International Research Journal of Engineering and Technology (IRJET) e-ISSN: 2395-0056
Volume: 11 Issue: 08 | Aug 2024 www.irjet.net p-ISSN: 2395-0072

Flexural response of corroded RC members: A review

Manpreet Singh Bains[1], Prof. Yuvraj Singh[2], Prof. Harvinder Singh[3]

[1]PG Student, Guru Nanak Dev Engineering College, Ludhiana, Punjab, India
[2]Assistant Professor, Guru Nanak Dev Engineering College, Ludhiana, Punjab, India
[3]Professor, Guru Nanak Dev Engineering College, Ludhiana, Punjab, India

***

Abstract - *The durability of reinforced concrete (RC) structures is significantly compromised by the corrosion of reinforcement bars (rebars), which poses a serious threat to their performance and longevity. Corrosion leads to an increase in rebar volume, induces crack formation, and reduces the cross-sectional area of the reinforcement. These changes weaken the bond between concrete and rebar, resulting in increased slippage and a substantial reduction in the flexural strength of RC beams. Consequently, the load-carrying capacity, ductility, and service life of the structure are reduced, raising concerns about its safety. Corroded beams often exhibit behaviour contrary to their design intentions, with early failure occurring due to the rupture of weakened rebars. Understanding the effects of corrosion on RC beams at various stages of degradation is therefore critical. This review synthesizes research findings on the flexural response of corroded RC members, highlighting the key factors influencing their degradation and the resulting structural outcomes.*

Key Words: Flexural strength, rebar corrosion, residual capacity, RC members, structural degradation

1. INTRODUCTION

Concrete is a major construction material used throughout the world. It is well known for its compressive strength, durability and can be moulded to any required shape. It deteriorates with time and requires huge costs for its repairs and maintenance. Therefore, it becomes essential to consider the problems associated with the use of concrete, when using it for a specific purpose. Strength, service life, losses, cost-effectiveness, and environmental impacts are the factors considered before using it for respective purposes [1], [2]. Besides its applications, it has some limitations too. It is weak in tension, formation of wide cracks, brittleness, shrinkage, and creep.

To impart the tensile strength to concrete, steel reinforcement bars are embedded into it. [3]. Plain concrete is much more resistant to marine environments whereas the reinforcement bars in reinforced concrete undergo self-damages, which adversely affects the properties of concrete [4], [5]. Reinforcement bars are susceptible to corrosion due to the aggressive environment in which the members are present [6]. Marine structures are mostly affected by the corrosion of reinforcement bars [7], [8]. Steel reinforcement bars have a passive layer of concrete around them, which protects the rebars from corrosion. The passive layer is destroyed by the ingress of chlorine ions and carbonation attack from the surrounding environment. The rust products formed due to corrosion have a much higher volume than the original volume of rebar, which leads to the cracking of the concrete cover [9], [10], [11], [12].

Corrosion degrades the properties of RC members. It results in reduced load-carrying capacity, compromised ductility, concrete-rebar bond deterioration, crack origination and propagation, and spalling of the concrete cover. The cracks and spalling provide space for moisture to enter the concrete, further making it more prone to corrosion [12]. The corrosion can be divided into two types, namely uniform corrosion, and pitting corrosion. The corrosion of the rebars throughout its length is known as uniform corrosion. Pits form on surface of rebar at random locations, such that the rebar cannot be classified into category of uniform corrosion is known as pitting corrosion. Pitting corrosion is much severe than uniform corrosion. Flexural strength is the resistant of members to failure in bending. Beams and slabs are specially designed to sustain bending stresses. Damage caused by corrosion may also have a negative impact on load bearing behavior of members throughout their lifespan. Depending on the level of exposure and the level of the protection, the deterioration process begins at the beginning and continues at a corrosion rate. Since corrosion cannot always be prevented, it is important to make sure that structural performances are preserved and do not deteriorate because of corrosion [13]. Accurate data regarding the serviceability and load carrying capacity of corroded reinforcing steel beams is crucial and a topic of extensive research [14].

In natural environments, reinforcement corrosion is a slow process that is influenced by a number of variables, including moisture, humidity, oxygen, aggressive conditions, concrete quality, and the ratio of reinforcement to concrete. It can take years to notice the first corrosion crack on a concrete surface under typical exposure conditions, which makes it challenging to quickly examine the detrimental effects of reinforcement corrosion on the structural performances of RC structures. Therefore, to achieve a target amount of reinforcement corrosion in a short duration of time, the corrosion process is accelerated [15]. Fig-1 presents a deteriorated concrete beam.

Fig -1: Corrosion of RC beam [16]

1.1 Mechanism of corrosion

Corrosion of steel reinforcement bars is a slow process. In this process, anodic and cathodic reactions take place on the same rebar. Corrosion occurs due to chlorination and carbonation. Both phenomena can either be initiated individually or at the same time. The corrosion becomes severe when these mechanisms occur simultaneously [17]. Chlorination involves the ingress of chloride ions into the concrete. These chloride ions de-passivise the steel, iron is oxidized and it lose two electrons. The free electrons from iron react with moisture and oxygen to form Hydroxide ions. Ferrous Hydroxide Fe(OH)2 is formed, which is a rust product. Carbonation is defined as the reaction of Calcium Hydroxide and Calcium Silicate Hydrate gel with carbon dioxide from the environment. It forms Calcium Carbonate which lowers the pH of concrete and the embedded reinforcement bar becomes prone to the corrosion in presence of water and oxygen.[18] Equation 1,2 and 3 presents the corrosion formation process.

$$Fe \rightarrow Fe^{2+} + 2e^{-} \quad (1)$$

$$\frac{1}{2}O_{2} + H_{2}O + 2e^{-} \rightarrow 2OH^{-} \quad (2)$$

$$Fe^{2+} + 2OH^{-} \rightarrow Fe(OH)_{2} \quad (3)$$

1.2 Effects of corrosion

The major effect of corrosion is the reduction in the cross-sectional area of reinforcement bars. This further tends to affect other properties of the concrete and the reinforcement. The formation of non-uniform pits changes the cross-sections at certain regions. The bond strength reduces due to the formation of rust products. The formation of rust products on the surface of rebars leads to the increase in volume up to six times the initial volume of rebar. The formation of cracks at concrete surfaces reduces the concrete strength [12], [19], [20], [21]. The corroded beams fail suddenly, without showing any warning sign before its failure. The serviceability of those structures gets compromised [6]. Fig-2 includes the major effects of corrosion of steel reinforcement bars.

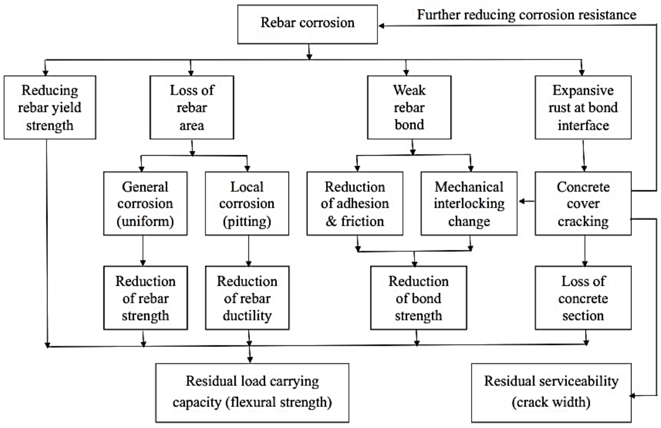

Fig -2: Effects of corrosion [21]

2. FLEXURAL STRENGTH OF BEAMS

Researchers investigated the effect of corrosion and its response on the flexural response of RC beams. The research conducted on beams included artificial corrosion. To understand the exact behaviour and change in properties due to corrosion, researchers created a similar environment to that of natural conditions [14], [22], [23], [24], [25]. To fasten the corrosion process with a study point of view, accelerated corrosion methods have been used in most of the current studies [9], [13], [15], [16], [26], [27], [28], [29], [30], [31], [32], [33], [34], [35]. The concrete-rebar bond deterioration and the loss of cross-sectional area of reinforcement bars reduce the flexural strength of corroded RC beams [15], [26], [32], [35]. The studies pointed out that the corroded beams showed brittle failure after a certain loss of rebars [6], [13], [28], [33], [34], [36].

Different responses were discovered for different corrosion levels. Higher the corrosion level in reinforcement bars, lower the peak load, cracking load, and displacement. The corroded beams failed earlier due to cracking in the concrete cover due to expansion occurring during corrosion. Similar strength reductions were observed for entire reinforcement area corrosion and corrosion at rebars at the mid-span of beam i.e. constant moment area while corrosion in rebars near supports i.e. constant shear area had less effect on ultimate flexural strength [6], [27]. For corrosion levels of 7-10% and lesser, the corroded beams failed in a ductile manner, which was similar to the mode of failure observed for uncorroded beams [26], [28]. The failure mode changed from ductile to brittle after 30% of the average cross-sectional loss or 18% gravimetric loss of rebars [13], [28].

A percent of cross-sectional loss in the reinforcement bar leads to 1-2% loss of the ultimate carrying capacity of the beam [13], [22], [35]. The load-deflection curves for corroded and uncorroded beams had no difference up to 60% of the load. Average crack widths hold a good relation with the flexural strength of corroded RC beams. Lower flexural strength of beams was observed for beams with wider cracks [32], [35]. Corroded beams with 5-7% mass loss experience increases flexural strength due to the formation of rust on the surface, enhancing the friction between concrete and rebar. Corrosion not only reduces the strength but also reduces the formation of warning signs in the form of cracks. Corroded beams failed suddenly with minimum signs of failure. The flexural strength of corroded RC beams is not majorly affected by the yield strength of the reinforcement bar, but instead by the cross-sectional loss of rebar. The reduced cross-sectional area lowers the bond strength of the rebar [6], [30]. The flexural strength of beams reduces due to the corrosion process. The net strength of beams due to the corrosion is stated as residual strength. In the literature, researches proposed different models to predict the residual strength of beams.

1.2 Flexural models

The models for residual strength of corroded RC beams available in the literature are mentioned in Table 1. With known cross-sectional loss or the mass loss, the residual strength of corroded RC beams can be computed. Most of the models available in the literature provide a linear model for prediction of the residual strength of corroded beams. The study by Ahmad et al. (2022) provides a generic model including the effective yield strength and effective cross-sectional area of rebar [15]. It is the only model among others, which has been derived from forces acting in a RC beam. The other models are based on the plots from residual strength and the steel loss.

Table -1: Models for residual strength of beams

Literature	Model
Dasar et al. (2022) [22]	$P_c/P_{uc} = 1.3965\,\Delta_{avg} - 5.6431$ $(\Delta_{avg} \leq 30\%)$
Ahmad et al. (2022) [15]	$M_c = A_{st} f_{yc}(d - x)$ $+0.85\, f'_c\, \beta_c\, x\, b_c(x - a/2)$
Hansapinyo et al. (2021) [13]	$P_c/P_{uc} = -0.01\,\Delta_{avg} + 1$ $(\Delta_{avg} \leq 30\%)$
	$P_c/P_{uc} = -0.015\,\Delta_{avg} + 1$ $(\Delta_{avg} > 30\%)$
Xia et al. (2012)[31]	$M_c/M_{uc} = -1.2902\, m + 1$
Nasser et al. (2021) [35]	$P_c/P_{uc} = -0.02\,\Delta_{avg} + 1$

P_c → Ultimate load value for corroded beam
P_{uc} → Ultimate load value for uncorroded beam
M_c → Moment carrying capacity for corroded beam
M_{uc} → Moment carrying capacity for uncorroded beam
Δ_{avg} → Average cross-sectional loss of rebar
m → Mass loss of rebar

3. FACTORS AFFECTING FLEXURAL STRENGTH

3.1 Bond strength

The flexural strength of RC beams reduces due to bond failure. In the case of deformed bars, the mechanical interlocking between the rebar and the surrounding concrete is just as important as adhesion and friction in determining the bond strength. The ribs of deformed rebar undergo a change in shape and angle due to reinforcement corrosion, which alters the bond properties. Due to accumulation of corrosion products, corrosion also affects the mechanical interlocking at the rebar bond interface by lowering adhesion and frictional force. The load carrying capacity of concrete structures of the corroded concrete beams reduces as a result of the corrosion-induced loss of rebar bond strength. The failure mode corroded RC beams can change due to insufficient rebar bond strength. Tensile rebars fails by yielding at lower corrosion extends, while the anchorage slip is experienced by rebar for mild corrosion. Extreme corrosions cause rupture failure of rebars, without neck formation before failure. However, for corroded beams, the cross-sectional area decreases steel bar's contact surface reduction and improper rebar-concrete bond. Because of this poor force transfer between rebar and concrete, slip occurs in the reinforced concrete beam. A lower displacement is experienced by such members [34].

Crack widening indicates that the bond between the concrete and rebar has already been reduced or destroyed. The bond between the rebars and concrete gets destroyed at 10-15% of rebar loss [15], [27], [28]. As the rebar cross-section reduces, the cracks appear and widen up. The rebars get separated from the concrete, causing the bond failure [26], [30], [33]. Therefore, a lesser number of cracks appear in the case of corroded RC beams [35].

3.2 Crack pattern

The origination of longitudinal cracks along the longitudinal reinforcement reduced the moment-carrying capacity of corroded RC beams [27]. There are three general phases to the process of concrete performance deterioration caused by corrosion in the steel reinforcement: the crack initiation phase, the crack propagation phase, and the residual life phase. The phase of crack initiation commences during construction and ends when corrosion-induced cracking at the interface between the concrete bond and rebar begins. Bond strength of rebars reduces due to the crack initiation phase, which causes a progressive reduction in load carrying capacity as cover concrete cracking advances. Concrete cracks get wider as steel rebar corrodes more, and eventually the corroded concrete structures become unserviceable [34].

More cracks with lesser crack width were observed for uncorroded RC beams. The crack spacing analysed from the literature was more in uncorroded beams. Bond reduction lowers the possibility of stress transfer from concrete to steel. Concrete itself has low tensile strength. Hence, fewer cracks develop and concrete fails in crushing [26], [28], [36]. Uncorroded beams sustained much higher loads than the design loads. The beams were still able to withstand loads, by showing flexural cracks and widened shear cracks. The crack widths follow the same pattern of corrosion pit depths. The deeper the pits on the rebar surface, the greater the rust products and wider crack widths at those respective points [28]. Concrete beams with lower concrete cover had more cracks at short distances [29]. Lesser crack widths were noticed when the concrete cover was greater and the diameter of the reinforcement bar was smaller [31].

3.3 Rebar loss

Few pits were observed for reinforcement bars with average percentage mass loss up to 20% and more pits in longitudinal bars beyond 30% average percentage mass loss when rebars were extracted from corroded beams [15]. Pitting corrosion location becomes the governing factor for the type of failure in corroded beams. The reduction in flexural strength depends upon the cross-sectional loss and the location of corrosion. Average cross-sectional losses in rebar cannot define the load-deflection behaviour of the corroded beams. Beams failed relatively at lower load values for corrosion on rebar at mid-span. The corroded rebars can have minimum cross-sectional area, even less than the average cross-sectional area at the point of maximum bending moment i.e. mid-span. Therefore, the maximum cross-sectional loss of rebar at the critical location becomes the worst-case scenario. The minimum cross-section of the corroded reinforcement bar should be kept in consideration instead of average cross-sectional loss while accessing the residual strength of corroded beams [6].

The early failure of corroded beams occurs due to a reduction in the cross-sectional area of tensile reinforcement, which then changes the failure mode from ductile to brittle [14], [23], [24], [36]. The corrosion of ribs at longitudinal and transverse reinforcement has no major role in strength reduction [24]. Lesser pit depths were observed at locations of stirrups, which states that stirrups reduce the formation of major pits at the junction point of longitudinal and transverse reinforcement [36]. The small diameter reinforcement bars have a more negative impact on the residual strength of corroded beams [29]. The corrosion levels achieved during accelerated corrosion vary from the calculated target percentage mass loss of reinforcement due to different chemical compositions of reinforcement bars, the resistivity of concrete and crack development [15]. The beams with the same corrosion time can have different corrosion levels even within the same beam specimen [28].

3.4 Concrete cover

The cover plays an important role in deciding the failure mode of the rebar. Concrete with a lower concrete cover is more susceptible to rebar corrosion. The beam with greater cover made beams fail in a ductile manner whereas the beam with lower concrete cover experienced brittle failure under the same corrosion conditions [22]. Cracks appear on the interface of concrete and the reinforcement bars due to the corrosion products. The bond strength and the load carrying capacity starts reducing with widening of cracks. Rebars with smaller diameters has an adverse effect on concrete cracking. The smaller the diameter of the rebar, the greater the number of cracks that originate [29]. These cracks widen up so much that becomes a topic of concern and members become unserviceable [34]. Since, the cracks are measured from the surface of concrete, the beams with greater concrete cover will have wider cracks [31]. Beams with greater concrete cover delay the corrosion process, which is an important parameter for designing a RC member with a lifespan of more than 50 years [22]. The design codes also mention the minimum concrete cover to be provided with respect to environmental conditions.

3.5 Tensile strength of rebars

The beams degrade due to a reduction in the tensile strength of the rebar and the concrete-rebar bond. The percentage loss of moment carrying capacity is approximately equal to the percentage loss of tensile strength of the reinforcing bar [22]. Corrosion causes a reduction in the ultimate tensile strength of reinforcement bars and the failure occurs in a brittle manner [6], [36]. The tensile reinforcement fails at the location of maximum pitting for corroded beams and failure occurs at random locations within the bar for uncorroded beams [36]. The post-yield response stress-strain curve for corroded rebars had a steeper slope than for the control samples. This suggests that after reaching the yielding point, the strain hardening modulus of corroded rebars is greater than the control bars. [24]

3.6 Ductility

The ductility of corroded RC beams reduces with the amount of corrosion [6], [23], [24], [28]. Due to localised corrosion, pits form on the surface of rebars, which causes a reduction in the cross-section of rebars and failure occurs at the weakest point [6], [30], [36]. Due to the formation of pits, stress concentrates on the respective area and brittle failure occurs without the formation of neck [23] The ductility of corroded RC beams reduces when the average cross-sectional loss of rebar is more than 30% [13]. Loss of ductility is more prominent for reinforcement bars with smaller diameters, whereas rebars with large diameters have minimal ductility reduction [14]. The corroded bars went through a hardening stage after the yield stress and did not exhibit a yield plateau. Ultimate strain and the ductility by reduced by reaching the ultimate strength far sooner than the non-corroded rebar. It clarifies that corrosion alters the stress-strain curve of corroded RC beams [24].

4. CONCLUSING REMARKS

Based on the results obtained, the following conclusions can be drawn:

- The load-carrying capacity of RC beams decreases as the rebar's cross-sectional area or mass loss increases due to corrosion.
- Corroded beams with a rebar mass loss of 7-10% exhibit similar behavior to uncorroded beams. Interestingly, an increase in flexural strength is observed at a 5-7% mass loss, likely due to enhanced bond strength between the concrete and rebar.
- The corrosion of reinforcement bars within the pure flexural zone is identified as the most critical factor affecting the performance of corroded RC beams.
- The tensile strength of corroded rebars and the ductility of corroded RC beams decrease as the level of corrosion increases. Greater concrete cover helps mitigate the risk of reinforcement corrosion.
- Severely corroded beams, with more than a 30% loss in rebar cross-sectional area, failed without exhibiting warning signs, shifting the failure mode from ductile to brittle.

REFERENCES

[1] N. Faris, T. Zayed, E. M. Abdelkader, and A. Fares, ‘Corrosion assessment using ground penetrating radar in reinforced concrete structures: Influential factors and analysis methods’, Autom Constr, vol. 156, p. 105130, Dec. 2023, doi: 10.1016/j.autcon.2023.105130.

[2] Q. Li and X. Ye, ‘Surface deterioration analysis for probabilistic durability design of RC structures in marine environment’, Structural Safety, vol. 75, pp. 13–23, Nov. 2018, doi: 10.1016/j.strusafe.2018.05.007.

[3] S. Sadati, M. Arezoumandi, and M. Shekarchi, ‘Long-term performance of concrete surface coatings in soil exposure of marine environments’, Constr Build Mater, vol. 94, pp. 656–663, Sep. 2015, doi: 10.1016/j.conbuildmat.2015.07.094.

[4] H. Van Damme, ‘Concrete material science: Past, present, and future innovations’, Cem Concr Res, vol. 112, pp. 5–24, Oct. 2018, doi: 10.1016/j.cemconres.2018.05.002.

[5] P. E. Smith, ‘Design and specification of marine concrete structures’, in Marine Concrete Structures, Elsevier, 2016, pp. 65–114. doi: 10.1016/B978-0-08-100081-6.00003-9.

[6] Y. Du, M. Cullen, and C. Li, ‘Structural effects of simultaneous loading and reinforcement corrosion on performance of concrete beams’, in Construction and Building Materials, 2013, pp. 148–152. doi: 10.1016/j.conbuildmat.2012.05.006.

[7] S. Meet, C. Trishna, and K. Naveen, ‘Investigating the nonlinear performance of corroded reinforced concrete beams’, Journal of Building Engineering, vol. 44, p. 102640, Dec. 2021, doi: 10.1016/j.jobe.2021.102640.

[8] S. Sadati, M. Arezoumandi, and M. Shekarchi, ‘Long-term performance of concrete surface coatings in soil exposure of marine environments’, Constr Build Mater, vol. 94, pp. 656–663, Sep. 2015, doi: 10.1016/j.conbuildmat.2015.07.094.

[9] G. Malumbela, M. Alexander, and P. Moyo, ‘Variation of steel loss and its effect on the ultimate flexural capacity of RC beams corroded and repaired under load’, Constr Build Mater, vol. 24, no. 6, pp. 1051–1059, Jun. 2010, doi: 10.1016/j.conbuildmat.2009.11.012.

[10] A. A. Torres-Acosta, S. Navarro-Gutierrez, and J. Terán-Guillén, ‘Residual flexure capacity of corroded reinforced concrete beams’, Eng Struct, vol. 29, no. 6, pp. 1145–1152, Jun. 2007, doi: 10.1016/j.engstruct.2006.07.018.

[11] F. Pedrosa and C. Andrade, ‘Corrosion induced cracking: Effect of different corrosion rates on crack width evolution’, Constr Build Mater, vol. 133, pp. 525–533, Feb. 2017, doi: 10.1016/j.conbuildmat.2016.12.030.

[12] R. K. Biswas, M. Iwanami, N. Chijiwa, and K. Uno, ‘Effect of non-uniform rebar corrosion on structural performance of RC structures: A numerical and experimental investigation’, Constr Build Mater, vol. 230, p. 116908, Jan. 2020, doi: 10.1016/j.conbuildmat.2019.116908.

[13] C. Hansapinyo, V. Vimonsatit, M. Matsushima, and S. Limkatanyu, ‘Critical amount of corrosion and failure behavior of flexural reinforced concrete beams’, Constr Build Mater, vol. 270, pp. 1–13, Feb. 2021, doi: 10.1016/j.conbuildmat.2020.121448.

[14] V. H. Dang and R. François, ‘Prediction of ductility factor of corroded reinforced concrete beams exposed to long term aging in chloride environment’, Cem Concr Compos, vol. 53, pp. 136–147, 2014, doi: 10.1016/j.cemconcomp.2014.06.002.

[15] S. Ahmad, M. A. Al-Huri, M. A. Al-Osta, M. Maslehuddin, and A. H. Al-Gadhib, ‘An Experimental Approach to Evaluate the Effect of Reinforcement Corrosion on Flexural Performance of RC Beams’, Buildings, vol. 12, no. 2222, pp. 1–21, Dec. 2022, doi: 10.3390/buildings12122222.

[16] J. S. Jung, B. Y. Lee, and K. S. Lee, ‘Experimental Study on the Structural Performance Degradation of Corrosion-Damaged Reinforced Concrete Beams’, Advances in

Civil Engineering, vol. 2019, pp. 1–14, 2019, doi: 10.1155/2019/9562574.
[17] J. A. Gonzalez, J. S. Algaba, and C. Andrade, 'Corrosion of Reinforcing Bars in Carbonated Concrete', British Corrosion Journal, vol. 15, no. 3, pp. 135–139, Jan. 1980, doi: 10.1179/bcj.1980.15.3.135.
[18] K. Y. Ann, S.-W. Pack, J.-P. Hwang, H.-W. Song, and S.-H. Kim, 'Service life prediction of a concrete bridge structure subjected to carbonation', Constr Build Mater, vol. 24, no. 8, pp. 1494–1501, Aug. 2010, doi: 10.1016/j.conbuildmat.2010.01.023.
[19] G. Campione, F. Cannella, and L. Cavaleri, 'Shear and flexural strength prediction of corroded R.C. beams', Constr Build Mater, vol. 149, pp. 395–405, Sep. 2017, doi: 10.1016/j.conbuildmat.2017.05.125.
[20] C. Fang, K. Lundgren, L. Chen, and C. Zhu, 'Corrosion influence on bond in reinforced concrete', Cem Concr Res, vol. 34, no. 11, pp. 2159–2167, Nov. 2004, doi: 10.1016/j.cemconres.2004.04.006.
[21] A. Chen, Z. Pan, and R. Ma, 'Mesoscopic simulation of steel rebar corrosion process in concrete and its damage to concrete cover', Structure and Infrastructure Engineering, vol. 13, no. 4, pp. 478–493, Apr. 2017, doi: 10.1080/15732479.2016.1164730.
[22] A. Dasar, D. Patah, H. Hamada, D. Yamamoto, and Y. Sagawa, 'Life performance of 40-year-old RC beams with different concrete covers and bar diameters in natural corrosion environments', Structures, vol. 46, pp. 2031–2046, Dec. 2022, doi: 10.1016/j.istruc.2022.11.033.
[23] I. Khan, R. François, and A. Castel, 'Structural performance of a 26-year-old corroded reinforced concrete beam', European Journal of Environmental and Civil Engineering, vol. 16, no. 3–4, pp. 440–449, 2012, doi: 10.1080/19648189.2012.667992.
[24] R. François, I. Khan, and V. H. Dang, 'Impact of corrosion on mechanical properties of steel embedded in 27-year-old corroded reinforced concrete beams', Materials and Structures/Materiaux et Constructions, vol. 46, no. 6, pp. 899–910, Jun. 2013, doi: 10.1617/s11527-012-9941-z.
[25] W. Zhu, R. François, D. Coronelli, and D. Cleland, 'Effect of corrosion of reinforcement on the mechanical behaviour of highly corroded RC beams', Eng Struct, vol. 56, pp. 544–554, Nov. 2013, doi: 10.1016/j.engstruct.2013.04.017.
[26] N. N. Tan and N. D. Nguyen, 'An experimental study on flexural behavior of corroded reinforced concrete beams using electrochemical accelerated corrosion method', Journal of Science and Technology in Civil Engineering (STCE) - NUCE, vol. 13, no. 1, pp. 1–11, Jan. 2019, doi: 10.31814/stce.nuce2019-13(1)-01.
[27] H. Kim, S. Yang, T. Noguchi, and S. Yoon, 'An Assessment of the Structural Performance of Rebar-Corroded Reinforced Concrete Beam Members', Applied Sciences, vol. 13, no. 19, pp. 1–17, Oct. 2023, doi: 10.3390/app131910927.
[28] F. Di Carlo, A. Meda, and Z. Rinaldi, 'Structural performance of corroded R.C. beams', Eng Struct, vol. 274, pp. 1–16, Jan. 2023, doi: 10.1016/j.engstruct.2022.115117.
[29] L. Wang, Y. Ma, W. Ding, J. Zhang, and Y. Liu, 'Comparative Study of Flexural Behavior of Corroded Beams with Different Types of Steel Bars', Journal of Performance of Construction Facilities, 2014, doi: 10.1061/(ASCE)CF.1943-5509.0000661.
[30] C. Jiang, H. Ding, X. L. Gu, and W. P. Zhang, 'Failure mode-based calculation method for bending bearing capacities of normal cross-sections of corroded reinforced concrete beams', Eng Struct, vol. 258, May 2022, doi: 10.1016/j.engstruct.2022.114113.
[31] J. Xia, W. L. Jin, and L. Y. Li, 'Effect of chloride-induced reinforcing steel corrosion on the flexural strength of reinforced concrete beams', Magazine of Concrete Research, vol. 64, no. 6, pp. 471–485, Jun. 2012, doi: 10.1680/macr.10.00169.
[32] H. Naderpour, F. Ghasemi-Meydansar, and M. Haji, 'Experimental study on the behavior of RC beams with artificially corroded bars', Structures, vol. 43, pp. 1932–1944, Sep. 2022, doi: 10.1016/j.istruc.2022.07.005.
[33] J. Sun, Q. Huang, and Y. Ren, 'Performance deterioration of corroded RC beams and reinforcing bars under repeated loading', Constr Build Mater, vol. 96, pp. 404–415, Aug. 2015, doi: 10.1016/j.conbuildmat.2015.08.066.
[34] H.-P. Chen, 'Residual Flexural Capacity and Performance Assessment of Corroded Reinforced Concrete Beams', Journal of Structural Engineering, vol. 144, no. 12, Dec. 2018, doi: 10.1061/(asce)st.1943-541x.0002144.
[35] H. Nasser, C. Van Steen, L. Vandewalle, and E. Verstrynge, 'An experimental assessment of corrosion damage and bending capacity reduction of singly reinforced concrete beams subjected to accelerated corrosion', Constr Build Mater, vol. 286, pp. 1–14, Jun. 2021, doi: 10.1016/j.conbuildmat.2021.122773.
[36] W. Zhu and R. Francois, 'Corrosion of the reinforcement and its influence on the residual structural performance of a 26-year-old corroded RC beam', Constr Build Mater, vol. 51, pp. 461–472, 2014, doi: 10.1016/j.conbuildmat.2013.11.015.