

A statistical comparison between calculated and experimentally evaluated crack spacing measures given in practise codes for the design of reinforced concrete elements made with self-healing concrete

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Abstract. Available design codes provide formulations to evaluate the maximum spacing between the cracks, which then is used to calculate the crack width in concrete structures. This paper discusses the parameters controlling the crack spacing and develops an experimental test program on a set of industrial-scale reinforced concrete elements cast with self-healing concretes to be tested under flexural actions. This study provides a wide picture of the limits of maximum, minimum, and average spacing occurring in the beams. A comparison is highlighted between the calculated and experimentally evaluated measures. It was observed that the provisions given in Eurocode 2 and Model code 2010 present a good approach for the calculation, always with a small degree of overestimation for concrete without fibres. On the other hand, the values calculated using recommendations from NFP 18-710, the overestimation is higher. The influence of loading levels seems to not affect the number of cracks with an increase in concrete cover. The experimentally evaluated ranges to relate maximum and minimum spacing with the average value in a loaded region are given. No influence of using self-healing agents was detected.

1 Introduction

The deterioration of concrete structures has gained high momentum in the past few decades. The premature loss in the functionality of the structure or any part of it during its service life results in an economic and social loss. At the structural design stage, cracks are expected, and an important responsibility in this stage is to ensure that the possible cracking does not exceed the acceptable limits given in design codes. These limits given are empirical and lack credibility. Structural cracking can cause durability issues such as corrosion of rebar, spalling of cover, and loss of functionality of the structural element. Using self-healing agents can help in mitigating the effects of cracking in serviceability and durability. No previous studies reported the information on the effect of self-healing agents in the crack shape of concrete structures, and some studies on real size elements using self-healing agents are reported [12,13].

It is of great importance for the structural designer to control the possible cracking that may occur due to the imposed loading or other non-structural reasons, at the design stage, that can be done either by a) avoiding the occurrence of cracks; b) allowing cracking at regions where their effect can be coped with; c) cracks may be allowed to form randomly, and the reinforcement is detailed to limit the resulting crack width. The

formulations given in the design codes deal with the last type of cracking control. These formulations are based on certain models, and the best attempt is made to be able to predict the response of the concrete structure in the said loading and environmental situations. These deemed-to-satisfy approaches given are mainly based on empirical observations over several years of experience. Since the onset of the twentieth century, several researchers have contributed to trying to understand and then formulate the cracking occurring in concrete elements.

In 1903, the very first attempt was made to understand the cracking phenomenon by Armand Considère [1]. A chapter in the book describes the changes in stress when a concrete beam is loaded axially. At the crack location, the tensile stress in concrete reaches zero, whereas the tensile stress in steel reaches the maximum value. The effect of the crack is up to the transfer length (S_0), which controls the spacing occurring between the cracks. The resulting spacing (S) varies from transfer length to double the length, see equation 1.

$$S_0 < S < 2S_0 \quad (1)$$

Two initial theories by Saliger [2] and Base [3] emerged in the twentieth century, to predict crack spacing, which was based on bond-slip and no-slip theory, respectively. The majority of the formulations given in the

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design codes are in one or another way a combination of the parameters in these two theories. The two parameters considered are the concrete cover and the ratio $\frac{\Phi}{\rho}$, equation 2:

$$S_m = k_1 c + k_2 \frac{\Phi}{\rho} \quad (2)$$

where, S_m is the mean spacing; c is the concrete cover, Φ is the diameter of the rebar; ρ is the steel area to the effective concrete area ratio.

The resulting crack width given in the codes formulates crack width (either the maximum or design or average) as the product of maximum spacing occurring in the concrete element and the mean strain difference between reinforcement and the concrete up to a certain length, depicted as:

$$w_k = \int_0^{S_{r,max}} \{\varepsilon_s(x) - \varepsilon_c(x)\} dx = S_{r,max} (\varepsilon_{sm} - \varepsilon_{cm}) \quad (3)$$

In the project SMARTINCS, the contribution of using Self-Healing Agents (SHA) in closing the cracks and improving the protection against aggressive environments is evaluated. The two self-healing functionalities used in the program are bacteria and Crystalline admixture. It is expected that the incorporation of self-healing agents does not influence the cracking response of the beams. This paper deals with the analysis of the cracking response of an experimental program on beams made at the industrial level to scale up the SHA efficiency on improving durability.

2 Influence of parameters

The parameters included in the design codes for evaluating crack spacing are concrete cover, the diameter of the bar, reinforcement diameter to effective reinforcement ratio (Φ/ρ), rebar characteristics, the loading type (tension or bending), and rebar spacing. These parameters have different degrees of influence on the final calculated maximum spacing value. It is imperative to understand that the principle of crack spacing is based on the concept of transfer length – a distance up to which the impact of a crack stays in the concrete matrix. It is important to keep in mind at which location the crack width is being evaluated. The crack width at the most tensioned surface will be higher than the crack width at the level of the reinforcement, due to shear lag occurring along the perpendicular crack length and at the rebar length increasing the crack width at the surface [5]. Table 1 gives an overview of formulations mentioned in different codes to evaluate the maximum crack spacing values to calculate the crack widths. The formulation given in ACI 224, considers only the condition when the concrete member is loaded in tensile, which largely depends on the steel stress and the effective concrete area.

2.1 Concrete cover

A. W. Beeby [5] states that a major part of the crack spacing obtained is due to the concrete cover, about two-third. A larger concrete cover leads to larger crack width at the surface, which tends to produce a more localised corrosion if exposed to aggressive environments. Whereas smaller concrete covers produce more uniform corrosion.

2.2 Factor Φ/ρ

A rigorous analysis of this factor is addressed in the article by A W Beeby [5]. This factor reflects the bond properties of the reinforcement and concrete at the bar surface. The kind of strain profile generated in the cross-section seems to be an important factor, which is addressed only in Eurocode 1992 [7]. MC 2010 [9] does not consider the effect of the strain profile during loading on the crack spacing measure.

Table 1. Formulations in codes.

Design code	Formulations
EC 1992 [7]	$S_{r,max} = k_3 c + k_1 k_2 k_4 \frac{\Phi}{\rho}$
Model Code 2010 [9]	$I_{s,max} = kc + \frac{1}{4} \frac{f_{ctm}}{\tau_{bms}} \frac{\Phi}{\rho}$
ACI 224.2R-92 [6]	$w_{max} = 0.011 f_s \sqrt{d_c} \times 10^{-3}$
Model Code 2010, FRC [9]	$I_{s,max} = \left\{ k_c + \frac{\Phi s(f_{ctm} - f_{ftsm})}{4 \cdot \rho_s \cdot \tau_b} \right\}$
NFP 18.710, FRC [8]	$S_{r,max,f} = 2.55(l_0 - l_t)$ $l_t = 2 \left[0.3 k_2 \left(1 - \frac{f_{ctfm}}{K_{global} f_{ctmel}} \right) \frac{1}{\delta \eta} \right] \frac{\Phi}{\rho_{eff}} \geq \frac{l_f}{2}$ $\delta = 1 + 0.4 \left(\frac{f_{ctfm}}{K'_{global} f_{ctmel}} \right) \leq 1.5$ $l_0 = \frac{1.33c}{\delta}$

2.3 Spacing between shear reinforcements

The detailing of reinforcement resulting in specific reinforcement spacing is not directly linked to the evaluated crack spacing. The position of shear reinforcement acts as a preferable location for crack localization. This is the reason no internal shear reinforcement was used in this program. Shear reinforcement was provided externally to allow the loading of the beams to the required level of cracking.

3 Experimental program

To understand the influence of these parameters in the crack spacing formula, the following test program was devised. Full-scale beams of four-meter length were produced in PREFFOR in Valencia, Spain. These beams were then stored in the industry to later crack. The four-point bending system was employed to crack the beams to three different levels to obtain the cracking of the desired range as specified in table 1. Low and high levels of cracking were designated keeping in mind the cracking level, resulting in maximum crack width as given in codes for exposure to seawater condition. Three different qualities of concrete were studied – conventional concrete (OC), high-performance concrete (HP), and ultra-high-performance concrete (UH) with fibers 1.5 % vol. Two beams of each category were cast, stored, and loaded identically way to observe the variation in the cracking response of the beams. Two different covers were considered. Although SHA incorporation was not expected to influence the cracking response, the program includes concretes with two different SHAs: Crystalline admixture (from Penetron) and bacteria (from Basilisk). A beam pair (OC_20_0) without cracking was chosen to compare the results of beams in terms of corrosion study later, with different parameters – concrete cover and cracking level. Beams with no addition are referred to as A type (e.g., OC_20_300_A), the ones with bacteria as B type (e.g., OC_20_100_B and the ones with CA as C type (e.g., OC_20_300_C)). The final cracking level was different from the target level, as mentioned in table 2.

Table 2. Experimental plan with target and achieved cracking level.

Specimen ID	Cover (mm)	Target w_{max} (μm)	Achieved w_{max} (μm)	no.
OC_20_0_A	20	0	-	2
OC_20_100_A	20	100	91 & 110	2
OC_20_100_B			130 & 146	2
OC_20_100_C			117 & 124	2
OC_20_300_A	20	300	185 & 254	2
OC_20_300_B			185 & 238	2
OC_20_300_C			192 & 187	2
OC_30_300_A	30	300	346 & 310	2
HP_20_100_A	20	100	127 & 89	2
HP_20_300_A	20	300	250 & 257	2
HP_30_300_A	30	300	-	2
UH_20_50_A	20	50	103 & 89	2
UH_20_50_B			46 & 60	2
UH_20_50_C			70 & 62	2
UH_20_100_A	20	100	84 & 173	2
UH_20_100_B			207 & 197	2
UH_20_100_C			89 & 82	2
UH_30_300_A	30	300	142 & 142	2

3.1 Concrete mix design

The constituents of the mix design are given in table 3 for the three types of concrete qualities. The beams were cast using steel sections as formworks on a flat steel surface. The pouring of concrete was started from one end and

continued to the other end, to ensure no layer formation and uniform spread of fibers in UHPFRC.

3.2 Test specimen

Thirty-six beams were cast in a factory setting. The dimensions of the beams with reinforcement detailing are shown in fig.1. The beams are 4 m long and 100 mm wide with a depth of 250 mm; two $\Phi 16$ rebars are provided at the top and the bottom part of the beam. The cover to the tension rebar is 20 and 30 mm, as shown in table 2. No internal shear reinforcement was provided in the beams. Only in the beams with high load requirements, external stirrups were provided in the shear span to avoid unexpected failure in this zone.

Table 3. Concrete mix design for three concrete qualities.

Constituents	OC	HP	UH
CEM I 42.5 R/SR	370	450	1125
Silica fume	-	50	
Silica flour	-	-	
Water	150	160	160
Silica sand	-	-	902
White sand	211	200	-
Red sand	897	750	-
Aggregate 4/7	-	570	-
Aggregate 7/10	354	200	-
Aggregate 12/20	377	-	-
VC 5970	3	-	-
VC 20 HE	-	3.5	30
Air reducer – 0.4%	1.48	-	-
Steel fiber (13/0.2)	-	-	120
Total	2363.48	2383.5	2377
w/c	0.41	0.36	0.2
Expected f_{ck}	50	90	150

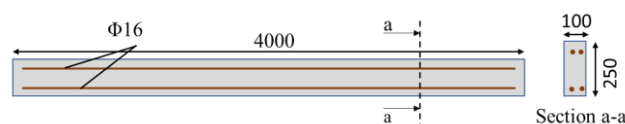


Fig. 1. Beam dimensions and reinforcement (all the dimensions in mm)

3.3 Loading setup

Two identical beams were loaded in such a way that the outer surfaces cracked in tension while the inner surfaces worked in compression. Two spacers (concrete blocks) were placed in the center of each pair 1 m apart, acting as support points, as shown in fig. 2. The load cells were attached to the thorough high-strength bars that act as the loading points. Three LVDTs were placed at the two loading points and one at the center of the beam to record the deflections occurring due to loading. The loading setup imitates a 4-point bending test where the center 1 m length experiences a constant bending moment. The cracking induced in this region is purely due to flexural stresses and was the area of study.

3.4 Evaluation of crack spacing

The cracking obtained due to imposed loading was assessed using demec points placed on the two surfaces of the beam - the most tensioned lateral surface and the top surface with 250 mm width. The crack widths occurring at the most tensioned surface of the beam were studied and recorded using a DinaCapture 2.0 microscope. The distance between the cracks was recorded using a measuring tape. The compressive strengths obtained for each concrete quality are given in table 3. The characteristic strength was evaluated by dividing the average strength by a factor 1.2, based on the factory quality control records.

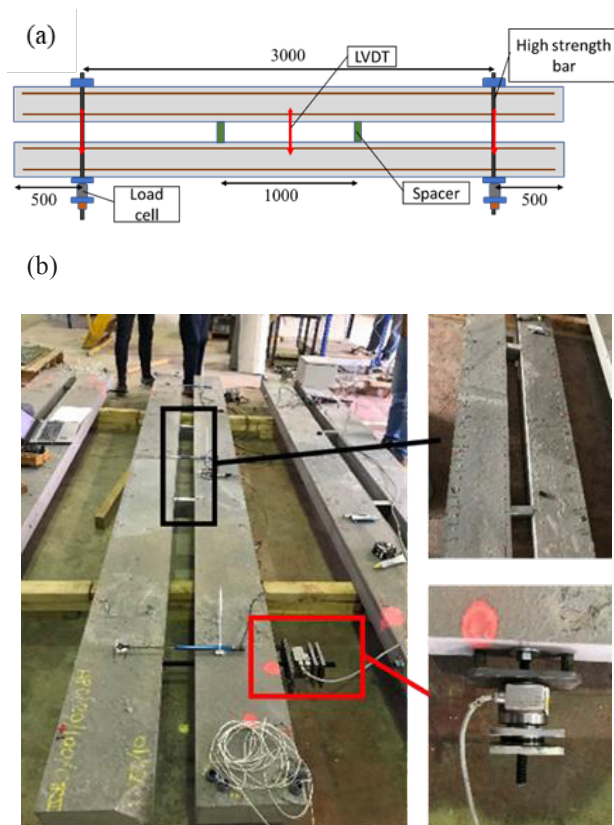


Fig. 2. Loading setup (a) schematic diagram; (b) pictures from the experiment (all the dimensions in mm)

Table 4. Compressive strengths of concrete qualities.

Compressive strength (MPa)			
ID	f_m	COV (%)	f_{ck}
OCA	51.7	5.55	43.1
OCB	60.8	5.11	50.6
OCC	77.2	11.15	64.3
HPA	70.8	15.8	59
UHA	143	6.04	120
UHB	162	1.23	134.9
UHC	152	0.76	126.4

4 Results and Discussions

The results obtained from the tests carried out in the experimental program are mentioned in the following segments. The spacing values were obtained by measuring at the edge of the crack in the most tensioned surface. A comparison is highlighted in the sections below. Table 5 shows the minimum, maximum, and

average spacing with their COV in all measurements, for OC and HP beams. Table 6 shows the results for UH concrete beams that had extensive cracking, and only the average value of crack spacing was evaluated.

4.1 Minimum crack spacing

For beams with ordinary concrete, the least value of crack spacing obtained due to imposed loading ranged from 19 - 27 mm for lesser concrete cover chosen as 20 mm and loaded up to a level to create a maximum crack width of about 100 microns. In the beams where the cracking level is increased to achieve the maximum crack width of 300 microns, the minimum spacing value observed increased to the range of 28 - 34 mm. For the larger cover of 30 mm, the minimum spacing varied from 28 - 32 mm. The minimum spacing observed in all test specimens was 5 mm, which may have resulted due to the adjacent cracks spaced more than double the transfer length in the beam. The design codes do not present any recommendations to evaluate the minimum crack spacing. This factor may be of importance when trying to understand the transfer length around the crack influencing the cracking.

$$\frac{S_{min}}{S_{av}} = 0.27 \text{ to } 0.48, c = 20 \text{ mm and } w_{max} = 100 \mu m \quad 4(a)$$

$$\frac{S_{min}}{S_{av}} = 0.52 \text{ to } 0.61, c = 20 \text{ mm and } w_{max} = 300 \mu m \quad 4(b)$$

$$\frac{S_{min}}{S_{av}} = 0.3 \text{ to } 0.62, c = 30 \text{ mm and } w_{max} = 300 \mu m \quad 4(c)$$

The beams with enhanced quality HP showed increased minimum spacing measures. For the level to achieve a crack width of the order of 100 microns, the minimum spacing found was 15 mm. For the same cover of 20 mm but increased cracking level (to reach 300 microns), the minimum crack spacing was 26 mm.

4.2 Average crack spacing

For the lesser cover of 20 mm, the range of average spacing varied from 44 - 59 mm, averaging 53 mm. For larger cracking of the order of 300 microns, the average spacing varied from 49 - 62 mm, averaging 54 mm. For the cover of 30 mm, the average spacing between the cracks was 77 mm, ranging from 74 - 79 mm.

For the beams with fibers (UHPC), the average value of crack spacing ranged from 20 to 29 mm for the desired maximum crack width of the order of 50 microns. With higher cracking of the order of w_{max} 100 microns, the average spacing was 13 to 27 mm. For higher cover and higher cracking level, the average spacing observed was 17 mm in both identical beams. For conventional concrete, the formulation (eq. 5) was proposed for average crack spacings by Chowdhury [10], where l_{cr} , c , s , Φ , and ρ are in mm; and s denotes the average spacing between the rebars. In equation 6, the formula from Eurocode is adjusted to account for the effect of fibers in the evaluation of mean spacing for UHPC; l_f and d_f are the fiber length and its diameter, all in mm [11].

$$l_{cr} = 0.6 (c-s) + 0.1(\Phi / \rho) \quad (5)$$

$$S_{r,max} = \{50 + 0.25k_1k_2(d_b/\rho)\} \{50/(l_f/d_f)\} \quad (6)$$

4.3 Maximum crack spacing

In a concrete region with various spacing measures between the cracks, the maximum value is of the most importance both for serviceability and durability issues and is also given in the codes. For a cover of 20 mm and a cracking level of 100 microns, the maximum crack spacing ranged from 72 – 95 mm, averaging 90 mm. For the larger cracking level of 300 microns, the maximum cracking measure varied from 72 – 93 as in the lower cracking level. For a cover of 30 mm, the maximum spacing ranged from 113 to 130 mm, averaging 122 mm.

The ratio of maximum spacing to the average value can be evaluated using equation 7, given in the literature [10]. The factors obtained in this program are given in table 4. The results from the experimental study for OC (eq. 8) and HP (eq. 9) are:

$$S_{max}/S_{av} = 1.5 \text{ to } 1.7 \quad (7)$$

$$\frac{S_{max}}{S_{av}} = 1.61 \text{ to } 1.78, c = 20 \text{ mm and } w_{max} = 100 \mu\text{m} \quad (8a)$$

$$\frac{S_{max}}{S_{av}} = 1.39 \text{ to } 1.58, c = 20 \text{ mm and } w_{max} = 300 \mu\text{m} \quad (8b)$$

$$\frac{S_{max}}{S_{av}} = 1.43 \text{ to } 1.76, c = 30 \text{ mm and } w_{max} = 300 \mu\text{m} \quad (8c)$$

$$\frac{S_{max}}{S_{av}} \approx 1.58, c = 20 \text{ mm and } w_{max} = 100 \mu\text{m} \quad (9a)$$

$$\frac{S_{max}}{S_{av}} \approx 1.75, c = 20 \text{ mm and } w_{max} = 300 \mu\text{m} \quad (9b)$$

The comparison between the experimentally evaluated and the calculated values are shown in figure 3.

Table 5. Exp. crack spacing results for OC and HP (mm).

Specimen ID	S _m in	S _{av}	CV (%)	S _{max}	S _{max} /S _{av}	no. cracks
OC 20 0 A1*	-	-	-	-	-	7
OC 20 0 A2*	-	-	-	-	-	5
OC 20 100 A1	19	51	37	90	1.76	25
OC 20 100 A2	5	50	36	89	1.78	26
OC 20 100 C1	26	59	31	95	1.61	20
OC 20 100 C2	27	56	29	95	1.70	20
OC 20 300 C1	33	62	31	93	1.50	20
OC 20 300 C2	34	56	21	78	1.39	21
OC 20 100 B1	12	44	30	72	1.64	22
OC 20 100 B2	27	56	36	92	1.64	21
OC 20 300 B1	26	49	29	72	1.47	25
OC 20 300 B2	29	50	28	79	1.58	25
OC 20 300 A1	28	54	24	76	1.41	22
OC 20 300 A2	32	54	28	80	1.48	22
OC 30 300 A1	46	74	32	130	1.76	17
OC 30 300 A2	24	79	37	113	1.43	16
HP 20 100 A1	15	63	39	91	1.62	20
HP 20 100 A2	35	61	33	94	1.55	20
HP 20 300 A1	26	58	42	102	1.75	19
HP 20 300 A2	43	59	34	120	1.75	18

*These beams demonstrated cracking without loading, which may have occurred due to drying shrinkage or handling of beams in the factory

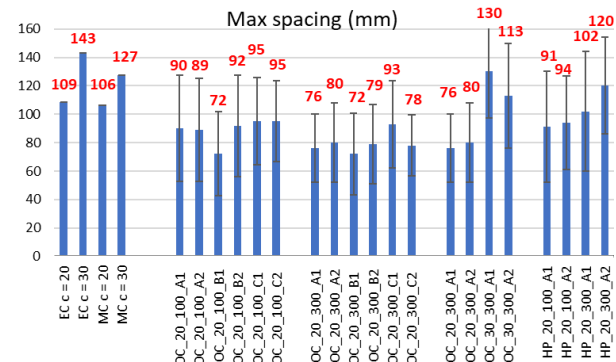


Fig 3. Maximum crack spacing experimentally obtained results for OC and HPC (in mm)

It can be observed from figure 3 that the calculated values are overestimated for all beams when calculated according to the Eurocode and Model code. For EC 2, the mean overestimation is 18 %. The effect is more pronounced when the stressing in steel is increased, which results in a greater number of cracks, reaching the crack stabilisation state. With higher cover values (30 mm here), the maximum spacing value experimentally evaluated is 130 mm and 113 mm whereas the calculated value is 143 as per EC and 127 as per MC, respectively.

For beams with UHPC, the experimentally obtained average spacing was lesser than half of the calculated measures for maximum spacing. Table 6 shows the values obtained and calculated. It is worth noticing that, in this table, the reported spacing value is the average. Assuming a max/average spacing ratio of 1.7, the mean overestimation of the calculated values using NFP is 80 percent higher than when calculated using EC 2 for OC and HP (18%).

Table 6. Crack spacing experimental and calculated results for UH (in mm).

Specimen ID	Exp	Calc.values		No. ofcracks
		S _{av}	MC 2010	
UH 20 50 A1	26	59.1	73.1	48
UH 20 50 A2	22	59.1	73.1	56
UH 20 50 C1	29	59.1	73.1	42
UH 20 50 C2	26	59.1	73.1	47
UH 20 50 B1	-	59.1	73.1	-
UH 20 50 B2	20	59.1	73.1	62
UH 20 100 A1	16	59.1	73.1	74
UH 20 100 A2	19	59.1	73.1	65
UH 20 100 C1	27	59.1	73.1	46
UH 20 100 C2	23	59.1	73.1	54
UH 20 100 B1	13	59.1	73.1	90
UH 20 100 B2	16	59.1	73.1	77
UH 30 300 A1	17	87.3	105	73
UH 30 300 A2	17	87.3	105	74

4.4 Number of cracks

For durability reasons, the number of cracks that originated due to imposed loading may be of importance. With a smaller concrete cover and a large number of cracks, uniform corrosion may occur; whereas, with a lesser number of cracks, which usually emerge with larger cover zones, the corrosion occurring may be more concentrated and lesser uniform. Table 5 shows the number of cracks that emerged in the beam specimens. With the increase in cover value, the number of cracks reduced. A comparison can be seen in figure 4.

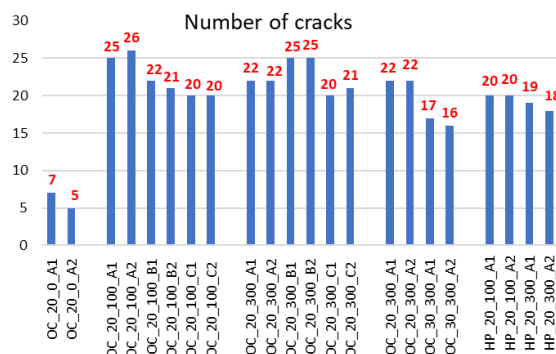


Fig 4. Number of cracks experimentally evaluated for OC and HPC

5 Conclusions

The following ideas can be deduced from this article:

1. As a general conclusion, it can be accepted that the provisions from EC 2 and MC 2010 provide a good approach to the experimental results, always with a small overestimation for OC and HP. The values obtained using NFP 18-710 for UH concretes, this average of the overestimation is excessive.
2. The number of cracks emerging in the beams reduced with an increase in concrete cover, as expected. The increase in loading levels seems to not influence the number of cracks.
3. The experimentally obtained maximum spacing was 12 % lesser, for a cover of 20 mm. For a cover of 30 mm, the experimental value was 9 % lesser than the calculated value.
4. When calculated using the Model Code 2010, for the lesser cover of 20 mm, the evaluated values are 11% lesser than the calculated values. For a larger concrete cover of 30 mm, the experimentally obtained values are close to the calculated values.
5. It seems from the results that these formulations are more appropriate when used for higher concrete cover – 30 mm in this case.
6. From this program, the experimental range for S_{max}/S_{av} is from 1.39 to 1.78, in the case of reinforced concrete elements without fibers. The range for S_{min}/S_{av} is from 0.27 to 0.62.
7. The used self-healing agents show no effect on the cracking response.



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