Evaluación estructural de estructuras de hormigón con armaduras corroídas y el Eurocódigo 2

Structural evaluation of concrete structures affected by steel corrosion and the Eurocode 2

Jesús Rodríguez

PhD in civil engineering, Associate Professor, Technical University of Madrid (UPM), jesus.rodriguez@upm.es

Resumen

La corrosión de las armaduras es el tipo de deterioro más habitual en estructuras de hormigón. La mayor parte de los códigos se orientan al proyecto de estructuras nuevas con apenas información acerca de la evaluación de las estructuras existentes. En este sentido, el Eurocódigo 2 de estructuras de hormigón ha sido recientemente actualizado por el Comité Europeo de Normalización CEN, pero con información insuficiente acerca de las estructuras existentes con armaduras corroídas. Este artículo incluye algunas reflexiones sobre la evaluación estructural de estructuras corroídas para el futuro Eurocódigo 2.

Abstract

Corrosion of reinforcement is the most common type of deterioration damage in the concrete structures. Most of existing codes deal with the design of new structures with almost no information on the assessment of the existing ones. With this regard, the Eurocode 2 on concrete structures has been recently updated by the European Committee for Standardization CEN with insufficient information on existing corroded concrete structures. This paper includes some thoughts on the structural evaluation of corroded concrete structures for a future Eurocode 2.

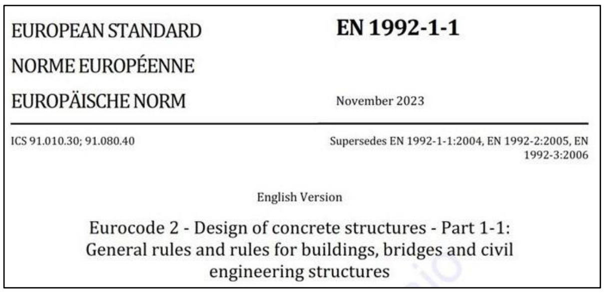
PALABRAS CLAVE: estructuras de hormigón, evaluación, corrosión, Eurocódigo 2
KEYWORDS: concrete structures, assessment, corrosion, Eurocode 2.

1. Introduction

Corrosion of reinforcement is the most common type of deterioration damage that affects the performance of concrete structures during their service life and mainly when they are in aggressive environmental conditions. Most existing codes and standards deal with the design of new structures with almost no information on the assessment of the existing ones.

With this regard, the Eurocode 2 on concrete structures has been recently updated by CEN TC250/SC2 and it has been published in November 2023 as the new EN1992-1-1:2023 Eurocode 2- Design of concrete structures (Figure 1). It includes 19 Annexes and between them the informative Annexes I on Assessment of existing structures and J on Strengthening of existing concrete structures with CFRP between other [1] and [2], with insufficient information on existing corroded concrete structures.

This paper includes some thoughts on the structural evaluation of corroded concrete structures for a future Eurocode 2.


EUROPEAN STANDARD
NORME EUROPÉENNE
EUROPÄISCHE NORM

EN 1992-1-1

November 2023

ICS 91.010.30; 91.080.40

Supersedes EN 1992-1-1:2004, EN 1992-2:2005, EN 1992-3:2006

English Version

Eurocode 2 - Design of concrete structures - Part 1-1: General rules and rules for buildings, bridges and civil engineering structures

Figure 1. Eurocode 2 CEN EN 1992-1-1: 2023 [1]

2. Assessment of existing concrete structures at Eurocode 2

Annex I on the assessment of existing concrete structures [1] [3] covers:

- Additional rules for materials and systems not considered for the design of new structures
- Additional rules for assessing structures where the detailing does not comply the provisions for new structures
- Additional rules for the anchorage of plain bars
- Some considerations for deterioration of existing structures affected by reinforcement corrosion, external sulphate attack, alkali-aggregate reaction, frost attack and leaching and acid attack.

It does not provide predictive methods for estimating the deterioration rates associated with the various deterioration mechanisms for concrete structures.

In the assessment of concrete structures affected by deterioration (chapter I.4 in [1]), it recommends for corroded structures to consider:

- Reduced concrete section due to delamination and spalling
- Reduced cross sectional area and ductility of the reinforcement
- Stress concentration due to localized corrosion
- Reduced concrete-steel bond

At the Structural analysis (chapter I.7 in [1]), it is stated that when linear analysis with redistribution, plastic or non-linear analysis is performed, the effect of reduced ductility of deteriorated concrete and reinforcement should be considered.

At Ultimate Limit States (chapter I.8 in [1]), the contribution of the concrete cross section might be considered either with the complete section but with a reduced compressive strength or with a reduced concrete section without the cover depth, depending on the level of corrosion, crack width, ratio of longitudinal and transverse reinforcement, bar diameter, etc. Besides, for the contribution of the corroded reinforcement, it should take into consideration:

- Failure of stirrups heavily corroded or with pits that might cause buckling of the compressed bars in columns and beams and premature shear failure in beams
- Reduction of steel ductility by reduction of elongation at maximum stress

Finally, when dealing with concrete-steel bond (chapter I.11 in [1]), it is stated that the anchorage length l_{bd} must be increased due to the reduction of bond strength by corrosion which highly depends on the level of corrosion, the confinement of the bar, the concrete quality, etc. Its effects might be considered through a reduction of the concrete cover size in the expression to obtain l_{bd} values.

The Eurocode 2 [1] does include information neither on how to quantitatively evaluate the structural performance nor predictive methods for corroded concrete structures.

3. Future version of the Eurocode 2

The future Eurocode 2 should include detailed information on integrating consolidated material deterioration models into structural ones for the evaluation of corroded concrete structures at both ULS and SLS, covering at least:

- Deterioration models for concrete
- Deterioration models for reinforcement
- Deterioration models for concrete-reinforcement bond
- Structural analysis
- ULS on bending with or without axial force, shear, punching and fatigue, integrating material deterioration
- SLS on deflection and cracking, integrating material deterioration

It should also include predictive models for the evolution of the previous mentioned models considering the corrosion rate and the time and, perhaps, some considerations on the combined effect of several deterioration mechanisms.

Most of the rules for the design of new structures have been developed to describe tests results, as accurately as possible, and have been simplified for the design. However, as these simplified rules are conservative, this fact needs to be considered when being applied to existing structures.

Some adjustments and modifications to the procedures for new structures to be applied to deteriorated ones have been mainly obtained thanks to some experimental studies. The results coming from tests should allow developing empirical expressions or to modify the existing ones for new structures, to be applied to the assessment of deteriorated structures, in terms of characteristic values and the scope of application of these expressions must be explicitly indicated [4].

Numerical methods are being calibrated using experimental results although these numerical tools are not particularly useful for daily practical applications but might allow obtaining complementary expressions to the ones coming from the experimental works through numerical tests.

An effort should be done to share the existing and future databases coming from the experimental and numerical tests and the processes to obtain the expressions for the assessment of corroded concrete structures to get a worldwide acceptance to be considered in the future Eurocode 2. Besides, it should cover concrete structures affected by a combination of deterioration mechanisms.

An overview is presented by some authors on the content that is needed to consider the assessment of deteriorated corroded structures in the fib Model Code [5], [6], [9] and [10] and in the next sections of this paper some comments for the future Eurocode 2 are presented.

4. Material models

A huge amount of research has been developed in the field of material deterioration due to corrosion, but a worldwide agreement is needed in this field to include the consolidated and accepted models in the Eurocode 2 to be integrated in the structural models of existing corroded concrete structures.

Corrosion of the reinforcing steel produced either uniform attack penetration in case of carbonation or local corrosion (pits) in case of chlorides. In the first case, gravimetric method for samples taken from the structures allow obtaining the depth of corrosion. In the second one, calliper measurements will identify the depth of the pits [6] [7]. In both cases, electrochemical measures of the corrosion rate will help to estimate the corrosion depth [7].

Thus, the future Eurocode 2 should include:

- Rules on how to consider the reduced cross-sectional area of the reinforcement
- Suggested values for the α factor as the relation between the maximum corrosion depth at pits and the average depth that would be needed to obtain the cross-sectional area. Some authors suggest values of 8-10 and other comment that these values decrease for high levels of corrosion.

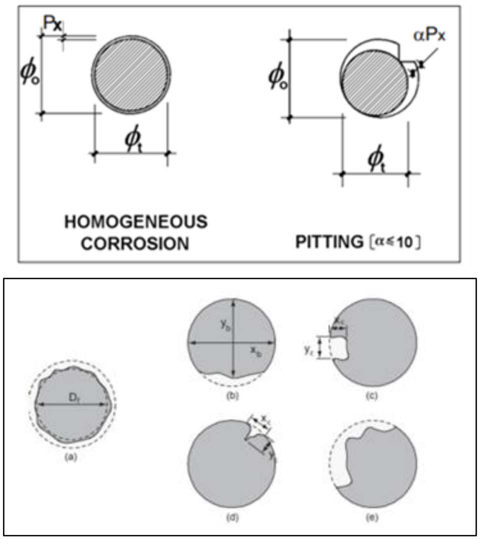


Figure 2. Residual corroded steel cross sections in Contecvet (top) [7] and in BA38/98 (bottom) [8]

There is some agreement on the mechanical properties of the uniform corroded steel where the yield stress is almost not modified although some loss of ductility is produced but no agreed values on the reduction of the strain at maximum load are available [9]. The situation is a bit less clear about localized corrosion where some stress concentration might happen at pits [11] and with the prestressing steel with stress corrosion. Anyhow, in all these cases, the Eurocode 2 should include:

- The stress-strain curves for corroded reinforcing and prestressing steel for different levels of corrosion. Some authors indicate the stress values as the ratio between the reduced tensile force values in the corroded bar and the initial cross-section without reduction due to corrosion. However, it is recommended to use the reduced cross sections when obtaining these stresses from the tests with corroded bars [4].
- Model for fatigue verification in corroded reinforcement.

Concrete might crack and spall due to the expansion of the corroded embedded steel which impacts its strength in the compression zones. There are a lot of proposals to correlate the crack width with the corrosion level. Besides, there are some proposals for a reduction factor of the compressive strength in cracked concrete either comparing it with the reduced values suggested for the compression fields and struts crossed or deviated by a tie in the Codes or with expressions depending on the depth of the corrosion attack at the compressive bars [5].

On the other hand, consolidated approach is needed coming from the existing research on how and when a reduced concrete cross section should be considered without the concrete cover due to the spalling [7] [12] [13].

Thus, models are needed in the Eurocode for:

- Crack width related to the level of corrosion
- Reduction of the compressive strength in cracked concrete depending on the level of corrosion and the number, spacing and diameter of the embedded corroded steel bars.
- Reduced concrete section due to the delamination and spalling depending on the level of corrosion and the detailing.
- Model for fatigue verification in cracked concrete due to steel corrosion
- Effects due to the combination of corrosion with other deterioration mechanisms

The composite action between concrete and steel is crucial for the concrete structures and corrosion produces some bond deterioration that depends on a high number of factors as the level of corrosion, the cover size, the number and spacing of stirrups and the external pressure [4] [5] [14] [15], and there is not enough consensus at worldwide level. Besides, more discussions on transfer and anchorage lengths in prestressing steel are also needed [16].

Thus, the Eurocode should include:

- Modified expressions to calculate the anchorage and lap lengths with corroded bars, including the stirrups for shear and punching resistance, for both plain and ribbed bars.
- Modified expressions for transfer and anchorage lengths in prestressing steel.
- Expressions for reduced bond strength to be applied in some verifications as the support and internal nodes in the strut-and-tied methods.
- Effects due to the combination of corrosion with other deterioration mechanisms.

5. Structural resistance models

The resistance of members subjected to bending or to bending and axial force can be estimated integrating the material deterioration models into the structural ones. Some additional information should be included in the Eurocode 2 as:

- The rotation capacity of the plastic hinges in the redistribution of bending moments with some limitations due to the loss of ductility of the corroded reinforcement depending on the level of corrosion

- The confined concrete with corroded stirrups in the plastic hinges
- Enlargement of the buckling length of the compressive bars due to the decrease of sectional area of both the stirrups and the bar
- Buckling of the compressive bars due to some possible premature failure of the stirrups with pits

Shear and punching resistance need some considerations to extend the present approach of Eurocode 2 based on the Critical Shear Crack Theory CSCT for members without shear reinforcement [17] [18] to corroded structures besides the material deterioration models.

Figure 3 represents the effect of corrosion on shear performance at the Critical Shear Theory with shear V values versus strain ε_v values at the longitudinal reinforcement, being ε_y the yield strain. The straight lines represent the shear action effects, and the curves lines the shear resistance. The lower curve in red shows the shear failure values at the critical crack when the reduction of both the steel cross section and the bond strength due to corrosion have been considered.

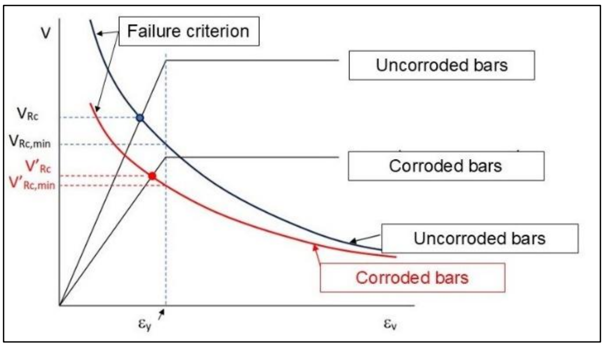


Figure 3. Crack bond deterioration due to corrosion at Critical Shear Theory

When dealing with shear, Eurocode 2 should include:

- Limitation of the contribution of the longitudinal reinforcement through ϱ_l ratio affected by a k_{bond} factor with values depending on the bond strength reduction due to corrosion, in expression 8.27 [1] (Figure 4).

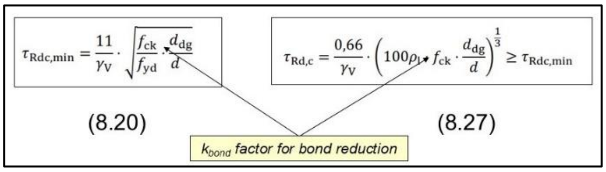


Figure 4. Effect of bond reduction in shear

- Effect of corrosion on the strain values ε_v of the longitudinal reinforcement for a refined verification with expression I.7 [1].

When dealing with shear with reinforcement, Eurocode 2 should include (Figure 5):

- Limitation of the maximum rotation of the compressive struts θ depending on the ductility of the corroded stirrups
- Effects due to bond strength reduction:
  - Limitation for θ_{min} due to the coupling of shear and bond failures by the bond strength reduction at the longitudinal bars [5]
  - Combination of the beam and tied arch actions for intermediate levels of stirrups corrosion towards tied arch action alone for high level of corrosion, to be replaced by strut-and-tied models

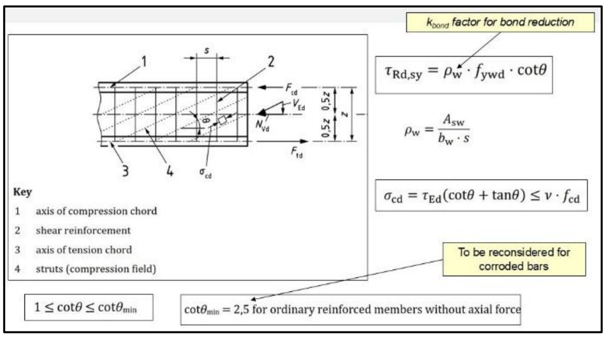


Figure 5. Corroded members with shear reinforcement

- Risk of premature shear failure due to pitting at stirrups

When dealing with punching, Eurocode 2 should include:

- Limitation of the contribution of the flexural reinforcement through ϱ_l ratio affected by a k_{bond} factor with values depending on the bond strength reduction due to corrosion, in expression 8.94 [1]
- The effect of corrosion on the maximum rotation ψ of the slab around the supported area when using the alternative procedure of expression I.16 [1]

Design with strut-and-tie models and stress fields, [5] and [19], might be appropriate when dealing with corroded concrete structures, both in B and D regions, considering the deterioration models of steel, concrete and bond.

Eurocode 2 should include the effects of the reduction of the ductility of the corroded reinforcement on the deformation capacity for the adopted strut-and-tie models.

6. Safety items

Reliability and safety items need to consider what is being developed within the framework of Eurocodes for the assessment of existing structures at the prEN1990-2 [20] and Eurocode 2 should include:

- Both new empirical expressions or the corresponding modified ones from new structures to be applied to corroded ones, for material models and structural resistance ones, to be presented in the characteristic values and, then, the partial factor format might be used [20] and [21].
- I.4.2 Verification by partial factor method and Annex A Adjustment of partial factors for materials in [1] to be revised, if it is needed, considering the additional level of uncertainties that corrosion might include in the assessment of the corroded structures.

7. Remaining service life of structures with corroded reinforcement

Eurocode 2 should include not only rules on how to evaluate the bearing capacity of the existing structures but also provide predictive methods for estimating deterioration rates associated with the various deterioration mechanisms for concrete structures, including corrosion, to estimate the remaining service life.

The rate of corrosion along the time should be established in function of the environmental conditions of each part of the structures (Table 1).

Table 1: Exposure conditions and I_{corr} values [7]

Exposure conditions	I_{corr} ($\mu A/cm^2$)
Partially carbonated	
- Dry	~0.01
- Wet-rarely-dry	0.1-0.5
- Moderate humidity	0.05-0.1
- Cyclic wet-dry	0.01-0.2
Partially carbonated	
- Dry	~0.01
- Wet-rarely-dry	0.2-0.5
- Moderate humidity	0.1-0.2
- Cyclic wet-dry	0.2-0.5
Chloride corrosion	
- Moderate humidity	0.1-0.2
- Wet-rarely-dry	0.1-0.5
- Cyclic wet-dry	0.5-1.0
- Airborne sea water	0.5-5.0
- Submerged	0.1-1.0
- Tidal zone	1.0-10

There are documents [7] [9] where corrosion rate values are shown for different environmental conditions. These predicted values and the time are to be included in the deterioration material models (see 4) to be then considered in the structural resistance models (see 5) to estimate the evolution of the resistance in a specific future period of an existing structure. This prediction always needs to be complemented along the time with the appropriate maintenance and survey strategy.

Thus, as in [9], Eurocode 2 should include:

- Values of the corrosion rate for the different exposure classes indicated in section 6 [1]

- All material and resistance models in function of the depth of the corrosion deterioration that will be estimated from the corrosion rate values and the time.

8. Final comments

The transfer of consolidated knowledge from research to daily engineering evaluation of corroded concrete structures has a relevant impact as soon as this knowledge is accepted and included in codes as the Eurocode 2.

Thus, it is expected that the application of the future of Eurocode 2 will allow a quantitative assessment and prediction of corroded concrete structures.

In the meantime, fib Model Code 2020 [9] or others might be a reference when evaluating corroded concrete structures.

Acknowledgements

The author wishes to acknowledge the contribution of Professor Pedro Miguel from Polytechnical University of Valencia (Spain) in figure 3 on the effect of corrosion at Critical Shear Theory for elements without shear reinforcement.

Besides, the author wishes to acknowledge the initiative of the CRACS DAYS 2023 at the University of Parma (Italy) for the fruitful discussion on the capacity assessment of corroded concrete structures: from research to daily engineering evaluation.

References

[1] CEN. 2023. Eurocode 2, Design of concrete structures: Part 1-1: General rules and rules for buildings, bridges and civil engineering structures, EN 1992-1-1:2023

[2] Arrieta JM, Rodríguez J and Ganz H. 2023. "The Origins and Some Highlights on the New Proposal for Eurocode 2". Hormigón y Acero, https://doi.org/10.33586/hya.2023.3115

[3] Díaz-Pavón E, Rodríguez R, Ley J and López P. 2023. "Contributions of the Future Eurocode 2 for Assessment of existing structures". Hormigón y Acero. https://doi.org/10.33586/hya.2023.3103

[4] Rodríguez J and Anaya P. 2020. "Some thoughts of the Structural Performance of Corroded Concrete Structures arising from past experimental results". Proceedings of the fib CACRCS DAYS 2020, 187-195

[5] Coronelli D. 2020 "Resistance of Corroded RC beams: Extending fib Model Code 2010 models". Structural Concrete 1747-1762. https://doi.org/10.102/suco.201900311

[6] Walraven J. 2021. "Assessment of concrete structures with corroded reinforcement: development and recommendations. Proceedings of the fib CACRCS DAYS, 85-90

[7] CONTECVET IN30902I, 2001. "A validated user's manual for assessing the residual life of concrete structures, DG Enterprise, CEC. https://www.ietcc.csic.es/wp-content/uploads/1989/02/manual_contecvet_ingles.pdf

[8] BA38/98 Assessment of the fatigue life of corroded reinforcing steel bars. 1998

[9] fib Model Code for Concrete Structures (2020). Version 1 [2023]

[10] fib Bulletin 111 Modelling structural performance of existing concrete structures, June 2024.

[11] Andrade C, Oller S and Pérez-Trujillo FJ. 2022. "Basis for calculation the residual mechanical properties of corroding bars". Structural concrete. https//doi.org//10.102/suco/202200310

[12] Ding H, Jiang C, Gu X and Zhang W. 2021. "Simplified calculation methods for bearing capacities of corroded reinforced columns in uniaxial compression". Proceedings of the fib, 97-100

[13] Higgins C, Holcomb GR et al. 2003. Shear capacity Assessment of Corrosion-Damaged Reinforced Concrete Beams. Technical Report Form DOT F 1700.7 (8-72) . Oregon Department of Transportation & Federal Highway Administration.
[14] Prieto M, Tanner P and Andrade C. 2016. ”Multiple linear regression model for the assessment of bond strength in corroded and non-corroded steel bars in structural concrete“. Materials and Structures, 4749 – 4763
[15] Blomfors M, Zandi K and Lindgren K. 2018. “Engineering bond model for corroded reinforcement”. Engineering Structures 394-410
[16] Anaya P, Martín-Pérez B, Rodríguez J. and Andrade C. 2022. Transfer length of corroded wires in prestressed concrete members. Structural Concrete. https:/doi.org/10.1002/suco.202100265
[17] Miguel P, Fernández MA, Hegger J and Schmidt M. 2023. Shear resistance of members without shear reinforcement in presence of compressive axial forces in the next Eurocode 2. Hormigón y Acero https://doi.org/10.33586/hya.2023.3112
[18] Muttoni A, Simoes JT, Faria DMV and Fernández Ruiz M A. 2023. “A mechanical approach for punching shear provisions in the second generation of Eurocode 2”. Hormigón y Acero. https://doi.org/10.33586/hya.2022.3091
[19] Prieto M and Tanner P. 2021. “Assessment procedure of corrosion damaged structures with stress field models”. Proceedings of the fib CACRCS DAYS, 113-116
[20] CEN 2021. Eurocode 0 “Basis of assessment and retrofitting of existing structures: General Rules and Actions”. prEN1990-2
[21] Tanner P, Hingorani R, Lara C. 2022. “New or existing, does it matter?”. Acta Polythecnica CTU Proceedings. https://doi.org/10.14311/APP.2022.36.0286