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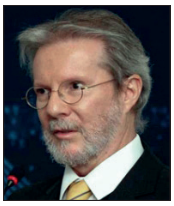
Concrete structures. Contribution to the safety assessment of existing structures

Estruturas de concreto. Contribuição à análise da segurança em estruturas existentes



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Abstract

The safety evaluation of an existing concrete structure differs from the design of new structures. The partial safety factors for actions and resistances adopted in the design phase consider uncertainties and inaccuracies related to the building processes of structures, variability of materials strength and numerical approximations of the calculation and design processes. However, when analyzing a finished structure, a large number of unknown factors during the design stage are already defined and can be measured, which justifies a change in the increasing factors of the actions or reduction factors of resistances. Therefore, it is understood that safety assessment in existing structures is more complex than introducing security when designing a new structure, because it requires inspection, testing, analysis and careful diagnose. Strong knowledge and security concepts in structural engineering are needed, as well as knowledge about the materials of construction employed, in order to identify, control and properly consider the variability of actions and resistances in the structure. With the intention of discussing this topic considered complex and diffuse, this paper presents an introduction to the safety of concrete structures, a synthesis of the recommended procedures by Brazilian standards and another codes, associated with the topic, as well a realistic example of the safety assessment of an existing structure.

Keywords: structures safety, existing concrete structures safety, concrete structures evaluation.

Resumo

A avaliação da segurança de uma estrutura de concreto existente difere daquela adotada no projeto de estruturas novas. Os coeficientes de ponderação das solicitações e das resistências, adotados na fase de projeto, levam em conta incertezas e imprecisões relacionadas com os processos de construção das estruturas, variabilidade da resistência dos materiais, além das aproximações numéricas dos processos de cálculo e dimensionamento. Entretanto, quando se analisa uma estrutura acabada, um grande número de fatores desconhecidos durante a etapa de projeto já se encontram definidos e podem ser mensurados, o que justifica uma redução nos coeficientes de majoração das ações ou de minoração das resistências.
Diante disso, entende-se que analisar a segurança de uma estrutura acabada é muito mais complexo que introduzir a segurança no projeto de uma estrutura nova, pois requer inspeção preliminar, ensaios, análises e vistoria criteriosa. São necessários sólidos conhecimentos e conceitos de segurança em engenharia estrutural e também conhecimentos sobre os materiais de construção empregados, de forma a identificar, controlar e considerar corretamente a variabilidade das ações e das resistências na estrutura. Com a intenção de discutir este tema considerado complexo e difuso, apresenta-se neste artigo uma introdução à segurança das estruturas de concreto, uma síntese da revisão bibliográfica dos procedimentos recomendados por normas nacionais e normas internacionais associadas ao tema, bem como um exemplo prático de avaliação de uma estrutura existente para verificação da segurança.

Palavras-chave: segurança de estruturas, segurança de estruturas existentes, avaliação de estruturas de concreto.

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1. Introduction

Due to recent events related to the collapse of structures in Brazil[1] and the world[2], the attention of the technical community to structural safety issues grows increasingly. There are several cases of buildings that are breaking down even before handed over to the customer, that is, during the construction period. In addition, there is a growing market for retrofit of existing structures, which makes this current and of great practical interest matter, for a large part of structural engineers do not mastered the concepts, models and safety criteria of assessment of an existing structure.

Although they are subject to depreciation over time, being exposed to the environment and also the use, and even if they have or not properly maintained, as required by the *ABNT NBR 5674:2012* [1], is unworkable and unacceptable, economic and environmentally, that the buildings are simply replaced when they reach the end of their design life (VUP), provided in accordance with *ABNT NBR 15575:2013* [2].

It is also unacceptable that existing structures are analyzed according procedures applicable only in new structures, often resulting in unnecessary interventions and strengthening, which could make unfeasible the business by term and/or excessive costs, created by a mistaked project.

Therefore, given the complexity of the study and analysis of existing structures, the evidence of the frequency of partial or total collapse of structures in use or under construction[3], and considering that Brazil has an immense amount of buildings with advanced age, with incalculable heritage built in concrete, the discussion about the security of these structures is even more necessary and urgent.

Table 1 – Motives, scopes and actions that justify safety assessment of existing structures (Helene (3))

Motives	Scope	Actions
Concrete receipt control, in new work site, points that $f_{ck,est} < f_{ck}$	Search for the new fck, to redesign or assessment of structural safety	Transform concrete compressive strength results obtained by drilled cores in values that are equivalent to concrete characteristic strength of the new structure, in order to allow the use of the same safety methods adopted for design of new structures.
Concrete looking improper or not complying with the ordered/specified	Analyze concrete for comparison with orders/ specifications	Search for composition, mix design, specified strength and other properties of the delivered concrete for casting of a structural element, as ordered for the concrete supplier. Usually, these are commercial issues between the companies.
Concrete exposed to aggressive environment	Analyze concrete characteristics e properties related to its resistance to the aggressive environment	Complex concrete life cycle analysis in that environment based on the design service life of the structure, preventive maintenance prescriptions of the structure use and maintenance manual, eventual accelerated tests or assessment of similar existing buildings. With the concrete compressive strength, characteristics and properties, apply service life models available in the technical literature.
Quality of structure execution	Analyze concrete homogeneity, dimensions of casted elements, tolerances	Analysis aided by use of semi destructive and nondestructive tests, topography resources, level and laser plummet, columns eccentricity, geometrical dimensions and drilled cores sampling of complementary areas, intended to the quality assurance of concreting services complying with codes requirements.
Survey	Inspection and diagnosis to clarify pathologic issues	Application of recognized and sophisticated techniques for field inspections and lab and field tests, eventual load tests, drilled cores sampling, intended to the diagnosis and prognosis of partial or full collapses, a severe repair issues and severe deformations.
Change of use, retrofit	Assess the conditions of the existing structure	As built structural analysis with inspection of dimension, reinforcement, concrete, drilled core sampling, etc., intended to the safe change of use of the structure, with no increase of overloads.
Corrective intervention or structural rehabilitation	Assess the present safety conditions and design necessary interventions	Application of recognized and sophisticated techniques for field inspections and lab and field tests, eventual load tests, drilled cores sampling, intended to the diagnosis, assessing structural safety for design of interventions.

1 *Torre de moinho desaba e deixa 5 feridos em Maceió; moradores são retirados. Describes the collapse of a structure of 50 years of age, even after reforms increased weight together had no structural reinforcement. The accident left injured and damaged homes. Available in:http://g1.globo.com/al/alagoas/noticia/2014/09/moinho-que-desabou-em-maceio-tinha-problemas-estruturais-diz-laudo.html. Access: October, 08th 2014.*

2 *Once investigaciones por caso Space precluyeron: Fiscal. Describes unfortunate tower collapse case in Colombia, followed by demolition and implosion of similar towers by serious mistake project. Available in: http://www.vanguardia.com/actualidad/colombia/279832-once-investigaciones-por-caso-space-precluyeron-fiscal. Acess: October, 01st 2014.*

3 *As an example, we can mention the significant recent collapses: Building Sand White (Pernambuco, 2004. Building with 25 years, delivered in 1979, collapsed completely due to execution failed connections shoes and pillars), Royal Building Class (Pará , 2011. collapsed under construction due to errors in design and construction), building Freedom (Rio de Janeiro, 2012. He collapsed, taking with him two adjacent buildings, and revealed errors in the reform of procedures), Shopping Rio Poty (Piauí, 2013. building under construction that collapsed due to failure to execute related to shoring).*

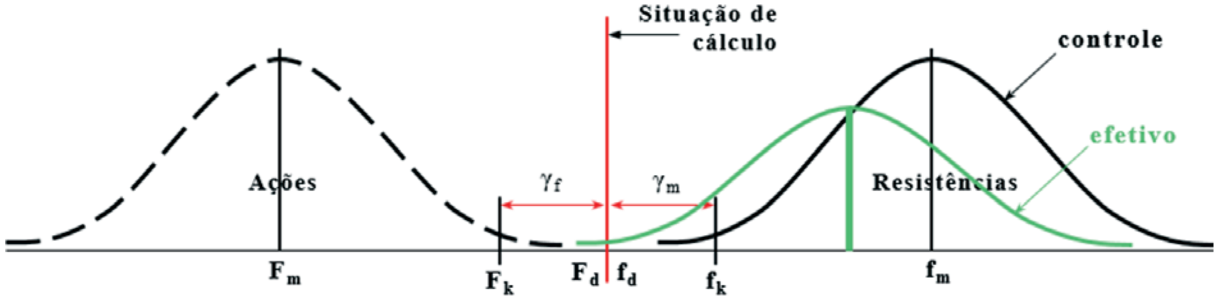
There are several reasons that can lead to the need of assessing an existing structure safety, leading to different scopes of work, set out in Table 1.
The safety assessment of an existing concrete structure is different from that adopted for a new one [4]. According to standard *ABNT NBR 8681:2003* [5] and *ABNT NBR 6118:2014* [6], the partial factors for actions and strength, adopted in the design phase, take into account uncertainties and inaccuracies related to the construction processes of structures, variability of materials strength, in addition to numerical approximations of calculation and design processes.
However, when analyzing a finished structure, a large number of these unknowns factors during the design phase, are already defined and can be measured, which justifies a modification in actions increasing factors and in strength reduction factors [7].
This issue was already addressed in 1983 by the *Committee Euro-International du Beton* (CEB). Regarding to actions, the CEB [8] already indicated that, at least for the sustained loadings, the increasing factors adopted for existing structures analysis should be lower than usual, based on geometric measurements, actual densities and more accurate load estimations.
With regard to materials, the CEB also warned about the values of “characteristic” compressive strength of concrete, to be considered in the analysis of existing structures. By definition, a characteristic value is linked to a concept of security and quality of the structures before construction, which makes this aplication inconsistent for existing structures, in which geometries and properties of used materials are better known.
In addition, it was also mentioned the need of considering a second problem: the age at which the characteristic value should be referenced, since most of the design codes was based on nominal strength values at 28 days (as to this day). As in that time, today the study of structures age conversion for 28 days is still little used, controversial and uncertain.
Therefore, it is understood that analyze the security of a finished structure is much more complex to enter the safety of a new structure design, it requires preliminary inspection, testing and careful survey. It takes solid security knowledge and concepts in structural engineering as well as knowledge of the construction materials used in order to identify, control and properly consider the variability of actions and strength in the structure.
In order to discuss this topic considered complex and diffuse, is presented in this paper an introduction to the safety of concrete structures, a synthesis of the literature review of the procedures recommended by Brazilian regulations and international standards established and respected in Brazil associated with the topic as well as an assessment of the implementation of the hypothetical example of an existing structure for security verification.

2. Safety in design of concrete structures

The concept of security structures, in general, is associated with statistical tools and is characterized by probabilistic analysis of a structure to maintain its bearing capacity, preventing their ruin [9]. This way are defined limits states (ultimate or service) to the structure and, regardless of the method of calculation used, the project should be performed in order to always maintain the relationship $\boldsymbol{R_d} \geq \boldsymbol{S_d}$[4].
Fig.1 shows a simplified view of probabilistic safety consideration. Through the of semi-probabilistic analysis of variables influencing the safety of structures, namely increase actions and reduce material strength, it is possible to perform the design of new structures and assess the security of existing structures, this time with effectively measured or field estimated values.
To this end, the *fib Model Code 2010* [10] recommends four safety model checking, of whom an cites two: Security Probabilistic Method and Partial Safety Factor Method (or Semi probabilistic method).

- Probabilistic Method: because of its complexity and even lack of knowledge of the variables, it is not the most used and therefore will not be subject of discussion in this article;
- Partial Safety Factor Method: also known as semi-probabilistic method makes use of predetermined conversion coefficients for calculating characteristic values of values.
  The *ABNT NBR 8681:2003* [5] offers stress calculating tools based on this method, as the following concepts:

Figure 1 – Representation of safety analysis according to probabilistic method



4 *Design Strengths (R_d) must be greater than Design Actions values (S_d).*

For actions:

$$F_d = F_k \cdot \gamma_f \quad (1)$$

$$\gamma_f = \gamma_{f1} \cdot \gamma_{f2} \cdot \gamma_{f3} \quad (2)$$

γ_{f1} : considers variability of actions;
γ_{f2} : combination coefficient (ψ0 - simultaneity);
γ_{f3} : considers possible assessment errors of the actions effects due to construction method or calculation method.
For materials strength:

$$f_d = f_k / \gamma_m \quad (3)$$

$$\gamma_m = \gamma_{m1} \cdot \gamma_{m2} \cdot \gamma_{m3} \quad (4)$$

γ_m : can refer to concrete (in this case, is called γ_c) and to steel (γ_s).
γ_{c1}: takes into account the variability of the effective strength of the concrete structure, which is always greater than the variability of resistance "potential" of the concrete in their production source, as evaluated by molded specimens;
γ_{c2}: considers the differences between the effective resistance of the concrete in the structure and the potential resistance measured in conventionally standardized specimens;
γ_{c3}: considers the uncertainties in the determination of resistant requests, whether as a result of the construction methods, whether as a result of the method (model) of employee calculation.
Cremonini [11] explains that the coefficients γ_{c1} and γ_{c2} can be determined by experimental measurements and statistical analyzes as γ_{c3} is found by means of empirical criteria. In the case

Table 2 – Strength reduction factors utilized for design of new structures

Factor	ABNT NBR 6118 (Fusco (12))	fib Model Code 2010 (10)
γ_c	1,4	1,5
γ_{c1}	1,2	1,39
γ_{c2}	1,08	1,05
γ_{c3}	1,08	1,05

of concrete, it can be considered that decomposes γ_c approximately the following parts:

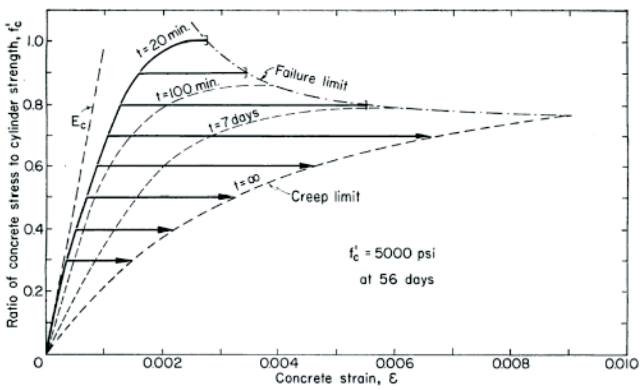
$$\gamma_c = 1{,}07 \text{ a } 1{,}32\ (\gamma_{c1}) \cdot 1{,}10\ (\gamma_{c2}) \cdot 1{,}10\ (\gamma_{c3}) \quad (5)$$

The result of the product of the plots varies between 1.30 and 1.60. Table 2 shows the comparative values adopted by Brazilian standards compared to the requirements of fib Model Code 2010 [10]. Some researchers believe, mistakenly, that aspects related to the strength and variability of the constituents of concrete materials are covered by γ_c, but it is clear that, conceptually, this coefficient exclusively covers the differences between the concrete strength control procedures, well established in *ABNT NBR 5738:2003* [13] and in *ABNT NBR 5739:2007* [14], and the procedures adopted in construction site [15].
Therefore, the coefficients γ_{c1} and γ_{c1} (product of order 1.3 to 1.45), as stated by the *ABNT NBR 8681:2003* [5], cover the unknown differences between the geometry of the standard specimen and the structural component geometry as well as their actual characteristics of density, launch, healing, shoring removal and early loading, which in general are different from standard procedures in *ABNT NBR 5738:2003* [13].
It is evident that the work procedures are unlikely to be as accurate as the control prescribed by *ABNT NBR 12655:2006* [16], such that the effective resistance of the concrete compression in the structure will always be less (of 1.3 or order less) that resistance of the concrete compressive assessed by *ABNT NBR 12655:2015* [16].
An experimental approach to γ_c coefficient can be obtained through actual comparison studies between the strength control from *ABNT NBR 12655:2015* [16], which results in production of average strength potential (f_{cm}), with the actual average strength, as measured trough core ($f_{c,ef,m}$). According Cremonini [11], the average difference walks around 24% (i.e., 1.24).

3. Effects of sustained loads

The sustained loading affects the concrete compressive strength. The variation of the retained strength of the concrete under load, also known in Brazil by "*Rüsch effect*", is considered in the present semi-probabilistic safety method release for structural design. This consideration is made using an additional reduction coefficient, included in the idealized stress-strain diagram of *ABNT NBR 6118:2014* (*item 8.2.10.1*) [6], the value, for $f_{ck} \leq 50$MPa and the loading at 28 days, is 0.85.
According Rüsch research [17], the concrete when subjected to long lasting loading (t > 20minuts), undergoes compressive strength loss, a phenomenon similar to the relaxation (Fig.2).
On the other hand, it is known that the Portland cement concrete, throughout his life, due to cement hydration, gains strength as it appears to the right of Fig. 3.
Thus, the load resistance of concrete can be easily provided as a result of the product of two coefficients: β_{cc} which depends on the rate of growth of strength of concrete compressive load from the date of application,and $\beta_{c,sus}$, which depends on the permanence of load effect, also called the Rüsch effect in Brazil.
The growth rate of the concrete compressive strength, can be

Figure 2 – Influence of duration and intensity of axial loading in concrete compressive strength (Rüsch (17))



expressed by the model suggested by fib Model Code 2010, namely:

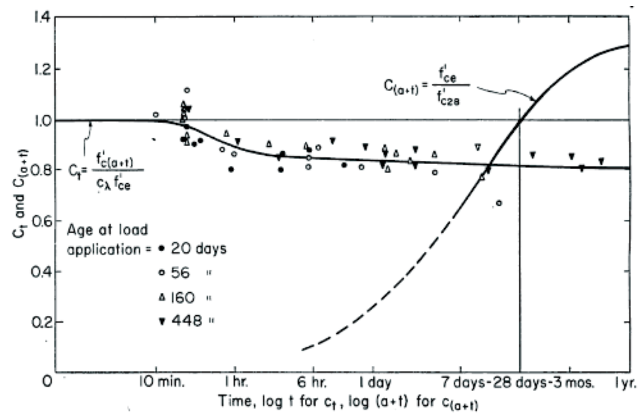
$$\beta_{cc} = \frac{f_{c,j}}{f_{c,28}} = e^{s*\left(1-\sqrt{\frac{28}{j}}\right)} \quad (6)$$

where:
$f_{c,j}$: the concrete compressive strength, measured in "j" days old;
$f_{c,28}$ concrete compressive strength, measured at 28 days;
s : coefficient that depends on the cement, the w /c ratio, and moisture conditions of the concrete.
For $\beta_{c,sus}$ *value*, the same *fib Model Code 2010* suggests the following model:

$$\beta_{c,sus} = \frac{f_{c,sus,t}}{f_{c,t_0}} = 0{,}96 - 0{,}12 \cdot \sqrt[4]{\ln\{72 \cdot (t - t_0)\}} \quad (7)$$

where:
$f_{c,sus,t}$: compressive strength of concrete under sustained load at t age, counted from the date t_0 of load application, in MPa;
$f_{c,t0}$: potential compressive strength of the concrete, at the time t_0, just before application of long lasting load in MPa.
In the case of ABNT NBR 6118: 2014, the value of $\beta_{cc} \cdot \beta_{c,sus}$ = 0,85 referred to t_0=28days old, i.e., it is assumed that the growth of the concrete compressive strength from 28days to 50years will only, β_{cc}=1,17 (17%), wich corresponds to the index s = 0,16, and the decrease of compression strength of concrete due to the load applied to 28 days until 50 years and maintained, the Rüsch effect, will be $\beta_{c,sus}$ = 0.73, whose product results $\beta_{cc} \cdot \beta_{c,sus}$ = 1,17 · 0,73 = 0,85.
It is observed that it is very conservative value, because actually the growth of resistance of concrete from 28 days to 50 years always exceeds 17%, and the decrease due this effect, according to Rüsch, would be at most 0.75.
In Fig. 4 it can be seen the resulting ($\beta_{cc} \cdot \beta_{c,sus} \cdot f_{cm}$) of growth and reduction effect, due long term loads, on the concrete strength, according Rüsch [17].

Figure 3 – Effects of age of loading in concrete compressive strength (Rüsch (17))

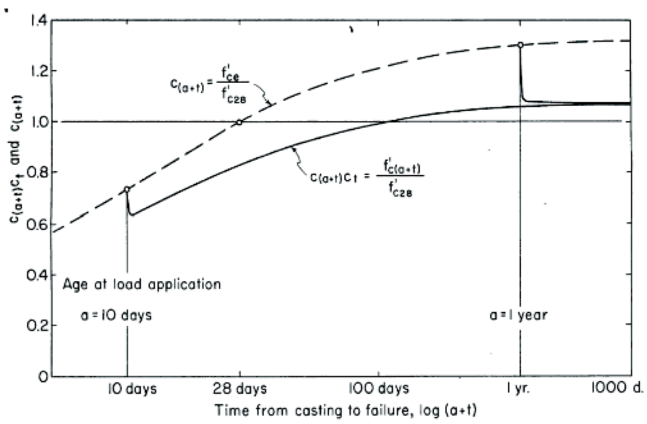


In this regard it should be noted that in the case of a loaded structure, when analyzing the resistance from concrete cores, should be borne in mind that the resistance obtained may also be under the influence of the Rüsch effect. This fact will depend on the structure loading history and also of its age, and there is still no clear consensus on how to consider this phenomenon in structural safety for existing structures.

4. Built structures assessment

Are presented some requirements of Brazilian and international standards recognized and respected in Brazil. The main focus is to analyze the specific technology issues and assessment and

Figure 4 – Compressive strength (product $\beta_{cc} \cdot \beta_{c,sus} \cdot f_{cm}$) as a function of long term axial loading (Rüsch (17))



verification of safety on existing structures, answering the following basic questions:

- How to get the concrete characteristic strength equivalent to the concrete samples from concrete cores?
- What are the key safety parameters to be considered in the analysis of existing structures?
- What are the differences with respect to the design of the usual parameters used for new structures

4.1 General cases and brazilian standards

To evaluate the strength of concrete compression on existing structures in order to verify the safety of the structure, should be employed the concepts and requirements of the standards *ABNT NBR 8681*:2003 [5], *ABNT NBR 6118:2014* [6] and *ABNT NBR 7680:2015* [18], which is the Brazilian standard most appropriate and most recent review on the concrete *in situ* via concrete cores.

Therefore, considering that the steel strength does not change with time (provided it is kept in a good concrete), the unknown is greater when the characteristic concrete compressive strength, the 28 days of age agreed to f_{ck} and measured by the *ABNT NBR 12655:2006* [16], *ABNT NBR 5738:2003* [13] and *ABNT NBR 5739:2007* [14].

In the case of existing structures this resistance should be judged from the strength of the evidence taken from a different age 28 days, which may be termed core resistance $f_{c,ext}$. To get f_{ck} from $f_{c,ext}$, *ABNT NBR 7680* prescribes a number of standard procedures that take into account the differences between the measured resistance in the concrete sampled from the concrete mixer and subjected to ideal conditions of standard (f_{ck}) with the effective resistance of the concrete in the work ($f_{c,ext}$), always less than "potential".

4.1.1 First step

Therefore the first step consists to inspect and analyze the structure of obtaining a $f_{ck,equivalent}$ from $f_{c,ext,}$ comparing it with the design strength, f_{ck}. Since $f_{ck,equivalent} \geq f_{ck}$ design, analysis or verification of safety can be considered met and approved.

In case that $f_{ck,equivalent} < f_{ck}$ design , the Security check should proceed with the second step, which is to check the safety with this new f_{ck}.

4.1.2 Second Step

For review and verification of structural safety and global stability, considering the ultimate limit state (ULS), *ABNT NBR 6118:2014* on its entry 12.4.1, admits that in the case of f_{ck} obtained from extracted testimonies of structure, is adopted: f_{ck} obtained from extracted testimonies of structure, is adopted:

$$\gamma_c = \frac{\gamma_{c,original}}{1,1} \quad (8)$$

Therefore, in usual cases, γ_c = 1,4/1,1 = 1,27, which is equivalent mathematically, to multiply the core result by 1.1, that is, increase it by 10%, once the core result represents better the effective strength of the concrete near from the drilled region in the structure. For service states verifications purposes, shall be adopted γ_c =1,0.

If the safety check with this new γ_c 1,27 or 1,0 is met, the process over at this point.

4.1.3 Third step

If the line is not met, the security check can proceed to the third step, which is the careful observation of the finished structure giving geometrical measures position armor, armor rate, eccentricity tolerances, level and plumb, thickness slabs, or checking the accuracy of execution of the structure.

This last step is also advisable to review by sampling the specific masses of materials, calculate the variability of the concrete strength, carefully review the medium loads and variability as well as check the concurrency loads.

If the rigor of execution is within the tolerance limits as described in *ABNT NBR 14931:2004* [19] (equivalent to *Chapters 5* and *6* of *ACI 318-11* and *Chapter 8* of the *fib Model Code 2010*), the security check may adopt mitigation coefficients of smaller concrete strength 1,27 and steel, g_s 1.05 for ULS, and perform verification with actual load values (effective density), effective concurrency, etc.

4.1.4 Fourth step

Staying non conformity of the structural safety for these conditions of use, choose from the following alternatives:

- determine the structure use restrictions;
- provide repair and strengthening project;
- decide on the partial or total demolition.

4.2 International standards

International standards have a methodology for analysis of similar existing structures and adhering to these concepts, especially with the first two steps, and also apply the last two steps.

4.2.1 *ACI 318-11 Building code requirements for structural concrete and commentary* [20] e *ACI 214.4R-10 Guide for obtaining cores and interpreting compressive strength results* [21]

4.2.1.1 Structures under construction, first step

During concrete control in a work in progress and forward the results of low results of resistance of concrete compression, the ACI 318-11 (Chapter 5, item 5.6.5) requests the extraction of three cores to the affected region.

If the mean value of the three cores strength is higher than 85% of the design resistance (f'_c) and the values are below 75% of f'_c, the structure shall be considered compliant and the process ends here, and this procedure shall be taken as a first step.

It is observed that this requirement is equivalent to multiply, respectively, the mean and the lowest value of the drilled cores by 1.18 and 1.33, i.e., $f_{ck,equivalent}$=1,18·$f_{cm,ext}$ or $f_{ck,equivalent}$=1,33·$f_{c,minimum,\ ext}$.

4.2.1.2 Existing Structures, first step

When the first step does not achieve compliance or wherever

Table 3 – Strength reduction factors (φ) according to ACI 318-11

Strength reduction factors		Chapter 9 (design of new structures)	Chapter 20 (assessment of existing structures)	Difference %
Tension-controlled sections		0,9	1,0	11,1
Compression-controlled sections	Members with spiral reinforcement	0,75	0,9	20,0
	Others reinforced members	0,65	0,8	23,1
Shear and torsion		0,75	0,8	6,7
Bearing on concrete (except for post-tensioned anchorage zones and strut-and-tie models		0,65	0,8	23,1

there are existing structures, *ACI 318-11* (*Chapter 20*) requires estimation of equivalent strength f'_c a more accurate way, through *ACI 214.4R-10*, on which should be considered some correction factors related to test effects, geometry and moisture of the core, as follows:

$$f_c = F_{l/d} \cdot F_{dia} \cdot F_{mc} \cdot F_d \cdot f_{core} \quad (9)$$

where:
f_c = corrected core strength;
f_{core} = drilled core strength, directly obtained in the compression test;
$F_{l/d}$ = correction factor due to core height/diameter ratio;
F_{dia} = correction factor due to core diameter;
F_{mc} = correction factor due to moisture condition;
F_d = correction factor due to drilling effect.
After correction of the compressive strength of each core, related to test variables and concrete intrinsic aspects, the standard *ACI 214.4R-10* recommend two methods for obtaining final equivalent compressive strength of concrete. They are:

• **Tolerance factor method**

$$f'_{c,eq} = \overline{f}_c - \sqrt{(K \cdot s_c)^2 + (Z \cdot s_a)^2} \quad (10)$$

where:
$f'_{c,eq}$ = sample equivalent strength;
$\overline{f}_c$ = mean equivalent strength of tested drilled cores;
K = factor that takes in account the unilateral tolerance limit for a 10% quantile (*ACI 214.4R-10, Table 9.2*) which depends on the desired reliability level in the design;
s_c = sample standard deviation;
Z = factor that takes in account the uncertainty of the use of strength correction factors (*ACI 214.4R-10, Table 9.3*) and also depends on the desired reliability level;
s_a = standard deviation of strength correction factors *(ACI 214.4R-10, Table 9.1).*

Alternative method

$$\left(\overline{f}_c\right)_{CL} = \overline{f}_c - \sqrt{\frac{(T \cdot s_c)^2}{n} + (Z \cdot s_a)^2} \quad (11)$$

$$f'_{c,eq} = C \cdot \left(\overline{f}_c\right)_{CL} \quad (12)$$

Onde:
$f'_{c,eq}$ = sample equivalent strength;
$\overline{f}_c$ = mean equivalent strength of tested cores;
T = factor obtained by Student *t*-distribution with (n-1) degrees of freedom, depending on desired reliability level (*ACI 214.4R-10, Table 9.4*);
s_c = sample standard deviation;
Z = factor that takes in account the uncertainty of the use of strength correction factors (*ACI 214.4R-10, Table 9.3*) and also depends on the desired reliability level;
s_a = standard deviation of strength correction factors *(ACI 214.4R-10, Tabela 9.1);*
n = number of tested cores;
C = coeficiente related to intrinsic variability of materials strength in structure (*ACI 214.4R-10, Table 9.5*).

4.2.1.3 Second step, new structures under construction or existent

In case equivalent strength obtained by *ACI 214.4R-10* does not meet the design strength, safety must be verified adopting new coefficients for reduction of concrete strength, named strength reduction factors (φ), present in *ACI 318-11*, Chapter 20, as shown in Table 3.
Although it is contained in the same concepts of the general case adopted in Brazilian standard, *ACI 318-11* does not prescribe a strength reduction coefficient for concrete, γ_c, and in safety assessment of existing structures this coefficient reduction ranges

between 6,7% a 23,1% according to the main type of action, while in Brazil this reduction is fixed, conservative and equal to only 10% (with exception of old *ABNT NBR 6118*, from 1978 to 2003, that permitted a 15% reduction in some cases).
It is observed that in *ACI 318-11* that the introduction to safety in structural design differs from the adopted in *ABNT NBR 6118*. In the American code, the reduction factor (φ) is applied once only for steel and concrete strength. It is different from the Brazilian code procedure, in which the strength reduction factors are applied separately for concrete (γ_c) and steel (γ_s).
For example, the axial compressive strength of a short column designed through *ABNT NBR 6118:2014*, is shown in eq.13, and for *ACI-318-11*, the strength is given by eq. 14.

$$N_d = 0{,}85 \cdot \frac{f_{ck}}{\gamma_c} \cdot A_c + \frac{f_{yk}}{\gamma_s} \cdot A_s \quad (13)$$

where:
N_d = Maximum axial load, design value;
f_{ck} = characteristic compressive strength of concrete;
γ_c = strength reduction factor of concrete;
A_c = gross area of concrete section;
f_{yk} = yield characteristic strength of steel;
γ_s = strength reduction factor of concrete of steel;
A_s = steel area.

$$\phi \cdot P_{n,\max} = 0{,}80 \cdot \phi \cdot \left[0{,}85 \cdot f_c' \left(A_g - A_{st}\right) + f_y \cdot A_{st}\right] \quad (14)$$

where:
$\varphi . P_{n,max}$ = Maximum axial compressive strength, design value;
φ = Strength reduction factor;
f'_c = specified compressive strength of concrete;
A_g = gross area of concrete section;
A_{st} = total area of nonprestressed longitudinal reinforcement;
f_y = specified yield strength of reinforcement.
Therefore, comparing a short column with dimensions of 50x50cm, with f_{ck} of 35MPa and hypothetical CA-50 steel reinforcement area of 37,70cm², using *ABNT NBR 6118:2014*, the design maximum axial load would be 6951,8kN, while the same element designed using *ACI318-11* method, with reduction factor (φ) equal to 0,65, results in axial compressive strength of 4789,48kN.
This demonstrates that the American code is more conservative than Brazilian code when assessing safety in design phase.
However, assessing safety in *Chapter 20* of *ACI-318-11*, the strength reduction factor, or reduction coefficient (φ), can be increased, which means to assume an increase of the existing element strength, due to the greater knowledge of structure actual state and the reduction of the admitted variability.
For the hypothetical example above, item 20.2.5 of *ACI-318-11* restricts the increase of coefficient (φ) to 0,80 at most, in other words, an increase of 23% for the element compressive strength.
In *ABNT NBR 6118* model, it is allowed a reduction of coefficient γ_c from 1,4 to 1,27, when analyzing drilled concrete cores. In this case, altering only the factor related to concrete, the increase in the column strength would be of 7,8%. Along with another reduction in steel coefficient g_s from 1,15 to 1,0, the total element strength increase would be of 11,3%, both cases far below from the values obtained by *ACI* method.
The third and fourth steps, cited previously in the general case are no explicit in ACI 318-11, but are clearly applicable.

4.2.3 ACI 562-13 Code requirements for evaluation, repair, and rehabilitation of concrete building and commentary [22]

This document proposes a *preliminary assessment*, including design review, construction data, reports and other available documents (research for used materials) and comparison of obtained information with all requirements of standards applicable at the time of the project.
In case it is not possible to obtain sufficient information through design, specifications and other documents, consider concrete compressive strength values according to *Table 6.3.1a*, or according to values from drilled cores tested in laboratory, in order to acknowledge the actual concrete characteristics.
When decided to test concrete drilled cores, it is recommended

Table 4 – Reliability index (β) according to fib Model code 2010 (p. 31 e 32) (10)

Limit state	Safety assessment model	Reference age	New structures	Existing structures	Notes
Serviceability (SLS)	Probabilistic safety method	50 years	β = 1,5	–	Same assessment criteria for new and existing structures
	Partial safety factor method	Residual service life	–	β = 1,5	
Ultimate (ULS)	Probabilistic safety method	50 years	3,1 ≤ β ≤ 4,3	3,1 ≤ β ≤ 3,8	Allows the reduction of minimum reliability for existing structures
	Partial safety factor method	50 years	β = 3,8	3,1 ≤ β ≤ 3,8	

to estimate concrete equivalent strength () through the equation:

$$f_{ceq} = 0{,}9 \cdot \overline{f_c} \cdot \left[1 - 1{,}28 \cdot \sqrt{\frac{(k_c \cdot V)^2}{n} + 0{,}0015} \right] \quad (15)$$

where:
f_{ceq} = equivalent compressive strength of concrete;
$\overline{f_c}$ = mean core compressive strength, already corrected to consider core diameter and seasoning conditions;
V = standard deviation of effective core strength;
n = number of teste drilled cores;
K_c = modification factor of coefficient of variation (depends of complying with *ACI 562 Table 6.4.3*).
After determining equivalent compressive strength, the structure safety should be assessed according to Chapter 20 of ACI 318-11. Thus, this document from ACI does not sum much more information to ACI 318-11 and ACI 214.4R-10, only modifying the procedure for obtaining equivalent strength (first step) of concrete in existing structures, and keeping the second step, and also the third and fourth steps from the general case.

4.2.4 fib Model code for concrete structures 2010

In assessment of existing structures, the *fib Model Code 2010* [10] recommends that reduced values of γ_m are adopted, in order to account real active actions, effective dimensions and properties of materials used in the structure. For the factor γ_{Rd}, which represents the product $\gamma_{Rd1} \cdot \gamma_{Rd2}$, equivalent to the product $\gamma_{c2} \cdot \gamma_{c3}$ (Brazilian code), the standard recommends assuming the value of 1,0.
The γ_{Rd} expresses a the uncertainties in geometry and calculation methods. It is noted that in the assessment of an existing structure, there are fewer uncertainties, allowing a reduction of this factor from 1,10 to 1,00.
For a pure probabilistic method, *fib Model Code 2010* [10] suggests

Table 5 – Utilized γ_c factors in assessment of existing structures (EUROCODE 2)

γ_c original	γ_c reduced	Difference (%)
1,5	1,4	7,1
1,5	1,45	3,4
1,5	1,35	11,1
1,5	1,3	15,4

that analysis should be based in reliability indexes, frow which will be obtained new safety factors. Table 4 presents some apectcs of the reliability index (β) to be considered in design of new structures and in assessment of existing structures.

4.2.5 EUROCODE 2. EN 1992. Dec. 2004. Design of concrete structures. General rules and rules for buildings [23] e EN 13791. Jan. 2007. Assessment of in-situ compressive strength in structures and precast concrete components [24]

Similarly, the *EUROCODE 2* also recommend reduced values to be adopted for g_c and g_s, as long as uncertainties for strength calculations are minimized.
For determination of equivalent compressive strength (**first step**), *EN 13791* shall be applied, bringing calculation methods shown below in eqs. 16 and 17 below (it is always adopted the lesser value).
• **15 cores or more**

$$f_{ck,is} = f_{m(n),is} - 1{,}48 \cdot s \quad \text{or} \quad f_{ck,is} = f_{is,lowest} + 4 \quad (16)$$

where:
$f_{ck,is}$ = sample equivalent strength;
$f_{m(n),is}$ = mean equivalent strength of tested cores;
s = sample standard deviation;
$f_{is,lowest}$ = lowest compressive strength value of tested cores.
• **3 a 14 cores**

$$f_{ck,is} = f_{m(n),is} - k \quad \text{or} \quad f_{ck,is} = f_{is,lowest} + 4 \quad (17)$$

where:
$f_{ck,is}$ = sample equivalent strength;
$f_{m(n),is}$ = mean corrected strength of tested cores;
k = factor that depends on the number of tested cores (*EN 13791 Table 2*);
$f_{is,lowest}$ = lowest compressive strength value of tested cores.
Standard *EN 13791* also recommend the correction of drilled cores compressive strength before the estimation of equivalent strength, in the same way as for *ACI 214.4R-10*, taking into account h/d ratio, diameter, seasoning effect, drilling effect, among others.
In case the structure is submitted to rigorous quality control, assuring that unfavorable deviations in element sections are within the limits of *EN 1992 Table A.1*, and if the coefficient of variation of concrete strength if lower than 10%, γ_c can be reduced from 1,5 to 1,4 (**second step**).
Even more, if the calculus of the design strength is based in critical geometric data (reduced by deviations and measured in the built structure), the recommendation is to reduce g_c to 1,45. In the same case, since that the coefficient of variation of the concrete strength does not exceed 10%, could be adopted γ_c = 1,35.
When the evaluation of finished structure is based on tests and *in situ* assays on the built structure (e.g. core testing), g_c shall be reduced by the conversion factor η = 0,85 [5].
Table 5 show the percentage of reduction suggested by *EUROCODE 2* for the safety factor γ_c.
Is realized that, in the case of EUROCODE, the new strength reduction coefficient, for the concrete resistance, used to safety assessment in built structures, since that is based in core testing, is equivalent to the Brazilian standard, i.e., equal to 1,27.

5 *Segundo o próprio Eurocode o valor resultante de γ_c não deveria ser inferior a 1,3, porém, aplicando esta redução ao γ_c de 1,5, daria um valor de 1,27 para o novo γ_c.*

Table 6 – Data of drilled concrete cores

n	1	2	3	4	5	6	7	8
$f_{ci,ext}$	15,4	15,4	17,6	19,1	19,5	19,9	16,6	17,6

Finishing this second step, if the safety does not to be checked, remaining the third and fourth steps from general case.

5. Exemple

So as to perform a benchmark between the different codes, is presents below an exemple of a structure that knows that was designed with a f'_c equal to 25MPa, where was adopted some data from core tests (Table 6), and then was applied the different codes in its analysis. On the subject region, was obtained 8 cores, amount that complies with minimum criteria of all codes used on this paper. For this, was used standard cores with 10cm of diameter and h/d ratio = 2. All values of strength are expressed in MPa (Mega Pascal).

5.1 First step: equivalent strength

If it were a building structure, for analysis according to ACI 318-11 (Chapter 5), should be used only 3 results in the region with problems. For conservative reasons, of the eight available values, was used only 3 lower values.

From the results 15.4; 15.4 and 16,6MPa, is obtained $f_{c,equivalent}$ = 18.6 MPa (multiplying the average of the results by 1.18). This condition does not meet the criteria of the standard, so there is the need to find a new f_c, equivalent to further analysis.

In the Table 7 shows the correction of $f_{ci,ext}$ proposed by ACI 214.4R-10, Chapter 9.1. For this practical example, we adopted a 95% confidence level.

From the corrected values of **fc,** there is need to find the value of $f_{c,equivalent}$. This parameter can be also obtained by ACI 214.4R-10, ACI 562-13 and EN 13791: 2007, as presented in Table 8.

5.2 Second step: safety assessment

After corrections and obtaining $f_{c,equivalent}$, should be proceed with the safety evaluation, as Chapter 20 of ACI 318-11 (or Ch. 5.4 of *ACI 562-13* [6]) or the Eurocode 2.

According to the ACI 318-11, assuming that it is not a reinforcement spiral column, it would be to modify the φ safety factor from 0.65 to 0.80, or a equivalent way is to top up the equivalent resistance (f_{ceq}) obtained in Table 8 at 1.23 (and continue using φ = 0.65 in design verification).

Table 7 – Corrections according to ACI 214.4R-10 (results in MPa)

n	$f_{ci,ext}$	Correction factors ACI-214.4R-10 Cap.9.1				f_c Cap. 9.1
		$F_{l/d}$	F_{dia}	F_{mc}	F_d	
1	15,4	1 (V=0%)	1 (V=0%)	1,09 (V=2,5%)	1,06 (V=2,5%)	17,8
2	15,4					17,8
3	17,6					20,3
4	19,1					22,1
5	19,5					22,5
6	19,9					23,0
7	16,6					19,2
8	17,6					20,3

Table 8 – Values for $f_{c,equivalent}$ proposed by standards ACI 214.4R-10, ACI 562-13 and EN 13791

ACI 214.4R-10		ACI 562-13	EN 13791
$f'_{c,eq}$ Cap. 9.4.1	$f'_{c,eq}$ Cap. 9.4.2	f_{ceq} Cap.6.4.3	$f_{ck,is}$
Tolerance factor method	Alternate method		
15,0	15,4	17,1	14,4

NOTE: Standard EN 13791:2007 presumes the same adjustments for factors influencing drilled cores strength, such as: h/d ratio, diameter, moisture effects, drilling effects, among others.

6 *A análise de segurança do Cap. 5.4 do ACI 562-13 é a mesma contida no Cap. 20 do ACI 318-11.*

Table 9 – Concrete equivalent compressive strength values for safety assessment, according to ACI 318-11

ACI 318-11 Cap.20		
ACI-214.4R-10		ACI 562-13
$f'_{c,eq}$ Cap. 9.4.1	$f'_{c,eq}$ Cap. 9.4.2	f_{ceq} Cap.6.4.3
Tolerance factor method	Alternate method	
18,4	19,0	21,0

Table 10 – Values of f_{ck} for safety assesment, according to EN 13791:2007 (assuming γ_c = 1,5)

$f_{ck,is}$ EN 13791	A.2.2 (2) $\gamma_{c,Red3}$ = 1,35	A.2.3 (1) $\gamma_{c,Red3}$ = 1,19
14,4	16,0[a]	18,8[a]

[a] The presented values were increased, considering that in item A.2.2 (2) $f_{ck} = f_{ck,is} \cdot(\gamma_c/\gamma_{c,Red3})$, and item A.2.3 (1) $f_{ck} = f_{ck,is} \cdot(\gamma_c/\gamma_{c,Red4})$.

Thus, the resistance values to be adopted under this concept would be shown in Table 9. From the point of view of *EUROCODE* 2, got the $\boldsymbol{f_{ck}}$ value, is by EN 13791 (even $\boldsymbol{f_{ceq}}$ ACI), then one should apply the security analysis criteria, as described els4ewhere. Similarly to run in the previous analysis in Table 10 are exposed patches of each of the items included in its Annex A.

There is, an overall assessment and with reference to this example, the final strength calculation ranged from 16MPa to 21MPa, according to the criterion that is adopted, as shown in Table 11.

This variability demonstrates, once again, the need to always use common sense in making decisions and seek to address the problem with a holistic vision that aims to cover all variables without unduly hold a number obtained mathematically that, it is known and has been shown, can have meaning relative and not absolute.

In the safety assessment, is checked that all codes consulted, allows a large reductions in their partial factors, since the variables after a structure is built, can be measured and considered in the desing as effective values. Thus, as there is no more a lot of unknowns and uncertainties, we can work with lower safety margin and more rational.

6. Final considerations

In the universe of the actual codes was observed several criteria, however all the codes analyzed have in common the fact that the reduction of certain portions of the partial coefficients is completely feasible, without compromising structural safety.

However, to make use of new coefficients, it is necessary to have a greater knowledge of the structure, and in this respect comes the important inspection activity, in which the rigor of execution, and the geometric parameters and quality of the materials must be properly checked.

The ***fib Model Code 2010***, the composition of the material coefficient of resistance mitigation, considers explicitly, beyond the portion related to the lack of resistance of the material, the portion that takes into account the geometric uncertainties that could possibly occur during execution . In this respect, if it is found that the structure was performed using geometry was within acceptable standards with concrete strength and knowledge of the structure (through core), it would be able to effect the reduction of γm.

In the North American standard, as regards the strength of concrete, the separation of material analysis and safety analysis is evident, the first item specified by ACI 214.4R-10 or by ACI 562-13, dealing with correct inherent variables the test and the intrinsic properties of the concrete, while security is handled in accordance with Chapter 20 of ACI 318-11.

The Eurocode 2 operates analogously to fib Model Code 2010, allowing the reduction of γc coefficients since the geometry of the structure has been performed accurately and such measures are considered in the calculation (characteristic measured by an effective quality control in construction).

The new text of ABNT NBR 7680: 2015 proves to be aligned with the main standards, and the correction of the extracted testimonies resistance values close to the results calculated by different methods. However, for the analysis and reduction of the safety factor (γc), yet must-carry as prescribed in ISO 6118: 2014.

On the statements relating to the influence of age and long lasting loads in the evaluation of concrete strength, these researchers found in the

Table 11 – Concrete compressive strength values to be adopted in safety assessment (MPa)

ACI 318-11	ACI 214.4R-10		ACI 562-13	ABNT NBR 7680:2015	EN 1992-1-1 EUROCODE 2	
	Tolerance factor method	Alternate method			A.2.2 (2) $\gamma_{c,Red3}$ = 1,35	A.2.3 (1) $\gamma_{c,Red4}$ = 1,19
18,6	18,4	19,0	21,0	19,6	16,0	18,8

available literature, no mention of the need to backdate the strength of concrete at 28 days. No text was found considering the increase or decrease of the concrete strength after 28 days when considered in existing structures and aged lot or a little longer than 28 days.

A practical recommendation of the authors, would be considered in the design verification, the resistance obtained in the age of testing without any regression, and proceed with the calculations according to standard theory.

General and holistic way, it was found that article that the security check of an existing structure is a complex and differentiated analysis, which depends on thorough knowledge of the structure and concrete technology, as well as the security concepts.

In short, it is necessary that the professional engineering responsible for examining the existing structure know the variables involved in the process and learn to despise those who have worked, ensuring a reliable assessment which results in safe and economic decisions. In addition, to ensure the structural performance, often must be monitored the buildings and the inspections and necessary and periodic maintenance.

For new construction, the rationalization of construction, the Project Quality Control (PTC) and the Technological Control (CT) of the works should be encouraged and implemented, in order to obtain safe works within the design conditions and well build rules.

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