi d^2}{4} - S_1 - S_2 & p \le \frac{\sqrt{2}}{2}d \\ S_1 - S_2 & \frac{\sqrt{2}}{2}d < p \le d \\ 0 & p > d \end{cases} \quad (2)$$

In the previous formula, S_1 and S_2 represent two semi-elliptic areas outside the shaded area, which can be expressed by the following formula:

$$S_1 = \frac{1}{2}\left[\beta_1\left(\frac{d}{2}\right)^2 - a\left|\frac{d}{2} - \frac{p^2}{d}\right|\right]$$
$$S_2 = \frac{1}{2}\left[\beta_2 p^2 - a\frac{p^2}{d}\right]$$
$$a = 2p\sqrt{1 - \left[\frac{p}{d}\right]^2} \quad (3)$$
$$\beta_1 = 2\arcsin\left(\frac{2a}{d}\right); \beta_2 = 2\arcsin\left[\frac{a}{p(t)}\right]$$

In Stewart [15], it is pointed that the yield strength f_{yc} of steel bar after pitting corrosion is linear:

$$f_{yc} = \left(1 - \lambda\frac{A_s - A_{sc}}{A_s} \times 100\right) f_y \quad (4)$$

In the formula f_y represents the yield strength of steel bar without corrosion; A_s is the section area of steel bar without pitting corrosion; λ is the experimental parameter, and the value of λ is 0.0035 for plain steel bar and ribbed steel bar.

2.2. Calculation of bending stiffness of corroded RC beam strengthened by steel plate

The effect of bond degradation between steel bar and concrete caused by steel bar corrosion on the stiffness of members is manifested in the hysteresis of steel bar strain at the maximum moment section of members. The steel bar strain hysteresis at the section with the maximum bending moment is reflected by the coefficient $m(\eta_s)$ of steel bar strain hysteresis, that is:

$$m(\eta_s) = \frac{\bar{\varepsilon}_{sc}(\eta_s)}{\bar{\varepsilon}_s(\eta_s)} \quad (5)$$

In Eq. (5), $\bar{\varepsilon}_{sc}(\eta_s)$ is the average tension strain of concrete at the position of tensile reinforcement; $\bar{\varepsilon}_s(\eta_s)$ is the average strain of tensile reinforcement after the degradation of bond force.

The strain non-uniformity coefficient ψ_c of corroded steel bar and the stain non-uniformity coefficient ψ of intact steel bar can be corrected by the following formula:

$$\psi_c = n(\eta_s)\psi \quad (6)$$

$$\psi = \frac{1.1 - 0.65 f_{\text{tk}}}{\left(\rho_{\text{te}}\sigma_{\text{sk}}\right)} \tag{7}$$

$$\rho_{\text{te}} = \frac{\left(\alpha_{\text{sc}} A_s + \alpha_{\text{py}} A_{\text{yp}}\right)}{\left(0.5\text{bh}\right)} \tag{8}$$

$$\sigma_{\text{sk}} = \frac{M}{0.87 h_{\text{sp}} \left(\alpha_{\text{sc}} A_s + \alpha_{\text{py}} A_{\text{yp}}\right)} \tag{9}$$

In the formula, α_{sc} is the strength utilization coefficient of steel bar; $\alpha_{\text{py}} = f_{\text{yp}}/f_{\text{yc}}$; M is the bending moment of section, and generally, $M = (0.5–0.7)M_u$, of which M_u is the maximum bending moment of section.

Fig. 2 shows the stress distribution and stress–strain distribution in the middle section of the pure bending section of the corroded RC beam strengthened by steel plate:

From the equilibrium conditions, it can be concluded that:

$$M = \omega\sigma_c b x_{\text{cr}} \eta h_{\text{sp}} \tag{10}$$

$$\omega\sigma_c b x_{\text{cr}} = \sigma_s A_{\text{sc}} + \sigma_{\text{py}} A_{\text{py}} \tag{11}$$

$$\beta\left(\alpha_{\text{sc}} f_{\text{sc}} A_{\text{sc}} + f_{\text{py}} A_{\text{py}}\right) = \alpha_1 f_c b x_{\text{cr}} \tag{12}$$

$$x_{\text{cr}} = \frac{\beta\left(\alpha_{\text{sc}} f_{\text{sc}} A_{\text{sc}} + f_{\text{py}} A_{\text{py}}\right)}{b\alpha_1 f_c} \tag{13}$$

In the formula, ω is the coefficient of shape integrity of stress in the compression zone; η is the coefficient of internal moment arm on the crack section; β is the coordinated working coefficient of the steel plate and longitudinal steel bar. It is generally believed that β = 0.8–0.95, and the reference value in this paper is β = 0.85. x_{cr} is the height of the concrete compression zone after pasting the steel plate.

The effective section of the corroded RC beam strengthened by the anchor plate will change, but the deformation law of the corroded beam still confirms the assumption of the average strain plane section. The effective section of the corroded RC beam can be converted to the effective section height h_{sp}, which is the distance between the joint point of the corroded tensile steel bar and the steel plate and the top of the beam. Eq. (14) is as follows:

$$h_{\text{sp}} = \frac{\alpha_{\text{sc}} f_{\text{yc}} A_{\text{sc}} \left(h - a_s\right) + f_{\text{py}} A_{\text{yp}} \left(h + t_p / 2\right)}{\alpha_{\text{sc}} f_{\text{yc}} A_{\text{sc}} + f_{\text{py}} A_{\text{yp}}} \tag{14}$$

In Eq. (14), f_{py} is the yield strength of the steel plate; A_{py} is the section area of the steel plate; t_p is the thickness of the steel plate; a_s is the distance from the bottom of the beam to the center of gravity of the steel bar.

The bending stiffness B and the curvature ϕ of the section can be expressed as:

$$B = \frac{M}{\phi} \tag{15}$$

According to the stiffness theory in material mechanics, the section curvature can be determined by the geometrical condition, physical relation, and equilibrium condition of the section.

Geometrical condition:

$$\phi = \frac{m\left(\eta_s\right) n\left(\eta_s\right) \cdot \psi \cdot \varepsilon_{\text{sc}} + \varepsilon_{\text{cc}} + \varepsilon_{\text{sp}}}{h_{\text{sp}}} \tag{16}$$

In the Eq. (16), ε_{cc} is the top concrete strain in the compression zone; ε_{sc} is the strain near the tensile steel bar; ε_{sp} is the average strain of the bottom steel plate; $n(\eta_s)$ is the correction coefficient of bond degradation. ψ can be selected from the specification for the design of the concrete structure.

The physical relationship between stress and strain:

$$\varepsilon_{\text{cc}} = \frac{\sigma_c}{E_c},\ \varepsilon_{\text{sc}} = \frac{\sigma_{\text{sc}}}{E_s},\ \varepsilon_p = \frac{\sigma_{\text{py}}}{E_p} \tag{17}$$

In Eq. (17), σ_c, σ_{sc}, and σ_{py} are the stresses of concrete, tensile reinforcement, and steel plate on the top of the beam respectively; E_c is the elastic modulus of concrete; E_s is the elastic modulus of tensile reinforcement; E_p is the elastic modulus of steel plate:

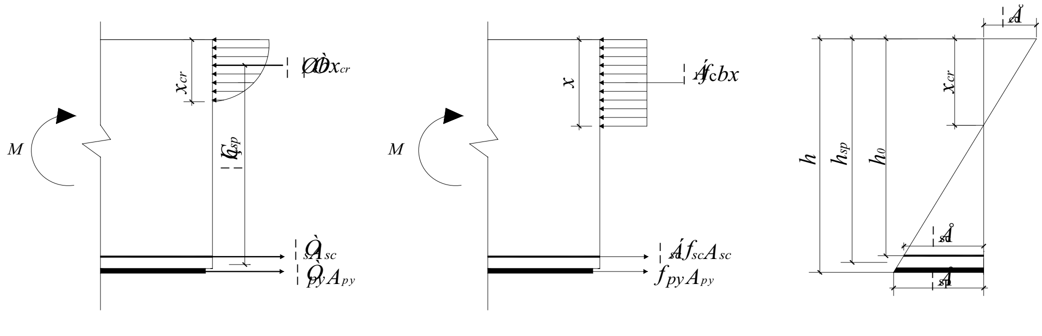

Fig. 2. Stress analysis of pure bending section of corroded RC beam strengthened by steel plate: (a) force, (b) equivalent force, and (c) section stress–strain diagram.

$$B = \frac{E_s A_{py} h_{sp}^2}{m(\eta_s) n(\eta_s) \psi A_{py} \dfrac{2a_s + d + t_p - 2\eta\left(h_{sp} - h_0\right)}{\eta\left(2a_s + d + t_p\right) A_{sc}} + \alpha_s \dfrac{A_{py}}{\omega b x_{cr} \eta} + \dfrac{2\alpha_s \left(h_{sp} - h_0\right)}{a_s + d + t_p}} \quad (18)$$

After obtaining the bending stiffness, the deflection value of the beam can be calculated by the following simplified formulas, that is:

$$\delta = S \frac{M l_0^2}{B} \quad (19)$$

In Eq. (19), S represents the calculation coefficient of deflection related to load and support conditions. For 4-point loading, S = 13/216, and for concentrated load in mid-span, S = 1/12.

3. Experimental study

3.1. Test beam design

A total of nine reinforced concrete test beams with the same size and reinforcement are designed in the test, with a size of 150 mm × 300 mm × 1,600 mm and a section width × height of 150 mm × 300 mm. The grade of the concrete strength of test beams is all C30, the grade of the longitudinal tensile reinforcement of the beam is HRB335 and the thickness of the concrete protective layer is 30 mm. The concrete reinforcement and structure are shown in Fig. 3.

The corrosion rate of steel bar is designed at 10%. Reinforcement corrosion is a method of rapid electrochemical corrosion through the corrosion chamber of the laboratory. The components are immersed in sodium chloride solution with a concentration of 15%. The cathode of a constant DC power supply is connected with the stainless steel in sodium chloride solution, and the anode is connected with the reinforcement of the components. Under the action of the current, the anode steel bar releases electrons to be oxidized, which leads to the corrosion of the anode steel bar. Before powering on, the RC beam was immersed in the solution for 3 d, and the corrosion current was 0.05a. Fig. 4 shows the corrosion conditions of RC beam and steel bar.

The steel plate used to reinforce corroded beam is Q235 steel plate, with the dimensions of 1,400 mm long, 100 mm wide, and the thickness of 3, 4, and 5 mm, respectively. The anchor bolts structural glue used for reinforcement are JN-S anchor bolts and JN structural glue produced by Goodbond Company (No. 18 Luyun Road, High-tech Zone, Changsha, Hunan Province, China).

3.2. Test loading and measuring contents

After strengthening the steel plate of corroded RC beam, the static load test of test beam is carried out by using single point graded loading method. During the process of test, the deflection, concrete strain, steel plate strain, etc. of

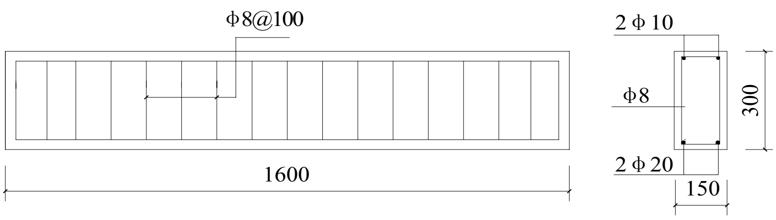

Fig. 3. Reinforcement drawing of test beam.

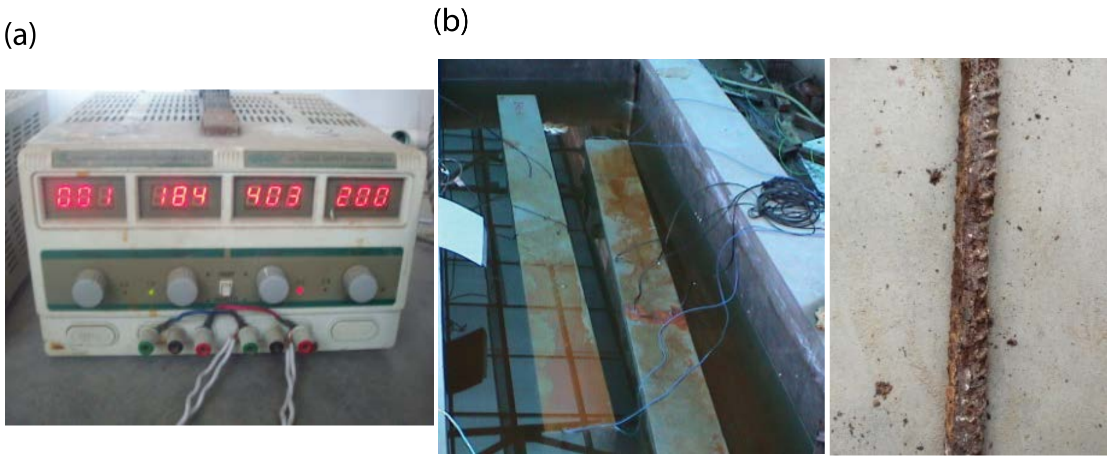

Fig. 4. Corrosion drawing of test beam and steel bar: (a) test beam corrosion by electrochemical method and (b) steel corrosion.

bearing, mid-span, and four-point under various loads are measured, and the development of cracks and failure modes are recorded in detail. Fig. 5 shows the test loading device.

4. Analysis of test results

After completing the static load test, the steel bar is removed after the corroded reinforced beam is broken and the corrosion rate of the steel bar is measured. The parameters of each test beam and the main test results are shown in Table 1.

4.1. Influence of steel plate thickness on the deformation performance of beam

Because there is a deviation between the measured corrosion rate and the design value in this test, beams with the similar corrosion rate are selected for comparison. Fig. 6 is the load-mid-span deflection curve of the test beam with the same protective layer and different thickness of steel plate. As can be seen from the Fig. 6, when the thickness of concrete protective layer is the same and the corrosion rate of steel bar is similar, the stiffness of the test beam is obviously lager as the thickness of steel plate increases from 3 to 4 mm. However, as the thickness of steel plate continues to increase, the steel degree of the test beam increases gradually. Under the same load, the mid-span deflection of the strengthened beam decreases with the increase of the reinforcement thickness of steel plate. The ductility of the stiffness of test beam decreases with the increase of the thickness of steel plate.

4.2. Influence of the thickness of protective layer on the deformation performance of the beam

Fig. 7 shows the load-mid-span deflection curve of test beam with different thickness of concrete protective layer with the same thickness of steel plate. As shown in Fig. 7, when the thickness of steel plate is 4 mm, the thickness of the concrete protective layer is changed, and the

Fig. 5. Loading device of test beam.

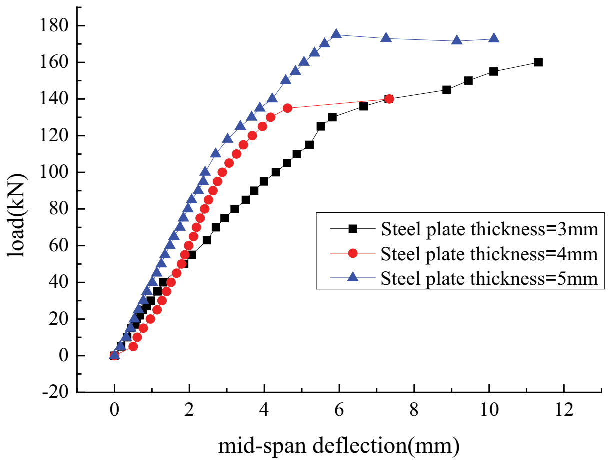

Fig. 6. *P*–δ curve of *c* = 35 mm beam.

Table 1
Main parameters and test results of test beams

Beam number	c (mm)	t_p (mm)	f_c (MPa)	f_{yc} (MPa)	A_{yp} (mm^2)	A_{sc} (mm^2)	Measured corrosion rate (%)	Ultimate capacity P_u (kN)	Maximum mid-span deflection f (mm)	Failure mode
P-1	25	3	33.4	333.74	300	687	9.65	163	9.82	Diagonal tension
P-2	25	4	35.8	327.32	400	674.9	11.2	158	9.59	Diagonal tension
P-3	25	5	34.5	325.72	500	671.8	11.6	154	9.77	Diagonal tension
P-4	30	3	32.6	342.44	300	703.5	7.425	171	11.52	Diagonal tension
P-5	30	4	33.9	330.93	400	681.7	10.3	159	8.34	Diagonal tension
P-6	30	5	33.7	328.37	500	676.9	10.94	175	10.19	Diagonal tension
P-7	35	3	34.5	330.53	300	690.5	10.4	143	7.34	Diagonal tension
P-8	35	4	35.6	330.73	400	681.3	10.255	159	11.32	Diagonal tension
P-9	35	5	32.4	335.54	500	681	9.15	173	10.13	Diagonal tension

Note: c is the thickness of the concrete protective layer; t_p is the thickness of the reinforced steel plate; f_c is the measured compressive strength of concrete; f_{yc} is the measured yield strength of steel bar after corrosion; A_{yp} is the section area of reinforced steel plate; A_{sc} is the average section area of steel bar after corrosion.

Table 2
Comparison between the measured and calculated deflections

Beam number	Measured deflection f_{mea} (mm)			Theoretical calculated deflection f_{cal} (mm)			f_{mea}/f_{cal}			Mean
	$0.5P_u$	$0.6P_u$	$0.7P_u$	$0.5P_u$	$0.6P_u$	$0.7P_u$	$0.5P_u$	$0.6P_u$	$0.7P_u$	
P-1	2.40	3.22	3.89	2.06	2.73	3.26	1.16	1.18	1.19	1.18
P-2	2.12	2.60	3.58	1.93	2.42	3.39	1.07	1.03	0.99	1.03
P-3	2.45	3.29	4.02	2.17	2.73	3.59	1.13	1.20	1.12	1.15
P-4	2.08	2.66	3.52	2.21	2.70	3.17	0.94	0.98	1.11	1.02
P-5	2.47	3.26	4.09	2.16	2.87	3.66	1.01	1.14	1.12	1.09
P-6	2.47	3.40	4.04	2.29	3.20	3.70	1.08	1.06	1.09	1.08
P-7	2.06	2.42	2.88	2.12	2.57	3.01	0.97	0.94	0.96	0.96
P-8	2.24	2.57	2.92	1.98	2.36	2.70	1.13	1.09	1.04	1.09
P-9	2.52	3.41	4.05	2.05	2.77	3.28	1.17	1.19	1.16	1.18

P–δ curves of each test beam are very close in the loading process. This indicates that when the corrosion rate of reinforcement is similar, the thickness of steel plate is the same when the corroded beam is strengthened, and the deformation performance of the beam is less affected by changing the thickness of the concrete protective layer.

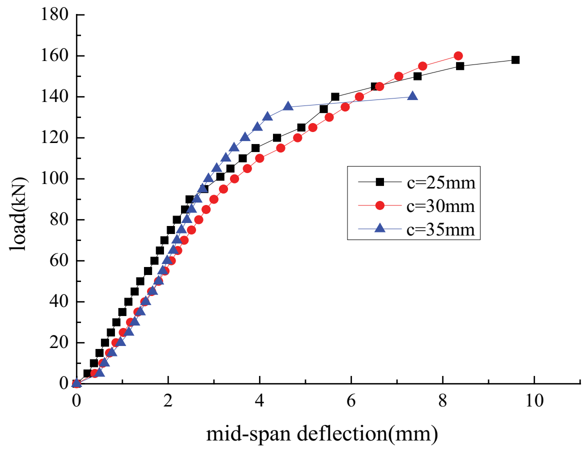

Fig. 7. *P*–δ curve of beam with 4 mm thickness of steel plate.

5. Comparisons between experimental and theoretical values of deflection

After calculating the short-term bending stiffness of the test beam after reinforcement according to Eq. (18), the mid-span deflection of each test beam under the action of 0.5, 0.6, and $0.7P_u$ is calculated according to Eq. (19). The comparison between the measured and calculated deflections is shown in Table 2. It can be seen from Table 2 that the average variation range of the ratio between the measured results and the deflection results calculated by the formula is 0.96–1.18, and the test results are in good agreement with the theoretical calculation results.

6. Conclusions

In terms of the degradation phenomenon of bearing capacity of RC structures caused by steel plate corrosion in the marine environment, in this paper, by introducing the strain hysteresis coefficient $m(\eta_s)$ and the strain non-uniformity coefficient $n(\eta_s)$ of steel bar to reflect the influence of bond degradation caused by steel corrosion on the stiffness, and the short-term bending stiffness calculation model of corroded RC beam strengthened by steel plate is derived. Through the test results of nine pieces of beams, the correctness of the formula derived from deflection is verified, and the influence of the thickness of steel plate and the thickness of concrete protective layer on the stiffness of the corroded beam strengthened by steel plate is studied. The following conclusions are drawn:

- The failure mode of the corroded beam after strengthening with steel plate are all diagonal-tension failure. The ductility of the test beam decreases after strengthening with steel plate, and the ductility shows a decreasing trend with the increase of the thickness of steel plate.
- Under the condition of similar corrosion rate of steel bar, keeping the concrete protective layer unchanged, increasing the thickness of steel plate can increase the stiffness of member, but with the increase of steel plate thickness, the increasing range of thickness decrease; keeping the thickness of steel plate constant, the influence of changing the thickness of concrete protective layer on deformation behavior of the beam is not obvious.
- The theoretical calculation results of mid-span deflection are close to the experimental results, and the theoretical calculation formula can better predict the stiffness and deflection values of corroded beam.

Acknowledgments

This work is supported by Foundation items: project of science and technology of the Henan China-International cooperation projects (182102410068).

References

[1] B. Sun, D.T. Niu, Q.L. Wang, Calculation method for flexural capacity of corroded RC beams, China Civ. Eng. J., 14 (2008) 1–6.

[2] T.E. Maaddawy, K. Soudki, T. Topper, Analytical model to predict nonlinear flexural behavior of corroded reinforced concrete beams, ACI Struct. J., 102 (2005) 550–559.
[3] S.-Y. Yang, X.-L. Liu, Y.-B. Leng, Prediction of flexural deformation of a corroded RC beam with a polynomial tension-stiffening model, J. Struct. Eng., 139(2013) 940–948.
[4] J. Wu, C.X. Wang, J. Xu, Z. Xiao, F.H. Wu, Study on flexural behavior of corroded reinforced concrete beams under fatigue loads, China Civ. Eng. J., 45 (2012) 118–124.
[5] G. Brandonisio, G. Lucibello, E. Mele, A.D. Luca, Damage and performance evaluation of masonry churches in the 2009 L'aquila earthquake, Eng. Fail. Anal., 34 (2013) 693–714.
[6] K.V. Harish, J.K. Dattatreya, M. Neelamegam, Experimental investigation and analytical modeling of the σ–ε characteristics in compression of heat-treated ultra-high strength mortars produced from conventional materials, Constr. Build. Mater., 49 (2013) 781–796.
[7] N.M. El-Shafey, E. Al-Sherif, Wild medics from different original habitats can be used as forage legumes in salt affected soil, J. Clean WAS, 4 (2020) 32–40.
[8] M.Y. Ke, C.Y. Jin, X.L. Hong, Experimental study of reinforced concrete beam strengthened by epoxy-bonded steel plates, Hydro Sci. Eng. J., 4 (2001) 27–32.
[9] S. Aykac, I. Kalkan, B. Aykac, S. Karahan, S. Kayar, Strengthening and repair reinforced concrete beams using external steel plates, J. Struct. Eng., 139 (2013) 929–939.
[10] E. Rosida, Sudrajat, M.A. Marfai, Environmental quality analysis due to tidal flood in pasirkratonkramat sub-district Pekalongan, Indonesia, Environ. Ecosyst. Sci., 4 (2020) 38–44.
[11] L.X. Liu, D.Y. Sang, R.Y. Wang, Experimental study on flexural properties of RC beams steel plate anchored by rivets, Build. Struct., 37 (2007) 6–9.
[12] W. Cheng, Experimental Study on Flexural Properties of RC Beams Strengthened by Steel Plate Anchored with Rivets, Zhengzhou University, Zhengzhou, 2006.
[13] B. Prabal, H.R. Syed, Aquatic health index of coastal aquaculture activities at south-eastern coast of Bangladesh, Water Conserv. Manage., 4 (2020) 51–57.
[14] D.V. Val, R.E. Melchers, Reliability of deteriorating RC slab bridges, J. Struct. Eng., 123 (1997) 1638–1644.
[15] M.G. Stewart, Mechanical behaviour of pitting corrosion of flexural and shear reinforcement and its effect on structural reliability of corroding RC beams, Struct. Saf., 31 (2009) 19–30.