Therefore, following conclusions can be drawn: for small values of f_{ck}, the reliability index is low and can be smaller than 3.8. The reliability index corresponds with the CoV of f_{ck} which is given by CoV(f_{ck}) = 5 MPA / f_{ck}. For larger values than f_{ck} (35 MPa), there is almost no significant influence on the failure probability.

6. Summary and Outlook

In this paper, structural RC members without shear reinforcement according to EC2 are investigated using probabilistic concepts. Reliability-based evaluations using first (FORM) and second (SORM) order methods as well as Monte Carlo methods are described and applied. The evaluation is conducted for different types of structural members, like slabs, bridge decks and foundations. Discrete examples and ranges of material and geometric properties are thoroughly investigated.

The results of reliability index β and uncertainties of material and geometric properties are shown and differences between evaluation methods are discussed. Here, the parameters according to EC2 with-out any National Annex and according to the German National Annex are applied. Following conclu-sions can be drawn:

1. The reliability methods addressed in this paper calculate almost similar reliability indices β for FORM, SORM and Monte Carlo .
2. Simulations with different values of $C_{\mathrm{Rk,c}}$ aimed to compare the difference between EN 1992-1-1 and DIN EN 1992-1-1; they show that a difference of 20% of $C_{\mathrm{Rk,c}}$ has a larger influence on the reliability index than 20%.
3. For small values of d, the reliability index is smaller than 3.8. The reliability index corresponds with the CoV of d. For large values of d (> 0.5m), there is almost no influence on the safety level.
4. For small values of f_{ck}, the reliability index is low and smaller than 3.8. The reliability index corresponds with the CoV of f_{ck}. For large values of f_{ck} (35 MPa) there is almost no significant influence on the safety level.

Future studies will include more extensive parameter studies with variation of more basic variables. Moreover, further development of the above-described guideline for the application of reliability methods in civil engineering will take place with the goal to boost the progress of reliability-based research applied to structural engineering

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Bridge Reliability Analysis Based on a Global Safety Methodology

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Abstract

Many reinforced concrete existing structures need to be re-evaluated due to the loss of its structural capacity, new design requirements or new loads to be considered. For this, new probabilistic analysis tools have been developed. Some of these methods intend to consider more realistic situations near to collapse than the ones defined in the current design following the Ultimate Limit States. In this paper, a methodology based on the concepts of the Global Resistance Format, as defined in fib Model Code 2010, with a step-by-step evaluation of the reliability coefficients is presented. The proposed methodology is applied in the re-evaluation of an existing bridge. Bayesian updating of the material properties is also applied in the analyses. With the proposed method it is possible to evaluate the need for rehabilitation or not, from the point of view of structural safety, directly depending on the reliability of the structure in view of new regulatory requirements.

Keywords: *reliability; reinforced concrete; Global safety approach.*

1 Introduction

This paper presents a proposed methodology for assessing the safety of existing structures on a probabilistic basis. This procedure can be useful when deciding whether or not to rehabilitate an existing bridge. The need for the rehabilitation of a bridge may arise from the loss of its resistance capacity due to its deterioration over time or from a change in the regulatory requirement, for example, by increasing the permitted tonnage for heavy vehicle traffic.

The example that will be presented is of a bridge located in Brazil. The proposed procedure includes a Bayesian reassessment of the strength of the bridge materials, especially the concrete, combining data available at the time of the design and construction with data obtained later. It also includes a safety assessment, through a Global Resistance format approach, in which design forces are increased until the structure fails, with the probability of collapse being assessed throughout this increase in loading.

Regarding the assessment of safety in structures, analysed by the methods of Global Resistance format and by complete probabilistic analyses, there are still few studies found, as those of Cervenka (2013), Allaix *et al.* (2013) and Silva (2013). Regarding the *fib* Model Code 2010 (2013), the introduction of the Global Safety format, become very attractive, especially for existing structures. The importance of these concepts is increasing, although there are still few references and studies in this specific subject.

2 Safety

2.1 Safety approaches

According to NP EN 1990 (2009), a structure performs well during the useful termed fundamental performance requirements, namely, safety, serviceability and durability. The safety requirements aim to ensure that the structures have the capacity to resist extreme actions, with low probability of occurrence, albeit potentially suffering serious but controlled damage, in order to minimize the risk to human life. The serviceability requirements are intended to ensure that the structures behave properly under normal conditions of use. The durability requirements have in mind that the deterioration of the structure, throughout its useful life, should not reduce its performance below a prescribed level, taking into account the environment and the expected maintenance level.

Most international regulations use the concept of Limit State to verify safety and serviceability requirements. Limit State is a condition in which the structure no longer meets one or more requirements, being impaired in the performance of the functions for which it was built. Thus, the ultimate limit states, associated with safety requirements, and serviceability limit states, arise.

The safety verification generally involves some kind of conventional hypothesis of type $E \leq R$, where E is related to the effects of the actions that act on the structure and R refers to the structure's resistance against these effects.

2.2 Verification of safety using partial safety factors

In the verification of safety through the partial safety factors, the variability of the actions and the resistance characteristics of the materials is considered through representative, nominal or characteristic values, associated with partial safety factors. The characteristic values are defined through the mean values, the standard deviations and the probabilistic distribution function considered.

Under the partial safety factor method, global safety is not evaluated, but is guaranteed by an appropriate formulation of the partial safety factors and selection of the magnitude of the values adopted for them.

Probabilistic methods shall be involved to inform the process of setting the magnitude of the values adopted for the partial safety factors.

2.3 Probabilistic security approach

The verification of safety through a probabilistic approach consists of determining its probability of failure (or its reliability index β), in relation to a given failure function. It is also an appropriate approach for assessing the safety of existing structures.

In the probabilistic approach, the quantities E and R are modelled as random variables. Note that E is related to the actions that act on the structure and can correspond to an imposed load or displacement. And the magnitude R refers to the resistance of the structure in relation to the acting action, and its quantification generally involves some kind of conventional hypothesis. Once E and R probability distributions are assigned, the probability of the $E > R$ event can be assessed, that is, p_f (failure probability). In the probabilistic approach to structural reliability, the probability pf is sought below a value previously accepted as the maximum allowable, p_{fT}.

2.4 Safety approach by Global resistance method approach

2.4.1 General

In this approach, the uncertainties of structural behaviour are dealt with, as defined by the condition of limit state, in the level of structural safety. The effects of the various uncertainties (of material properties, geometric quantities, actions, etc.) will be integrated into a global design resistance, which can be expressed by a global safety factor.

The representative (average) values of the global resistance variables and the global safety factors must be chosen in such a way that the reliability requirements for the verification of existing structures and for the design of new structures, in terms of reliability index β related to the defined reference period, are met.

2.4.2 Bayesian approach

The Bayesian approach in statistical inference proposes to combine data obtained from observations with subjective assessments or judgments. In the Reliability Analysis, especially when the samples are available in a very small number, the classic statistical inference does not provide the appropriate answers, as it does not allow the use of previous experience with similar models, nor the opinion of experts. The Bayesian approach appears as a tool indicated for the use of all available information, be it objective, provided by test results, or subjective, dictated by experience, as exposed by Jacinto (2011).

2.4.3 Global safety factor

The various uncertainties present in the structural design are considered through the adoption of a global safety factor (λ), as defined in the *fib* Model Code 2010 (2013) - refer Section 4.6.2.2 Design condition. This single factor is adopted for the joint consideration of the uncertainties present in the structure, unlike the usual semi-probabilistic approach / partial factor format, in which partial safety factors are adopted for each variable in the project, as shown in Figure 1.

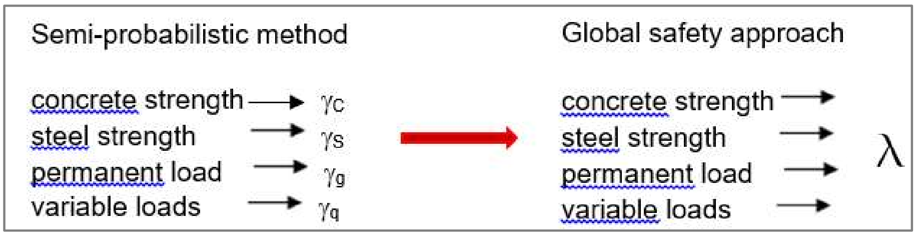


Figure 1 - Uncertainty and semi-probabilistic methods global probabilistic global security

The λ factor is used to increase one or more loads acting on the structural model, until the structure collapse situation is reached. That is, the numerical value of λ that causes the structure to collapse is considered to be the overall safety factor of the analysis performed.

In order for the analysis to be free from arbitrary definitions of characteristic values, in determining the probability of failure and the reliability index (β) associated with the global safety factor (λ), the resistance and stress variables are taken with their average values.

3 Methodology

3.1 Methodology for Existing Structures

This methodology will indicate whether the level of safety that the structure will provide in its remaining working life is acceptable (Interlandi, 2020). An overview of the methodology is shown in Figure 2.
The first and non-trivial question to ask is "is there a design for this structure?" For a positive answer, the next step is to know the degree of degradation of this structure; in case of negative answer, a field survey should be carried out as detailed as possible. Afterwards, it is mandatory to inspect the structure, in order to identify any kind of degradation, and to obtain the real data of the structural material, by means of concrete tests, for example. It is also important to make a detailed check on all applicable standards for this case, with special attention to possible regulatory changes, especially with regard to applied load.
The next step is to perform a Bayesian update of the strength of the materials. All of these studies will provide the necessary information for decision making: elaborating a new structural model or updating the existing one. The next steps are: definition of the average loads and resistances for the global analysis, definition of the critical variable loads for this analysis and the execution of the global analysis for different levels of variable loads with the respective calculation of β for different values of λ.

In the final analysis, the decision to be taken is whether the safety is acceptable or some type of rehabilitation is necessary for this structure, to increase $\lambda_0 \rightarrow \lambda_1$. This methodology will indicate if the level of safety that the structure will provide in its remaining useful life is acceptable.

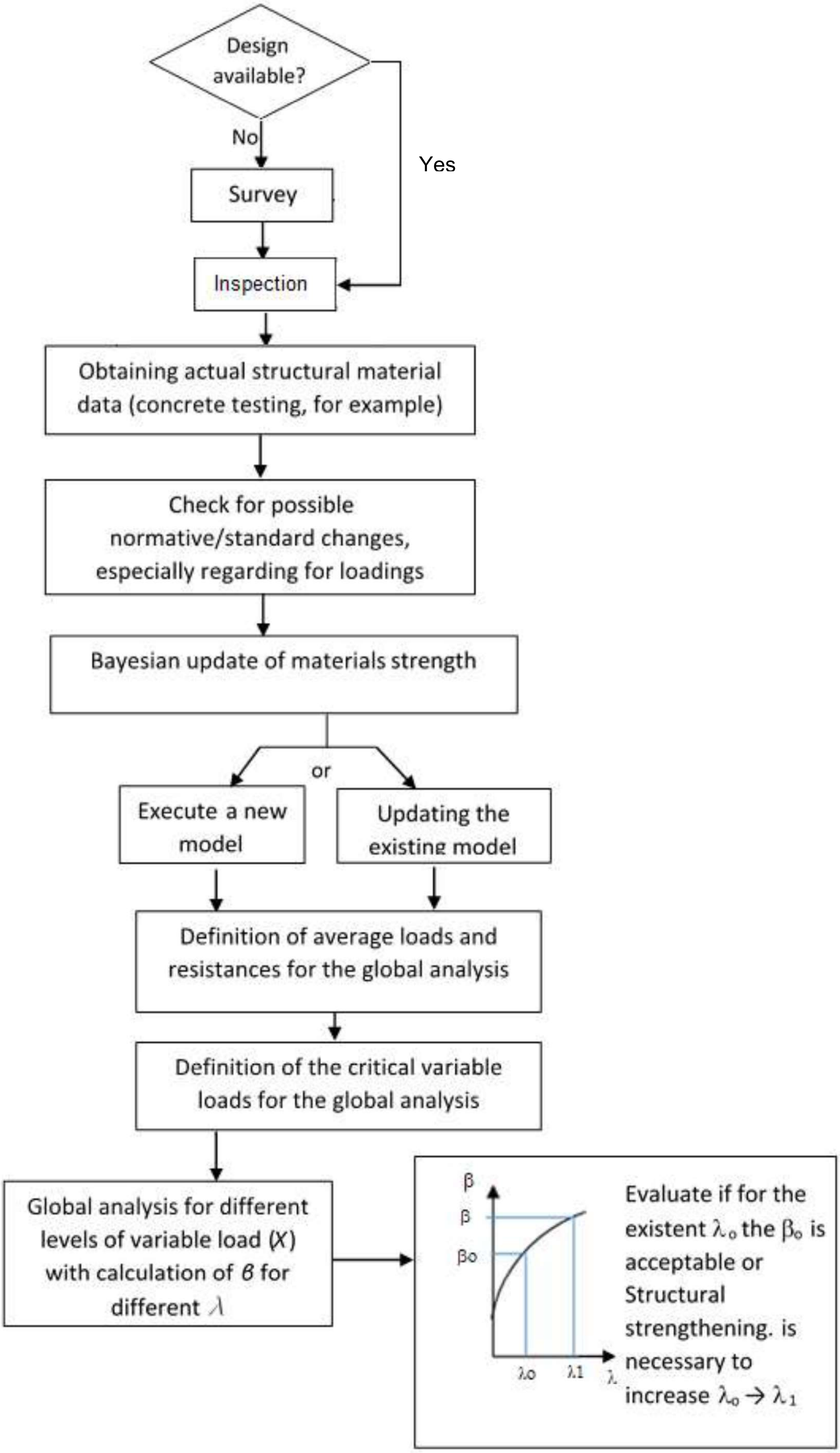


Figure 2 - Methodology for an existing structure

4 Case study

4.1 Seismic requirements

4.1.1 NBR15421 seismic requirements

The general requirements for seismic resistance of structures and seismic resistance of buildings are defined in NBR 15421 (2006). The horizontal accelerations of reference in “Rock” type of subsoil are shown in the map reproduced in Figure 3, of this Standard.

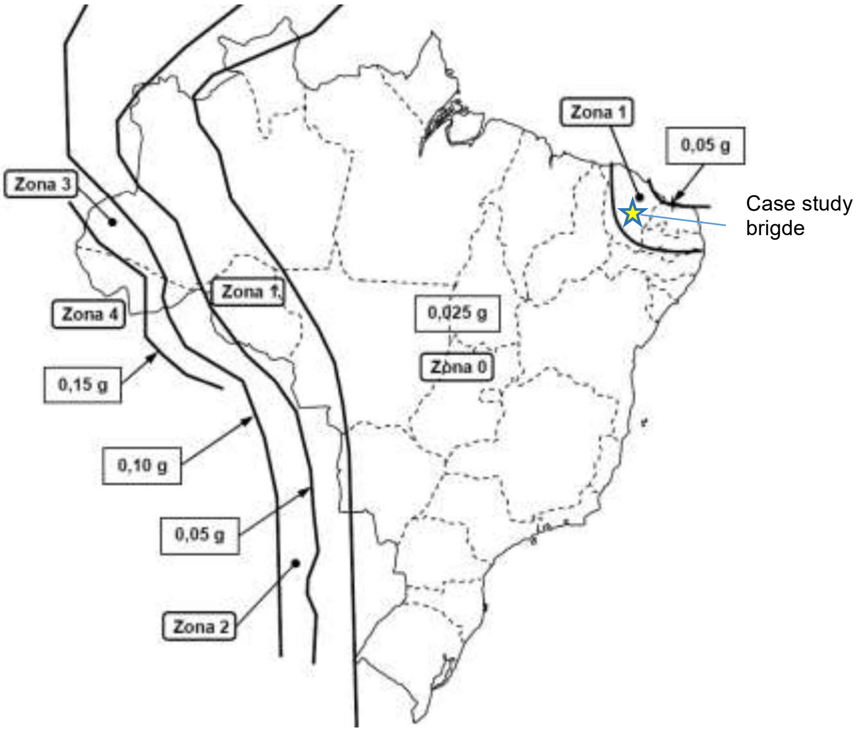


Figure 3 - Map of Brazilian seismic zones

4.1.2 Seismic requirements of the NBR 7187 revision

In the specific case of the bridge project, NBR 7187 (2006), currently under review, will define requirements complementary to those of NBR 15421 (2006). For Ceará (located in Seismic Zone 1), dynamic analysis is not required and bridges must withstand horizontal loads in both orthogonal directions, with a value equal to Fx = 0,01 w_x where, Fx is the design seismic force in a given direction, w_x is the effective bridge weight, including half the weight of the columns plus 20% of the live load on road bridges and 30% on railway bridges.

Response coefficients (R_c) (or behavior coefficients), in the case of bridges, will be more severe than those considered in the design of buildings, as can be seen in Table 1 below. These response coefficients reduce the forces obtained in a purely linear analysis to evaluate the nonlinear responses of the bridges under seismic action.

Table 1 - Response coefficients for bridges

Seismic resistant systems	Bridges with usual detailing	Bridges with special detailing
Structures in general	1.5	2.5
Structures rigidly linked to the soil	1.0	1.0
Arch bridges	1.2	2.0
Foundations	1.0	1.0

The project spectrum that corresponds to the region is shown in figure 4, considering the data: $a_g = 0{,}05$ g (ground rock maximum acceleration, according to Figure 3); Ca = 2,5 (Soil amplification factor related to Type E (weak) Soil); $a_{gs0} = 0{,}125$g.

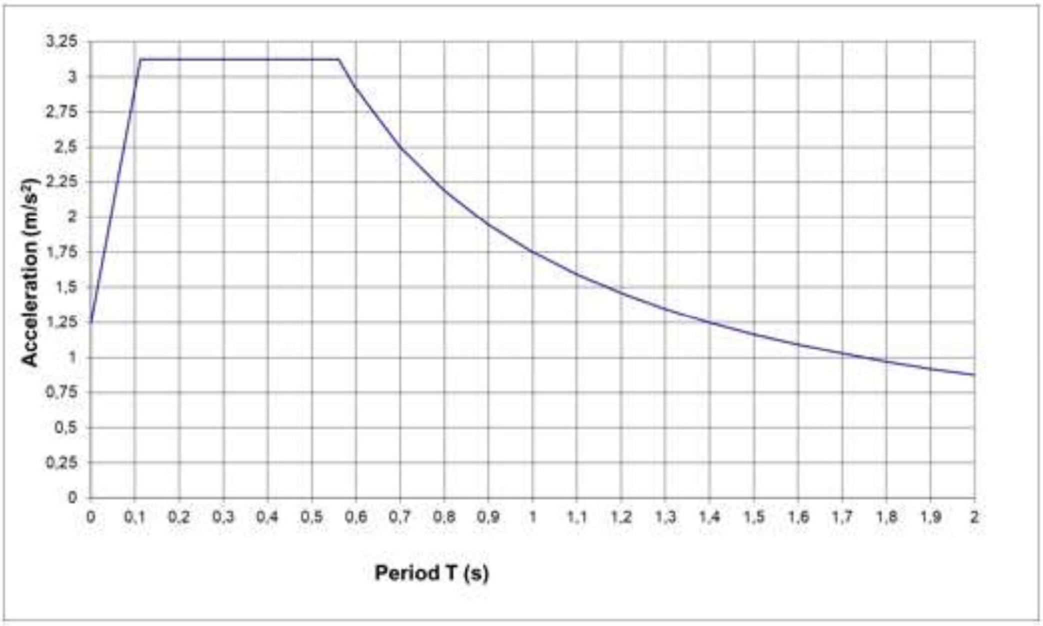


Figure 4 - Project spectrum (period x acceleration)

4.1.3 Structural verification of bridges in seismic conditions - Global Resistance

The verification process in the Ultimate Limit States can be refined, considering the Global Resistance Method and the Bayesian Update.

In a traditional probabilistic approach, failure functions are defined, which take into account the probabilistic variables related to resistances and loads, obtained from the average values and the coefficients of variation of each of the considered variables. Thus, the corresponding reliability index (β) can be obtained.

In the Global Resistance approach that is considered here, a global load increase coefficient (λ) is applied to calculate the required resistances, and for each of these λ values, the corresponding reliability indexes are evaluated (β).
In this way, it is possible to determine, for the analyzed case, the global coefficient λ which corresponds to a required reliability index β.

In the case of an existing structure, as is the case studied, it can thus be inferred whether the reliability index obtained in this global approach can be considered acceptable or not.

4.2 Three-dimensional numerical model

Figure 5 shows a general idea of the geometry of the bridge over the Madeira River, municipality of Sobral, state of Ceará.

Figure 5 - Madeira Bridge (Sobral- CE- Brazil)

A finite element model was developed for the spectral seismic analysis of the bridge, in the SOFISTIK program (2017). Further details of this analysis can be found in Santos *et al.* (2020).
The developed model is reproduced in Figure 6. The first mode of vibration is in the transversal direction, presenting the frequency of 3,935 Hz.

Although the bridge, being located in Seismic Zone 1, does not require a dynamic analysis, it is processed, including to confirm the adequacy of this dispensation.

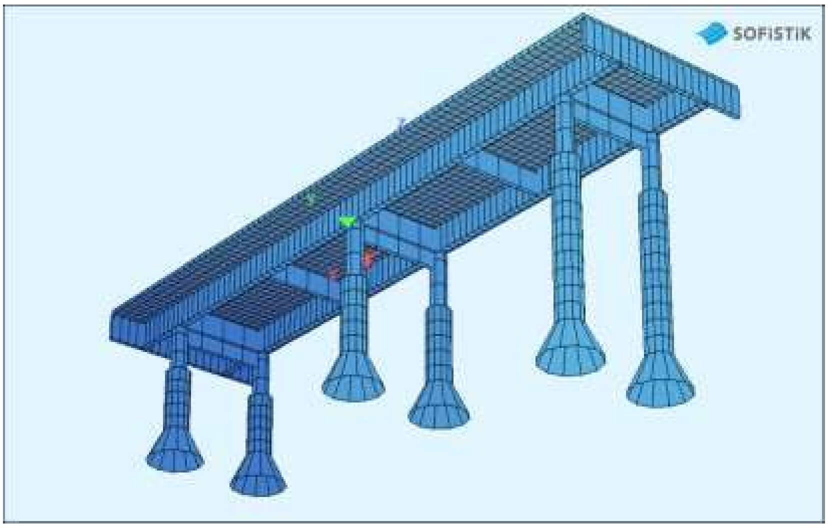


Figure 6 - 3-D model

4.3 Structural verification of the bridge under seismic conditions - Ultimate Limit State

The check of the critical section at the base of the columns for two load combinations are presented in Figure 7. Combination 1 refers to a situation where all live loads are applied. Combination 2 corresponds to a combination of earthquake in the transverse direction together with 20% of the live loads.

The verification of the column with the earthquake stresses and with the existing reinforcements is done with the PCALC1 program (2020). According to the flexural check in of the Ultimate Limit State shown in Figure 7, the column section, withstands the acting forces.

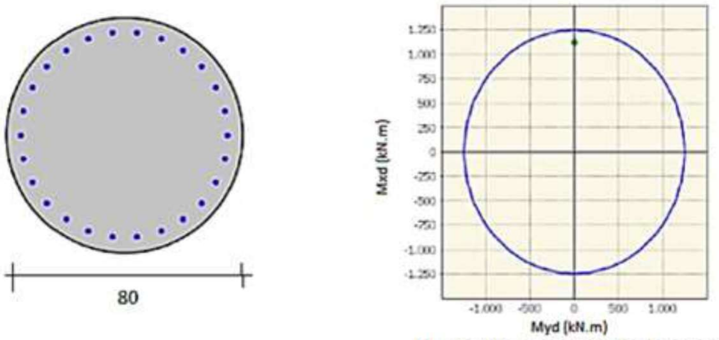


Figure: Interaction diagram (Comb.2)

Reinforcement: 26ϕ20 mm(As= 81,68cm2)
Materials: Concrete fck= 25 MPa
Steel fyk= 500 MPa

Combination	Na	Mxd	Myd
1	-2634	22	0
2	-1625	1118	0

Table: Loads combination (kN, kNm)

Figure 7 - Checking the critical section at the base of the columns

4.4 Structural verification in seismic conditions through the Global Resistance approach

4.4.1 Bayesian resistance update

The safety verification process in the Ultimate Limit State can be refined, considering the Global Resistance Method and the Bayesian Update. This update was applied to the available concrete tests, leading to a reduction in the f_{ck} from 25 MPa to 24 MPa, as described by Santos et al. (2019). In this update analysis, it is considered:
a) Previous knowledge:
As previous knowledge, it is admitted that each mix has been properly dosed to provide the required f_{ck} considering a variation coefficient of 10%.
For n_0 (confidence index associated with previous knowledge), it is adopted $n_0 = 10$.
The following numerical data were considered, with respect to "prior knowledge":

- arbitrated number of samples: $n_0 = 10$;
- average resistance: μ_0 = 30,9 MPa; standard deviation: s_0 = 3,09 MPa

These values correspond to the characteristic resistance f_{ck} = 25 MPa of the t-Student distribution.

b) Actual tests:
From the results of the technological concrete control, the values 25,7 MPa and 26,3 MPa are obtained, in tests for 28 days in the concrete. For the analysis:

- number of samples: n = 2; average strenght $\overline{x}$ = 26 MPa; standard deviation: s = 0,42 MPa

c) "A posteriori" distribution (obtained with a Mathcad application):

- average resistance: $\overline{x}$ = 30,1 MPa; standard deviation: s = 3,54 MPa
- characteristic resistance: f_{ck} = 23,77 MPa

4.4.2 Definition of probabilistic variables

The probabilistic analysis is done in terms of resistance and acting moments.

$$F_{lim} = M_{res} - M_{atuante}$$

For the calculation of the acting moments, a relationship between maximum moments in the column and acceleration in the base is considered:

$$M_{atuante} = FATOR.acel$$

The acceleration function is defined based on the relationship between recurrence periods and horizontal accelerations for the Northeast Region that was presented by Santos *et al.* (2010). The curve that represents this relationship is reproduced in Figure 8 ("PGA").

Also in this figure is represented the Gumbel function that is used in the probabilistic analysis for representing the Recurrence Function ("Gumbel"). Also shown are the recurrence periods of 475 years and 2475 years that were used as the basis for adjusting the curve. Considered Gumbel function:

$$p_f(a_h) = 1 - \exp[-exp(-\alpha(a_h - u))]$$

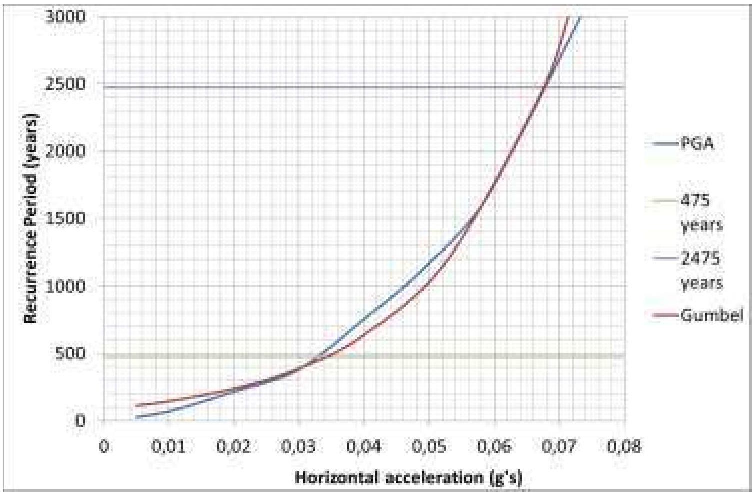
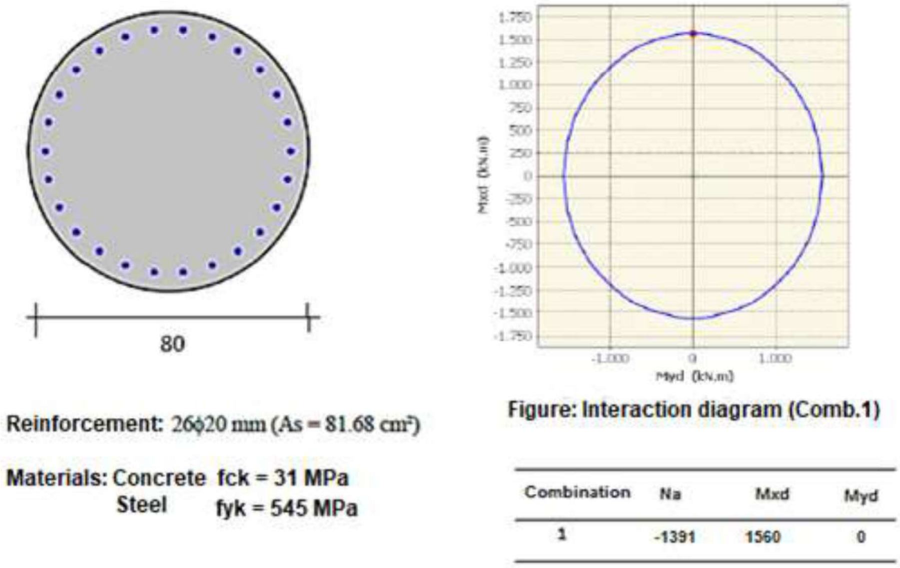


Figure 8 - Gumbel approximation for the recurrence function

4.4.3 Definition of probabilistic resistance variables

For defining the probabilistic resistance variable, in relation to the moment in the base, the PCALC program must initially be reprocessed with the average values of the variables as Figure 9. Following the sequence of item 4.3 and the updating of the strength of the concrete, it is obtained:

- Concrete: f_{cm} = 1,328 × 24000 = 31872 kPa
- Steel: f_{ym} = 1,089 × 500000 = 544500 kPa



Combination	Na	Mxd	Myd
1	-1391	1560	0

Figure 9 - Analysis of the column with mean values of the variables

For the probabilistic analysis, the following equation is finally considered:

$$F_{lim} = MRES.MODRES - 22140.ACEL.MODCAR.FACTOR$$

The variables considered in the bridge analysis are defined in Table 2. A coefficient of variation of 0,1 is adopted for the resistance moment and FACTOR serves for inputting the factors λ.