BENDING PERFORMANCE OF CORRODED RC BEAMS USED FOR MANY YEARS

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ABSTRACT : It is essential to check the safety performance of existing reinforced concrete (RC) structures because the number of existing RC structures that have been in service for many years is still increasing. However, an appropriate method for evaluating the effect of severely corroded reinforcing bars on the safety performance is not established yet. This is because only insufficient knowledge is available with regard to the effect of the corrosion on the mechanical properties. This paper presents the results of an experimental investigation conducted to examine the effect of corrosion of reinforcing bars on the mechanical performance and behavior of a RC beam under static loading. The beam was taken from a real railway frame structure that had been used as a viaduct for approximately 70 years. Close examinations of the beam before and after the loading test revealed that the reinforcing bars in the beam had been corroded to a large extent due to the carbonation of concrete, and the corrosion had induced cracking and spalling of the cover concrete. When a bending force was applied to the beam, the main crack at the mid-span shows about 50 mm width at ultimate because of the debonding of the longitudinal bar due to corrosion and failure of cover concrete. The corroded reinforcing bar is modeled by tensile test results and measured values of distribution of cross section investigated by caliper and 3D scanner. Using this analytical model of the corroded bar, fiber analysis for the beam specimen is carried out. It was indicated that the bending strength of the corroded RC beam could be estimated to a satisfactory accuracy if the distribution of net cross section of reinforcing bar excluding the corroded portions was taken into account in its calculation.

KEYWORDS: existing structure, corrosion, net cross section, bending strength, carbonation

1. INTRODUCTION

To utilize existing infrastructures effectively, it is important to check the effect of the deterioration. Therefore it is essential to check the performance of existing reinforced concrete (RC) structures. In many cases the effect of the corrosion of the reinforcing bar is checked under the viewpoint of the prevention from stain the appearance, but it is also important to evaluate the safety performance when the reinforcing bars is seriously damaged by the corrosion. On the other hand, it should be considered that existing structures are designed in accordance with the old design standard and constructed using old materials and production methods different from those of today. This paper was aimed to present an typical example of the evaluating test for old structural members based on the old design code deteriorated after its long-term service.

2. TEST PROGRAM

Test program was conducted as follows: For the first step, inspection survey of the appearance and the measurement of the position of the reinforcing bars were carried out for the specimen using the non-destructive bar detector. In the next step, static loading test was carried out to the beam specimen after

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providing sensors to measure the strain or the displacement. Finally, the loading test result was verified by the analysis after required checks on the deterioration of concrete and reinforcing bars.

3. TEST SPECIMEN

Fig.1 shows the outline of the objective structure. This is a RC rigid-framed pier used as a railway viaduct in a warm urban area away from coast. The specimen is beam portion of this structure cut off by a wire saw at the line of the column side surface as shown in Fig.1. Shoe bearing provided on the top of the columns instead of the beam segment sustained the weight of the girder. The structure has been in service for nearly 70 years since its construction.

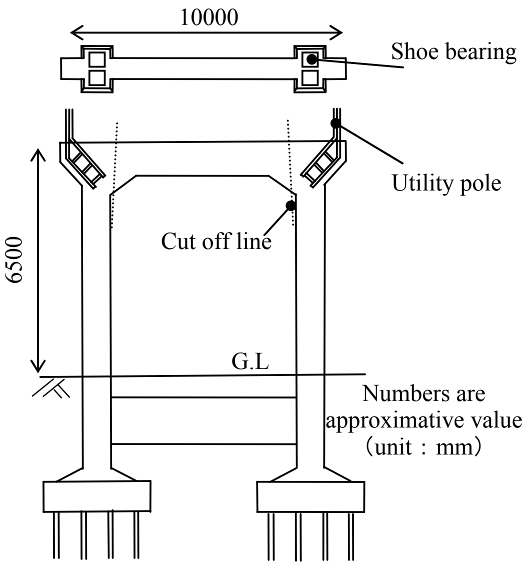


Fig.1 Outline of objective structure

Fig.2 shows the details of the specimen and the names of the sides and reinforcing bars referred in the following chapters. The reinforcing bar arrangements shown in this figure was verified at several major positions with the use of an electromagnetic wave radar and an electro-magnetic induction meter. The followings can be pointed out comparing with the today's conventional railway viaduct:

(1)The ratio of tensile reinforcement is 0.37 percent, which is less than that of the ordinary railway structures today.

(2)The lap splices with the semicircular hook in tensile reinforcements are provided at the same cross section at the quarter span of the beam. At present, the lap splices are not provided in general at such positions subjected to high stresses because the lap splices in bar reinforcement tend to become weak spots.

(3)The tensile reinforcing bars are not the deformed bar but the round bar, and they are bent up at the beam-column joints. Bending moment at the ends of the beam caused by the seismic load is transmitted by the reinforcement at the haunches.

(4)Four longitudinal reinforcing bars are respectively arranged and encircled by stirrups separately.

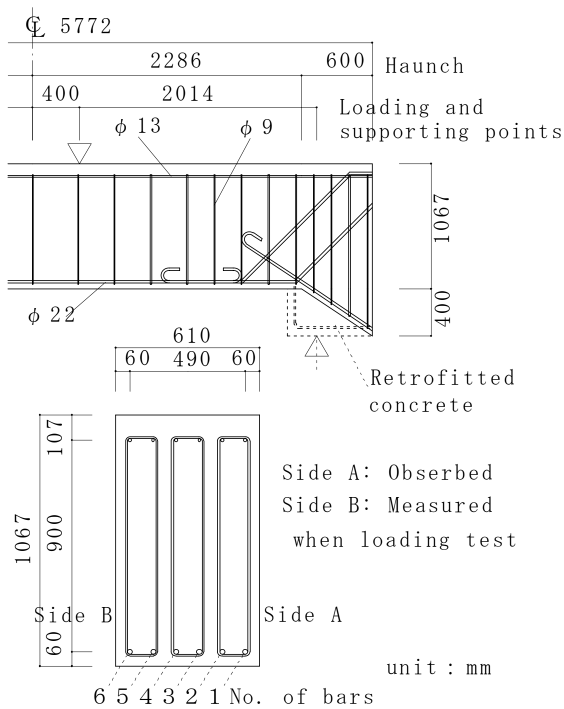


Fig.2 Details of beam specimen

Fig.3 shows the bottom view of the beam specimen. The side and bottom surface of the specimen was stained with the sand from the railway girder upheld. Thus it was conceivable that the water was provided continuously to this beam and induced the corrosion of the tensile reinforcing bar at the mid-span. The cover mortar without gravel was spalled and stripped off the beam, while the ordinary concrete is arranged in another region of the cover concrete. In addition, a very large gravel (approximately 300mm or larger in diameter) existed at the particular position. It is supposed that these regions had existed since the completion considering the existence of the continuous vestige of the mold joint recognized at the bottom surface of the specimen. These situations suppose the possibility that the structure had been constructed in the following procedure; large gravels were used as the bar spacer to keep bars at the arranged position, the aperture was filled with poor mixed mortar and the ordinary concrete was cast to the remaining major part of the beam section above the longitudinal reinforcing bars.

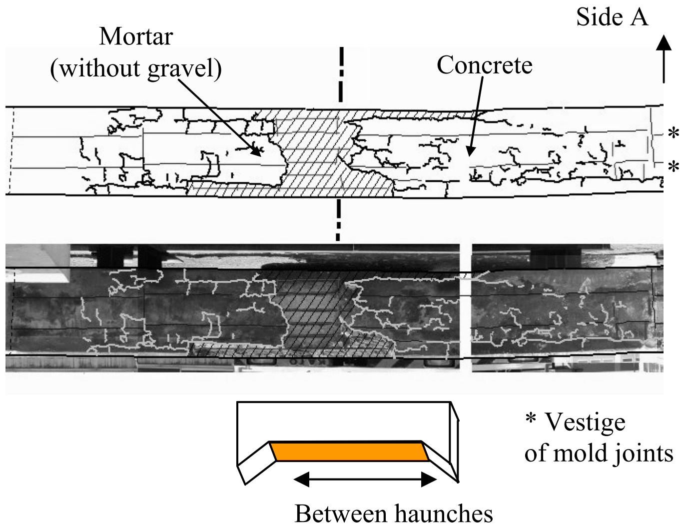


Fig.3 Bottom view of the beam specimen

4. LOADING TEST

4.1 Loading method

The beam specimen was tested by four-point static bending to determine their load-deflection curves. Fig.2 shows the test setup and the loading / supporting points. The length of the pure bending region is 800 mm, and shear span-depth ratio is approximately two. Because supporting points are located at the haunch, new reinforcing bars are arranged and new concrete is cast in this haunch portion to get stable reaction force. The concrete strength of newly cast is approximately 29.4 N/mm^2 at the age of 16 days. To improve insufficient anchorage of the longitudinal reinforcement, small steel plates were welded at the end of the reinforcing bars. The beam specimen was loaded under the loading program shown in Fig.4, where P_{ycal} indicates the calculated value of the yield

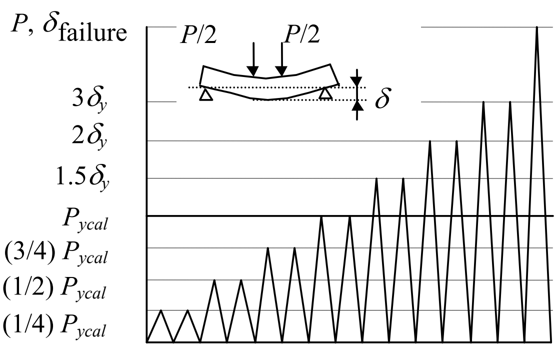


Fig.4 Loading program

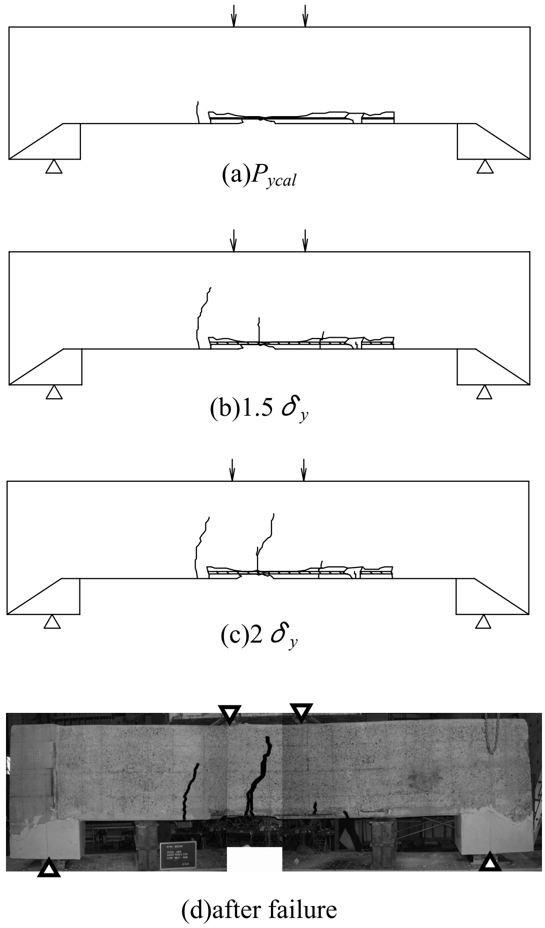


Fig.5 Crack pattern caused by loading test

strength and δ_y indicates the deflection at the yield.

4.2 Test results

After yielding of the longitudinal reinforcement, the deflection at the mid-span has been proceeded. Though compression failure at the top side was observed, sudden failure was not observed. The number of the cracks is only two. The main crack at the mid-span shows approximately 50 mm width at the last loading step. Fig.5 shows the crack pattern observed in the loading test. The reason of a small number of the cracks is assumed to be that the bond strength between the longitudinal reinforcement and the concrete was reduced by the followings. (1)The longitudinal reinforcement is not the deformed bar but the round bar. (2)The cover concrete at the mid-span almost falls because of the corrosion. The lap splice of the longitudinal reinforcing bar does not fail in this loading test.

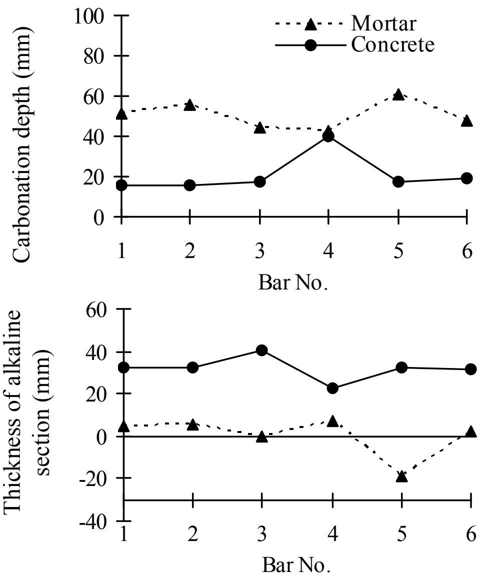


Fig.6 Results of carbonation test

5. DETERIORATION CHECKS

Fig.6 indicates the investigation results of carbonation of the concrete, which was tested by the solution of the phenolphthalein splayed at the fresh surface exposed by the partial demolition removal of the cover concrete. Thickness of alkaline section (which was calculated by the difference between the thickness of the cover concrete and the carbonation depth) at the place of the cover mortar is smaller than 10 mm, which leads the reinforcing bar to corrode. It is evident that the beam specimen had been corroded by carbonation of the cover concrete or mortar.

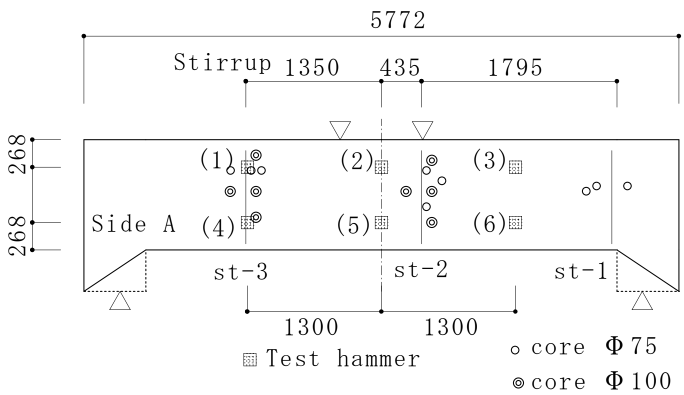


Fig.7 Test position of concrete strength (unit:mm)

Fig.7 shows the test position of the concrete strength. It was measured by the compression test of the cylindrical core samples extracted from the beam specimen whose diameters were about 75mm or 100mm. Fig.8 shows the test results of the concrete strength compared with the estimated value by the Schmidt Test Hammer. Concrete strength measured by the compress-

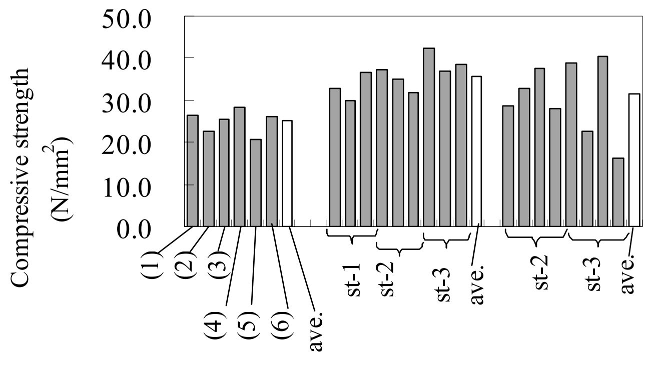


Fig.8 Test results of the concrete strength

ion test is larger than the estimated value of the test hammer. The averaged test result for the elastic modulus is approximately 18.4N/mm^2, which is smaller than the calculated value by the design code.

Fig.9 shows the net area ratio of the cross section of the corroded longitudinal reinforcing bar excluding the corroded portions, which was measured by a caliper after the loading test and removing the cover concrete. The net area ratio is calculated by the cross sectional area of the corroded reinforcing bar divided by that of the non-corroded bar (diameter is 22 mm). The cross sectional area is assumed to be equal to the area of the circle whose diameter is to be the minimum value measured by the caliper in every direction.

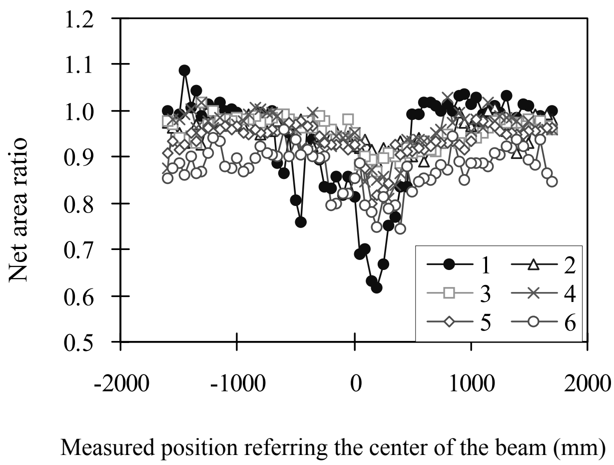
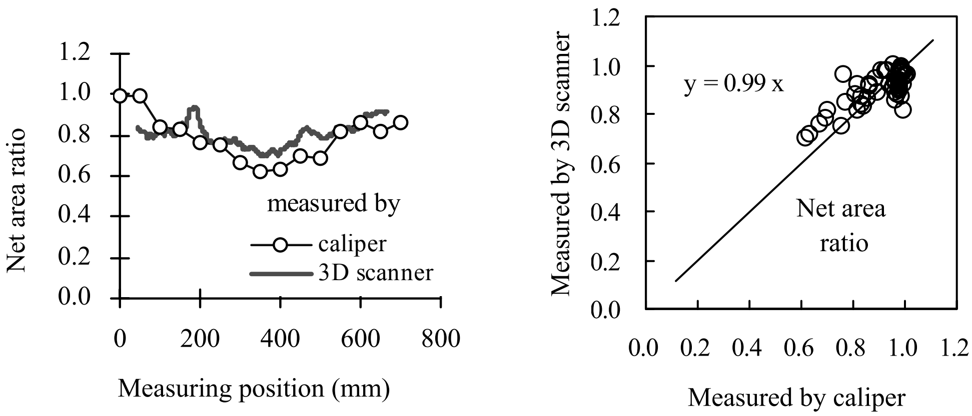


Fig.9 Net area ratio (measured by caliper)



(a)example of a test piece

(b)Averaged in each test piece

Fig.10 Comparison of values measured by caliper and 3D scanner

Fig.10 shows the comparison of the measured values between caliper and 3D scanner. The 3D scanner can digitize the shape of the objective measuring article set on the turn-table by tracing the position of the laser beam spot. According to the Fig.10(a), the net area ratio measured by caliper has sufficient accuracy. However, the measured area by caliper is totally a little larger than that by the 3D scanner according to the Fig.10(b).

According to Fig.9, the net area ratio of the bar No.1 located at the corner of the cross section (see in Fig.2) is small. It is the effect of the water provided from the railway girder upheld. The net area ratio of the cross section averaged in the 400 mm span at the beam center is approximately 0.85.

6. ANALYSYS TO VERIFY LOADING TEST

In order to verify the load-deflection relationship of the loading test of the beam specimen, an analytical program is conducted considering the material characteristics of the deteriorated concrete and reinforcing bar. The test results of the concrete strength for the sampled core and the reduced strength of the reinforcing bar considering the effect of the corrosion have been adopted.

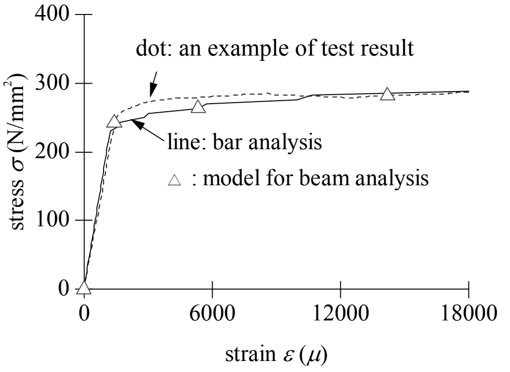


Fig.11 Stress-strain relationship of the corroded reinforcing bar

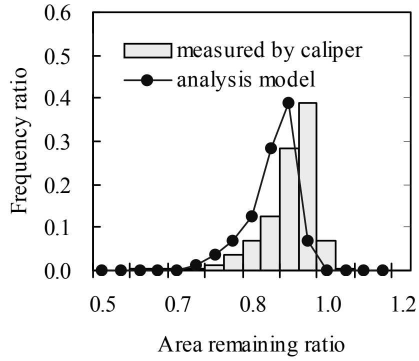
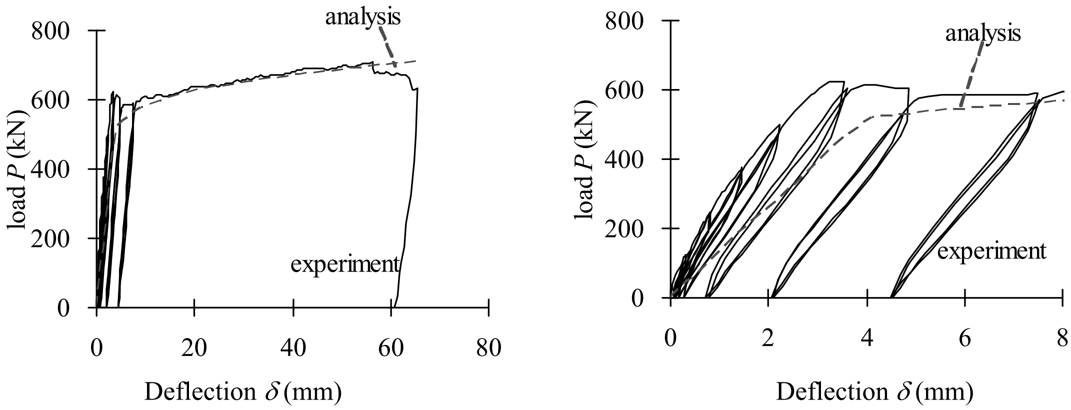


Fig.12 Distribution of net cross section of the corroded reinforcing bar



(a) Gloval view

(b) Yield point

Fig.13 Load deflection curve of the beam specimen

To determine the stress-strain relationships of the corroded reinforcing bar, tensile strength test and analysis has been carried out following the previous procedure (Oyado, 2006). In the tensile strength test, targets were attached to both ends of the test span to measure the elongation of the bar. The dotted line in Fig.11 indicates the test result of the stress-strain relationship. The stress is the applied load divided by the nominal cross-sectional area without corrosion, and the strain is the measured elongation divided by the gauge length (352mm) between the targets. The solid line indicates analytical result calculated by the infinite element method. In this analysis, the reinforcing bar is modeled dividing into infinite elements along the axial direction, and the stress-strain relationship obtained from the non-corroded bar is adopted for each element. The cross sectional area for each element is assumed to have the distribution shown in Fig.12, which corresponds to the observed results shown in Fig.9.

Fig.13 indicates the load-deflection curve of the beam specimen obtained by the loading test and the fiber analysis. The assumption that the fiber strain is proportional to the distance from the neutral axis is adopted for the analysis. According to Fig.13, the test result after the yield point and ultimate strength is almost equal to the analysis result. However, the test result of the load-deflection curve before the yield point is different from the analysis result. It is assumed that the difference was caused by the crack pattern and the reduction of the bond strength between the reinforcing bar and the concrete.

7. CONCLUSION

In order to clarify the effects of the corrosion on the mechanical performance of the RC beams, the loading test and analysis were carried out for the old RC beam specimen that was in service for 70 years. When a bending force was applied to the beam, the main crack at the mid-span shows about 50 mm width at ultimate because of the debonding of the longitudinal bar due to corrosion and failure of cover concrete. The corroded reinforcing bar is modeled by tensile test results and fiber analysis for the beam specimen is carried out. It was also indicated that the bending strength of the corroded RC beam could be estimated to a satisfactory accuracy if the distribution of net cross section of reinforcing bar excluding the corroded portions was taken into account in its calculation.

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