# The effect on cracking of high covers in RC beams

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**Abstract:**This study focuses on the effect of large covers in RC beams on crack formation. The motivation for this work came from the need to clarify the implications of using these high covers. With the help of Regulations such as REBAP, EC2-2010, NBR 6118, ACI 318-95, CEB-FIP Model Code 1990 and 2010, and with the results of tests preformed by Alejandro Caldentey it was possible to conclude that the size of crack width increases with the size of the cover of the reinforcement.

**Key-Words:** crack formation, RC beams, cover, REBAP, EC2-2010, NBR 6118, ACI 318-95, CEB-FIP MC 90, Model 2010 and crack widht.

## 1 Introduction

The main goal of this work is to study the effect of cover on the cracking behavior of reinforced concrete elements. Important theoretical aspects are discussed, including where the crack width is estimated by current codes formulations as well as a detailed study of each Code, mentioned above. And to finish this study, a comparison between results given by current codes and experimental tests is made, concluding that crack widths estimated by mathematical formulations, given by REBAP, EC2, NBR, ACI, CEB-FIP 90 and Model Code 2010, are smaller that the ones estimated by experimental tests.

These experimental programme involving 12 beams specimens was carried out at Structures Laboratory of the Civil Engineering School of the Polytechnic University of Madrid from May to October 2009.

The specimens were coded XX-YY-ZZ, with XX referring to bar diameter (12 or 25), YY referring to cover (20 or 70 cm) an ZZ referring to stirrup spacing (00 for no stirrup, 10 and 30, for 10 cm and 30 cm spacing, respectively.

## 2 Crack width by Regulations

### 2.1 Rebap

REBAP requires that cracking should be limited to a level that does not impair the proper functioning of the structure or cause its appearance to be unacceptable. The code stipulates that the design and mean crack width be evaluated from the following expression:

$$w_k = 1{,}7.\, w_m \qquad (2.1)$$

$$w_m = S_{rm} . \varepsilon_{sm} \qquad (2.2)$$

with,

$S_{rm}$: average stabilized crack spacing;

$\varepsilon_{sm}$: average reinforcement strain wthin segment lenght $l_{s,máx}$;

Average Stabilized crack spacing is expressed as:

$$S_{rm} = 2.\left(c + \frac{s}{10}\right) + \eta_1 . \eta_2 . \frac{\phi}{\rho_r} \qquad (3)$$

with,

c: cover of reinforcement;

s: spacing of the reinforcement;

$\eta_1$= 0,4 for deformed bars;

= 0,8 for plain bars;

$\eta_2$ = $0{,}25.\frac{\varepsilon_1+\varepsilon_2}{2\varepsilon_1}$

$\phi$: bar diameter;

$\rho_r$: effective reinforcement ratio $\frac{A_s}{A_{c,eff}}$;

The effective concrete area is e shown in Figure 2-1.

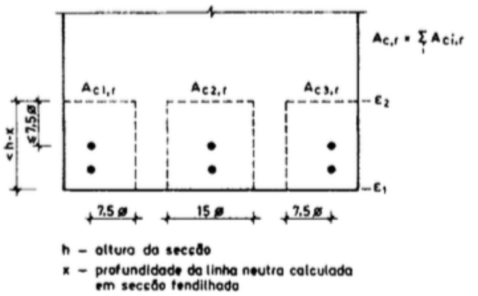


*Figure 1-1: Effective concrete área for REBAP*

The average reinforcement strain is obtained from the following expression:

$$\varepsilon_{sm} = \frac{\sigma_s}{E_s}.\left( 1-\beta_1.\beta_2.\left(\frac{\sigma_{sr}}{\sigma_s}\right)^2\right) \qquad (4)$$

with,

$\sigma_s$: reinforcement stress at the crack;

$E_s$: Modulus of elastecity of the reinforement;

$\beta_1$: coefficient accounting for bar bond characteristics (=1,0 for deformned bars and 0,5 for plain bars);

$\beta_2$: coefficient accounting for load duration (=1,0 for single short-term loading and 0,5 for sustained or cyclic loading);

$\sigma_{sr}$: stress in the tension reinforcement computed on the basis of a crack section under loading conditions that cause the first crack;

$$\varepsilon_{sm} \geq 0{,}4.(\sigma_s/E_s). \qquad (5)$$

## 2.2 EC2

The Eurocode EC2 requires that cracking should be limited to a value of maximum design crack of 0,3 mm, for sustained load under normal environmental conditions. This ceiling is expected to be satisfactory with respect to appearance and durability. Strcker requirements are stipulated for more severe environmental conditions.

The code stipulates that the design crack width be evaluated from the following expression:

$$w_k = S_{r,máx}.(\varepsilon_{sm}-\varepsilon_{cm}) \qquad (2.2.1)$$

$(\varepsilon_{sm}-\varepsilon_{cm})$ is obtained from the following expression:

$$\varepsilon_{sm}-\varepsilon_{cm} = \frac{\sigma_s-k_t.\frac{fct,eff}{\rho_{p,eff}}.(1+\alpha_e.\rho_{p,eff})}{E_s} \geq 0{,}6.\frac{\sigma_s}{E_s}$$

(2.2.2)

with,

$\alpha_e$= $E_s/E_{cm}$;

$h_{c,eff}$ = min (2,5.(h-d), (h-x)/3, h/2);

$k_t$ : coefficient accounting for load duration (=0,6 for short-term loading and 0,4 for sustained or cyclic loading);

The effective concrete area is e shown in Figure 2-2

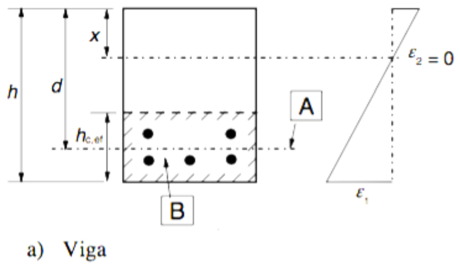


*Figure 2-2: Effective concrete area for EC2.*

The average Stabilized crack spacing is expressed as:

$$S_{r,máx} = k_3.c + k_1.k_2.k_4 \ .\Phi/\rho_{p,eff} \qquad (2.2.3)$$

$$S_{r,máx} = 1{,}3.(\text{ h-x}) \qquad (2.2.4)$$

Expression (2.2.3) is used when s $\leq$ 5( c+ $\Phi/2$ and (2.2.4) when s > 5( c+ $\Phi/2$.

with,

$k_1$ = 0,8 for defornmed bars and 01,6 for plain bars;

$k_2$ = 0,5 for bending and 1,0 for pure tension;

$k_3$ = 3,4 (according to A.N.);

$k_4$ = 0,425 (according to A.N.);

## 2.3 NBR 6118

The code stipulates that the design crack width is the minimum from the following expressions:

$$w_k = \frac{\phi_i}{12{,}5\eta_1}\frac{\sigma_{si}}{E_{si}}\frac{3\sigma_{si}}{f_{ctm}} \qquad (2.3.1)$$

$$w_k = \frac{\phi_i}{12{,}5\eta_1}\frac{\sigma_{si}}{E_{si}}\left(\frac{4}{\rho_{ri}}+45\right) \qquad (2.3.2)$$

with,

$\eta_1$ = 2,25 for deformed bars;

The effective concrete area is e shown in Figure 2-3.

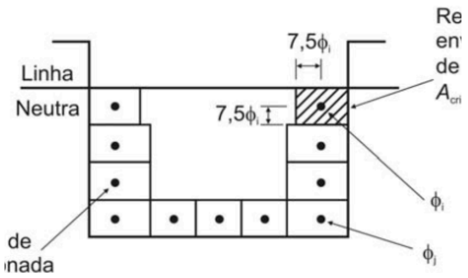


*Figure 2-3: Effective concrete area for NBR.*

## 2.4 ACI 318-95

The equations thst were considered to best predict the probable maximum bottom and side crack widths are expressed in (2.4.1) and (2.4.2).

$$w_b = 0{,}091.\sqrt[3]{t_b.A}.\beta.(f_s-5).10^{-3} \text{ (in)} \qquad (2.4.1)$$

$$w_s = \frac{0{,}091.\sqrt[3]{t_b.A}}{1+\frac{t_s}{h_1}}.(f_s-5).10^{-3} \qquad \text{(in)} \quad (2.4.2.)$$

$w_b$: most probable maximum crack width at bottom of beam, in;

$w_s$: most probable maximum crack width at level of reinforcement, in;

$f_s$: reinforcing steel stress, ksi;

A: area of concrete symmetric with reinforcing steel divided by number of bars, $in^2$;

$t_b$: bottom cover to center of bar, in;

$t_s$: side cover to center of bar, in;

$\beta$: 1,2 in beams;

$h_1$: distance from neutral axis to the reinforcing steel, in;

ACI Committee 318 now believes that it can be misleading to purport to effectively calculate crack widths, given the onherent variability in cracking. The three important parametersin flexural cracking are steel stress, cover, and bar spacing. Althought, steel stress is the most importante parameter.

A reevaluation of cracking data (Frosch 1999) showed that previous crack width equations are valid for a relatively narrow range of covers ( up to 63 mm).

## 2.5 CEB-FIP MC90

For all stages of cracking, the design crack width may be calculated according to (2.5.1):

$$w_k = l_{s,máx} \cdot (\varepsilon_{sm} - \varepsilon_{cm} - \varepsilon_{cs}) \leq w_{lim} \quad (2.5.1)$$

$l_{s,máx}$: denotes the lenght over which slip between steel and concrete occurs; steel and concrete strains, which occur within this length, contribute to the width of the crack;

$\varepsilon_{sm}$: is the average steel strain within $l_{s,máx}$;

$\varepsilon_{cm}$: is the average concrete strain within $l_{s,máx}$;

$\varepsilon_{cs}$: denotes the strain of concrete due to shrinkage; it has to be introduced algebraically;

$w_{lim}$: should be consulted in Table of Figure 2-4

| Exposure condition | Crack width in. | Crack width mm |
|---|---|---|
| Dry air or protective membrane | 0.016 | 0.41 |
| Humidity, moist air, soil | 0.012 | 0.30 |
| Deicing chemicals | 0.007 | 0.18 |
| Seawater and seawater spray, wetting and drying | 0.006 | 0.15 |
| Water-retaining structures† | 0.004 | 0.10 |

*Figure 2-5: $w_{lim}$ for CEB-FIP MC90*

If (2.5.2) happens it may be assumed that the stabilized cracking condition has been reached, otherwuise the formation of single cracks should be considered.

$$\rho_{s,eff} \cdot \sigma_{s2} > f_{ctm} \cdot (1+\alpha_e \cdot \rho_{s,eff}) \quad (2.5.2)$$

where,

$\rho_{s,eff}$: is the effective reinforcement ratio;

$f_{ctm}$ : is the mean value of the tensile strenght of the concrete;

$\sigma_{s2}$ : is the steel stress at the crack;

$l_{s,máx}$ is obtained from the fexpressions (2.5.2) and (2.5.3)., for stabilized cracking and for single crack formation, respectively.

$$l_{s,máx} = \frac{\phi_s}{3{,}6 \cdot \rho_{s,eff}} \quad (2.5.2)$$

$$l_{s,máx} = \frac{\sigma_{s2}}{2 \cdot \tau_{bk}} \cdot \phi_s \cdot \frac{1}{1+\alpha_e \cdot \rho_{s,eff}} \quad (2.5.3)$$

where,

$\tau_{bk}$: is the lower fractile value of the average bond stress; it may be taken from the table of Figure 2-4.

| | Single crack formation | | Stabilized cracking | |
|---|---|---|---|---|
| | $\beta$ | $\tau_{bk}$ | $\beta$ | $\tau_{bk}$ |
| Short term/instantaneous loading | 0.6 | $1.8 f_{ctm}(t)$ | 0.6 | $1.8 f_{ctm}(t)$ |
| Long term/repeated loading | 0.6 | $1.35 f_{ctm}(t)$ | 0.38 | $1.8 f_{ctm}(t)$ |

*Figure 2-4: $\tau_{bk}$ and $\beta$.*

For simplicity $(1+\alpha_e \cdot \rho_{s,eff})$ can be sete qual to 1.

$(\varepsilon_{sm} - \varepsilon_{cm})$ is estimated according to (2.5.4).

$$(\varepsilon_{sm} - \varepsilon_{cm}) = \varepsilon_{s2} - \beta \cdot \varepsilon_{sr2} \quad (2.5.4)$$

whith,

$$\varepsilon_{sr2} = \frac{f_{ctm\,(t)}}{\rho_{s,eff} \cdot Es} \cdot (1 + \alpha e \cdot \rho_{s,eff}) \quad (2.5.5)$$

where,

$\varepsilon_{s2}$: is the steel strain at the crack;

$\varepsilon_{sr2}$ : is the steel strain at the crack, under forces causing $f_{ctm}$ within $A_{c,eff}$;

For stabilized cracking the average widht may be estimaed on the basis of an average crack spacing of:

$$S_{rm} = \frac{2}{3} . l_{s,máx} \qquad (2.5.6)$$

The effective concrete area is e shown in Figure 2-6.

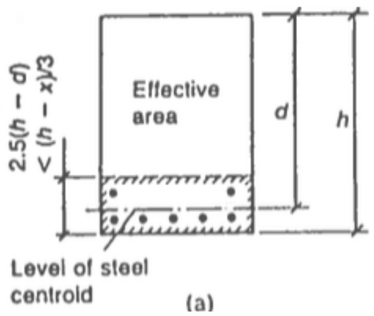


*Figure 2-6: effective concrete area for CEB-FIP MC 90.*

## 2.6 Model Code 2010

It should be ensured that cracks will not impair the serviceability and durability of the structure. cracks donot, per se, indicate a lack of serviceability or durability, in reinforced concrete structures

For all stages of cracking, the designg crack width $w_d$ may be calculated by (2.6.1):

$$w_d = 2.\ l_{s,máx} . (\varepsilon_{sm} - \varepsilon_{cm} - \varepsilon_{cs}) \qquad (2.6.1)$$

where,

$l_{s,máx}$: denotes the length over which slip, between concrete and steel occurs.

$\varepsilon_{sm}$: is the average steel strain over the lenght $l_{s,máx}$;

The length $l_{s,máx}$, can be expressed by (2.6.2):

$$l_{s,máx} = \text{k.c} + \frac{1}{4} . \frac{fctm}{\tau_{bms}} . \frac{\phi s}{\rho_{s,eff}} \qquad (2.6.2)$$

k : is an empirical parameter to take the influence of the concrete cover into consideration. As a simplification k =1,0 can be assumed;

c : is the concrete cover;

$\tau_{bms}$ : is mean bond strength between steel and concrete;

The relative mean strain follows from:

$$\varepsilon_{sm} - \varepsilon_{cm} - \varepsilon_{cs} = \frac{\sigma_s - \beta . \sigma_{sr}}{Es} + \eta_r . \varepsilon_{sh} \qquad (2.6.3)$$

where,

$\sigma_s$: is the steel strain in a crack;

$\sigma_{sr}$: is the maximum steel stress in acrack formation stage, which, for pur tension is:

$$\sigma_{sr} = \frac{fctm}{\rho_{s,eff}} (1 + \alpha_e . \rho_{s,eff}) \qquad (2.6.4)$$

$\beta$: is an empirical coefficient to assess the mean strain over $l_{s,máx}$, depending on the type of loading;

$\eta_r$: is a coefficient for considering the shrinkage contribution;

$\varepsilon_{sh}$: is the shrinkage strain;

The value for $\tau_{bms}$, $\beta$ and $\eta_r$ can be taken from Figure 2-7:

| | Crack formation stage | Stabilized cracking stage |
|---|---|---|
| Short term, instantaneous loading | $\tau_{bms} = 1{,}8 \cdot f_{ctm}(t)$<br>$\beta = 0.6$<br>$\eta_r = 0$ | $\tau_{bms} = 1{,}8 \cdot f_{ctm}(t)$<br>$\beta = 0.6$<br>$\eta_r = 0$ |
| Long term, repeated loading | $\tau_{bms} = 1{,}35 \cdot f_{ctm}(t)$<br>$\beta = 0.6$<br>$\eta_r = 0$ | $\tau_{bms} = 1{,}8 \cdot f_{ctm}(t)$<br>$\beta = 0.4$<br>$\eta_r = 1$ |

*Figure 2-7: $\tau_{bms}$, $\beta$ and $\eta_r$ values.*

In order to estimate the value of the crack width at the extreme tensile fibre, the crack width may be multiplied with a factor (h-x)/(d-x).

Equation (2.6.2) Is valid for structures where the concrete cover is not larger than 75 mm.

The effective concrete area is e shown in Figure 2-6, same as CEB-FIP MC 90.

# 3 Example of crack widht calculation according to Regulations

## 3.1 Example Definition

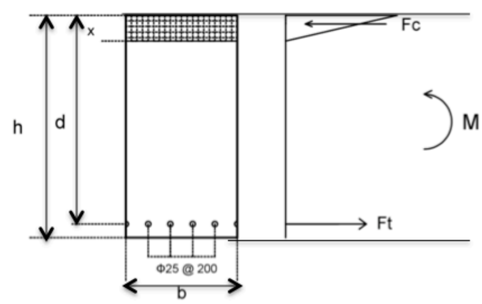


*Figure 3-1: RC beam studied for crack width.*

For the RC beam showed in Figure 3-1, a study of crack width was made, for this, it was used a range of covers, starting at 3cm, followed by 5, 7 and 10 cm.

The data for this exercise is showed bellow:

- M =1090 kN.m;
- $A_s$= 24,544 $cm^2$;
- $A$500 NR and C25/30;
- $h$ = 2,0 m and b = 1,0 m;
- Short term loading;

## 3.2 Comparison of Regulations Results

This comparison is made for cracks at reinforcement level, calculated by all six Regulations mentioned above. Table 2-1 and Figure 3-2 shows the final results.

| | | c(cm) | | | |
|---|---|---|---|---|---|
| | | 3 | 5 | 7 | 10 |
| wk (mm) | REBAP | 0,148 | 0,213 | 0,279 | 0,379 |
| | EC2 | 0,227 | 0,316 | 0,431 | 0,607 |
| | NBR | 0,279 | 0,284 | 0,291 | 0,3 |
| | ACI | 0,221 | 0,286 | 0,344 | 0,543 |
| | MC 90 | 0,356 | 0,528 | 0,705 | 0,804 |
| | MC 2010 | 0,285 | 0,35 | 0,361 | - |

*Table 2-1: Crack widths according to regulations*

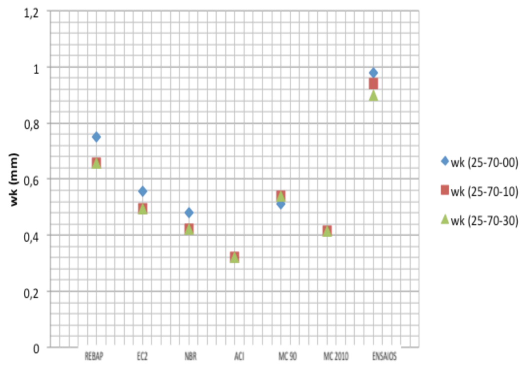


*Figure 3-2: crack width according to regulations.*

To this end, and with the help of Regulations such as REBAP, EC2-2010, NBR 6118, ACI 318-95, CEB-FIP Model Code 1990 and 2010, which were analyzed individually for the calculation of crack widht, for this range of values for covers, the first immediate conclusion was that the size of crack width increases with the size of the cover of the reinforcement.

These results confirm that cover is an important factor in the development of the cracking pattern.

# 4 Comparison with experimental tests

## 4.1 Description of tests

An experimental programme involving 12 beams specimens was carried out at the Structures Laboratory of the Civil Engineering School of the Polytechnic University of Madrid. All beams had a rectangular cross-section 0,35 m wide and 0,45 m deep, all specimens were concreted at the same time using the same concrete of strength class C25/33.

The parameters studied were cover ( 20 and 70 mm) and stirrup spacing $s_w$. For this, three configurations were considered, no stirrups, and stirrups spaced at 10 and 30 cm. Stirrup diameter was 12 mm, the specimens were coded XX-YY-ZZ, with XX referring to bar diameter (25 mm), YY referring to cover ( 20 or 70 mm) and ZZ referring to stirrup spacing (00 for no stirrups, 10 for 10 cm spacing and 30 for 30 cm spacing). The cross-sections of the specimens are shown in Figure 4-1.

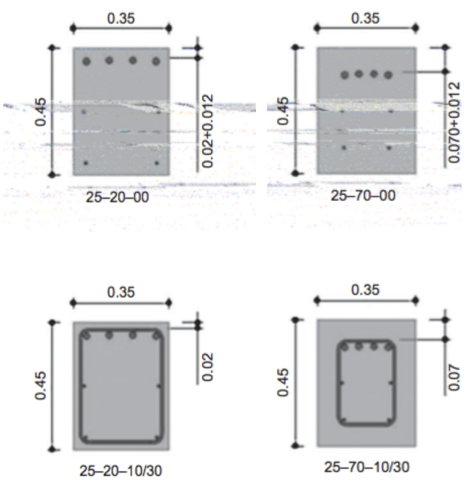


*Figure 4-2: Cross-section of the specimens.*

## 4.2 Test Results

A summary of test results in terms of mean $s_{r,m}$ and maximum $s_{r,max}$ crack spacing is given in Table 4-1 .

| Beam ID | $s_{r,m}$ [mm] | $s_{r,max}$ [mm] |
|---|---|---|
| 25-20-00 | 131 | 234 |
| 25-20-10 | 114 | 230 |
| 25-20-30 | 152 | 258 |
| 12-20-00 | 173 | 269 |
| 12-20-10 | 182 | 320 |
| 12-20-30 | 274 | 358 |
| 25-70-00 | 227 | 423 |
| 25-70-10 | 189 | 460 |
| 25-70-30 | 200 | 442 |
| 12-70-00 | 236 | 412 |
| 12-70-10 | 260 | 381 |
| 12-70-30 | 281 | 383 |

*Table 4-1: test results in terms of $s_{r,m}$ and $s_{r,max}$*

Figure 4-2 shows very clearly how cover increases crack width. This increase is clearly related to an increase in crack spacing. These results confirm that over is an important factor in the development of the cracking pattern.

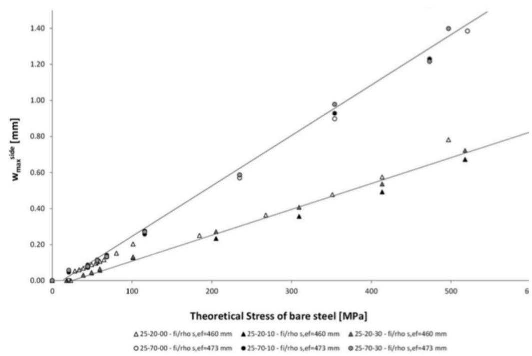


*Figure 4-1: Side maximum crack width vs effect of cover (ϕ = 25 mm)*

As said in [7] “From a theoretical point of view, the effect of cover on crack spacing can be understood by the need to transmit tension stresses generated at the bar-concrete interface to the effective concrete area surrounding the bar in order to generate actual cracking.

### 4.3 Experimental tests vs Regulation results

To make the comparison with test results, it was taken from Figure 4-2 the values of crack widths for $\sigma_s$= 350 and 415 Mpa, the values are showed bellow.

| $\sigma_s$ (Mpa) | Ensaio | $w_k$ exp. (mm) |
|---|---|---|
| 350 | $w_k$ (25-70-00) | 0,98 |
| 350 | $w_k$ (25-70-10) | 0,94 |
| 350 | $w_k$ (25-70-30) | 0,9 |

*Table 4-2: test results in terms of wk for $\sigma_s$= 350 Mpa*

| $\sigma_s$ (Mpa) | Ensaio | $w_k$ exp. (mm) |
|---|---|---|
| 415 | $w_k$ (25-20-00) | 0,575 |
| 415 | $w_k$ (25-20-10) | 0,5 |
| 415 | $w_k$ (25-20-30) | 0,55 |

*Table 4-3:: test results in terms of wk for $\sigma_s$= 415 Mpa*

The final results are shown in Tables 4-4 and 4-5 as well as in Figures 4-3 and 4-4.

| | $w_k$ (25-20-00) | $w_k$ (25-20-10) | $w_k$ (25-20-30) |
|---|---|---|---|
| REBAP | 0,422 | 0,301 | 0,301 |
| EC2 | 0,352 | 0,276 | 0,276 |
| NBR | 0,371 | 0,318 | 0,318 |
| ACI | 0,286 | 0,277 | 0,277 |
| MC 90 | 0,262 | 0,274 | 0,274 |
| MC 2010 | 0,358 | 0,313 | 0,313 |
| TESTS RESULTS | 0,575 | 0,5 | 0,55 |

*Table 4-4: $w_k$ for c = 2 cm and steel stress of 415 Mpa*

| | $w_k$ (25-70-00) | $w_k$ (25-70-10) | $w_k$ (25-70-30) |
|---|---|---|---|
| REBAP | 0,752 | 0,656 | 0,656 |
| EC2 | 0,558 | 0,494 | 0,494 |
| NBR | 0,48 | 0,423 | 0,423 |
| ACI | 0,322 | 0,32 | 0,32 |
| MC 90 | 0,51 | 0,538 | 0,538 |
| MC 2010 | | 0,414 | 0,414 |
| TEST RESULTS | 0,98 | 0,94 | 0,9 |

*Table 4-5: : $w_k$ for c = 7 cm and steel stress of 350 Mpa*

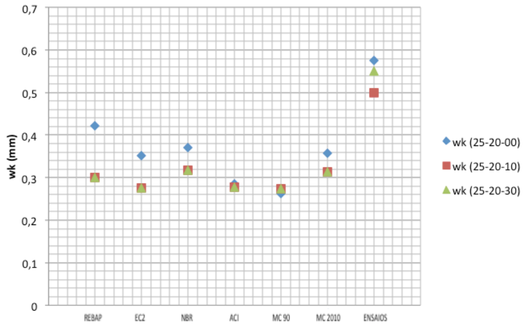


*Figure 4-3: $w_k$ for c = 2 cm and steel stress of 415 Mpa*

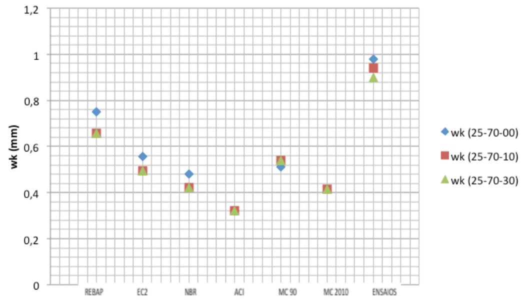


*Figure 4-4: $w_k$ for c = 7 cm and steel stress of 350 Mpa*

## 5 Conclusions

The first conclusion is that cover increases crack width. It was proved both with regulations and with experimental tests.

It was also possible to conclude that a large increase in the crack width happens as the crack is measured further away from the bar, the work of Husain and Ferguson can be cited as example of such results.

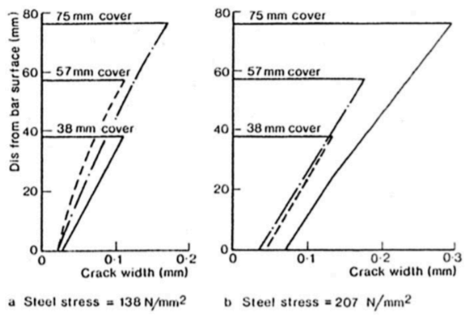


*Figure 5-1: Tests of Husain and Ferguson.*

The large difference between crack spacing at the reinforcement surface and crack spacing at the concrete surface observed in tests can be attributed to internal cracking, At the bar surface the differential strain between steel and concrete is distributed among the passing crack and the internal non-passing crack.

Other important fact verified was that crack width calculations using current codes is actuallly smaller that the ones measured in the experimental tests.

It can be seen, by Figure 5-2, that cracks tend to develop at the stirrup positions.

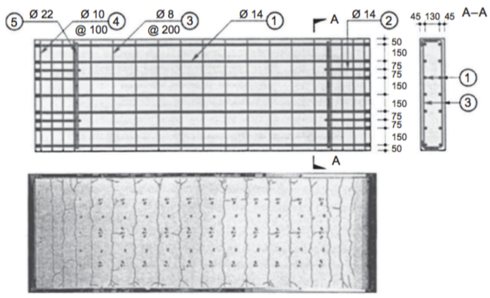

*Figure 5-2: Crack pattern governed by stirrup spacing in a test carried out by Gómez Navarro.*

Tests have also confirmed that stirrup spacing has an influence on crack spacing, but this influence is mainly relevant for mean crack spacing, we know that the variable important for the verification of serviceability limit state of cracking is maximum crack spacing, and this its influence on maximum crack spacing is much smaller.

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