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Estimating corrosion attack in reinforced concrete by means of crack opening

The corrosion of reinforcement in concrete is the most common degradation phenomenon of reinforced concrete structures. Reinforced concrete elements subjected to corrosion generally crack due to the expansive nature of oxides. One very important task is estimating the corrosion level using a non-destructive method in order to establish both the actual safety of the structure and a priority intervention plan.

Many researchers have studied the relationship between the corrosion phenomenon and the corresponding crack openings and their evolution; several statistical analyses, based on test data from experimental campaigns under a wide range of test conditions, are available.

The present work attempts to contribute to finding a relationship between the crack opening and the amount of corrosion induced in the reinforcing bars. The result of the analysis is that only a reduced number of tests can be used to establish an empirical model based on a reliable set of test data. A simple relationship between crack opening and corrosion penetration is not recommended, due to the different parameters that are able to influence this correlation. Therefore, two fundamental parameters, the ratio of the concrete cover to the rebar diameter and the concrete strength, have also been considered. The considerations made regarding these parameter test results have been rearranged and the result is a formulation that shows reduced scatter.

Keywords: crack opening, reinforcement corrosion, safety assessment

1 Introduction

The corrosion of reinforcement in concrete is one of the main detrimental problems for reinforced concrete (RC) structures. Its principal effects are:

i) a reduction in the resisting section of the reinforcing bars,
ii) damage to and cracking of the concrete surrounding the bars, caused by the expansion of the oxides,
iii) impairment of the bond between the reinforcement and the concrete, and
iv) the modification of the constitutive relationship of the corroded reinforcement in terms of stress–strain relationship and fatigue resistance.

Therefore, corrosion is able to impair the structural behaviour of an RC structure to a great extent. Under service conditions, corrosion influences the stiffness of the elements, due to variations in the bond–slip relationship after cracking of the concrete [1]. In particular, it is evident that, for low values of corrosion attack, it is possible to observe an increase in stiffness in the response under mechanical action, whereas for values that exceed a threshold value, which is generally assumed to be the level of corrosion able to produce crack formation on the outer concrete surface, a reduction in stiffness is mainly observed as a consequence of the reduction in bond [2]. At ultimate conditions, corrosion, other than being able to reduce the load bearing capacity, could also be responsible for modifications to the collapse mechanism. For example, shear failure can precede flexural failure [3], because of the effect of the reduction in the resisting area of the stirrups, which are the rebars nearest to the external surface. This could determine a transition from a ductile to a brittle type of failure. Furthermore, shear collapse can be attributed to the interaction between shear and bending mechanisms in the presence of corrosion as demonstrated in *Ghersi* et al. [4]. This issue could be particularly critical in the presence of seismic actions, in which case ductile behaviour is needed.

The detection of damage due to the corrosion of reinforcement is facilitated by the appearance of cracks on the surface of the element. Such cracks are caused by tensile stresses created by the expansive rust oxides, which are caused by the loss of passivity, which in turn is determined by a concentration of chlorides or by the carbonation of concrete. The rust formed acts like a gel that, through the cracks, reaches the concrete surface. However, stains on the surfaces or signs of drainage from hidden zones due to corrosion point out the presence of damage.

Cracks on the surface are visible, measurable and reveal the presence of a corrosion attack; their width is, in general, related to the level of reinforcement corrosion and to the density of bars in that area, as has been observed by several authors [5]. However, from an analysis of the experimental results available in the literature, it is evident that the correlation between crack opening and

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corrosion level shows a huge scattering. In [6], [7], [8] and [9] it has been underlined that, among other factors, the main influencing variables are the corrosion rate itself, the concrete microstructure and its strength, the ratio between concrete cover and bar diameter and the presence of confinement, which could act to prevent crack formation and its evolution. The variability in the corrosion attack penetration along the length of a crack opening could be also important [9], [10], even though it is generally considered to be constant. It is important to emphasize that localized corrosion may have a significant influence on the tensile strength of the reinforcing bars even though pitting corrosion can hardly be linked to uniform corrosion as some authors have shown due to highly scattered data [11], [12]. In order to correlate the measured crack widths on the surface of an RC element to the corresponding entity of corrosion, the influence of the aforementioned factors should not be disregarded.

In the present paper, an analysis of the results from the literature will be made in order to identify the possible relations between crack width and several variables and summarize the influences mathematically. Although a direct universal relation between crack width and degree of corrosion seems very difficult to reach, the present work tries to contribute to exploring the key influencing parameters.

2 Analysis of the experiments in the literature

Corrosion attack is a very aggressive phenomenon that in natural conditions takes time to produce its effects on cover cracking. Researchers have therefore normally used accelerated corrosion methods to study it. Few studies on naturally corroded elements can be found in the literature, e.g. [9] and [13]. *Andrade* et al. [9] monitored the corrosion rate and crack widths in a beam with 3 % admixed chlorides exposed to natural weathering for more than 20 years. The results indicate that although there is a linear relationship between crack width and time, the relation between crack width and corrosion rate was not unique, with the cracks varying from < 1 mm to 14 mm. *Torres-Acosta* and *Martinez-Madrid* [13] conducted a study on twelve 90×190×305 mm RC slabs with three 13 mm diameter bars and 25 mm concrete cover. The corrosion was of a natural type in a marine environment and an activated titanium electrode was used to evaluate the amount of current flowing into the concrete. The specimens were subjected to marine exposure for about 700 days. At the end of each test, the cracks were mapped and the average corrosion attack was measured. The maximum value of mass loss was 17.9 %. *Zhang* et al. [14] obtained results on crack formation and bond variation between steel and concrete in naturally corroded RC elements subjected to an aggressive environment for more than 20 years. Other than the difficulties encountered with very long experimental tests, the possibility of analysing real structures is hindered because they are generally still in service. Therefore, tests with accelerated corrosion methods are needed and they are usually the only way of studying this phenomenon. In structures subjected to accelerated corrosion, some authors (*Rodriguez* et al. [15]) observed that the current density flowing into the reinforcing bars can be highly variable, depending on the test conditions (wet/dry). Other accelerated corrosion tests ([7] and [16]) have dealt with the effect of current density variations on the formation of the first crack and its evolution overtime. The authors have observed that it is possible to obtain very different oxide products from corrosion, depending on the current density that is applied and the moisture conditions. Additionally, these oxides show different expansion coefficients from those that characterize the formation of a "natural" corrosion product.

Andrade et al. [17] recorded corrosion rates in natural and laboratory conditions in different environments. The maximum current densities registered were about 100 μA/cm^2, corresponding to cracked concrete in contact with seawater. This is also a normal current in the steel in other environments, indicating that higher levels of current density, if applied in accelerated corrosion tests, generally lead to the formation of oxide products with a lower density than those products obtained with low levels of current density. The structural effect of this volumetric variation of the accelerated mechanism is perceived as the formation of a crack on the surface, which could be of a small width due to the low pressure exhibited by the oxide product.

In addition to *Andrade*, other authors, e.g. *Clark* and *Saifullah* [18], also suggested using a current density < 250 μA/cm^2, because higher current density values could produce negative effects on the steel-concrete bond.

In an experimental test carried out by *Cairns* and *Ayop* [19], a substantial difference was observed concerning the effects of corrosion produced by two different current densities (80 and 400 μA/cm^2). *El Maaddawy* and *Soudki* [16] analysed a large number of experimental tests and suggested limiting the current density to a maximum of 200 μA/cm^2 in order to obtain reliable results. A comprehensive analysis of this topic is reported in *Mancini* and *Tondolo* [20].

On the basis of previous considerations, only some experimental tests whose accelerated level of the current density was < 200 μA/cm^2 will be commented on here. They are summarized in Table 1.

Andrade et al. [5] conducted experimental tests on 150×150×380 mm specimens with 16 mm diameter reinforcing bars and 20–30 mm concrete covers. Crack openings were measured using electric strain gauges glued to the external surface of the specimens. The electrochemical corrosion was obtained with a current density ranging between 10 and 100 μA/cm^2. An average 3.55 MPa tensile strength was evaluated for the concrete.

Research on cubic specimens, with reinforcing bars positioned at the corners, was presented in *Rodriguez* et al. [34]; the presence of transverse confinement was also studied. This kind of specimen, named "end beam element", reproduces a portion of the beam subjected to constant shear. The specimens had a cubic shape with 16 and 10 mm diameter ribbed bars and 8 or 6 mm diameter stirrups. The ratios of cover to diameter (c/ϕ) were 1.5 and 2.5 and the mean compressive strength of the concrete was 40 MPa. The elements were subjected to a current density of 100 μA/cm^2. At the end of the corrosion process, the specimens were analysed carefully and the crack patterns mapped. An evaluation of the corrosion penetration attack was obtained by means of a gravimetric procedure.

The results of the tests on eight beam specimens measuring 152×254×3200 mm are reported in *El Maaddawy* et al. [21]. Some specimens were simultaneously corroded and loaded in a four-point bending test, whereas the others were first corroded and then loaded. The reinforcement was in the form of two 15 mm diameter ribbed bars in the tension zone, two plain 8 mm diameter bars in the compression zone and plain 8 mm stirrups at 80 mm spacing along the shear span and 333 mm in the central part. The concrete cover was 33 mm and a current density of 165 $\mu A/cm^2$ was used to corrode the bottom bars. Corrosion levels of 8.9 and 31.6 % of mass loss were achieved. At the end of this process, the cracks were measured and mapped.

The experimental study reported in *Torres-Acosta* et al.[12] shows 12 reinforced 100×150×1500 mm concrete beams with 9.5 mm diameter ribbed bars and 20 mm concrete cover. The accelerated corrosion was obtained by means of a constant current density of 80 $\mu A/cm^2$. The current was applied for the time necessary to obtain an average reduction equal to 5, 10 and 15 % of bar radius. A custom-made multichannel galvanostat provided a regulated current source for each specimen. The mean compressive strength tested on the concrete cylinders was 27 MPa. At the end of the corrosion period, the crack positions and related widths were recorded.

The experimental tests by *Cairns* at al. [22] were performed on four different types of reinforced concrete beams with a rectangular 150×200 mm section, longitudinal reinforcement of 10 or 16 mm dia. bars and a cover thickness of 20 mm. The concrete mean strength at 28 days was 38.8 MPa. The electrochemical corrosion was obtained by means of a current density of 60 $\mu A/cm^2$ applied to the entire length of the rebars or to the central part of them depending on the type of specimen. The authors observed the specimens continuously in order to register the onset of cracking, which was measured by means of a mechanical extensometer. The mass loss ranged between 7.0 and 11.5 %.

The results of an experimental campaign on reinforced concrete elements are reported in *Al-Harthy* et al. [23]. The experiment was designed to investigate how the transverse reinforcement, the c/ϕ ratio and the longitudinal reinforcement influence crack formation. Slab elements with dimensions of 250×550×1000 mm were tested. The longitudinal reinforcement had a diameter of 16 or 27 mm, the concrete cover was 10 or 20 mm and the mean compressive strength of the concrete was 23.4 MPa. The corrosion was obtained by means of three different current densities of 59, 100 and 169 $\mu A/cm^2$, applied for a maximum period of 1860 h. The crack widths were measured using a mechanical strain gauge and they were evaluated, after demolishing the specimens, according to the ASTM G1-03 [24] procedure.

The results of an experimental survey of reinforced concrete specimens are reported in *Coronelli* et al. [25]. The specimens were end-beam elements, in agreement with a shear cracking scheme, reinforced with three ribbed 20 mm diameter steel bars. Two types of specimen were employed: with and without transverse bars. The stirrups for the former group were ribbed 8 mm diameter bars spaced 40 mm apart. The c/ϕ ratio was 1.5, the bonded length 210 mm and the current density for the accelerated corrosion 143 $\mu A/cm^2$, a value that was maintained for a period of time necessary to reach the 10 % mass reduction in the longitudinal reinforcement calculated with *Faraday*'s law. The mass reduction was checked a posteriori by weight loss measurement. The crack formation and its evolution were monitored continuously.

The experimental campaign reported in *Richard* et al. [26] was conducted for rectangular 250×100×1000 mm beam elements with two 20 mm longitudinal bars. The concrete cover was 25 mm. A constant current density of 100 $\mu A/cm^2$ was used for a period of about 700 hours. Corrosion only took place in the central 500 mm section of the beam. The crack width evolution was measured daily.

Twenty-eight "beam-end"-type pull-out tests were analysed in *Prieto* [27] in order to study the effect of corrosion on the bond properties between steel and concrete. Three different specimen typologies were prepared (confined with transverse reinforcement, confined using external pressure and unconfined) and subjected to a current density ranging between 100 and 200 $\mu A/cm^2$ in order to reach corrosion percentages of up to 9 % in terms of mass loss. The test setup gave results for the bar position chosen during the casting and on the concrete cover, whose ratio with respect to the bar diameter (12 or 25 mm) was 2.1 or 3. The crack dimensions on the external surface were recorded for 20 specimens at the end of the corrosion process.

The effects of the static and cyclic application of simultaneous loading and corrosion on RC specimens were studied in *Giordano* et al. [1]. Prismatic samples with a length of 500 mm and a transverse section 90 × 90 mm were used in the test; the reinforcement was a ribbed, centrally aligned 14 mm bar. The chosen current density was 200 $\mu A/cm^2$ and each test lasted 25 days. Static and cyclic tensile forces were applied; in the latter case 6.5×10^6 cycles were induced. The value of the crack opening was measured continuously during the test.

In 2014 some of the authors of the present paper performed pull-out tests on reinforced concrete specimens subjected to corrosion in the "Franco Levi" Laboratory at Politecnico di Torino. The specimens were 120 mm cubes that were reinforced with one ribbed 12 mm diameter bar according to RILEM pull-out recommendations. The bar embedment length was 60 mm and a ratio of cover to rebar diameter of 4.5 was used. A current density of 200 $\mu A/cm^2$ was used for the time needed to reach theoretical mass losses of 2, 5, 10 and 20 %. At the end of the corrosion procedure, during which the crack width evolution was monitored, pull-out tests were performed, and then the rust was removed according to ASTM G1-03 [24] in order to verify the actual mass losses, which were 2.5, 6.0, 10.6 and 24.8 % respectively.

All the previous experimental results, summarized in Table 1, were collected under the specific condition of being subjected to natural corrosion or accelerated corrosion with a limited density (200 $\mu A/cm^2$). However, it is possible to find a large number of tests in the literature [28], [29], [30], [31], [32] that do not fulfil this condition. A

Table 1. Experimental tests used for the statistical analysis of crack opening due to corrosion with corrosion progression

Research project	*J* [mA/cm²]	f_c [MPa]	f_t [MPa]	*c/ϕ* [–]	Simultaneous application of load
Andrade et al. (1993)	10 – 100	–	3.55	1.25; 1.9	NO
Torres-Acosta & *Martinez-Madrid* (2003)	natural corrosion	NA	1.9	1.9	NO
Rodriguez et al. (2004)	100	40	NA	1.9; 2.0; 2.1; 2.9	NO
El Maaddawy et al. (2005)	165	41	NA	2.2	YES/NO
Torres-Acosta et al. (2007)	80	27	2	2	NO
Cairns et al. (2008)	60	38.8	NA	1.6; 2.6	NO
Al-Harthy et al. (2010)	59; 100;169	23.8	8	0.37; 0.63;0.74; 1.25	NO
Coronelli et al. (2011)	143	34.3	NA	1.5	NO
Giordano et al. (2011)	200	25.2	NA	2.7	YES
Richard et al.(2012)	100	44.7	3.3	1.25	NO
Prieto (2014)	100; 150; 200	NA	2; 2.3; 2.5	2.1; 3; 4	NO
Pull-out test in Turin (2014)	200	33.2	3.4	4.5	NO

further condition in the selection was a crack opening no greater than 2 mm. This second condition was mainly chosen for two reasons: a dimension of 2 mm generally means a very large opening, so delamination is about to occur; additionally, the scattering of the results for crack widths > 2 mm is too high for a reliable statistical interpretation; in fact, only a few authors have reported cracks widths greater than the 2 mm limit [13], [34].

For the sake of studying the influence of variables, the crack openings of the experimental tests listed in Table 1 are plotted in Fig. 1 on a logarithmic scale as a function of the ratio of the average attack penetration, assuming a homogeneous generalized corrosion, to the radius of the reinforcement (X_{ave}/r_0) according to *Torres-Acosta*'s proposal [13]. Indeed, the interpolation function of the selected data is plotted in a continuous line. Furthermore, the interpolation function proposed by *Torres-Acosta* [13] is also drawn with a dashed line. It is important to note that the two interpolation functions were obtained from different sets of experimental data; in fact, some data used by *Torres-Acosta* are not included in the actual database. We interpreted that the larger current densities of the test setup, not included in this analysis but present in [13], are responsible for this discrepancy. For these tests, corrosion was obtained after a short time for values of current densities greater than 200–250 μA/cm², but unlike for the test executed with low current densities, the system is unable to create expansive oxides. Furthermore, wet and dry moisture cycles could also modify such kinds of oxide products and they take time to become effective. The interpolation curve for the selected dataset is drawn in the same graph in Fig. 1, resulting in

$$w_{max} = 11.13 \cdot \left(\frac{x_{ave}}{r_0} \right)^{0.827} \quad (1)$$

Which corresponds to a coefficient of determination R^2 equal to 0.705. This curve was obtained by means of a linear regression using a power law. The shape of the curve is in line with that observed by other authors [25]. The function proposed by *Torres-Acosta*, and used in our work, shows a determination coefficient of 0.563; the higher coefficient of determination corresponding to our proposal is justified by the higher homogeneity of the tests considered. For visualization purposes, the same graph has also been plotted on a normal linear scale in order to point out the reduction in scattering obtained with Eq. (1).

3 A new interpolation model

In order to improve the correlation between the selected crack opening database and the attack penetration through the variables involved during crack formation and evolution processes, some remarks based on experimental results and literature discussions are reported here. Once again, one of the most interesting factors is the ratio between concrete cover and bar diameter. In fact, with increasing corrosion penetration, a rebar with a large diameter produces cracks with a larger opening than a bar with a smaller diameter [33], assuming the same cover depth. The tensile strength of concrete is surely another parameter that influences the crack dimension; in fact, the higher the strength, the more likely it is that cracks due to the pressure of oxides are avoided, and once a crack appears, the more likely it is that its dimension remains smaller than in the case of a low-strength concrete.

In order to take into account the previous considerations, a new overall parameter, named CT, has been introduced. This parameter is able to take into account the tensile strength of concrete and the c/ϕ ratio simultaneously [34]:

$$CT = \left(\alpha \frac{c}{\phi} \right)^{-\frac{\beta}{f_{ct}}} \quad (2)$$

where:

c concrete cover

ϕ bar diameter

f_{ct} average tensile strength of concrete [MPa]

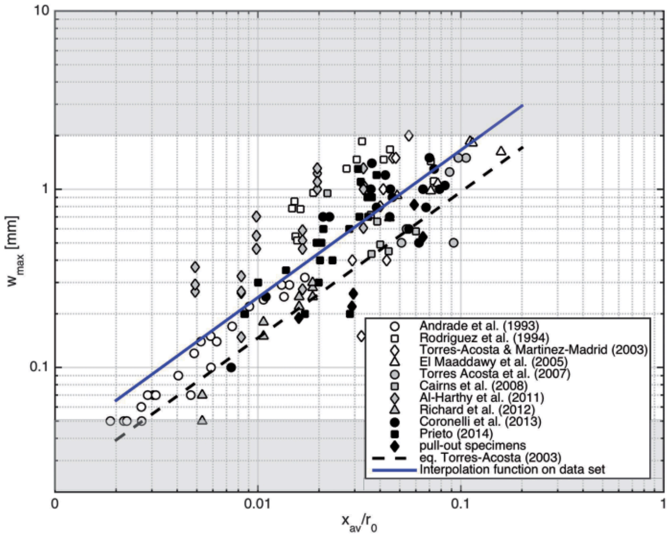

Fig. 1. Maximum crack openings with average attack penetration related to initial steel bar radius – logarithmic scale

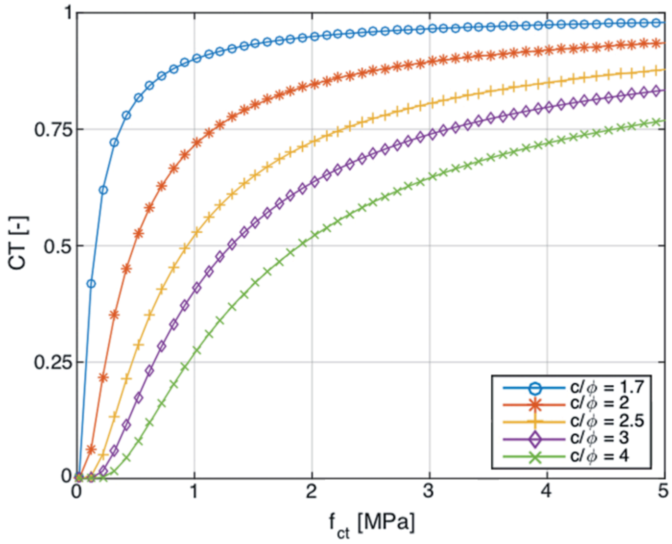

Fig. 3. *CT* as a function of f_{ct}

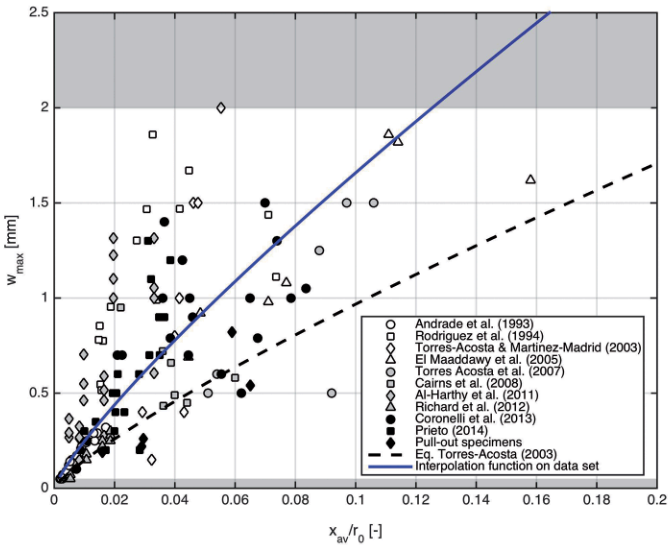

Fig. 2. Maximum crack openings with average attack penetration related to initial steel bar radius – linear scale

In the absence of data, it is possible to use the relation from the *fib* Model Code for Concrete Structures 2010 [35]:

$$f_{ctm} = 0.3 \cdot \left(f_{cm} - 8\right)^{2/3} \tag{3}$$

where:

f_{cm} average cylinder compression strength of concrete [MPa]

α, β two parameters that are determined by best fitting: α is dimensionless, β is expressed in MPa

The *CT* parameter will be used as a multiplication factor for the X_{ave}/r_0 ratio of the average attack penetration to the radius of the reinforcement.

As previously mentioned, the α and c values are calculated in order to minimize the coefficient of determination of the interpolation curve, considering the experimental data given in Table 1. This procedure leads to values of 0.63 and 1.41 MPa for α and β respectively.

The new interpolation function is expressed as follows:

$$W_{\max} = 15.863 \cdot \left(\frac{x_{ave}}{r_0} \cdot CT\right)^{0.928} \tag{4}$$

where the calculated value of $w_{\max}$ is expressed in millimetres.

It is also important to point out that the square of the coefficient of determination R^2 is now 0.786; this is a higher value than the one reported in Fig. 1.

The relationship between *CT* and the tensile strength is plotted in Figs. 3 and 4 for different cover/bar diameter values. It can be seen (Fig. 3) how for a given concrete tensile strength, *CT* decreases for an increase in the c/ϕ value, whereas for a given value of c/ϕ (Fig. 4), a lower tensile strength value results in a higher *CT* value.

The variation in *CT*, as a function of f_{ct}, for c/ϕ values varying over a range 1.7–4 is depicted in Fig. 3.

The variation in *CT*, as a function of c/ϕ, for tensile concrete strengths of 2, 3 and 4 MPa is shown in Fig. 4.

From these last two graphs it is evident that the influence of the c/ϕ ratio is more important than the concrete strength when determining the *CT* parameter.

Finally, the advantage of introducing the *CT* factor can be seen in Fig. 5. A reduced scatter can be observed, compared with the previous analysis shown in Figs. 1 and 2. This advantage is even more evident when the plot (Fig. 6) is performed on a logarithmic scale.

Furthermore, some experimental results obtained from two experimental tests performed by *Giordano* et al. [1], for which the specimens were loaded mechanically during corrosion, are presented in red and magenta in Fig. 7. The maximum and minimum values of the crack openings are reported for each test in order to show the maximum gap recorded for increasing corrosion levels. The first test refers to crack measurements for a specimen under simultaneous cyclic loading and corrosion, whereas the second one refers to a statically loaded specimen with simultaneous corrosion. The two

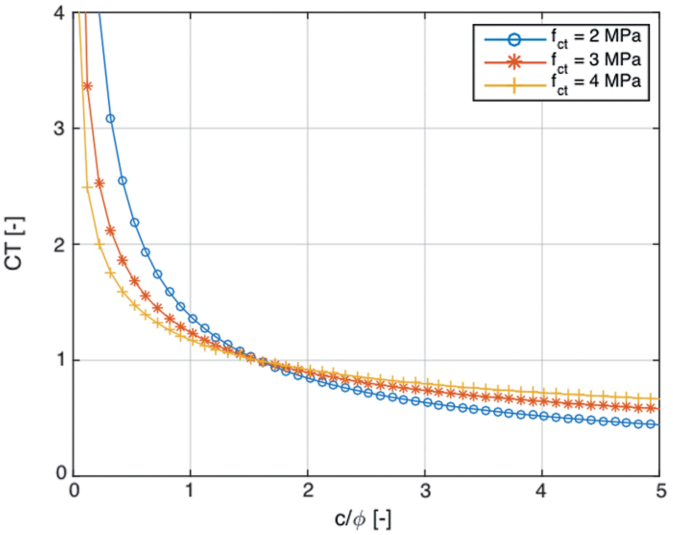

Fig. 4. *CT* as a function of *c/ϕ*

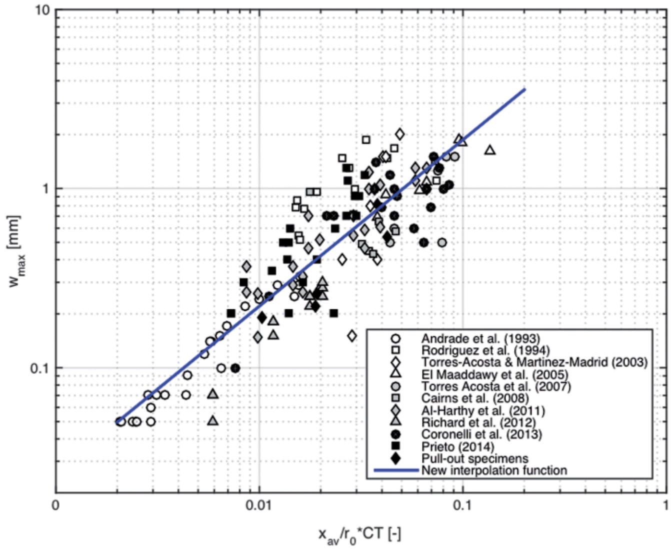

Fig. 6. Maximum crack openings with average attack penetration related to initial steel bar radius with correction parameter – logarithmic scale

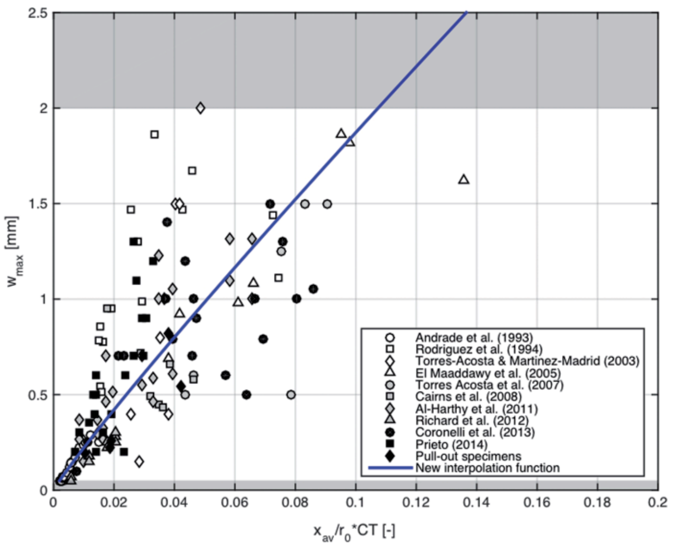

Fig. 5. Maximum crack openings with average attack penetration related to initial steel bar radius with correction parameter – linear scale

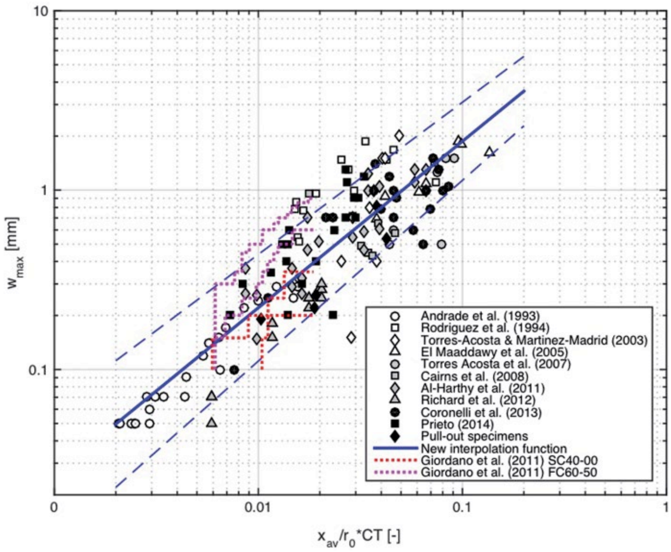

Fig. 7. Maximum crack openings with the average attack penetration related to initial steel bar radius with correction parameter – logarithmic scale

specimens were named FC60-50 and SC40-00 respectively in the paper. Upon formation of the first crack due to corrosion, the crack openings are in line with the results of the other experimental research and the interpolation function. As the test evolves, a higher crack width evolution rate can be seen for the specimen under cyclic loading compared with the specimen under static loading.

The functions obtained from a linear regression analysis, corresponding to a 95 % confidence interval, are also shown in Fig. 7. The expression for the lower bound could be used to assess a deteriorated RC structure (on the safe side).

The results of test data obtained from other experimental tests, which have not been included in the database used for determining the interpolation function, are reported in Fig. 8 for comparison purposes. It is evident that this plot shows increased data scatter due to the non-homogeneity of the added tests with respect to the first set due to the effect of the excessively high current density used during the experiments.

4 Conclusions

The selection of the experimental tests and the analysis and use of the factors that influence the related results has allowed a new interpolation function to be determined for the accelerated corrosion tests relating crack width to corrosion level. This function could be used to estimate the attack penetration of reinforcing steel bars in accelerated tests when a corrosion crack is produced on the external surface of the structural element. The function takes into account the influence of the concrete cover as well as that of the tensile strength of the concrete and the bar diameter. The presence of a new parameter *CT* determines the higher correlation of the results. It is important to state that this analysis is obviously valid only for accelerated tests in the presence

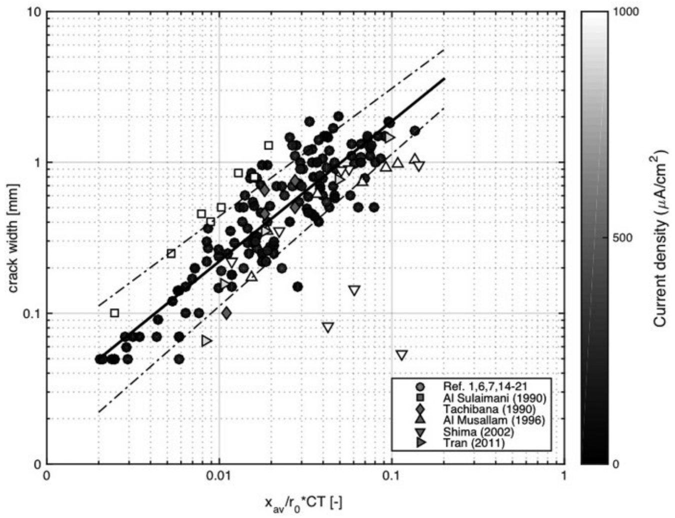

Fig. 8. Maximum crack openings with the average attack penetration related to initial steel bar radius with correction parameter – logarithmic scale; datasets from other experimental campaigns

of surface cracks, does not apply when the surface of the concrete is not cracked and should be applied to natural corrosion very carefully. The observed crack phenomenon in concrete due to corrosion shows significant scatter and has been derived for cracks with a minimum value of 0.05 mm, because smaller cracks are hard to detect. The upper bound value that has been considered for crack openings is 2 mm; in terms of corrosion penetration, wider cracks should be analysed with caution, due to the very large scattering of the data results. The tests selected, even with a good homogeneity, have different experimental conditions that could introduce variation into the structural effect of corrosion; for example, the test setup in accelerated methods varies between saturated and unsaturated conditions.

In real exposures, the crack width will depend on the same parameters as in accelerated conditions, even if the corrosion rate in the latter case is much higher than in natural conditions. In other words, values of about 1 $\mu A/cm^2$ are considered high values in natural conditions, whereas 100 $\mu A/cm^2$ is usual in accelerated conditions. The crack widths are larger for lower corrosion rates and then, depending on reinforcement detailing, the progression of the crack may be different in natural and in accelerated conditions. Therefore, this work can be used for estimating corrosion penetration in real structures together with the critical analysis of an expert and with the additional precaution that it should be applied only in conditions where homogeneous generalized corrosion is expected. In the cases of localized corrosion, failures due to stress concentration can happen and then the proposed relationship cannot be applied because it is not based on localized corrosion tests. This aspect is crucial when the ultimate strength capacity of the reinforced concrete member is under investigation. It follows that corrosion in chloride-contaminated concrete which results in a high localized bar diameter reduction has to be evaluated by means of other methods and supported by direct visual inspections. Moreover, further experimental surveys are needed and could help to clarify the difference between natural conditions and accelerated test setups in terms of the structural consequences of corrosion.

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