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Durability of Reinforced Concrete Structures: Comparative Study between Normative Prescriptions about Crack Control

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Abstract: The opening of cracks in RC (reinforced concrete) structures compromises their essential functions, such as their ability to support and protect against aggressive agents. Therefore, durability prescriptions related to the cracking process of the concrete parts can be found. The main objective of this article is to analyze the essential durability requirements for RC presented by fib Model Code 2010, EuroCode 2 and Brazilian Code NBR 6.118 Brazilian Association of Technical Standard (ABNT) including an analytical study of the recommended parameters. To this end, qualitative and quantitative analyses of the normative precepts were carried out with regard to: environmental aggressiveness, concrete strength, cover thickness and crack opening, in a double-supported beam. From the analyses carried out, it was possible to conclude that although the Brazilian standard, apparently, presents some parameters that are less restrictive than the international codes, such as the classification of environmental aggressiveness, its durability estimates are as rigorous as those of international codes that ensure durability.

Key words: RC, analytical modeling, performance, durability.

1. Introduction

Planning the serviceability capacity in the design of RC (reinforced concrete) structures is of great importance, and for this purpose, serviceability limit state analyses are carried out, which take into account factors such as appearance, tightness and durability of the parts [1]. In general, parameters such as: cover, diameter of bars and effective reinforcement of stirrups, which can interfere with the cracking behavior, are investigated, therefore, a good design results in benefits with regard to the performance of the structure [2].

It should be noted that, when RC structures are subjected to service actions, the critical values of the concrete tensile stress may be reached, causing the appearance of cracks in the structural elements, which, in turn, negatively impact their useful life. This fact is evidenced by the predisposition to attack by aggressive substances, which can cause carbonation and/or corrosion of the reinforcement. It should also be considered that in the sections between cracks, the phenomenon of tension stiffening occurs, related to the bond stress [3-6].

For this reason, the normative prescriptions study the durability of RC address cracking. In Brazil, the NBR 6.118 [3] is applied to RC projects, including their durability, however, it has been criticized by some authors regarding the subdivision of the environmental classification [7, 8] and omissions concerning the durability requirements for buried structures (piles, caissons, for example) [9], among others.

In this context, when seeking the state of the art about the properties of materials and technological advances in the field of engineering that, preferably, are guaranteed by parametric studies, it is possible to use international regulatory codes [10].

These highlight the concept of life cycle, relating the design criteria to: durability, functionality,

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reliability and sustainability [6]. Particularly noteworthy is the Model Code 2010, bulletin No. 55 of the Comité Euro-Internacional du Béton CEB-fip[6], which has several studies attesting its calculation models [11], comparing its parameters to those of other codes [12]. Another reference design code is the EN 1992, or EuroCode 2 [13] which, in addition to following the same standards for the production of concrete [6], that is, EN-206 [5], presents many similarities with regard to the parameters adopted to improve the PUL (project useful life).

Considering that some researchers developed so far present analyses referring to isolated parameters [7-9, 14], and assuming the presence of possible omissions in Brazilian standardization [3], the objective of this work is to perform a comparative critical analysis (qualitatively and quantitatively) between the Model Code 2010 [6], EuroCode 2 [13] and NBR 6.118 [3], regarding the durability of RC. At the same time, the identification of the singularities present between the standardizations is carried out, through an analytical study of all the parameters that influence the crack opening calculations in RC structures.

The importance of this work is to provide elements that can be revised and/or rectified in favor of improving the concept of durability of RC structures in the Brazilian territory.

2. Cracks in RC Structures

The formation of cracks in RC is associated with internal factors, such as cracks in the plastic state (resulting from inadequate curing of the concrete, excessive shrinkage, among others), and/or imposed deformations (external loads), and/or construction errors. On the other hand, factors such as the mechanical strength of the concrete, the effective reinforcement ratio, the thickness of the cover, the delimitation of loads and the dimension of the crack opening are of great importance [15-17].

Regarding the imposed deformations, especially the bending exhaustion, they are the target of great concern on the part of normative prescriptions in relation to durability since they reduce the performance in service. The process of formation of these cracks is generally divided into two stages: formation (sections b and c, see Fig. 1), characterized by the weakening of the bond stress and the increase of the axial tensile force [6] and the stabilization (sections c-e, see Fig. 1), when there are enough cracks so that new ones do not form, however, there may be an increase in the size of existing ones. To prevent this from happening, it must be provided twice the value of the transfer length (l_s) between consecutive cracks [11].

Furthermore, in Fig. 1, there is a dotted line (d), which represents the phase in which the steel bars start to support all the axial loading in the cracked areas. In these cases, in the remaining regions, the concrete that surrounds the reinforcement tends to contribute more to the tensile stresses, due to the bond stresses [18]. As a result, tension stiffening arises and, consequently, also arises damage to the performance of the part in terms of the performance in service [6].

In 1971, Goto [19] observed that in the tensile region of the RC there is a radial resultant of the bond stress, perpendicular to the axis of the bar, which causes the appearance of secondary cracks, resulting in the rupture of the steel-concrete bond if the stresses equal the characteristic strength of concrete [11, 18]. This fact shows the importance of parameters such as the cover, the diameter of the bars and the anchorage length of the reinforcement, among others, which are associated with the study of bonding [2].

Among the parameters examined in the study of steel-concrete bond, those associated with concrete (for example, mechanical strength) and steel (such as surface conformation) stand out. Cover thickness requires special attention with regard to cracking effects [6, 20, 21], as it provides physicochemical protection against the penetration of aggressive agents [16].

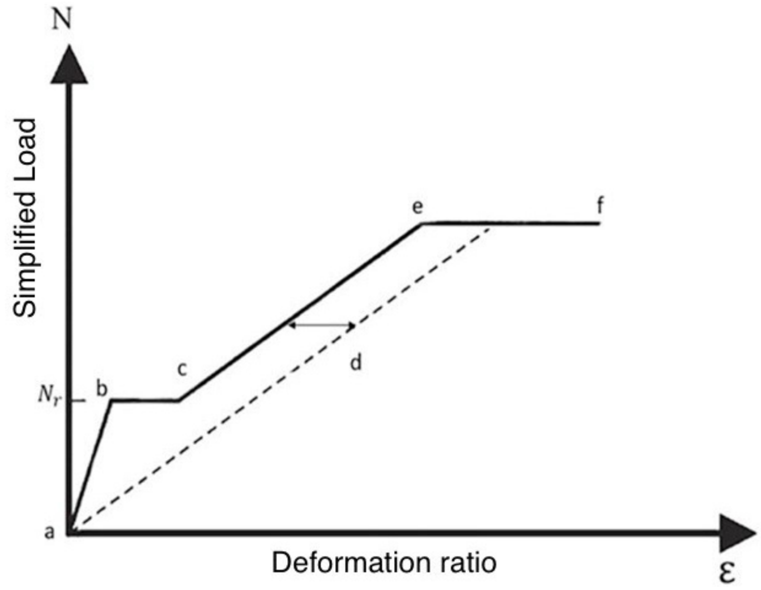

Fig. 1 Simplified load vs. Deformation ratio for a RC member subjected to tensile stress.

3. Methodology

Considering the technical normative prescriptions that ensure desirable characteristics to products and services, such as the fib Model Code (bulletin 55) [6], the EuroCode 2 [13] and the NBR 6.118 [3], a qualitative and quantitative analysis is carried out on the calculations to predict the opening of cracks, under service actions. The objects of study are the relation between reinforcement ratio and concrete strength, prescriptions related to environmental aggressiveness at its different levels and reinforcement cover thickness, among others.

First, the prescriptions for reinforcement rates, loadings and CEA (characterization of environmental aggressiveness), present in international codes [6, 13], are defined in relation to the Brazilian context. In short, the qualitative analysis aims to verify the singularities present in the texts of the three technical prescriptions studied (See Table 1).

Then, for the quantitative analysis, a double-supported cross-section beam is used (20 × 40 cm) (see Fig. 2b), with a free span of 5 m (see Fig. 2a), in which steel CA-50 (f_y = 500 MPa) is used with a reinforcement rate of $A_S = 15.75$ cm² (5×Φ20 mm) and the following loading: permanent of $M_{g,k}$ = 280 KN·m and variable of $M_{q,k}$ =50 KN·m. The following exposure categories were chosen, according to Table 2.

Beam A: category that has a risk of carbonation of concrete and moderate aggressiveness;

Beam B: category that has a risk of attack by chlorides of concrete and high aggressiveness;

Beam C: category that has a risk of attack by chlorides of concrete and very high aggressiveness.

So, in accordance with the MC [6], EC [13] and the NBR 6.118 [3], the relations in Table 1 were considered for the classes of environmental aggressiveness and nominal cover values (remembering that, depending on the CEA, a nominal cover value must be adopted). Thus, a more consistent analysis is made about the prescriptions on the estimation of crack opening (w_k) and durability, present in the normative prescriptions studied.

Subsequently, an analysis is carried out regarding the relation between the strength of the RC and the crack openings, that is, f_c and w_k. Therefore, the variability of the data studied occurred from 10 to 10 MPa, starting at 40 MPa, since the minimum value of f_c accepted by the MC [6], EC [13] and NBR 6.118 [3] is 35 MPa (see Tables 3 and 4). This resulted in the

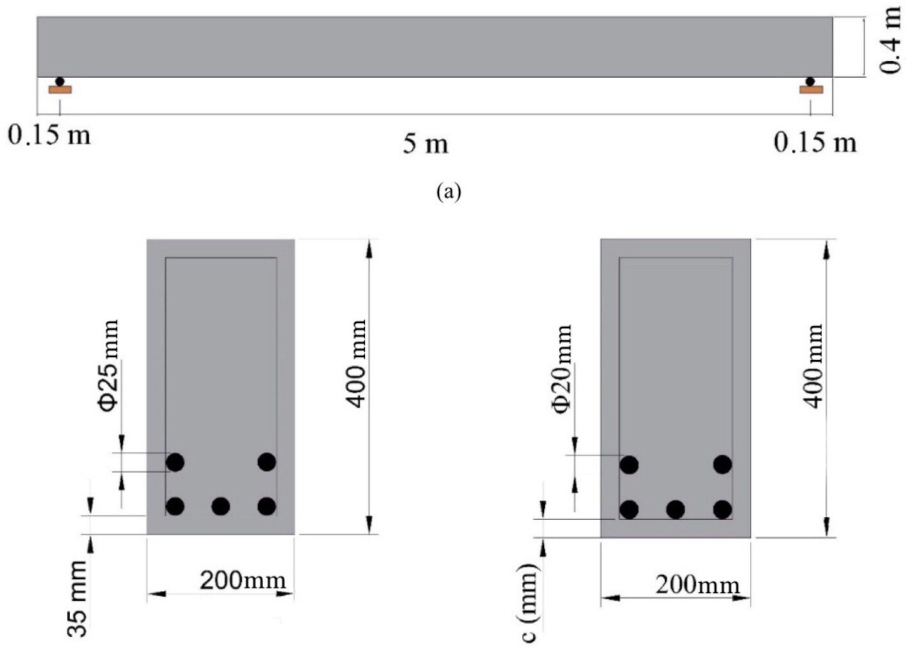

Fig. 2 a) Beam model used to estimate crack opening b) cross-section beam bar Φ25 mm c) cross-section beam bar Φ20 mm.

Table 1 Relations of values for durability for the models analyzed in this work, according to the prescriptions studied.

	Models	Model Code	EuroCode	NBR 6.118
CEA	A	XC3	XC3	II
	B	XS1	XS1	III
	C	XS3	XS3	IV
Cover in mm	A	35	33	25
	B	45	43	35
	C	55	53	45

Source: adapted from MC [6], EC [13] and NBR 6.118 [3].

Table 2 Description of the Environmental Aggressiveness Classes studied.

International codes											
Aggressiveness	X0	XC1	XC2	XC3	XC4	XD1	XD2	XD3	XS1	XS2	XS3
Characteristics	Very dry	Dry or permanently wet	Wet surfaces, rarely dry	Areas of moderate humidity (protected from the rain)	Wetting and drying cycles	Moderate humidity (exposed to chloride)	Wet pools rarely dry	Zones with splash for bridges on rivers	Marine area away from the coast	Submerged in sea water	Tidal zones
Risk of deterioration	No risk	Risk of carbonation				Risk of chloride attack on the structure					
Brazilian standard											
Aggressiveness	I		II	III		IV					
Characteristics	Rural	Submerged	Urban	Marine	Industrial	Industrial	Tidal splash				
Risk of deterioration	Insignificant		Low	High		Very high					

Source: adapted from MC [6], EC2 [13] and NBR 6.118 [3].

study of the following strength classes: 40 MPa, 50 MPa, 60 MPa, 70 MPa, 80 MPa and 90 MPa. Similarly, for the cover thickness, the minimum nominal cover value is considered, which fits all the prescriptions studied (see Tables 1-3), being considered c = 35 mm (see Fig. 2c).

4. Results and Analyses

4.1 Qualitative Analysis between Prescriptions

4.1.1 CEA

The design characteristics of RC structures are directly related to the CEA, ensuring the durability of the structural components. Table 2 presents the description of the subdivisions of environmental aggressiveness adopted by the Model Code [6], EuroCode (CEN 2004) and NBR 6.118 [3], and it is possible to observe that the Brazilian standard [3] is more summarized, adopting only 4 classes, while the others employ 18. It is worth mentioning that, regarding the MC [6] and EC [13], the most aggressive classes are not presented (XF1, XF2, XF3, XF4, XA1, XA2, XA; see section 4 of EN-206) [5]; since no information is provided about the cover thickness and the crack opening limit, the codes indicate that the designer should take a more detailed experimental approach to these CEAs. Furthermore, these CEAs do not represent commonly Brazilian environments (e.g. freeze and thaw action, brackish thaw, etc.)

However, it is possible to detect, in an initial examination, that the Brazilian standard:

(1) presents a deficient detailing as regards the attributes of the different CEA, requiring a greater detailing regarding relative humidity, level of degrading agents, pollutants, among others;

(2) lacks information concerning the description of the structure (such as architectural features that mitigate the effects of degrading agents), and only information regarding its geographic location is provided (e.g. rural and urban location and marine area);

(3) enables the adoption, at the discretion of the designer, of softer CEA (see item 6.4.2 of the NBR 6.118) [3];

(4) lacks information to assist in the study of degradation, such as the degree of aggressiveness, concentration of deteriorating agents (since the international codes present this information in Table 2, section 4.1 of the EN-206) [5].

4.1.2 Properties of RC

With regard to the quality of concrete, it is observed in Tables 3 and 4 that, in addition to indicating strength values (class of concrete), all prescriptions adopt values of water/cement factor for each CEA, in order to guarantee the quality of the RC structures. In Table 5, a comparison is made between the requirements to estimate a good quality RC, which are presented in the MC [6], EC2 [13] and NBR 6.118 [3].

Analyzing Tables 3 to 5, it can be seen that the international codes (MC [6] and EC2 [13]) and the Brazilian standard [3] have similar values regarding the strength values of concrete and the water/cement factor. With regard to the other factors (presented in Table 5), it can be observed that NBR 6.118 [3] presents the following differences:

- Does not separate the ν between cracked and non-cracked parts;
- Does not adopt an estimate for cracking energy;
- Does not check for the f_{yk} through equations.

Table 3 Relations for the better quality of the concrete, according to the Model Code and the EuroCode.

	Environmental aggressiveness classes										
	X0	XC1	XC2	XC3	XC4	XD1	XS1	XD2	XS2	XD3	XS3
w/c factor	--	0.65	0.60	0.55	0.50	0.55	0.50	0.55	0.45	0.45	0.45
Classes of concrete		≥ C30/37	≥ C35/45			≥ C40/50				≥ C45/55	

Source: adapted from EN-206 [5].

Table 4 Relations, according to the NBR 6.118, for the better quality of the concrete.

	Environmental aggressiveness classes			
	I	II	III	IV
w/*c* factor	≤ 0.65	≤ 0.60	≤ 0.55	≤ 0.45
Classes of concrete	≥ C20	≥C25	≥ C30	≥ C40

Source: adapted from NBR 6.118 [3].

Table 5 Comparison of the recommendations for the quality of RC among the prescriptions studied.

		Model Code	EuroCode 2	NBR 6.118
Resistance	Compression	$f_{ck,cube}$, $f_{ck(t)}$, $f_{cm}(t)$, $\beta_{cc}(t)$	$f_{ck,cube}$, $f_{ck(t)}$, $f_{cm}(t)$, $\beta_{cc}(t)$	f_c
	Tensile	$f_{ctk,inf}$, $f_{ctk,sup}$, f_{ctm}, G_F	$f_{ct,m}(t)$	$f_{ctk,inf}$, $f_{ctk,sup}$, $f_{ct,m}$
Relations of quality	Concrete	E_{cm} related to the composition of the components, $\nu = 2$ for non-cracked parts and $\nu = 0$ for cracked parts	E_{cm} related to the composition of the components, $\nu = 2$ for non-cracked parts e $\nu = 0$ for cracked parts	E_{ci} and E_{cs} related to the components, $\nu = 2$ cracked and non-cracked parts are not differentiated
	Reinforcement	$E_s = 200$ GPa, max. 0.2% of variation of f_{yk}, η and f_{bd}	$E_s = 200$ GPa, f_{yk}, η and f_{bd}	$E_s = 200$ GPa (active reinforcement) and $E_s =$ 210 GPa (passive reinforcement), f_{yk} given by the manufacturer, η and f_{bd}

Source: the authors.

$f_{ck,cube}$ is the strength of concrete dosage for cylindrical specimens; f_{ck} is the characteristic compressive strength of concrete; f_{cm} is the average compressive strength of the concrete cylinder; β is a coefficient linked to the loading of the part to calculate crack openings; f_c is the strength of concrete dosage; $f_{ctk,inf}$ is the lower characteristic tensile strength of concrete; $f_{ctk,sup}$ is the upper characteristic tensile strength of concrete; G_F is the fracture energy of concrete; f_{ctm} is the average value of the axial tensile strengths of concrete; E_{cm} is the secant Modulus of Elasticity (Deformation) of concrete; E_{ci} is the Modulus of Elasticity or Initial Tangent Modulus of Deformation of concrete; ν is the Poisson's ratio; E_S is the Modulus of Elasticity of the steel of the passive reinforcement; f_{bd} is the bond stress; f_{yk} is the value of the characteristic yield of steel; η is a coefficient used to estimate the bond stress.

In general, these factors are linked to the displacements of the part, the hardness of the concrete, the evaluations of the post-cracking conditions, the estimation of the maximum deformation of the structure, among others [11, 18, 22, 23]. Therefore, an evaluation of these differences is indicated, through the Brazilian standard.

4.1.3 Reinforcement Cover Thickness

According to Pérez Caldentey et al., this parameter "covering layer thickness" influences the opening of cracks, for this reason, a specific analysis must be carried out in this regard. The three prescriptions have the following expression for estimating the final or nominal cover C_{nom}:

$$C_{nom} = C_{min} + \Delta C \quad (1)$$

where:

C_{nom} is the nominal cover;

C_{min} is the minimum cover;

ΔC is the safety factor of execution (ΔC =8 mm for *c* and ΔC =10 for the MC [6] and NBR 6.118 [3].

The values of C_{min} and C_{nom}, presented and calculated according to the Model Code [6], EuroCode 2 (CEN 2004) and NBR 6.118 [3] to obtain a PUL of at least 50 years, are illustrated in Tables 6-8.

4.1.4 Crack Opening Models

With regard to cracking, the Model Code and the EuroCode 2 [13] adopt the calculation of the crack opening estimate w_k as being the product between the maximum transfer length and the difference in the average deformation of steel and concrete.

More specifically, for Model Code [6]:

$$w_k = 2l_{s,max}(\varepsilon_{sm} - \varepsilon_{cm} - \varepsilon_{cs}) \quad (2)$$

Table 6 Minimum cover values (in mm) for RC elements, according to the Model Code.

		Environmental aggressiveness classes										
		X0	XC1	XC2	XC3	XC4	XD1	XS1	XD2	XS2	XD3	XS3
Beam	C_{min}	10	15	25		30	35		40		45	
	C_{nom}	20	25	35		40	45		50		55	

Source: adapted from MC [6] and EC [13].

Table 7 Minimum cover values (in mm) for RC elements, according to the EuroCode.

		Environmental aggressiveness classes										
		X0	XC1	XC2	XC3	XC4	XD1	XS1	XD2	XS2	XD3	XS3
Beam	C_{min}	10	15	25		30	35		40		45	
	C_{nom}	18	23	33		38	43		48		53	

Source: adapted from MC [6] and EC [13].

Table 8 Nominal cover values (in mm) for RC elements, according to the NBR 6.118.

		Environmental aggressiveness classes			
		I	II	III	IV
Beam	C_{min}	15	20	30	40
	C_{nom}	25	30	40	50

Source: adapted from NBR 6.118 [3].

And for EuroCode [13]:

$$w_k = s_{r,max}(\varepsilon_{sm} - \varepsilon_{cm}) \quad (3)$$

where: $l_{s,max}$ is the maximum transfer length (see Eq. (4)); $s_{r,max}$ is the maximum spacing between cracks (see Eq. (5)); ε_{sm} is the average deformation of steel; ε_{cm} is the average deformation of concrete; ε_{cs} is the contraction stress of concrete.

To estimate the transfer length, Eq. (4) is used, for the Model Code [5]:

$$l_{s,max} = k \cdot c + \frac{1}{4} . \frac{f_{ctm}}{\tau_{bms}} . \frac{\emptyset_s}{\rho_{p,eff}} \quad (4)$$

where: k = 1.0; c is the cover; τ_{bms} is the steel-concrete bond stress; $\emptyset_s$ is the nominal diameter of the bars; and $\rho_{p,eff}$ is the effective rate of reinforcement for the tensile bar.

For the EuroCode, Eq. (5) uses the maximum spacing between cracks, calculated as follows:

$$S_{r,max} = k_3 c + k_1 k_2 k_4 \times \frac{\emptyset}{\rho_{p,eff}} \quad (5)$$

where: k_1 relates to the properties of steel; k_2 relates to the distribution of steel in the reinforcement; and k_3 and k_4 are worth, respectively, 3.4 and 0.425.

Regarding the calculation of the deformation, it is estimated in accordance with the crack opening phases (formation and stabilization). For the MC [6], this also assists in estimating internal and external crack openings (see item 7.6.4.4 of the MC [6]).

In the crack formation phase, the MC [6] is calculated as follows:

$$\varepsilon_{sm} - \varepsilon_{cm} = \left(\frac{\sigma_{sr}}{E_s}\right)(1 - \beta) - \eta_r \varepsilon_{sh} \quad (6)$$

where: β is an empirical coefficient that depends on loading (Table 7.6-2 [6]); η_r relates to retraction and ε_{sh} considers the deformation of the steel.

And the EC [13] is calculated as follows:

$$\varepsilon_{sm} - \varepsilon_{cm} = 0.60\left(\frac{\sigma_s}{E_s}\right) \quad (7)$$

where: σ_s is the stress in the tensile reinforcement in the cracked section.

With regard to the crack stabilization phase:

$$\varepsilon_{sm} - \varepsilon_{cm} = \frac{\sigma_s - \beta . \sigma_{sr}}{E_s} - \eta_r . \varepsilon_{sh} \quad (8)$$

where: σ_s is the stress of steel in a crack; σ_{sr} is the maximum stress in the reinforcement, $\rho_{p,eff}$ is the relation between the areas of reinforcement (see 7.6.4.4 of the MC [6]) and β relates to loading (see Table 7.6-2 of the MC [6]); E_s is the modulus of deformation of steel.

And, for the EuroCode [13], the following expression is used:

$$\varepsilon_{sm} - \varepsilon_{cm} = \frac{\sigma_s - k_t \cdot \frac{f_{ct,eff}}{\rho_{p,eff}} \cdot \left(1 + \alpha_e . \rho_{p,eff}\right)}{E_s} \quad (9)$$

where: σ_s is the stress in the tensile reinforcement in a cracked section; α_e is a relation between the modulus of elasticity; $\rho_{p,eff}$ is a relation between concrete area, diameter of steel bars and $A_{c,eff}$; k_t a coefficient that depends on the duration of the applied load, being 0.6 for short term loading and 0.4 for long term loading; $A_{c,eff}$ is the effective concrete stress area; E_s is the modulus of deformation of steel.

NBR 6.118 [3] indicates to perform the calculations of the load in the SLS and of the moments of inertia in the stages of deformation of the part (stage I or stage II, being that stage I has the characteristic of not forming visible bending cracks, and stage II has the characteristic of presenting cracks in the tensile zones, therefore, the concrete is discarded). With regard to the calculation of crack opening, the standard [3] indicates that it should adopt the lowest value obtained between:

$$w_k = \frac{\emptyset_i}{12{,}5\eta_1} \frac{\sigma_{si}}{E_{si}} \frac{3\sigma_{si}}{f_{ctm}} \quad (10)$$

$$w_k = \frac{\emptyset_i}{12{,}5\eta_1} \frac{\sigma_{si}}{E_{si}} \left(\frac{4}{\rho_{ri}} + 45\right) \quad (11)$$

where σ_{si}, $\emptyset_i$, E_{si} and ρ_{ri} are defined by case; η_1 is the surface conformation coefficient of the bars; ρ_{ri} is the bond rate of passive or active reinforcement; σ_{si} is the tensile stress at the center of gravity of the reinforcement in stage II.

In this context, NBR 6.118 [3], in its crack opening model, does not use the multiplication between the average deformation of the structure and the maximum transfer length, nor does it allow differentiating the internal and external crack openings. These, in turn, help to schedule preventive and predictive maintenance on the structure and, consequently, reduce post-construction costs. Consequently, there is the possibility of including the crack opening phases (formation and stabilization) in the models of the national standard, in order to configure their physical meaning, that is, the transfer length for the redistribution of efforts, as adopted by the Model Code [6]. It will thus help in maintenance programs and, consequently, in improving the performance and durability of RC structures.

However, it is important to point out that, in Section 4.2, more concise analyses are made regarding the crack opening. They help to verify this parameter, as well as to compare the Brazilian standard with international codes. They can indicate if the differences between the models, pointed out by Guedes and Rodrigues [24], have an impact on the useful life of the designed elements.

4.2 Quantitative Analysis of Crack Opening in RC

Fig. 3 presents the estimates of crack openings (W_k) for beams A, B and C, calculated using Eqs. (2), (3), (10) and (11), in addition to presenting the maximum allowed values ($W_{k,max}$) for each prescription.

Analyzing Fig. 3, it can be seen that:

(1) The estimated values of the crack opening, according to the prescriptions studied, are below the maximum allowable limits ($w_k < w_{k,\max}$), for an intended PUL of 50 years. This indicates that the sizing and service verification fit the durability prescriptions;

(2) The values calculated for crack opening (w_k) by the Brazilian standard are lower than those of the international codes, being more rigorous for the CEA, the more unfavorable environment. As an example, there is Beam C, in which the values of w_k for the NBR 6.118 [3] are 27% lower than those for MC [6] and 46% lower than those for EC2 [13];

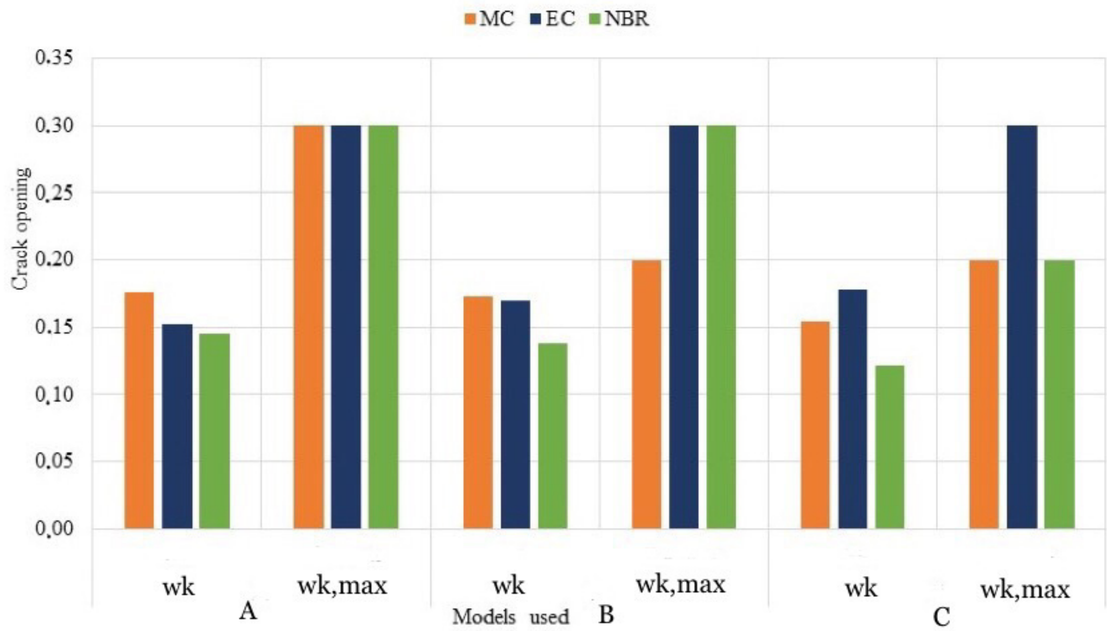

Fig. 3 Comparison between the calculated values and the maximum values for crack opening, according to the prescriptions studied.

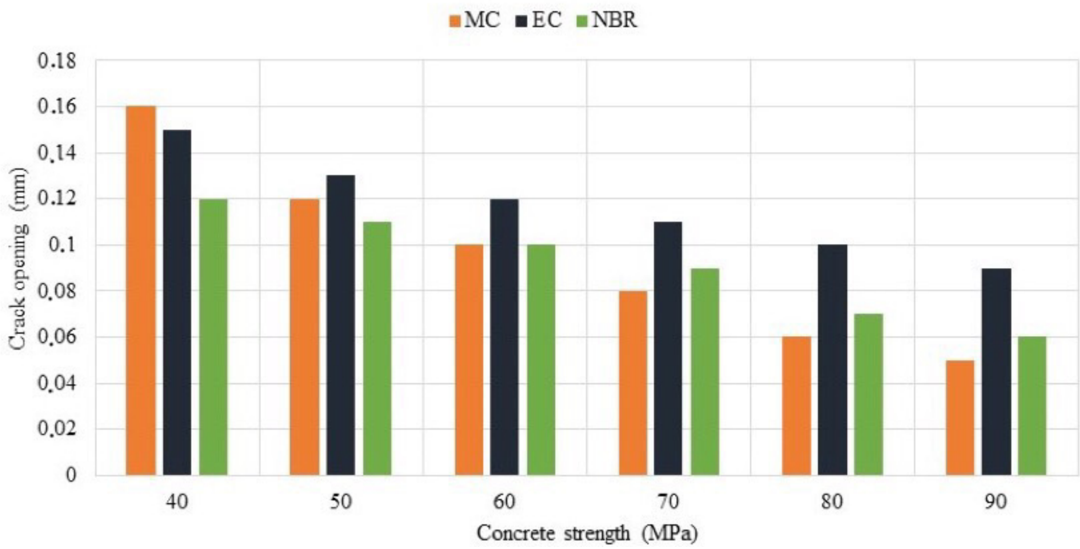

Fig. 4 Relation between concrete strength and crack opening values for each normative prescription studied.

(3) With regard to the limit values of crack opening ($w_{k,\max}$) (for a PUL of 50 years), there is a similarity in environments with risk of carbonation (Beam A). However, regarding regions where there is a high risk of chloride attack (Beams B and C), NBR 6.118 [3] and EC2 [13] are less restrictive than the Model Code [6];

(4) And, finally, a significant variation between the values of w_k and $w_{k,\max}$ can result in an oversized work and in higher construction costs, but it ensures an effective gain in the useful life of the structures. This procedure, adopted in the Brazilian standard [3], in a way, contributes favorably to mitigating the deficiency that is present in the requirements that

define the CEA, tending to minimize the errors of interpretation of the aggressiveness of the environment.

Fig. 4 presents the crack opening forecasts for the international reference codes (MC [6] and EC [13]) and for the Brazilian standard [3]. The values of mechanical strength of concrete vary (40, 50, 60, 70, 80 and 90 MPa) and the reinforcement ratio remain constant (5×Φ20 mm), for an environment that has a risk of carbonation of the concrete and moderate aggressiveness (CEA: XC3 for the MC [6] and EC [13], and II for the NBR 6.118 [3]).

It is possible to observe greater rigor with regard to the opening of cracks as the strength of the concrete increases. More specifically, the MC [6] presents values 52% lower, the EuroCode [13] 75% lower, and the NBR 6.118 [3] 70% lower; and it is important to emphasize that, for this purpose, the percentage differences between common concretes (40 and 50 MPa) and those with high strength (60 to 90 MPa) were considered. Therefore, it can be seen that for HPC (high performance concretes), more specifically HSC (high strength concretes), lower crack openings are expected. This can be explained, according to Ferreira and Hanai [25], by the fact that the stress propagation in these concretes (HSC) is classified as “almost-fragile” rupture, due to its high strength. In these cases, the presence of deeper microcracks is observed, especially with regard to the fracture planes, and, therefore, greater care is needed with regard to crack control.

5. Conclusions

It can be observed that the NBR 6.118 [3] presents differences, previously noted by Brazilian authors, with regard to aspects such as the subdivision of the environmental aggressiveness classes, the cover values (minimum and nominal) and the estimate for crack opening (equations used to dimension). In this sense, it is observed that the international codes, Model Code [6] and EuroCode [13], present greater detail with regard to the parameters mentioned above (environmental aggressiveness, cover and crack opening).

More specifically, the qualitative analysis in this work presented a comparison between the standards present in the three normative prescriptions studied, showing that the procedures adopted differ, mainly, in what concerns the CEA, verified as being the ruling parameter of the others (the values of cover thickness, mechanical strength and crack opening are estimated from it).

Through the quantitative analysis, it was possible to verify that the prescriptions (NBR 6.118 [3], MC [6] and EC [13]) are adequate to the verification of the maximum values, in addition to the fact that the Brazilian standard presents a greater restriction than the others regarding the opening of cracks. In summary, values 48% lower (on average) than the maximum allowed values can be observed for the NBR 6.118 [3], 26% lower (on average) for the Model Code [6], and 44% lower (on average) for the EuroCode [13].

As for the study of the strength of concrete, a greater restriction of the codes can be generally observed. Therefore, for HSC (f_c between 60 and 90 MPa) values are estimated, on average, 65% lower than those estimated for common concretes (40 and 50 MPa). This fact is also correlated with the type of rupture (almost-fragile) of HSC.

Finally, the singularities present in the prescriptions studied were highlighted, making an analysis regarding the Brazilian context. It also highlighted the need to review some points that could be improved in the Brazilian standard, such as the environmental aggressiveness classes and the cover thicknesses. Added to this is the fact that the Brazilian standard has been shown to be efficient in terms of limits to guarantee the durability of the structures.

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