Al-Azhar University Civil Engineering Research Magazine (CERM)
Vol. (40) No. (4) October, 2018

Rate of Reinforcement Corrosion in Two-Span Loaded and Unloaded Reinforced Concrete Beams

O.A. Hodhod [1], A.M. Sanad [2], M.M. El-Attar [1], H.A. Hassan [3]

[1] Prof. of Properties and Strength of Materials, Str. Eng. Dept., Faculty of Engineering, Cairo University, Egypt

[2] Prof. of Structural Engineering, Construction and Building Dept., College of Engineering, Arab Academy for Science & Technology, Cairo, Egypt

[3] Lecturer Assistant, Construction and Building Dept., College of Engineering, Arab Academy for Science & Technology, Cairo, Egypt

ملخص البحث

تبحث هذه الدراسة في معدل تآكل حديد التسليح في الكمارات الخرسانية المسلحة ذات البحرين. يتم تقديم مقارنة بين اختبار كمارات متآكلة بدون تحميل وكمارات بعد التحميل. تم تصميم اثنان وعشرون كمرة من الخرسانة المسلحة وصبها وتعريضها للتآكل المتسارع باستخدام تقنية التيار الكهربائى. تم تقسيم الكمرات إلى ثلاث مجموعات: واحدة محملة تحت وزنها فقط، والثانية محملة قبل التعرض للتآكل حتى 40٪ من الحمل النهائي، والثالثة محملة حتى 60٪ من الحمل النهائي. يتم عرض النتائج من حيث قراءات الجهد مقابل المدة لكل كمرة. أظهرت النتائج التأثير الكبير لتحميل الكمرات قبل التعرض للتآكل على معدل بدء التآكل وانتشاره.

Abstract

This paper investigates the rate of corrosion of reinforcement in two-span reinforced concrete beams. A comparison between testing a corroded unloaded beam and loaded beams is presented. Twenty-two reinforced concrete beams were designed, casted, and subjected to accelerated corrosion using the impressed current technique. Beams were divided into three groups: one loaded under own weight only, the second initially loaded till 40% of the ultimate load, and the third loaded till 60% of the ultimate load. Results are presented in terms of voltage readings versus duration for each beam. Results showed the great influence of initially loading the beams on the rate of corrosion initiation and propagation.

Keywords

Corrosion, Durability, Impressed current, Loaded beams, Reinforced concrete.

1. Introduction

Concrete reinforcement corrosion is one of the major factors affecting the durability of reinforced concrete (RC) members. Reinforced concrete is one of the most preferred construction materials along the world for its durability, versatility, and mechanical properties. However, the intrusion of corrosion agents as chlorides ions or carbon dioxide can lead to severe deterioration to the RC member and minimizing its load carrying capacity below the designed flexural and shear capacities. Increasing cracks width can be one of the factors that negatively affect the concrete cover quality, helping in increasing the chloride diffusion through the concrete surface and reaching the embedded steel rebars.

Many researchers studied the influence of rebars corrosion on the mechanical properties of both concrete members and steel reinforcement. Corrosion affects the steel rebars by reduction in the cross-sectional area, deterioration of properties as strength, elasticity, and ductility and may lead to brittle failure. For concrete, corrosion deteriorate the bond between reinforcement and the surrounded concrete, cracking and spalling of the concrete cover [1,2]. Researchers used to draw maps of corrosion cracks and tried to find a relation between cracks' patterns and the rate of corrosion of embedded steel rebars [3]. However, others found that the arrangement of steel bars inside the concrete had a strong influence on the extent of damage of concrete cover during corrosion and that the rate of steel loss was not dependent on the cracks' patterns [4]. The lower limit corrosion crack width of 0.3 mm is a common criterion for the end of service life of corrosion-affected RC structures in Eurocode 2 [5].

It is necessary for researchers studying the corrosion of rebars in RC members to accelerate the corrosion process to obtain needed results in a short time. However, there is no standard procedure for accelerating steel corrosion in RC specimens in laboratories. Unfortunately, structural damage and rate of steel corrosion are dependent on the accelerated corrosion technique used [6]. Some researchers started to mix concrete with chlorides ranging from 1% [7] to 5% [8] by weight of cement. Others used tanks filled with NaCl solution with concentration nearly equal to that of sea water which is about 3.5% to immerse their cured samples in. The NaCl concentrations in previous researches ranged from 3% [9] to 5% [1,2].

2. Materials and Test Set-Up

This paper is a part of a complete study investigating the effect of reinforcement corrosion on mechanical behavior of loaded and unloaded two-span reinforced concrete beams at various degrees of corrosion. The study includes a total of 22 beams: one control beam (non-corroded control beam, NC-CB) and 21 beams divided into three groups with 7 beams per group. The first group is corroded while unloaded (loaded under own-weight only, C-ow), the second is corroded after subjected to a load equals to 40% of the ultimate load specified after testing the NC-CB beam (C-40P), and the third group corroded after loaded till 60% of the ultimate load (C-60P). Beams dimensions are: 100 mm width, 250 mm height, and 3000 mm total length divided into two equal spans as shown in Fig. 1.

2.1 Materials

All beams are casted using Ordinary Portland Cement CEM I 42.5R, from the Egyptian market. Beams are reinforced using both longitudinal bars and stirrups. The longitudinal bars are 10 mm diameter high tensile steel bars with a strength class of $f_y \geq$ 400 MPa. The shear reinforcement bars are 8 mm mild steel with $f_y \geq 240$ MPa. The target strength required for concrete surrounded by severe environment is 40 MPa according to the ECP 203 (Egyptian Code of Practice).

Figure 1: Typical beam dimensions

Table 1 shows the proportioning of the concrete mixture and the average strength at 7 and 28 days for a trial mix. Both fine and coarse aggregates are clean washed aggregate to omit the variable of fine materials from the research results. The maximum size of the coarse aggregate was limited to 20 mm to agree with the beams' dimensions and reinforcement distribution.

Table 1. Concrete Mixture Proportioning and Strength Results

Cement Type	**CEM I 42.5R**
Cement (kg/m^3)	450
Water, w/c=0.4 (kg/m^3)	180
Fine aggregate, < 4.75mm (kg/m^3)	695
Coarse aggregate, 4.75 to 20mm (kg/m^3)	1016
Superplasticizer (kg/m^3)	5.4
Average strength after 7 days (MPa)	40.5
Average strength after 28 days (MPa)	45.5

2.2 Accelerated corrosion technique

Beams were reinforced with 2 bars (10 mm diameter) as lower reinforcement and the same as upper reinforcement. The upper rebars were protruding out at the end of the beam to be connected to an electric circuit during the corrosion process as well as a cathode bar located at 75 mm from the beam's upper edge. The stirrups are located along the length of the beam.

To accelerate the corrosion of the rebars, the impressed current technique was used. The corrosion process technique was designed taking into consideration the recommendations that were concluded from previous researches. According to these recommendations; the impressed current density must not exceed 200 µA/cm^2 [8]. The tested beam must not be submerged in NaCl solution tank, and selected face only must be contaminated with NaCl solution to avoid uniform corrosion of rebars [6]. In natural circumstances, the cathodic and anodic reactions occur inside the RC member.

Therefore, cathode bar must be placed inside the RC member [6]. The natural corrosion requires cycles of drying and wetting [6].

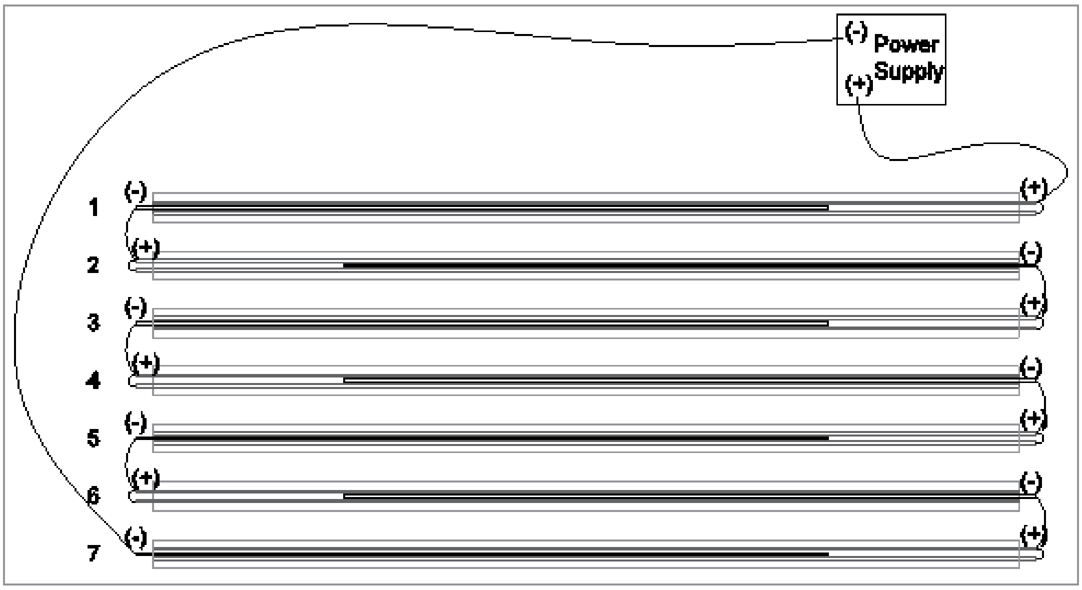

Figure 2: Schematic drawing for the corrosion circuit set-up

In this research, the target bars to be corroded are the two upper bars. The cathode bar used is chosen to be of the same material of the reinforcing bars. It is a 10 mm diameter steel bar. Figure 2 shows a schematic drawing for the corrosion circuit. As shown in the figure, the connection of the beams is a series connection, where the current flowing is the same in all beams while the voltage varies.

Figure 3: Acrylic ponds fixed at the selected sections and filled with 5% NaCl

The selected face to be corroded was at the middle upper face of the beam, where the maximum moment occurs. This is the section of the largest cracks' widths and therefore is more vulnerable to chloride ingress more than other sections. For contaminating the selected face only, an acrylic pond was fixed on the upper face of the beam at the selected section as shown in Fig. 3. This pond was filled with 5% NaCl solution during the wetting period (4 days) and was left empty during the drying period (3 days).

3. Results and Discussion

3.1 Compressive strength results statistical analysis

Three standard cubes were prepared from the mix of each beam. A total of 66 cubes were tested in a standard compressive test. A statistical analysis for the 66 strength results was performed and is shown in Figs. 4 and 5. The strength analysis for the 22 beams results showed success of all beams to meet the strength requirement and the specifications of the ACI 214R-11 *(Guide to Evaluation of Strength Test Results of Concrete).*

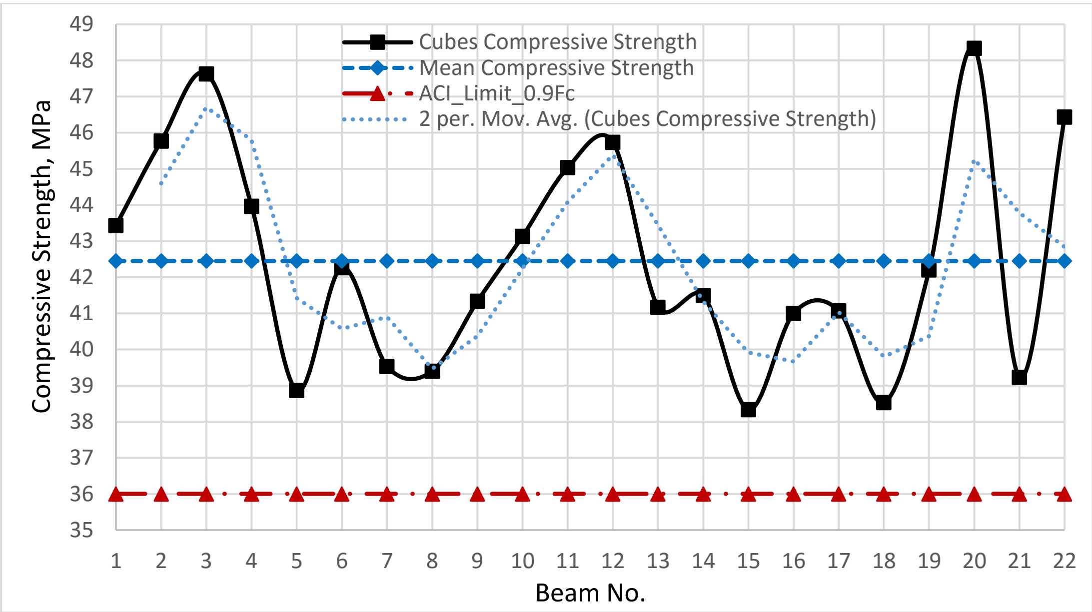

Figure 4: Statistical analysis of individual strength test for 22 beams

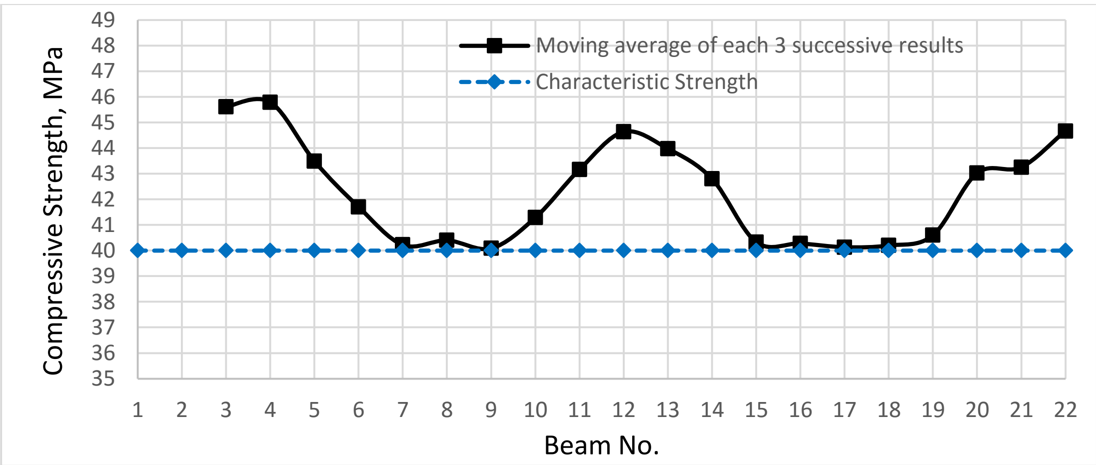

Figure 5: Moving average for each three successive results

3.2 Corrosion readings

The voltage reading for each beam in each group was recorded on daily basis by means of a digital multimeter. The rate of changing of the voltage readings with time is an indication of the corrosion initiation and propagation. The recording of the voltage readings started from the day of operating the circuit till the symptoms of corrosion appeared on the surface of all beams as shown in Fig. 6. Time for these symptoms to appear varies as the value of the initial loading changes. For the C-ow beams, it took about 91 days, for the C-40P beams, it took around 88 days, and for the C-60P beams, it took only 80 days.

C-ow C-40P C-60P

Figure 6: Corrosion products appearing on the surface of the corroded beams

The plot of the voltage readings versus the duration for the three groups of beams is shown in Figs. 7 to 9. The corrosion readings show a drop at first, which represents the passivation stage, where a thin film of rust is formed on the rebar surface protecting it from further anodic-cathodic reactions. The three groups showed similarity during the passivation stage. As the ingress of chlorides increases, the threshold value is reached, and the rust film increases and leaves the rebar surface without protection. Here the reaction continues and the transfer of electrons between anode and cathode increases rapidly, and this is the de-passivation stage. As the transfer of electrons increases, the voltage readings start to increase.

The C-ow beams' plot shows maximum voltage readings between 6 and 12 Volts. The C-40P beams recorded maximum values between 10 and 14 Volts, and the C-60P beams reached 14 to 16 Volts. The voltage versus duration plot for the three groups shows an inversely proportional relation between the value of the initial loading and the time for corrosion to initiate and propagate. The higher value of loadings increases the strains in the rebars and therefore inducing tensile cracks at the contaminated surface leading to higher values for chlorides ingress through the concrete cover.

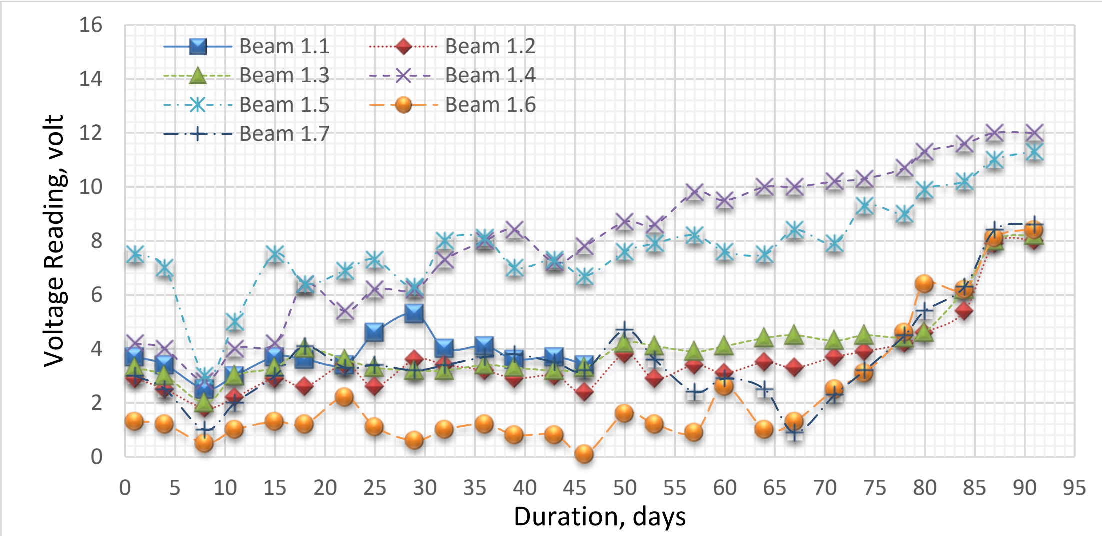

Figure 7: Voltage readings (Volts) vs. duration (days) for the C-ow beams

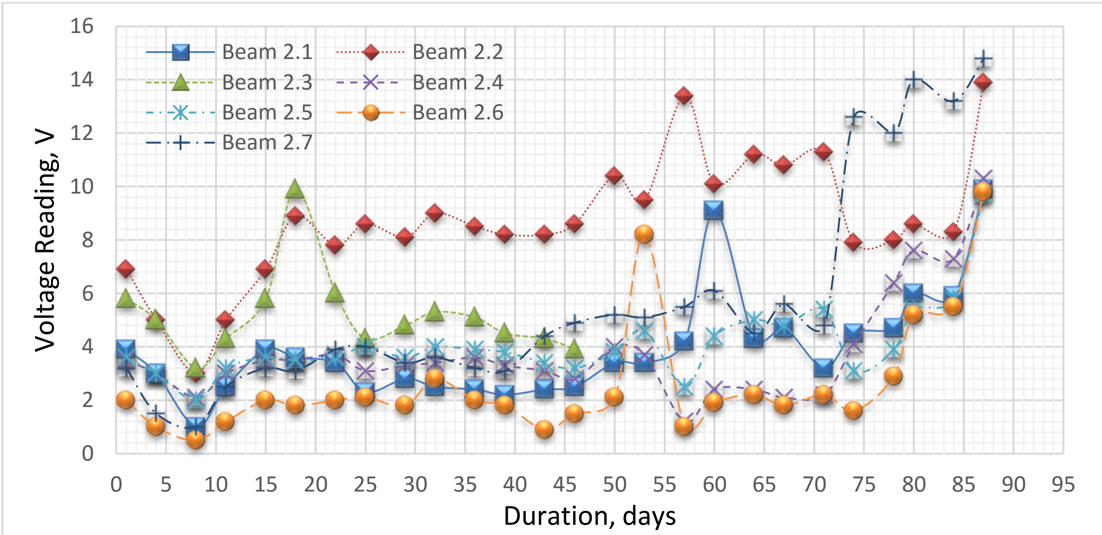

Figure 8: Voltage readings (Volts) vs. duration (days) for the C-40P beams

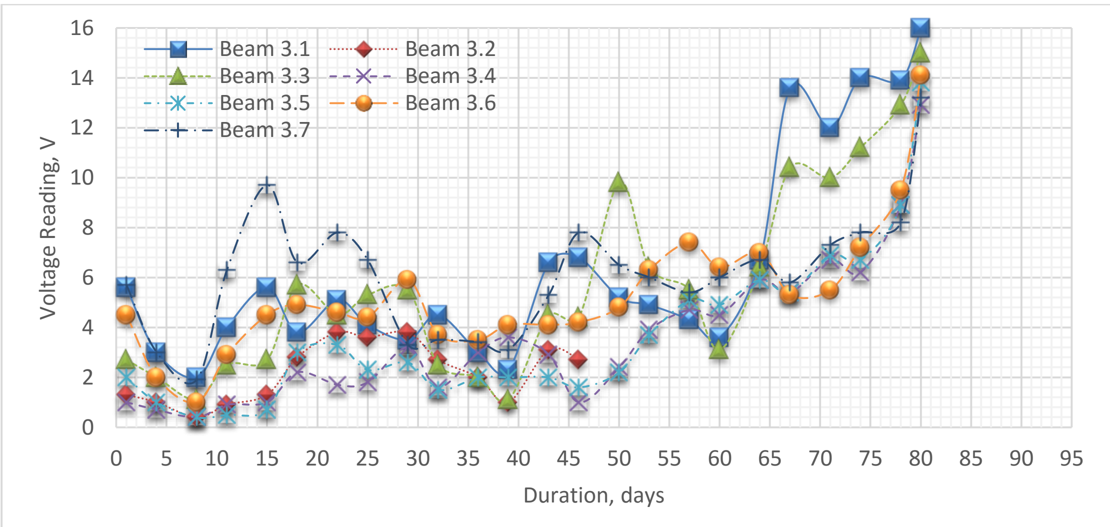

Figure 9: Voltage readings (Volts) vs. duration (days) for the C-60P beams

4. Conclusions

This paper studied the influence of initially loading a two-span RC beam on the rate of reinforcement corrosion initiation and propagation. Selected face of the beam was subjected to cycles of wetting and drying by 5% NaCl solution. 200 $\mu A/cm^2$ current density was applied to the beams in an electric corrosion circuit. The following points were concluded from this study:

i Initially loading a beam induces tensile cracks at the critical sections of the beam.

ii As the load increases, the tensile cracks' widths increase, and this make the cracked section more vulnerable to the ingress of chlorides.

iii Beams tested in accelerated corrosion in laboratories must be loaded before subjected to corrosion.

5. Acknowledgements

This work was supported by the Faculty of Engineering, Cairo University, Egypt, and the Construction and Building Engineering Department, Arab Academy for Science and Technology, Cairo, Egypt.

6. References

[1] Hassan, H.A., Sanad, A.M., and Moussa, M.A., (2013). "Effect of Environmental Corrosion on Sea Front Reinforced Concrete Structures", MSc Thesis, Arab Academy for Science and Technology, Cairo, Egypt.

[2] Dalia, S.M., Sanad, A.M., and Moussa, M.A., (2016). "Effect of Reinforcement Corrosion on Deterioration of Flexural Reinforced Concrete Members and the Effect of Nano-Technology in Corrosion Mitigation", MSc Thesis, Arab Academy for Science and Technology, Cairo, Egypt.

[3] Malumbela, G., Alexander, M., and Moyo, P., (2010). "Interaction Between Corrosion Crack Width and Steel Loss in RC beams Corroded Under Load", Cem Concr Res, 40:1419-28.

[4] Hariche, L., Ballim, Y., Bouhicha, M., and Kenai S., (2012). "Effects of Reinforcement Configuration and Sustained Load on the Behavior of Reinforced Concrete Beams Affected by Reinforcing Steel Corrosion", Cem Concr Compos, 34:1202-9.

[5] Eurocode 2: Design of Concrete Structures. Part 1-1: general rules and rules for buildings, Brussels, 2004.

[6] Malumbela, G., Moyo, P., and Alexander, M., (2012). "A Step Towards Standardising Accelerated Corrosion Tests on Laboratory Reinforced Concrete Specimens", Journal of the South African Institution of Civil Engineering, Vol. 54 No. 2, Pages 78-85, Paper 807.

[7] Mangat, P.S., and Elgarf, M.S., (1999). "Flexural Strength of Concrete Beams with Corroding Reinforcement", ACI Structural Journal, 96(1), 149-158.

[8] El Maaddawy, T.A., and Soudki, K.A., (2003). "Effectiveness of Impressed Current Technique to Simulate Corrosion of Steel Reinforcement in Concrete", J. Mater. Civ. Eng., Journal of Materials in Civil Engineering, Vol. 15, Issue 1. https://doi.org/10.1061/(ASCE)0899-1561(2003)15:1(41)

[9] Cairns, J., Du, Y., and Law, D., (2008). "Structural Performance of Corrosion-damaged Concrete Beams", Magazine of Concrete Research, 60(5): 359–370.