

Relation between crack width and corrosion degree in corroding elements exposed to the natural atmosphere

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ABSTRACT: Reinforcement corrosion leads into several damage types which influence the structural load-bearing capacity, among which can be mentioned the cracking of concrete cover. This work presents results of crack width generated in concrete elements fabricated in 1990 with chlorides added in the mix and exposed to the natural atmosphere of Madrid-Spain climate. These elements, one T beam and one column. Two expressions have been fitted to the results: $w = k P_x / (c/\phi)$ and $w = k P_x / R_o$, where w is a crack width in the time, k is a proportional factor, P_x is the corrosion penetration in the time, c/ϕ is the concrete cover/diameter relation and R_o is the original radius of the bar. The expressions were also fitted to results taken from the literature made applying a current. The beam shows larger crack widths than the beam and the accelerated tests give intermediate results. Based in all the results, although the scatter is important, it has been calculated the k and k' slopes which resulted respectively in values of 9.5 and 35.5.

KEY WORDS: Corrosion, crack width, concrete cover, formulas

1 INTRODUCTION

Corrosion of reinforcement produces iron oxides that induce cracking of concrete cover due the traction efforts induced by the generation of the rust. The cracks generate parallel to the direction of the bars (Beeby 1983, Reinhardt 1984). Three steps have been identified: 1) Period of initiation of cracking, during when the cracks are developed from the bar up to reaching the surface of the concrete, 2) Period of spread of the cracking, during which the width of crack grows, and 3) this spread progress coalescence several cracks may give place to the detachment of entire chunks of the concrete cover ending up in delaminations and spalling.

The relation between the crack opening and the quantity of oxide generated by the corrosion, expressed as penetration of the corrosion or loss of diameter of the bars, has been the subject of

previous works by the authors by means of different tests (both accelerated and not accelerated) (Andrade 1993, Torres-Acosta 1999). Furthermore, some models (Pantazopoulou 2001, Liu 1995) analyze cracking time as function of concrete cover, concrete and rust properties controlled by the rate of rust accumulation, while that other models (Andrade

1993, Martín-Perez 1998) assume constant rate of rust production. Another model (Leung 2001) obtain one upper and lower bound assuming the steel / concrete interface to be perfectly smooth or perfectly bonded. Various numerical approaches use a finite element method analyzing cracking with the fixed smear crack model, assuming linear softening of the concrete (Andrade 1993), assuming linear elastic fracture mechanics and movable mesh placed around the crack tip to capture the local stress concentration (Padovan 1997) and with boundary element approach (Ohtsu 1997). Another papers develop models based on a critical corrosion attack penetration to initiate cracking and they relate it to the rebar radius (Torres-Acosta 1998), steel cross section loss due to corrosion (Vidal 2004) and cover / diameter ratio and concrete characteristics (Andrade 1995, Rasheeduzzafar 1992). In all investigations the calculations an the simulated cracking patterns are compared to experimental observations. One has concluded that the beginning of the cracking depends principally on the relation concrete cover / diameter of the bars, the quality of the concrete and his tensile strength.

Also the porosity plays a role, as has been reported (Alonso 1998) that the voids around the bars can allocate the corrosion products after corrosion initiation. Then, the porosity around the bars initially may delay the pressure transmission. The oxides may later diffuse out of the steel/concrete interface throughout the pore network.

The majority of the mentioned studies were made by applying an external current. This procedure needs the gravimetric calibration because the electrochemical loss results in general smaller than the real ones (Alonso 1998). Also the crack width opening is smaller when the test is accelerated (Alonso 1998). Low corrosion rates produce wider cracks.

In present paper the study is made on elements exposed from 1990 to the action of a natural atmosphere in Madrid climate (Rodríguez 1993, Rodríguez 1996). These elements are a beam and a column fabricated with chlorides added to the mix in which the corrosion rate has been monitored together with the crack opening. The authors of present work have used the simplified formula used by Torres-Acosta (Torres-Acosta 1999) considering only the bar diameter and not the concrete cover depth and compare it to a similar one but including the cover depth. The comparison of previous formula for the crack with growing developed using accelerated corrosion, to the values registered in natural conditions during almost 15 years has enabled to calculate closer to reality fitting factors.

2 EXPERIMENTAL

2.1 Concrete elements

The studied elements are a column and a T beam that were made to study the evolution of the corrosion rate and the corrosion induce cracks when exposed to the atmosphere non protected from the sun and rain.

The column was of 200 x 200 mm in area and 2 m in length (Fig. 1). The reinforcement consists of two sections with different quantities. The first section has two top bars and two low ones of 12 mm in diameter and stirrups of 6 mm in diameter each 200 mm in length. The second section has six bars of 12 mm in diameter and stirrups of 6 mm each 100 mm in length. The cover is the same for the whole element being 30 mm.

The section of the T beam consists of a base of 300 x 100 mm a web of 200 x 100 mm. The reinforcement of the web are two bars of 16 mm in diameter and in the top part of the base there are four bars of 12 mm in diameter and in the low part, in the central part, two bars of 16 mm in diameter and, in the ends, two bars of 12 mm in diameter. The stirrups are 6 mm of diameter to each 200 mm. The cover of the element is also of 30 mm.

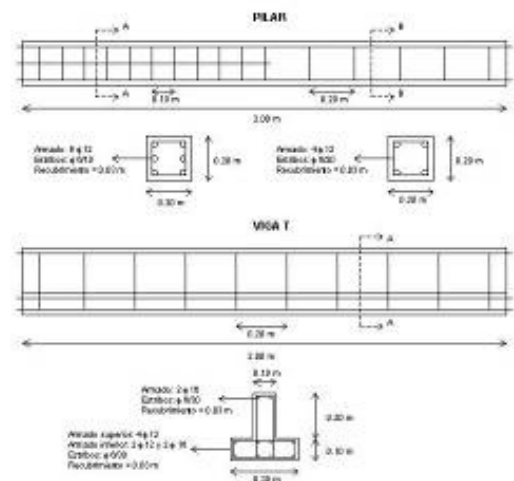


Figure 1. Detail of the sections of the studied elements.

Both elements were fabricated in 1990 and the nominal dosage of the concrete used was of: 360 kg/m³ of cement, 1080 kg/m³ of aggregate 5-12 mm and 840 kg/m³ of sand 0-5 mm. The w/c relation was of 0.7. In order to induce corrosion 3% of CaCl₂*2H₂O was added to the concrete mix. The curing was made during 7 days by means of the placement of plastic cover to avoid the desiccation with intermittent watering.

A view of the set of beams and columns fabricated and the disposition of the elements is so that a face of the elements remains in shade and the other facing the sun (Fig. 2). Madrid has a continental weather reaching temperatures around 0-5°C in winter and 35-40°C in summer. The RH evolves from around 10% in summer to 60-70% in winter as average values. Raining may appear around 75-100 days per year with around 3155 hours/year of TOW and around 600-700ml/m² collected annually. Snow may occur one to two times per year (Andrade, 2002).



Figure 2. Exposition of elements to the atmosphere.

2.2 Measurement of corrosion rate

Since elements fabrication until now, temperature and humidity, inside and outside of the concrete, have been measured by means of a hygrometer Vaisala (see Fig. 3). The relative humidity, RH, and temperature, T, are measured at the open atmosphere and inside a hole made in the beam (Fig. 3). The readings are taken after few minutes when the values show stability.

The measures are taken with the portable corrosion rate meter Gecor in its version 6 and 8 (Feliú 1990), which have modulated confinement of the current. That is the current is confined in a certain area and the corrosion rate is referred to that area. The corrosion rate values are calculated from the ratio between current applied and shift in potential removing mathematically the ohmic drop.



Figure 3. Corrosion rate meter measuring the internal relative humidity in the beam.

2.3 Measurement of cracking

From the manufacture of the elements the crack widths were measured in 11 dates for the T beam and 7 measurements for the column. The dates are given in the following table.

Table 1. Dates of measurements of the crack width.

T Beam		Column	
Measure	Date	Measure	Date
0	15/02/1990	0	15/02/1990
1	1/07/1993	1	25/08/1995
2	17/11/1993	2	28/05/1997
3	21/06/1994	3	26/03/1998
4	4/05/1995	4	1/07/1998
5	9/07/1996	5	18/03/2004
6	9/07/1997	6	13/09/2004
7	27/03/1998	7	14/09/2005
8	22/06/1998	8	16.09.2006
9	18/03/2004		
10	13/09/2004		
11	14/09/2005		
12	16.09.2006		

From all the measurements they have been obtained about 170 values for the T beam and 87 for the column.

In order to make a statistical analysis the measurements was always taken in the same position. All the data were considered: 33 points in the T beam and 24 in the column that are shown in Figure 4. Regarding the C/ϕ parameter, for the case of the T beam, there are different diameters of bars that influence the cracks and for each crack width detected, according to the zone and the form of the crack, there was assigned a value of the diameter of the bar, existing three different ones: 6 (stirrups), 12 (bottom bars) and 16 mm (top bars). For the case of the column, the diameters were 6 and 12 mm, and also they were considered in the calculation of k. In the formula, the cover was taken the actual in each case. The time used in the calculations, was that corresponding to the moment of measurement of the crack width.

2.4 Formulas used in the analysis

The main goal of present paper is to verify the accuracy of simple formulae to predict the average crack width produced in elements corroding in natural conditions, in function of the accumulated corrosion, P_x . In previous papers they have been proposed (Andrade 1993):

$$\text{The first formula is: } w = k \left(\frac{P_x}{C/\phi} \right) \quad (1)$$

where w is the crack opening in the time t , k is a factor of proportionality without dimensions, c/ϕ is the relation cover/diameter of the bar and P_x is the penetration of the corrosion in time t , where P_x is equal to:

$$P_x = 0.0115 I_{corr}^{rep} t$$

Replacing P_x in the equation and rearranging the terms:

$$k = \frac{w_{(mm)} C_{(mm)}}{0.0115 I_{corr}^{rep} (mm/a^?) t_{(a^?)} \phi_{(mm)}} \quad (2)$$

For the second formula the same procedure followed, only that used R_o that is the original radius of the bar instead of c/ϕ (Torres-Acosta 1999, Torres-Acosta 1999, Torres-Acosta 1998).

For what ultimately stays:

$$k' = \frac{w_{(mm)} R_{o(mm)}}{0.0115 I_{corr}^{rep} (mm/a^?) t_{(a^?)}} \quad (3)$$

k' has the dimensions of millimeters.

For the calculation of the factor of proportionality they have been taken as average annual values of corrosion rate $I_{corr}^{rep} = 1,5$ as said is the mean recorded in the T beam throughout 14 years of life of the elements, however for the sake of a sensitivity analysis also a value of $2,0 \mu\text{m}/\text{year}$ will be tried.

3 RESULTS

Figure 4 shows the results of corrosion rate I_{corr} obtained in the beam throughout the time. The average value is $0.128 \mu\text{A}/\text{cm}^2$ ($1.5 \mu\text{m}/\text{year}$). On the pillar only isolated measurements were made. The results indicated in it a higher value of the corrosion rate, then a value of $2 \mu\text{m}/\text{year}$ was also considered in the calculations.

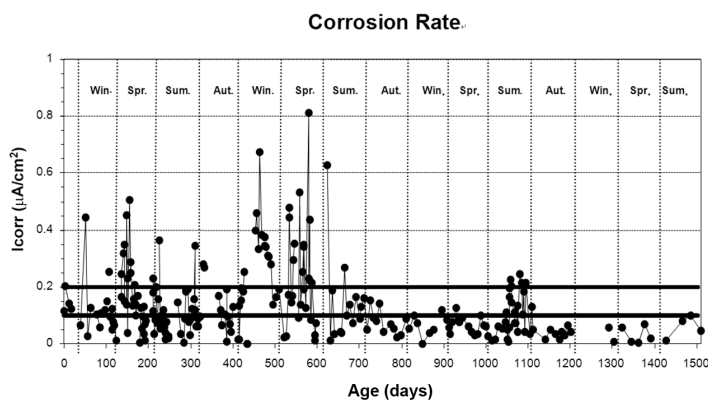


Figure 3. I_{corr} evolution measured in the beam during test time.

Regarding the crack widths, Table 3 shows the averaged values obtained in the tested elements at each date

Table 3. Mean and Standard deviation of the average crack width in the beam and the pillar shown in Figure 4.

	W_{aver} (mm)	Desv. Est.	
T Beam	1-Jul-93	0.31	0.34
	17-Nov-93	0.43	0.42
	21-Jun-94	0.48	0.46
	4-May-95	0.63	0.62
	9-Jul-96	1.07	1.02
	9-Jul-97	1.49	1.26
	27-Mar-98	0.86	1.11
	22-Jun-98	0.87	1.00
	18-Mar-04	2.38	1.86
	13-Sep-04	2.68	2.33
Column	14-Sep-05	3.41	2.78
	16-Oct-06	3.94	3.14
	25-Aug-95	0.20	0.21
	28-May-97	0.26	0.28
	26-Mar-98	0.28	0.26
	1-Jul-98	0.30	0.31
18-Mar-04	0.36	0.16	
13-Sep-04	0.39	0.12	
14-Sep-05	0.43	0.14	
16-Oct-06	0.51	0.15	

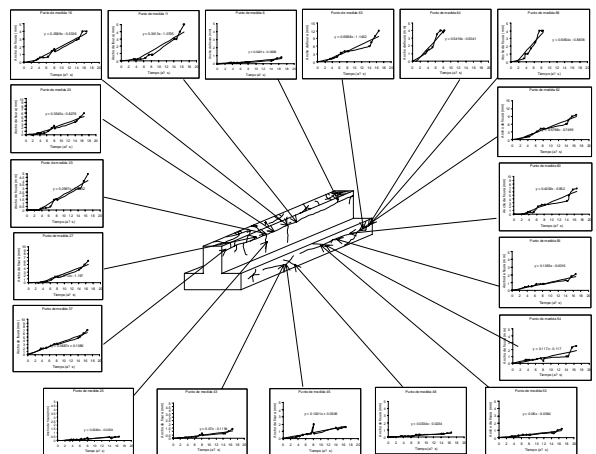
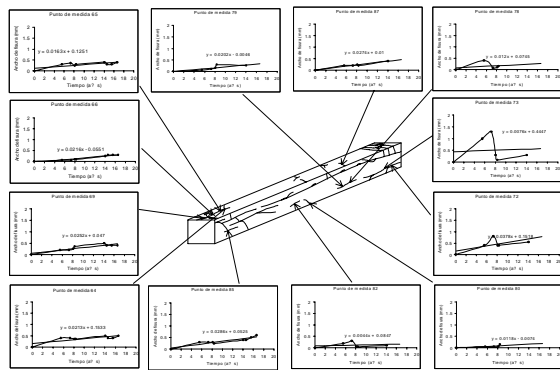
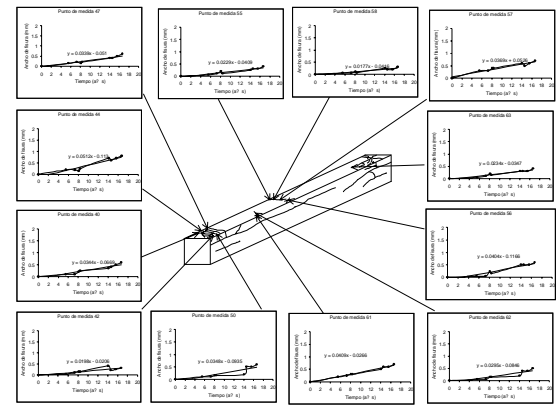


Figure 4. Position of the points of measurement of crack width and slopes with time.

The Figure 4 shows the evolution of crack width in the different locations selected in the beam and in the column. The cracks grow at different rates (the slopes of the trends) depending of the place. It has to be stressed that there is not a

unique value of the crack width. The reasons for this behaviour can be several: a) the bars have different sizes and the stirrups different cover depths, b) there are noticed pre-existing drying shrinkage cracks and c) the corrosion rate has likely been uneven along the bars in spite that the chloride was added in the mix.

The statistical distribution found is given for each element in Figure 5. The distribution is log normal and the crack widths are larger in the beam than in the pillar perhaps due to the reinforcement detailing,

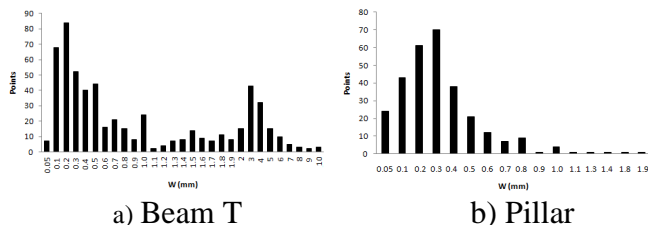


Figure 5. Statistical distribution of crack widths found under natural corrosion.

4 DISCUSSION

In order to make later a comparison, the equations proposed were first fitted to the experimental data in existing literature (Rodríguez 1996, Andrade 2002, Feliú 1990, Andrade 1993, Torres-Acosta 1999, Torres-Acosta 1998, Cabrera 1996). Table 2 shows the results obtained using the values of crack width and corrosion given by the authors mentioned in it.

In Figure 6 it has been analyzed present results plotting the crack width versus the C/ϕ (equation 2) or versus the bar radius R_o (equation 3). From the figure it can be deduced the linear trend in both cases but the relative value depends on the type of element in the case of the natural corrosion being higher the values of crack widths found in the beam than in the pillar.

With respect to the values obtained in accelerated tests in the laboratory, they show intermediate values between those of the beam and the pillar. This is an interesting fact as it enables to use accelerated tests to predict evolutions in real conditions.

Table 2. Results of the value of k for different authors calculated with the formulas (2) and (3).

	$k = w C / P_x$	$k' = w R_o / P_x$
Average of all	4.79	28.44
Torres	2.10	27.99
Castro	11.60	26.22
Andrade	3.41	30.52
Cabrera	0.61	18.67
Rodríguez 1	8.53	24.70
Rodríguez 2	8.58	41.23

In Figure 7 an averaged trend has been fitted to all results which enables in an averaged value for the slopes k y k' of 9.5 y 35.5 respectively which are 50 y 40% higher than those proposed before (Muñoz

2006). Although a more detailed analysis has to be made the slope values here calculated seems to reflect better an averaged behaviour.

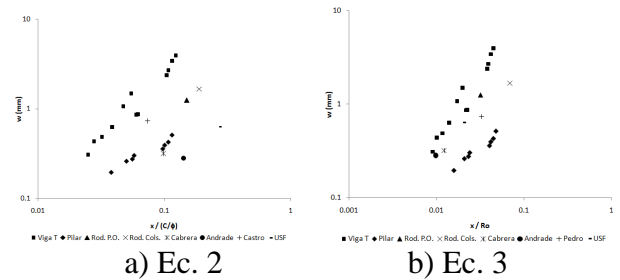


Figure 6. Representation of equations (2) and (3) plotting crack width versus corrosion penetration divided by c/ϕ or by the bar radius R_o .

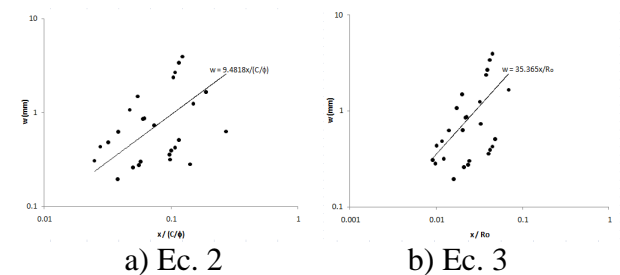


Figure 7. Fitting of an averaged trend in the data of natural and accelerated corrosion tests.

5 CONCLUSIONS

There has been studied the evolution of the cracks generated by the corrosion of two reinforced elements, a T beam and a column that contained chlorides from the mixing and have been exposed from 1990 to the atmosphere of Madrid. The conclusions that have been drawn up are:

1. The crack width evolution has been first fitted to two simple equations

$$(2) \quad w = k \left(\frac{P_x}{C/\phi} \right) \quad (3) \quad w = k' \left(\frac{P_x}{R_o} \right)$$

2. These expressions seem both to represent well the evolution of the crack width in time in natural conditions.
3. The values of crack widths have been larger in the T beam than in the pillar. The values of the accelerated tests published in the literature show intermediate values which indicate that the accelerated tests may be used for predictions in real conditions provided he applied currents are limited.
4. As for the values of the proportionality factors k and k' , that appears in the formula, they have been averaged with results obtained in accelerated tests. The values obtained have been 9.5 for equation 2 and 35.5 for equation 3.

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