Computational Aspects in the Evaluation an Existing Structure by the Global Safety Method

Claudia Interlandi[1], Luiz Fernando Martha[2], Sergio H. C. Santos[3], Luis O. Santos[4]

[1] *Doctor by PUC-Rio*
interlandiclaudia11@gmail.com, Lisbon, Portugal
[2] *Dept. of Structures, PUC-Rio*
lfm@tecgraf.puc-rio.br, Rio de Janeiro, Brazil
[3] *Dept. of Structures, UFRJ*
sergiohampshire@poli.ufrj.br, Rio de Janeiro, Brazil
[4] *Dept. of Structures, LNEC-Lisbon*
luis.osantos@lnec.pt, Lisbon, Portugal

Abstract. The re-evaluation requirement for existing reinforced concrete structures, considering new regulatory design requirements is an unquestionable reality. For this, computational analysis tools with an emphasis on probabilistic input data have been developed and improved over time. In order to be able to consider more realistic situations, where the structure is collapsed instead of those defined in the original project, following the Ultimate Limit States, refined and complex computer programs are increasingly needed. In this article, a methodology based on the concepts of the Global Resistance Format is presented, as defined in the *fib* Model Code 2010. The proposed methodology is applied in the re-evaluation of an existing bridge. Bayesian updating of material properties is also applied in computational analysis. Structural analysis programs and reliability analysis are considered in these studies. 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. The gain in computational terms, is to generate the input data update in a more refined way, generating more realistic results.

Keywords: reliability; reinforced concrete; computational analysis; 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 [1], Allaix et al. [2] and

Silva [3]. Regarding the *fib* Model Code 2010 [4], 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 [5], 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 Safety approach by Global resistance method approach

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.

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 [6].

2.3 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 [4] - 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.

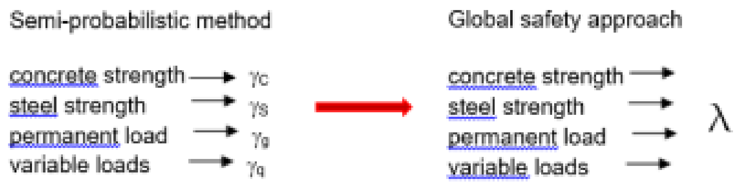


Figure 1. Uncertainty and semi-probabilistic methods global probabilistic global security

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.

2.4 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 [7]. 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 materials, 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 λ0 → λ1. This methodology will indicate if the level of safety that the structure will provide in its remaining useful life is acceptable.

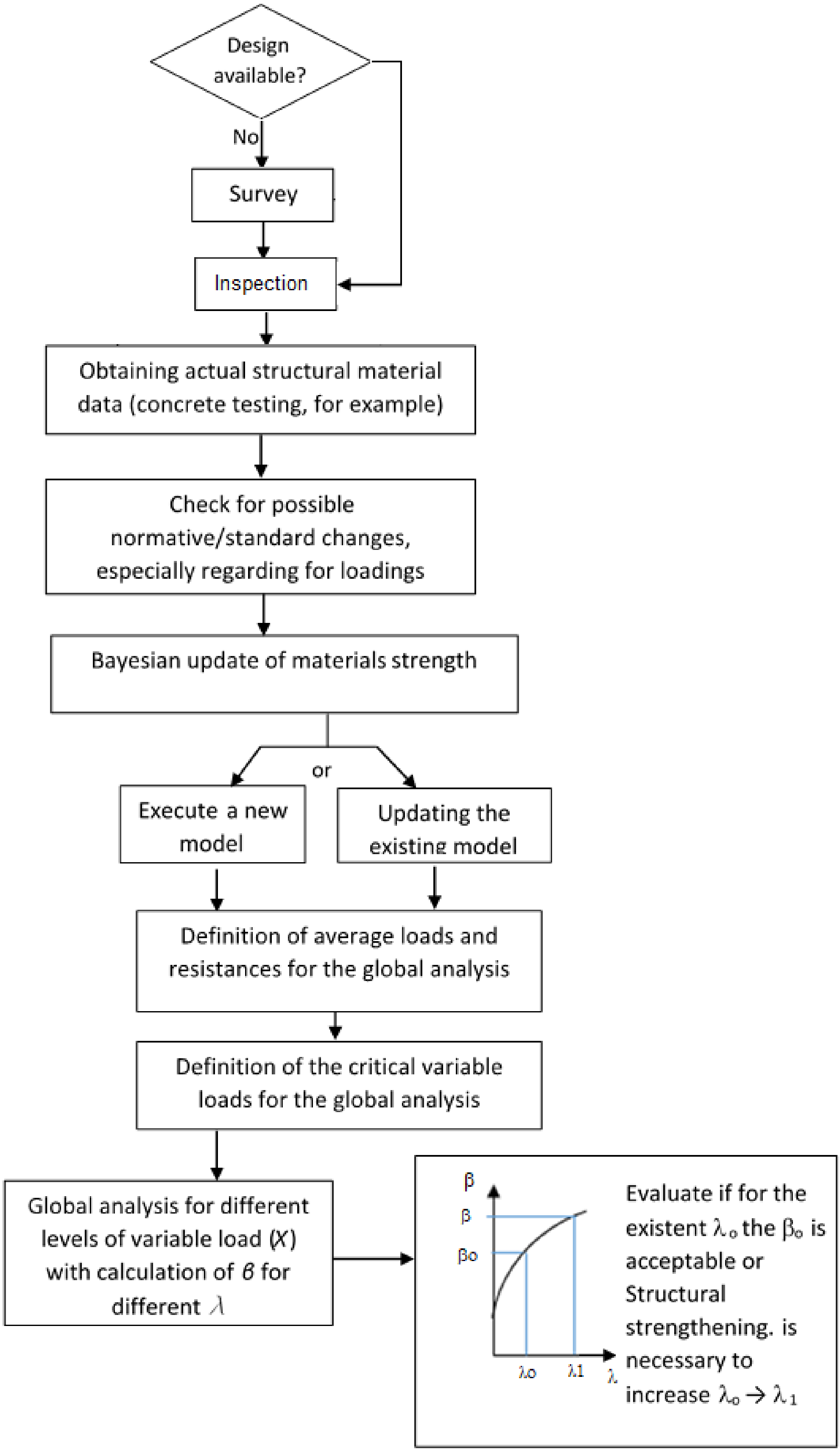


Figure 2. Methodology for an existing structure [7]

3 Case study

3.1 NBR15421 Seismic requirements

Traditionally, the effects of earthquakes were not considered in the design of reinforced concrete structures in the country. This is only required for structures of greater importance such as nuclear power plants, for instance. However, probabilistic analyses of the available data shown that the Brazilian territory is not free from such natural manifestations, even having regions with great seismic potential. There are few scientific studies in Brazil for the evaluation the damage caused to the structures and the only standard related to this issue in Brazil, deals with ordinary buildings, the NBR 15421 [8].

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.

3.2 Three-dimensional numerical model

A finite element model was developed for the spectral seismic analysis of the bridge, in the SOFISTIK program [9]. Further details of this analysis can be found in Santos et al. [10]. The developed model is reproduced in Figure 3. The first mode of vibration is in the transversal direction, presenting the frequency of 3,935 Hz presented in Figures 4 and 5.

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.

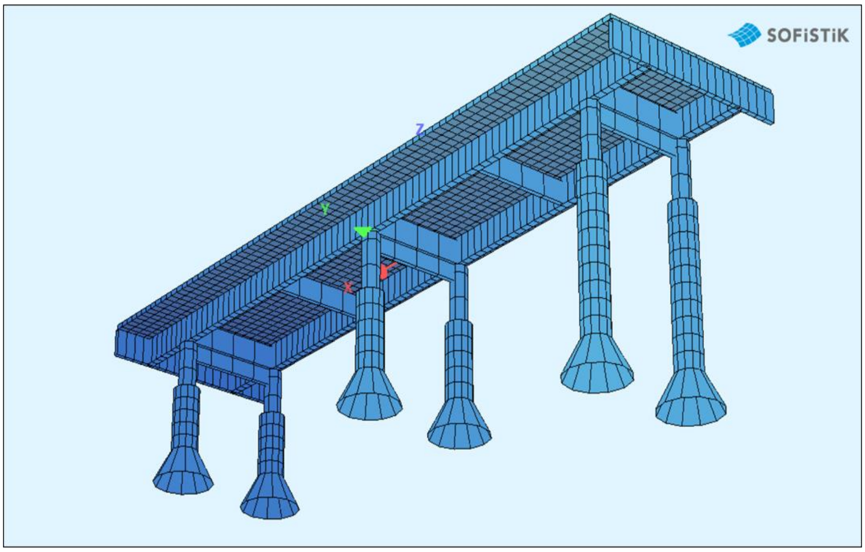


Figure 3. 3-D model

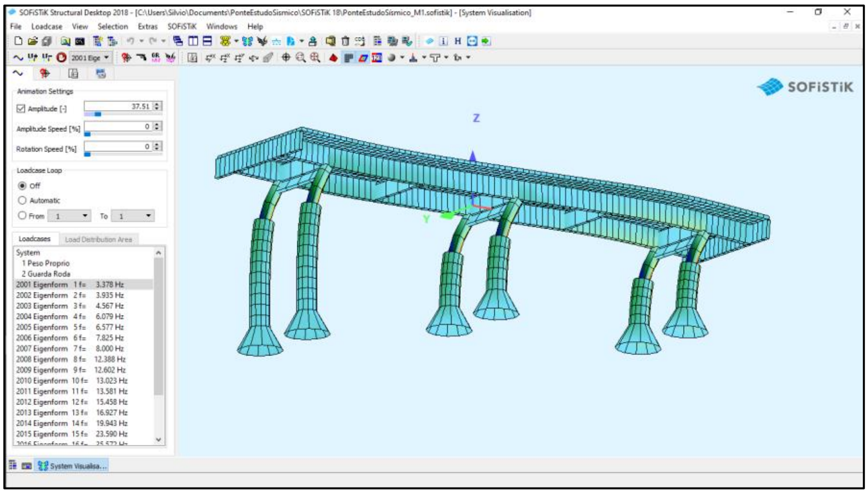


Figure 4. First vibration mode - longitudinal direction

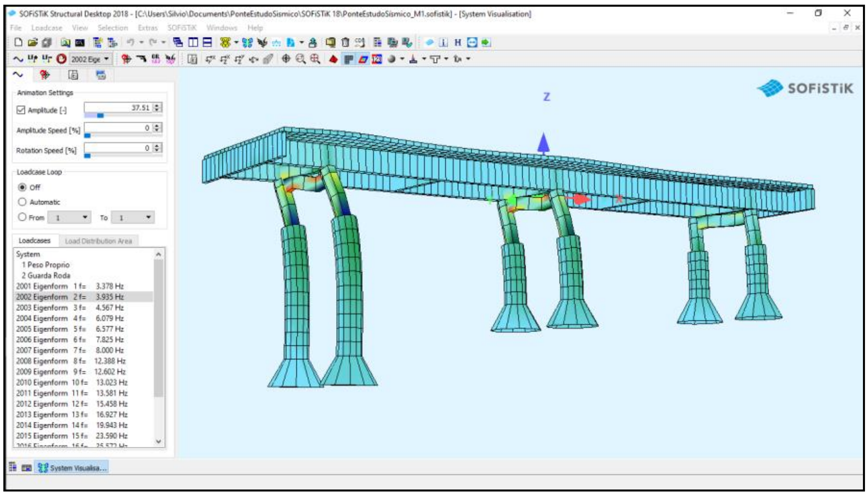
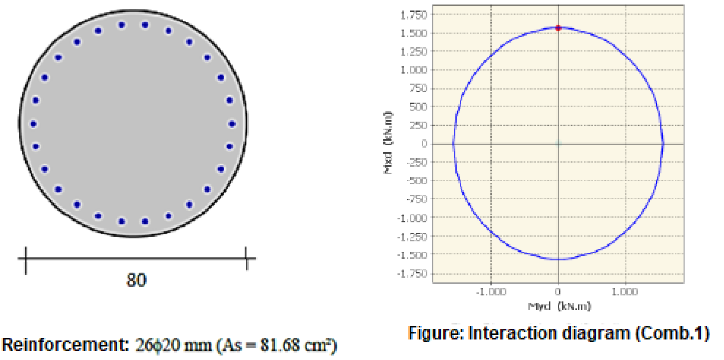


Figure 5. Second vibration mode - transverse direction

3.3 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 6. 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 [10]. According to the flexural check in of the Ultimate Limit State shown in Figure 6, the column section withstands the acting forces.



Reinforcement: 26ϕ20 mm (As = 81.68 cm²)

Materials: Concrete fck = 31 MPa
Steel fyk = 545 MPa

Combination	Na	Mxd	Myd
1	-1391	1560	0

Figure 6. Analysis of the column with mean values of the variables

3.4 Definition of probabilistic variables

The probabilistic analysis is done in terms of resistant and acting moments:

$$F_{lim} = M_{res} - M_{atuante} \tag{1}$$

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

$$M_{atuante} = FATOR.acel \tag{2}$$

The proportionality factor is found considering that, in the analysis presented in item 5.4, the total seismic moment of 1107kN corresponds to an acceleration of 0,05 g:

$$FATOR = \frac{1107}{0{,}05} = 22140 \tag{3}$$

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. [9]. The curve that represents this relationship is reproduced in Figure 7 (“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.

Gumbel function:

$$p_f(a_h) = 1 - \exp\left[-exp\left(-\alpha(a_h - u)\right)\right] \tag{4}$$

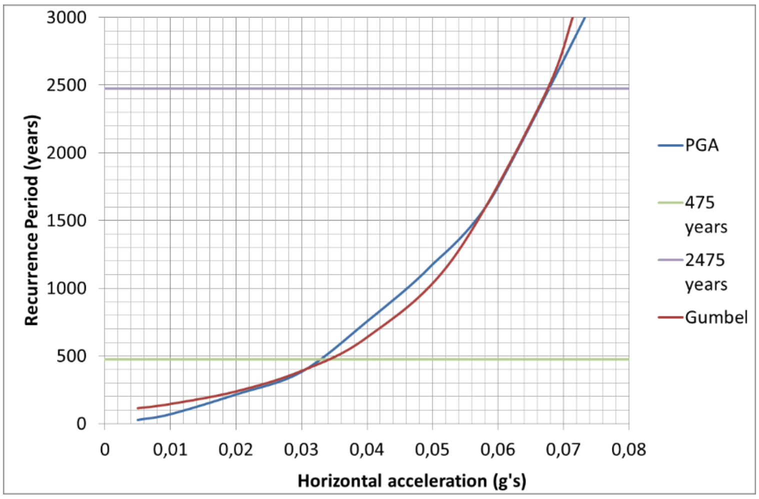


Figure 7. Gumbel approximation for the recurrence function

3.5 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. Following the sequence of item 3.4 and the updating of the strength of the concrete, it is obtained for Concrete a $f_{cm} = 1{,}328 \times 24000 = 31872$ kPa and for Steel a $f_{ym} = 1{,}089 \times 500000 = 544500$ kPa.

The normal load is considered to have its characteristic value as N = 1390,6 kN. With these data at their average values, the average resulting moment is 1560 kNm.

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

$$F_{lim} = MRES.MODRES - 22140.ACEL.MODCAR.FACTOR \quad (5)$$

The variables considered in the bridge analysis are defined in Table 1.

A coefficient of variation of 0.1 is adopted for the resistant moment and the variable FACTOR serves for inputting the factors λ.

Table 1 - Probabilistic variables for bridge reliability analysis

VARIABLE	DISTRIBUTION	AVERAGE	STANDARD DEVIATION
Resistant moment	Normal	1560	156
Resistance modelling	Normal	1	0,05
Acceleration	Gumbel	-0,079	0,026
Modelling of loads	Normal	1	1

The Reliability Analysis is performed with the VAP program [11], applying the FORM method. Figure 8 reproduces a program screen. This screen corresponds to λ =1.0.

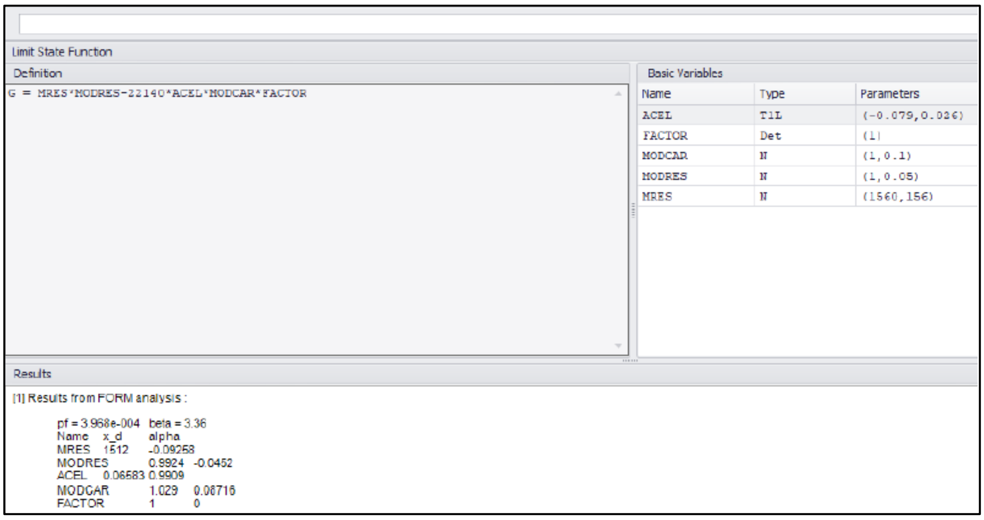


Figure 8. Probabilistic column analysis

This processing, which corresponds to considering all variables with their average values, presented the results (using the FORM Method):

- Reliability index $\beta = 3{,}36$
- Probability of failure $p_f = 3{,}968 \times 10^{-4}$

This value is quite reasonable for a rupture of the ductile type and compatible with the Recurrence Periods defined for the earthquake in NBR 15421.

Figure 9 shows the β values obtained with different λ values, where this variable represents "Global safety factor" for the seismic load.

Acceptable values of β (above 3) are obtained with the increase coefficient equal to 1, which is the one usually defined in the seismic standards.

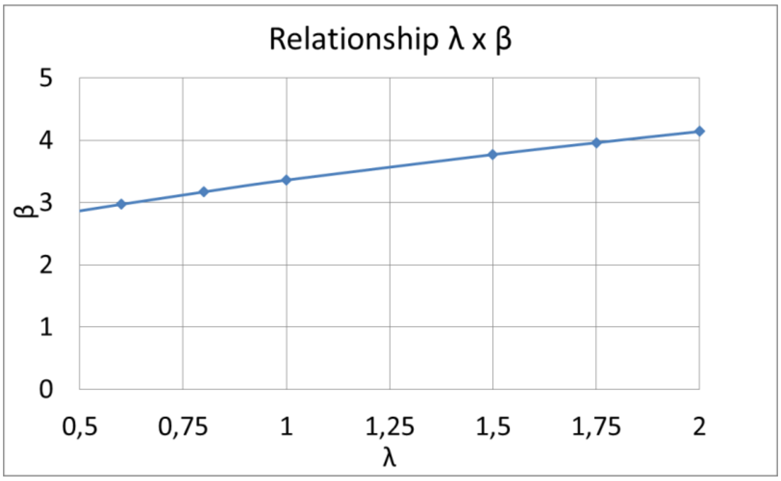


Figure 9. Values $\lambda \times \beta$

4 Conclusions

A methodology for assessing the safety of existing structures on a probabilistic basis was presented. This methodology, based on a Global Resistance approach and on Bayesian update, was applied to an existing bridge, due to new requirements regarding the seismic action imposed by the renovation of Brazilian seismic standard.

Although the relationships between the global safety factor (λ) and the reliability index (β) are specific to this case study, assuming different values for each structure, the developed methodology can be generally used to the assessment of existing structures, namely the numerous existing bridges in the Brazilian Northeast subject to the new requirements of seismic actions.

The proposed methodology provides an advanced safety assessment, contradicting, in some cases, the computational result of more conservative analyses such as those carried out through the partial safety coefficients. Thus, the proposed approach could be an important decision support tool, avoiding unnecessary and costly rehabilitation works, leading o a more efficient budget management.

References

[1] Cervenka, V. (2013). Reliability-based non-linear analysis according to fib Model Code 2010. https://doi.org/10.1002/suco.201200022.
[2] Allaix, D. L.; Carbone, V. I; Mancini, G. (2013). Global safety format for non-linear analysis of reinforced concrete structures. DOI: 10.1002/suco.201200017.
[3] Silva, P. M. O. (2013). Global safety factors for the structural elements resistance to assess the seismic safety in existing buildings (Desenvolvimento de fatores de segurança globais para a capacidade resistente de elementos estruturais para avaliação da segurança sísmica de edifícios existentes). Master Dissertation. Universidade do Porto (in Portuguese).
[4] *fib* - International Federation For Structural Concrete – Model Code for Concrete Structures. 2010.
[5] NP EN 1990. Eurocode – Actions on structures. IPQ, Instituto Português da Qualidade, Caparica, 2009, (in Portuguese).
[6] Jacinto, L. (2011). Safety assessment of existing bridges - Bayesian probabilistic approach (Avaliação de segurança de pontes existentes. Abordagem probabilística bayesiana). Doctoral Thesis. Universidade Nova de Lisboa, (in Portuguese).
[7] Interlandi, C. (2020) - Safety assessment of reinforced concrete structures with a global resistance approach. Doctoral Thesis. Pontifícia Universidade Católica do Rio de Janeiro.
[8] NBR 15421 – Structural design Resistant to Earthquakes - Procedure (Projeto de Estruturas Resistentes a Sismos – Procedimento). Associação Brasileira de Normas Técnicas (ABNT), Rio de Janeiro, 2006, (in Portuguese).
[9] SOFiSTiK AG. DYNA - Dynamic Analysis Manual, Version 18, 2017.
[10] Santos, S. H. C., Souza Lima, S., Hora, R. C. Seismic Analysis of a Bridge Considering the Proposed Revision of the Standard NBR 7187 (Análise Sísmica de Uma Ponte Considerando a Proposta de Revisão da Norma NBR 7187). Engenharia Estudo e Pesquisa, Vol. 20 nº 1. ISSN 2316-591X, 2020, (in Portuguese).
[11] PCALC1 – Columns design software. TQS Store, (in Portuguese).
[12] Petschacher Software und Projektentwicklungs GmbH – PSP, Software. VAP – Variables Processor, Version 4.0; 2017.