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Remaining Service Life of Corroding Structures

Durée de vie restante de structures corrodées

Restlebensdauer von korrodierten Stahlbetonbauten

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SUMMARY

The prediction of the remaining service life of a corroding structure has been calculated up to now using empirical approaches and without taking into consideration the possible progressive structural damage that corrosion provokes. In a first attempt, values of several corrosion rates were implemented in Tuuti's model on service life and some kind of quantitative calculation could be presented. In the present paper, engineering considerations are introduced in the approach and the loss in load-carrying capacity is calculated for different corrosion rates assuming several simplifications.

RÉSUMÉ

La prédiction de la durée de vie restante des structures en train de se corroder, est faite habituellement par calculs approximatifs et sans considérer les différents niveaux de détérioration que la corrosion provoque. Dans la première tentative, des valeurs de la vitesse de corrosion ont été introduites dans le modèle de Tuuti sur la durée en service et un certain niveau de quantification a pu être atteint. Dans la présente communication, quelques considérations structurelles sont introduites et des exemples de pertes de résistance mécanique sont calculés en fonction de la vitesse de corrosion.

ZUSAMMENFASSUNG

Die bisherigen Verfahren zur Bestimmung der Restlebensdauer von korrodierten Stahlbetonbauten waren empirische Näherungen ohne Berücksichtigung der zunehmenden Schädigungen. In einem ersten Versuch wurden im Modell aus Tuuti die Daten verschiedener Korrosionsgeschwindigkeiten verwendet, um quantitative Abschätzungen zu erhalten. In der vorliegenden Arbeit werden zusätzliche ingenieurwissenschaftliche Betrachtungen zur Einschätzung der Tragwiderstandsverminderung vorgenommen. Die Restlebensdauer wird, unter der Annahme gewisser Vereinfachungen, für verschiedene charakteristische Korrosionsgeschwindigkeiten abgeschätzt.

INTRODUCTION

Service life prediction is complex matter in which both technical and economical consequences are involved. The need to study parameter has arisen from the unexpected premature deteriorations shown by reinforced concrete structures exposed to aggressive environments. The corrosion of reinforcements has resulted to be one of the most frequent causes of these premature failures.

Different proposals intended to calculate, either the life time of a new structure or the remaining life of a deteriorating one, may be found in the literature (1). Three of the authors of this contribution have also suggested in previous papers (2)(3) a methodology to calculate the remaining service of structures damaged by rebar corrosion. This methodology could be proposed due the large amount of corrosion intensity values, i_{corr}, which were collected by the authors along 20 years of experiments. These i_{corr} values were determined from Polarization Resistance results, Rp, measured in specimens prepared in the laboratory and on-site in real structures. In this paper a new advance in this line of research is offered, which considers the conversion of corrosion rate values in loss of load-carrying capacity terms. Some simple examples for columns and beams are calculated.

CALCULATION OF THE REMAINING SERVICE LIFE OF A CORRODING STRUCTURE

Three main points need to be considered to attempt to calculate the remaining service life: 1) The type of deterioration process involved; 2) The main parameter which controls the deterioration rate; 3) The unacceptable level of damage which makes the structure unsafe.

In the evoked previous paper (3)(4), for the particular case of corroded structures the following answers were given to these points:

1. Tuuti's model (4) was adopted as a deterioration model for a corroding structure. This simple model considers an initiation and a propagation period.
2. The loss of bar cross-section of the rebar was taken as rate-determining parameter. This loss in cross-section was determined from real i_{corr} values, whether they remain constant along the propagation period of (2) whether they change with the moisture content of the concrete (3).
3. The levels of deterioration suggested by the CEB in its Bulletin no. 162 were those taken into account.

Figure 1 is the result of jointly considering all these aspects. This figure allows the approximate calculation of the residual service life in terms of corrosion rates and of the loss in bar cross-section, assuming that this loss in diameter decreases linearly with the corrosion rate. The following relationship may be stablished from Figure 1.

$$\emptyset (t) = \emptyset_i - 0.023 . i_{corr} . t$$

$\emptyset (t)$ = the rebar diameter at time t (mm)
$\emptyset_i$ = the initial diameter of the rebar (mm)
i_{corr} = the corrosion rate ($\mu A/cm^2$)
t = the time after the beginning of the propagation period (years)
0.023 = the conversion factor of $\mu A/cm^2$ into mm/year

However, the translation of these concepts into engineering terms is necessary, if the remaining load-carrying capacity and the safety of the structure are to be de - termined.

ENGINEERING CONSEQUENCES OF THE REBAR CORROSION

The main undesirable effects of the corrosion in the structure may be summarized as: a) a loss in the steel integrity: loss of cross-section and likely in the mecha nical properties; strenght and ductility; b) the splitting and spalling ot the cover with a loss in the concrete cross-section in the case of spalling; c) a loss in bond between concrete and steel in the case of cracks running paralled to the reinforcements and provided that the loss in steel section is high.

Very little attention has been paid in the literature to these effects (5)(6) and thus, the experimental data are scarce and usually obtained through and artificial acceleration of the corrosion process.

HYPOTHESES CONSIDERED IN THE PRESENT STUDY

The study of the load-carrying capacity loss will be approached at three different levels. A first one which consider the deterioration of a section in such a way that the strength loss against different action effects (bending moment, shear force, axial force, etc.) could be established. A second level which will introduce the deterioration model of an element, so that the loss in load-carrying capacity if isolated elements (for instance; simply supported beams) could be proposed. Finally a third level which will consider the whole structure and take into account the possible redistribution of the action effects, provided that it is allowed by the remaining materials ductility. For the purpose of the present study only the first level is going to be considered.

The assumption considered here may represent the case of corrosion in carbonated concrete where cracks are not produced in the cover because the concrete remains wet and therefore the oxydes may diffuse through the pores. They are:

- an homogeneous loss around the whole steel surface is supposed wheter i_{corr} remains constant or varies with ambient humidity. No pitting or localized corrosion is studied at this moment,
- no loss in bond is produced, which means that no parallel cracks were generated during the corrosion process and therefore the cover remains free from damages,
- no loss in steel mechanical properties is taken into account.

EXAMPLES AT THE CROSS-SECTION LEVEL

Ultimate bending moment (M_u)

The decrease in the ultimate bending moment has been studied at a cross-section 0.40 m deep and 0.25 m wide, with a tension reinforcement (4 Ø 14 mm or 2 Ø 20 mm).

Four corrosion rates have been considered (0.1, 1.0 and 100 $\mu A/cm^2$), kept constant along time, and it has been assumed that corrosion only affects the decrease in the diameter of the rebars, according to the equation given in the preceeding section.

In this way and bearing in mind the conventional hypotheses for reinforced concrete, the curves in figure 2 have been plotted, which show the decrease of the ultimate bending moment in terms of the time elapsed since the beginning of the reinforcement corrosion (propagation time). Thus, while corrosion rates of 0.1 and 1 $\mu A/cm^2$ result in a slight decrease of the safety factor along the 50 years of the service life assumed, rates of 10 and 100 $\mu A/cm^2$ result in the desappearance of the safety factor in lifetimes of 16 and 2 years respectively, when the sections have been reinforced with 14 mm diameter rebars.

In figure 2, it can also be observed that cross-sections reinforced with higher diameter bars are less sensitive to the damages produced. Thus, with two reinforcements with the same steel ratio but with different bar diameters (4 Ø 14 mm and 2 Ø 20 mm) and for the same corrosion rate (10 $\mu A/cm^2$), the loss of the safety factor is reached at different time lapses of 16 and 22 years, respectively, the corrosion damage being reached at an earlier time in the cross-section reinforced with the 14 mm diameter bar. The interest to use big-size rebars is thus shown in order to delay the damages if an adequate concrete cover is provided.

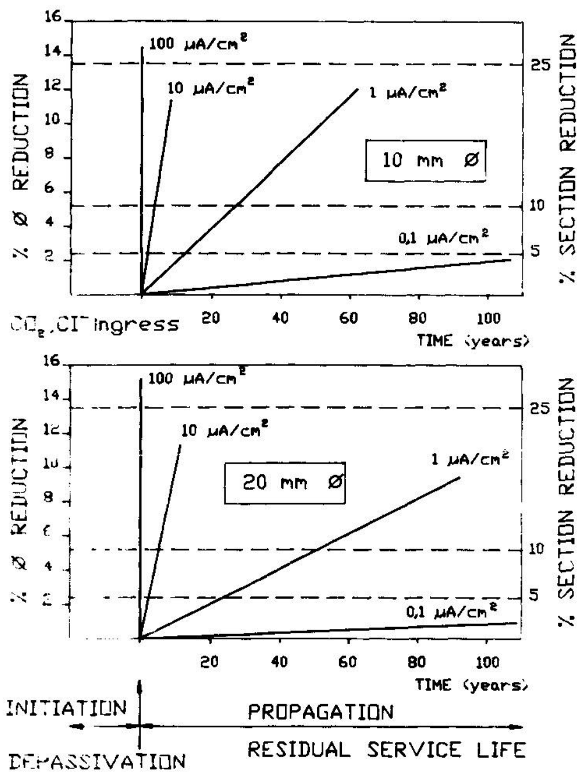

Fig. 1 - Rebar life time in function of its diameter and corrosion rate

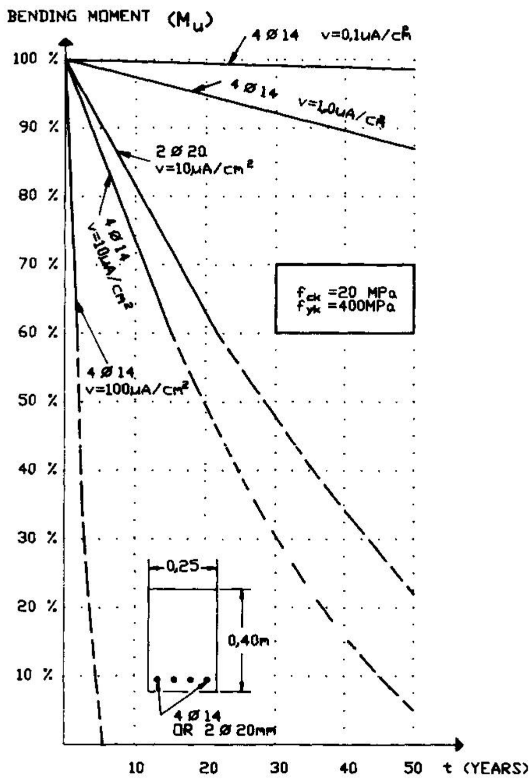

Fig. 2 - Loss in bending moment in function of the corrosion rate

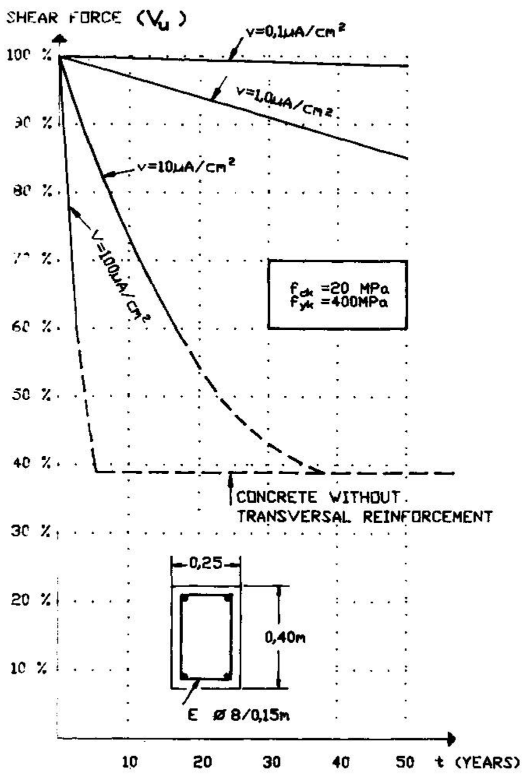

Fig. 3 - Loss in shear force in function of the corrosion rate

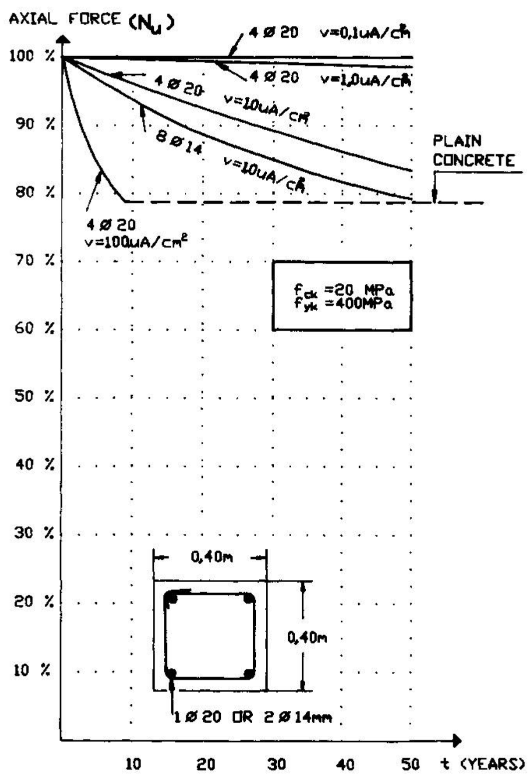

Fig. 4 - Loss in axial force in function of the corrosion rate

Ultimate shear force (V_u)

The decrease in the ultimate shear force of the same concrete cross-section reinforced with 8.0 mm diameter stirrups, located at 0.15 m distances, has also been investigated for different corrosion rates.

It is assumed that the deterioration of the longitudinal reinforcement is negligeable, what may be true, upon the reinforcement having a thicker cover, and that the shear force can be estimated by adding the shear carried by the concrete to the shear analysed by the truss analogy, which consists of the concrete and the longitudinal and transversal reinforcements.

The curves in figure 3 have thus been plotted which show again that corrosion rates of 0.1 and 1 $\mu A/cm^2$ scarcely impair that value of the shear force along the 50 years lifetime contemplated for the structure, while with corrosion rates of 10 and 100 $\mu A/cm^2$ the safety factor becomes zero along periods of 15 and 2 years respectively. At the latter two corrosion rates, the web reinforcement collapses along 4 and 35 years periods, and, from that time, the shear force is exclusively carried by the concrete itself and by the longitudinal reinforcement. This situation is somewhat theoretical, since, after these time periods and at these corrosion rates, the derioration of the longitudinal reinforcement must also be quite considerable, and therefore the shear force carried by this reinforcement must also be largely smaller than the shear shown in the horizontal lengths of the curves shown in figure 3.

Ultimate axial force (N_u)

Finally, the reduction in the bearing capacity of a 0.40 x 0.40 m cross-section axially loaded, reinforced with rebars at its four corners has also been studied for the same corrosion rates as indicated in the foregoing cases.

The curves plotted in figure 4 shown the evolution of the axial force along the time elapsed from the beginning of the reinforcement corrosion and have been estimated by adding up the axial force carried by the concrete to that carried by the reinforcement. There has not been taken into consideration the possible buckling of the longitudinal reinforcement, when neither the concrete cover nor the transversal reinforcement, also deteriorated can duly brace it.

At the cross-section reinforced with a 20 mm diameter rod at each corner, the damage caused is significative for corrosion rates of 10 $\mu A/cm^2$, so that, at 50 years life, most ot the axial force is virtually carried by concrete alone. For corrosion rates of about 100 $\mu A/cm^2$, the reinforcement disappears in its entire by before 10 years, so that the axial force is then carried by concrete only.

It is well known that a centrally loaded section is a theoretical situation, for these always appears certain eccentricities induced by the loads or by imperfections in the concrete cross-sections. In this connection, the possible irregular damaging of the reinforcement, may also result in a certain additional eccentricity which, combined with the previous eccentricities, results in a cross-section with a highly damaged reinforcement bearing with greater difficulting the theorical simple compressive stresses. Therefore, the horizontal lengths of curves in figure 4 give "optimistic" values, which will be reduced due to the higher sensitivity of plain concrete to the action of such "accidental eccentricities".

In figure 4 there can also be compared the different evolution of the axial force with the time elapsed, in cross-sections reinforced with the same steel ratio, but different rebar diameters (1∅ 20 mm or 2∅ 14 mm at each corner). It is shown again the interest of using greater diameters, taking in advance the precautionary measures mentioned above.

DISCUSSION

The estimation of the remaining service life of corroing structures has been, up to now, mainly based on empirical or qualitative models and on the subjetive experiencie of expertises. A quantitative method could not be found in the literature.

The methodology presented here relates the loss in load-carrying capacity with the loss in steel cross-section as a function of its corrosion rate. It is still a simplified method of approaching the prediction of the remaining service life and some simplifications had to be assumed due the lack of experimental information, but it offers a semiquantitative methodology to make predictions concerning the damage in the critical sections of the structure. Provided that, the corrosion intensity of a corroding structure and its age are known, an estimation of the time required to reach a critical loss, can be made.

For a more accurate estimation, several questions should be experiments. Aspects such as bond, steel mechanical properties, the presence of cracks, will have to be elucidated considering different corrosion or damage levels. Also, not only sections, but simple elements (beams and columns) and, finally, the whole structure will have to be investigated.

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