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Safety Assessment of Brazilian Concrete Bridges Through Reliability Analysis

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Abstract

This paper addresses the need for accurate and objective safety assessments of bridges in Brazil taking into account the increase in traffic load and limited funding for infrastructure. In Brazil, the usual method of ensuring bridge safety involves strengthening based on design codes using deterministic analysis and partial safety factors. This method leads to an increase in the maintenance cost of the bridges. Structural reliability assessment, a higher-tier assessment method, is recommended globally for assessing the safety of existing bridges beyond current deterministic methods. This paper presents a study that evaluates the structural safety of existing road bridges in Brazil using the semi-probabilistic method defined in Brazilian standards and the full probabilistic method. The study selected six case studies of existing reinforced and prestressed concrete bridges to evaluate their structural safety concerning current normative loads. The results suggest that the partial safety factors defined in the Brazilian standards are consistent with international standards. The reliability analysis can guarantee the bridges' safety, even with increased traffic loads, without additional costs for structural strengthening. Therefore, the paper highlights the importance of promoting reliability analysis in Brazil to ensure the safety of existing bridges and promote cost-effective and objective safety assessments.

Keywords: Reliability assessment; structural safety; bridge infrastructure; existing bridges; partial safety factors; Brazilian standards; bridge management

Introduction

Bridges are critical transportation infrastructure components, given their pivot role in facilitating social and economic development. Their failure can have catastrophic consequences, including loss of life and economic damage. Therefore, to establish a successful bridge management system (BMS) is essential to assess the safety of existing bridges to ensure they are structurally sound and can continue to provide safe and reliable transportation for people and goods. Furthermore, an adequate quality control plan and a classification of the structural reliability of bridges allow to guarantee a prolonged quality and, consequently, an adequate allocation of resources[1,2].

Over time, structural deterioration can be triggered by various factors such as ageing, environmental conditions, and increased traffic loads. Thus, regular evaluations of existing bridges are necessary to detect potential structural problems and assess their severity to determine if any repair, rehabilitation, or replacement is required. One of Brazil's main challenges in bridge management is the evolution of transport loads within the road network, which implies structural strengthening and financial investment. This load increase has been reflected in the constant updating of the standard code vehicle defined by road loading regulations[3].

By conducting safety evaluations, engineers can identify the critical components of a bridge, assess their condition, and calculate the load-carrying capacity of the structure. These assessments often involve calculating sectional capacity-to-demand ratios to ensure adequate safety. These ratios typically employ semi-probabilistic methods using partial safety factors, ideally calibrated for reliability against a benchmark safety level. This approach often called the rating factor method, assesses safety as a binary measure (yes/no). International bridge safety assessments typically involve tiered approaches. Each additional tier increases the complexity of achieving a more precise assessment of the bridge's safety. The rating factor approach leads to inherently conservative safety assessments, making higher-tier procedures more appealing and advantageous[4].

The international approach to bridge safety assessments involves using structural reliability theory to calculate safety as an objective measure that can be quantified. The resulting safety measure is then compared to a preselected benchmark safety level (e.g. Eurocode 1990[5], ISO 2394[6], ISO 13822[7], and JCSS[8]) to determine if the bridge is safe. By providing a clear understanding of the risks and an individualised safety level, this approach allows for more efficient utilisation of the bridge, unlike initial safety checks, which are overly conservative and based on a hypothetical worst- case scenario. Additionally, the reliability calculations offer valuable information to optimise strengthening measures, leading to greater bridge utilisation efficiency[4].

Although many international bridge assessment codes and standards allow for reliability[5–8], their use in Brazil seems limited. Despite the theoretical foundation having existed for several years[9,10], little guidance is available in the Brazilian bridge assessment codes on using reliability as a higher-tier assessment for structural elements deemed insufficient by the current methods prescribed.

It should be noted that the current Brazilian standardisation is focused on the design of new bridges[11–13], based on semi-probabilistic methods[14] using partial safety coefficients for actions and resistances. Additionally, the partial design factors of Brazilian structural design codes have not been calibrated using structural reliability theory[15]. Currently, there is a need for

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more guidelines for evaluating existing bridges since the current standards to verify existing bridges, intended for the design of new bridges, have proved to be conservative, when applied to existing bridges, resulting in unnecessary costs. Thus, a procedure for the structural verification of these existing bridges, which optimises the costs of maintenance and intervention, is required.

Only recently did NBR 7187/2021[12] make specific reference to existing bridges, allowing the reduction of the partial safety factors applied to actions, according to the content of Annex D. However, bridges must be in good structural condition to apply the reduction. Even allowing this reduction, the standard[12] still maintains the quantification of safety based on partial safety factors.

Some authors[15–18] have been concerned with the partial coefficients defined by the standards since they do not reflect the absolute safety that the bridge presents, which could cause the structural verification to reach conclusions that do not correspond to reality.

Comprehending structural safety as a probabilistic challenge often poses difficulties, particularly for non-experts as it involves accepting the possibility of failure. To bridge this gap, this article introduces two distinct safety assessment methodologies: the semi-probabilistic and probabilistic methods. This strategy offers a systematic framework for assessing structural safety.

By elucidating these methodologies, the article aims to promote a greater understanding and acceptance of reliability analysis in the Brazilian engineering community. Additionally, this article aims to assist Brazilian jurisdictions in adopting reliability engineering practices. As a result, they could realise the benefits of objective and accurate bridge safety assessments for optimal utilisation of existing bridge assets.

As part of the methodology, six case studies were conducted, focusing on bridges designed for the TB-360 train[19], which must now safely meet the TB-450 train[13], currently recommended by Brazilian standards. The evaluation was carried out using the method of partial safety factors, defined by standards[11–14] and the reliability method.

A key novel aspect of this study is the application of code-based semi- probabilistic methods as well as advanced probabilistic reliability analysis to typical Brazilian concrete bridges. The comparative assessment provides new insights into the consistency of current Brazilian code calibration and the additional value that can be gained from probability-based analysis. The case study bridges represent prevalent structural systems in the nation's infrastructure portfolio. Furthermore, the article demonstrates that reliability assessment can achieve greater accuracy by using accurate statistical data for Brazilian materials and loads to establish probability distributions. In summary, through its rigorous methodology and multifaceted results, this study delivers original and valuable knowledge to advance probability-based assessment practices for Brazil's existing infrastructure.

Structural Safety

When designing a bridge, one considers the economy, functionality, constructability, and guidelines that guarantee safety conditions established in the structural norms. Over time, several approaches have been developed to quantify safety. The first approach probably used the "intuitive" method based on the builders' experience by applying concepts obtained in previous cases and empirical rules. With the development of the mechanics of materials and the possibility of reproducing the structure's behaviour in determining displacements and internal forces, it became possible to compare them with resistance criteria[20].

Historically, structural safety was quantified through the method of allowable stresses. According to this method, the stresses in the structural elements could not exceed a certain fraction of the material's strength, divided by a coefficient greater than 1, called the safety factor. Obtaining these coefficients was mainly done empirically.

Furthermore, this method considered that the structural behaviour, the mechanical and geometric parameters, and the actions were deterministic, which does not correspond to reality[20].

There has been a shift towards using reliability assessment in recent years. Reliability assessment is a probabilistic approach that considers uncertainties in the inputs (materials, geometry, actions, and mathematical models) and provides a more accurate understanding of the safety and reliability of the structure. This approach has become increasingly popular as it offers a more rational and quantitative way to quantify safety and helps to reduce the risks associated with structural failures.

Semi-Probabilistic Method

When verifying structural safety by the semi-probabilistic method, the characteristic values define the random variables. The partial safety factors are used to obtain design values from the characteristic values[14]. Thus, uncertainties inherent to the actions and resistance of materials are considered indirectly through characteristic values and partial factors. The advantage of the partial coefficient method is the possibility of considering the uncertainty of the individual variable by adjusting (calibrating) the relevant factors and other reliability elements.

According to NBR 8681/2003[14], safety requirements can be expressed by the inequality:

$$\theta(F_d, f_d, a_d, \mu_d, C) \geq 0, \qquad (1)$$

where F_d represents the designed values of the actions; f_d represents the design values of the material properties; a_d represents the calculation values of the parameters that describe the geometry of the structure; μ_d represents the calculation values of the coefficients that cover the uncertainties of the numerical model; C represents the constants used.

When considering ultimate limit states (ULS), the calculation values of the actions (F_d) are given by *Equation 2*, where the partial coefficients relative to the actions (γ_F) take into account the variability of actions and possible errors in evaluating the effects of actions, either by constructive issues or deficiency in the numerical model used, and the coefficient ψ_{0j} considers the probability of simultaneous occurrence of two or more variable actions of different natures.

$$F_d = \sum_{i=1}^{m} \gamma_{Gi} F_{Gi,k} + \gamma_Q \left[F_{Q1,k} + \sum_{j=2}^{n} \psi_{0j} F_{Q,j,k} \right], \qquad (2)$$

where $F_{Gi,k}$ is the characteristic value of permanent actions; $F_{Q1,k}$ is the characteristic value of live actions considered as the primary action for the combination; $\psi_{0j}F_{Q,j,k}$ is the reduced combination value for each of the other variable actions.

The design resistance of the materials (f_d) can be obtained by *Equation 3*, where γ_m represents the partial factor related to the material properties, which takes into account the variability of the effective resistance, the differences between the effective resistance of the structure material and the uncertainties in the determination of resistance, either due to failures during the execution of construction methods or due to the numerical model employed.

$$f_d = \frac{f_k}{\gamma_m}, \tag{3}$$

where f_k is characteristic resistance value and γ_m is the partial factor relative to the material.

When safety is verified separately for each acting effort, the safety conditions take the simplified form of *Equation 4*.

$$R_d \geq S_d, \tag{4}$$

where S_d represents the designed values of the actions demand and R_d represents the designed values of the resistance.

Probabilistic Method

Reliability analysis allows estimating the structure's failure probability (p_f) for different limit states related to structural performance. The performance function for the limit state is given by:

$$z(R, S) = R(x) - S(x), \tag{5}$$

where R represents the probabilistic distribution function of resistance, S represents the probabilistic distribution function of loading, and x represents the random variables involved in the analysis.

The probability of failure (p_f) can be calculated using different limit state functions formulated in different ways, such as:

$$p_f = P(R - S < 0) = P(R < S) = P(z < 0) \tag{6}$$

If (x) represents the joint probability density function of all x random variables involved in the analysis, the p_f can be calculated by the following convolution integral over the entire failure domain:

$$p_f = \int_{z(R,S)\leq 0} f_x(x)dx \tag{7}$$

Furthermore, it is essential to understand that the probability of failure should only be interpreted in the Bayesian sense that expresses the degree of belief and not in the frequentist sense, i.e. that p_f does not directly mean that, on average, one in a million similar such bridges may be expected to fail[21].

A commonly used measure to represent the reliability of a system is the so- called reliability index (β). This concept assists in analyzing structural reliability by measuring and communicating the level of safety and the probability of failure of a civil engineering structure. The correlation between the probability of failure and the reliability index can be represented as follows:

$$\beta = -\Theta^{-1}(p_f), \tag{8}$$

where Θ^{-1} is the inverse standard normal distribution function.

An alternative approach to understanding the reliability index (β) is by expressing it in relation to standard deviations (σ_z) away from the mean (μ_z) of a specific performance function (z). This is demonstrated in Equation 9.

Figure 1 illustrates the interpretation of β for the function (R, S). The region of values less than zero on the graph is p_f.

$$\beta = \frac{\mu_z}{\sigma_z} \tag{9}$$

Beta Target

In the design of structures, the target reliability is used as a reference point to determine the required safety margins and assess the design's adequacy. A structure that meets or exceeds the target reliability is considered safe and reliable. In contrast, a structure that falls short of the target may require additional measures to improve its safety. The target is typically a reliability index (β) or a failure probability (p_f).

The importance of target reliability lies in its ability to ensure that a structure is designed and constructed to a level of safety that meets the desired level of performance. The target reliability is typically based on the failure consequences, the nature of the failure, the structure's expected service life, the economic, social, and environmental factors and sustainability[6].

Besides its use in designing, target reliability is also vital in the maintenance and management of structures. By regularly assessing the reliability of a structure and comparing it to the target, owners and operators can identify potential safety issues and take appropriate actions to ensure

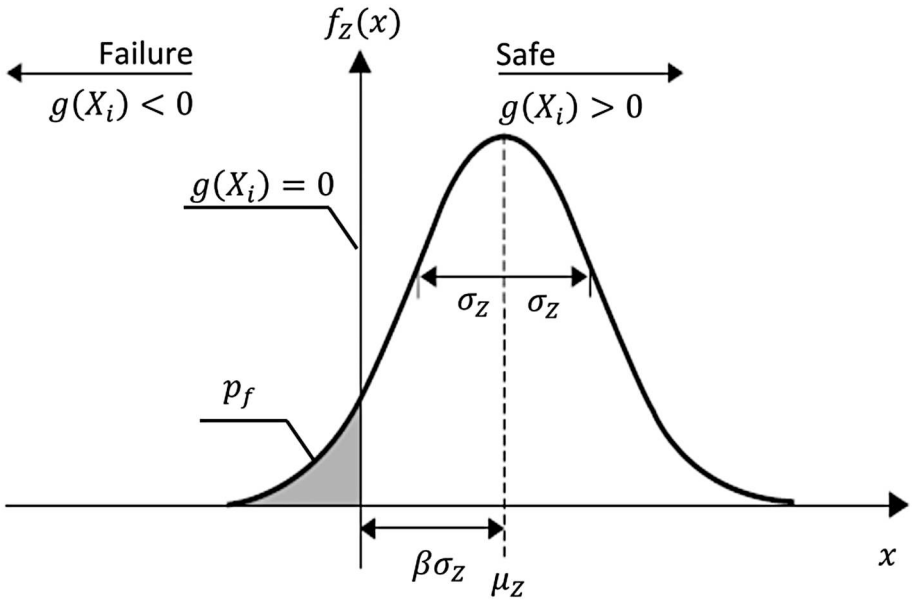


*Fig. 1: Probability density for limit-state (*X*)*

the ongoing safety and reliability of the structure.

Brazilian standards do not define the target reliability that structures must present. Notwithstanding, several authors[15–18] have adopted a target reliability index for a time reference of 50 years (β_{t50}) equal to 3. This value corresponds to the average of the reliability indices obtained using the partial factors defined by the standards[18], and it complies with the US standard[22].

Since there has not been a consensus on the structure target reliability indices in Brazil, international standards were consulted[5–8,23]. The target reliability index value in these standards is determined based on the consequence of failure and the improvement cost. Eurocode 1990[5] defines the target reliability indices (for new structures) by describing only the consequence of failures. However, ISO 2394[6] and JCSS[8] bring targets related to the consequences and cost of the improvement. In the case of existing structures, ISO 13822[7] proposes an optimisation approach to calculate the target reliability index by minimising the total cost since defining the exact target beta for existing and new structures would be uneconomical.

When defining the target reliability index for an existing structure, it is important to consider the high cost of increasing its safety. In addition, the remaining life span of the structure should also be considered, as it may affect the feasibility of increasing its safety to meet a certain target level. On the other hand, the cost of increasing safety is usually lower for new structures.

Regarding cost optimisation for existing structures, fib bulletin N80°[23] recommends that the most economical solutions for enhancing the safety of an existing structure should be identified and implemented. This can be achieved by performing a cost–benefit analysis, which evaluates the cost of the intervention against the benefits in terms of increased safety and extended service life. According to Ref. [23], cost optimisation studies show that a reduction of 0.5 of the β_t defined by the standards for new structures generates the best cost–benefit scenario.

Reference [23] defines an equation (*Equation 10*) for calculating the target reliability index for a bridge with a remaining life equal to or less than 50 years and a reference time equal to the remaining life (T). This equation is based on cost optimisation, on the premises defined in ISO 2394[6], and considers the frequency of a failure, the probability of fatalities due to a failure, and the number of fatalities in proportion to the collapsed span length (S). The illustration of the equation can be seen in *Fig. 2*.

$$\beta_{t,T} = \max\left[3.3: -\Theta^{-1}\left(\frac{2.75{*}10^{-5}(0.09{*}S)^{-2}{*}T}{0.055}\right)\right] \quad (10)$$

Random Variables Distributions

In reliability analysis, it is commonly assumed that the variables are random in nature and independent of each other. Nevertheless, in the context of civil engineering structures, it's important to recognise that real-world complexities can give rise to interdependencies. For each random variable, the distribution is presented in *Table 1* and detailed in the following paragraphs.

The probabilistic models of the variables follow recommendations from national and international studies. The statistical properties of the random variables are described by mean (μ), standard deviation (σ) and the distribution type. The other variables, not included in the table, are considered to have deterministic values.

It is important to emphasise that in this work, the data on the case studies were obtained by analysing prior existing information such as blueprints. This approach does not have any additional information on the current conditions of the material or the in- situ geometry of the assets. Therefore, the most appropriate probabilistic distributions were used in the contexts of the projects. Nevertheless, In the case of additional information, distributions should be updated to better match the existing structure's condition.

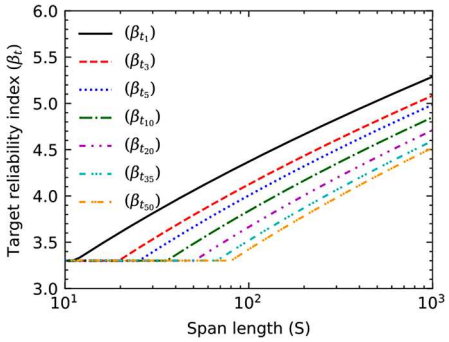


Fig. 2: Target reliability indices (β_t) for existing bridges, based on the residual service life (t_r) and span length (S)

In this study, the selected probabilistic distributions (*Table 1*) are mostly the normal distribution, widely known and commonly used to represent concrete and other materials. However, it is noteworthy that some standards[8] and research studies[4,9,16,22] have adopted the log-normal distribution as an alternative. The fundamental distinction between these distributions lies in their shapes and value ranges, with the normal distribution permitting negative values.

Despite the advantages of the log-normal distribution, the authors understand that simplicity is crucial in ensuring broader comprehension. To avoid introducing unnecessary complexity to an intricate problem domain, the authors have consciously opted for the normal distribution, promoting simplicity and reader-friendly comprehension. In this goal, it is worth mentioning that a truncated normal distribution has been considered to avoid the problem of negative values.

Nonetheless, it is crucial to recognise that this choice is a simplification and demands a conscious awareness of its limitations. Consequently, an analysis was conducted to ascertain that this choice would not influence the study's findings.

Encouragingly, the outcomes demonstrated minimal variations, with differences observable only up to the second or third decimal places (in the reliability index), having no relevance to the general conclusions.

Real-world scenarios may necessitate different distributions, prompting engineers to carefully assess the best fit for their specific needs. Furthermore, being informed about recommended distributions from standards can aid decision-making. In essence, a thorough understanding of probabilistic distributions empowers engineers to make informed choices that enhance the accuracy and reliability of their analyses.

Name	Variable	Distribution	Mean (μ)	Standard deviation (σ)	Reference
Concrete compressive strength	$f_c(C20)$	Normal	$1.3 * f_{ck}$	$0.2 * \mu$	[15]
	$f_c(C30)$	Normal	$1.22 * f_{ck}$	$0.15 * \mu$	[15]
	f_c	Normal	$f_{ck} + 1.65 * \sigma$	$4MPa$	[24]
Yield strength of reinforcement	f_y	Normal	$1.22 * f_y$	$0.04 * \mu$	[15]
		Normal	$f_{yk} + 2 * \sigma$	$30\ MPa$	[8]
Tensile strength of prestressing strands	f_{pt}	Normal	$1.07 * f_{ptk}$	$0.015 * \mu$	[15]
		Normal	$1.04 * f_{ptk}$	$0.025 * \mu$	[8]
Width	b_w	Normal	b_w	$4mm + 0.006 * b_w$	[8]
Height	h	Normal	h	$4mm + 0.006 * h$	[8]
Area of reinforcement	A_s	Normal	A_s	$0.02 * \mu$	[8]
Area of prestressing strands	A_p	Normal	$1.03 * A_{pn}$	$0.01 * \mu$	[15]
		Normal	Apn	$0.02 * \mu$	[8]
Concrete cover-Top	C_t	Normal	$C_t + 10mm$	$10mm$	[8]
Concrete cover-Bottom	C_b	Normal	C_b	$5mm$	[8]
Structural elements	G_1	Normal	$1.06 * G_{1k}$	$0.12 * \mu$	[15]
Asphalt	G_2	Normal	$1.10 * G_{2k}$	$0.25 * \mu$	[25]
Additional load	G_3	Normal	$G3k$	$0.25 * \mu$	[25]
Traffic load	Q	Gumbel 1	$0.94 * TB450_k$	$0.18 * \mu$	[26]
Resistance uncertainty	θ_S	Log-Normal	1	$0.1 * \mu$	[8]
Load effect uncertainty	θ_R	Log-Normal	1	$0.05 * \mu$	[23]

Table 1: Distributions for the random variables used in the reliability analysis

Material

Material properties can vary depending on several factors, such as the quality of the materials, the manufacturing process, and the environmental conditions. Using inaccurate material properties can lead to inaccurate predictions of the behaviour and performance of a structure, which can compromise the safety and durability of the structure. By obtaining the actual distribution of the material through testing and characterisation, engineers can make more accurate predictions and ensure that the structure is designed to meet the required performance standards. Having the actual distribution of the material is essential because the distribution provided by the codes, guidelines and research papers may not always accurately represent the properties of the material used in a particular project.

For the case of compressive strength of concrete (f_c), Ref. [27] conducted a study to assess the conformity of concrete strength across four different classes (C20, C30, C40, and C50) manufactured in Brazil. Reference [27] concluded that for classes C20 and C30, the mean strength (f_{cm}) and standard deviation (σ) values exceed those predicted in the standard[24]. The mean strength values for classes C40 and C50 fall below the predicted values. *Figure 3* (top-left) illustrates the probability distribution curve resulting from axial compression tests of concrete class C40 and compares it with the probability distribution curve of the concrete's preparation, control, and acceptance code[24], considering it complying with condition A ($\sigma = 4MPa$).

Figure 3 (top-right) illustrates the dissimilarities in probability distribution curves obtained for concrete (C40) produced in various regions across the country[27]. The analysis reveals that the behaviour of concrete varies across locations. The regional results demonstrate that the variability of concretes produced in the Southeast (SE) and Northeast (NE) regions is higher than those produced in the South (S) and Centre-West (CW) regions. Adequate control is indicated when strength values are closely clustered around the mean, resulting in a high and narrow distribution curve. Conversely, inadequate control leads to dispersed strength values, resulting in a low and wide distribution curve.

For the case of steel properties, Reference [15] presents the distribution characteristics of the yielding strength (f_y) and tensile strength (f_{pt}) obtained from the results of tensile tests performed in samples of CA-50 reinforcing bars and CP 190 low-relaxation prestressing strands, respectively, with different diameters and produced in several batches in Brazil. *Table 1* show the statistical characteristics of the materials. The result is illustrated in *Fig. 3* (bottom-left) for the case of CA-50 reinforcing bars and *Fig. 3* (bottom-right) for the case of CP 190 strands.

Geometry

Using statistical models to represent geometry distributions can provide valuable insights into structural performance and reduce uncertainty in the analysis. For example, changes in the height of a beam or the rebar/tendon position can significantly affect its strength.

The values for the height of the slab, considered here as the height of the flange (h_f), the height of the beam web (h_w) and the width of the beam web (b_w), are presented in *Table 1*. Due to the constructive method, in

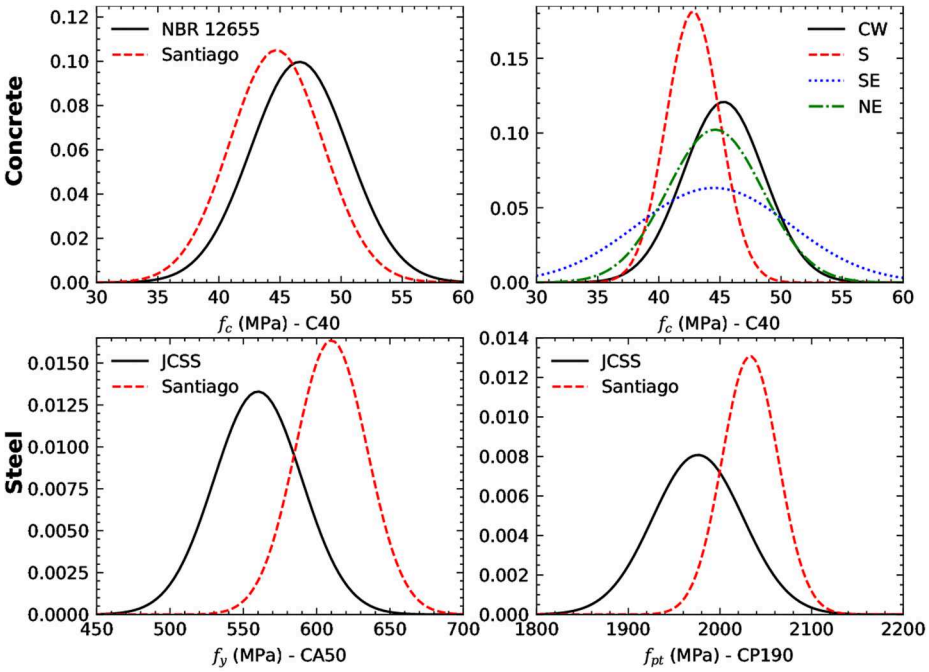


Fig. 3: Comparison between the distribution functions of concrete and steel presented by Ref.s [15,27], NBR12655 [24], and JCSS [8]

which the casting of the beams and the slab typically take place at different times, it was decided to consider these two variables as independent. The variation in the flange's width was not considered because it depends on the numerical model adopted, thus being considered in the numerical error model.

Another vital factor for beam strength is the geometry of the reinforcement, namely the section area (A_s) and its position within the beam section. In this way, two configurations were considered to position the reinforcements, one for the bottom (C_b) and one for the top (C_t). *Table 1* also presents the results for the cross-section area (A_p) in terms of the nominal area (A_{pm}).

Numerical Model

Numerical models are often used to simulate the behaviour of structures, but such models can also be subject to uncertainties. These uncertainties can arise from various sources, such as assumptions made during model development, simplifications of complex behaviours, and numerical errors in the analysis. The load effect uncertainty (θ_s) and resistance uncertainty (θ_R) variables are referred to as parameters that contain the model uncertainties and are treated as random variables.

Considering the uncertainties associated with numerical models when performing reliability assessments is essential. It helps to provide a more accurate estimation of the probability of failure. Additionally, identifying the sources of uncertainty in numerical models can guide efforts to improve the accuracy of the models and reduce the overall uncertainty in the assessment.

Load

Load distributions play a crucial role in the reliability assessment of structures. These load distributions can be obtained from statistical analysis of historical data, environmental conditions, or other sources of information. In this article, permanent and traffic loads were considered.

The permanent load was divided into three groups: self-weight of structural elements (deck slabs, longitudinal beams, and cross girders) and other reinforced concrete elements (parapets and barriers); asphalt pavement weight; and other additional loads (soil weight); represented by G_1, G_2 and G_3, respectively. Their respective probabilistic models are listed in *Table 1*.

Traffic loads are a significant source of uncertainty in the reliability assessment of bridges, particularly for highway bridges. The magnitude and frequency of traffic loads vary greatly depending on traffic volume and vehicle types. The uncertainty associated with these loads can significantly impact the predicted reliability of a bridge. Accurately modelling traffic load distributions is crucial for ensuring bridges' safety and reliability. By considering the uncertainties associated with traffic load distributions, engineers and decision-makers can make more informed decisions regarding bridge infrastructure design, maintenance, and management.

Many authors[25,28–30] have studied the traffic loads in Brazil. In this article, the traffic load (Q) considered was according to NBR 7188:2013[13]. Nevertheless, it is necessary to resort to another standard to convert the load model to a probabilistic distribution. The NBR 8681[14] says that the characteristic values of traffic loads correspond to values with a probability of 25% to 35% of being exceeded in an unfavourable way over 50 years[14]. Thus, an average value of 30% probability of being exceeded over 50 years would correspond to an average return period of 140 years.

The last step is to define a probabilistic function for the load. It is considered that the traffic load follows a type 1 Gumbel distribution, according to Ref. [26].

Since the bridge can be designed or evaluated for different lifetimes, a compatible function must be used. *Figure 4* shows the load distribution for different duration of exposure and the characteristic load defined in NBR 7188[13].

Structural Assessment

This chapter outlines the methodology for the structural assessment, including case study descriptions and a sensitivity analysis. The initial step involved a structural analysis to determine the acting moments on the bridge, considering both the permanent load (bridge weight, road surface, and sidewalks) and the traffic load (vehicles and pedestrians). Subsequently, the design resistance capacity and design moment values were calculated. Using a probabilistic approach, the resistance and loading curves were derived. Lastly, a sensitivity analysis to evaluate the impact of input parameters on the assessment outcomes is performed.

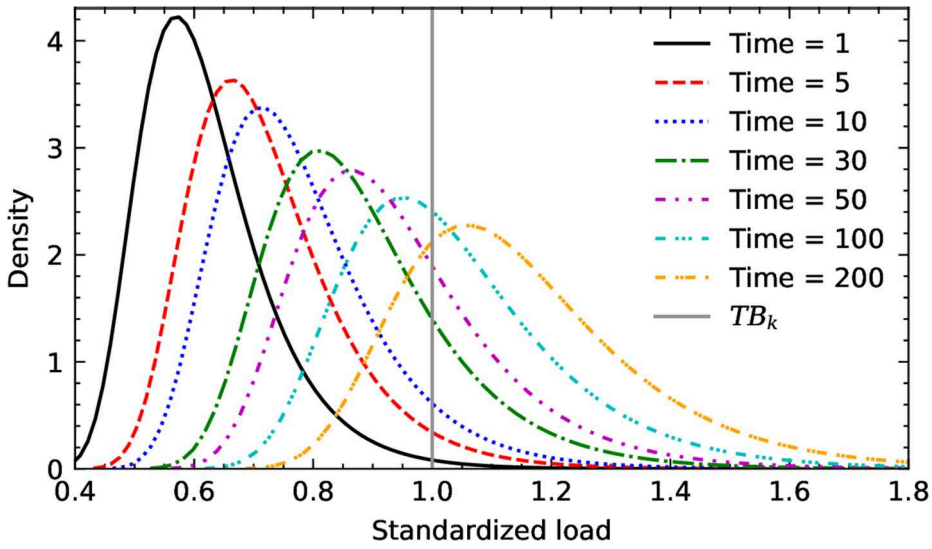


Fig. 4: Traffic load distribution for different duration of exposure

Case Study

Case studies are essential in demonstrating the reliability assessment of structures because they provide a real-world context for the methodology. They can help build confidence and provide insights. By presenting case studies, this article can showcase the reliability methodology, provide evidence of the approach's effectiveness, and demonstrate the value of reliability analysis in structural engineering.

For the purpose of safety assessment, a total of six bridges were selected as case studies, offering a platform to scrutinise the semi-probabilistic and probabilistic methods and facilitate a comparative analysis between the two approaches.

The rationale behind the choice of case studies rested upon the prevalence of specific structural and construction systems in Brazil. This strategic approach led to the inclusion of three reinforced concrete bridges and three prestressed concrete bridges.

These systems collectively account for approximately 70% of the nation's construction landscape[2]. Further insights into the attributes of these bridges can be gleaned from *Table 2* and *Fig. 5*.

It is paramount to underscore that all structures in the case study are assumed to be without defects, regardless of their age. In essence, this assumption implies that all bridges are in good condition. Consequently, they are in agreement with Annex D of NBR 7187/2021[12].

Numerical Model

The numerical model plays a critical role in the reliability assessment of structures because its quality and accuracy significantly impact the reliability assessment's outcome. To obtain reliable results, the model must accurately represent the structure's geometry, material properties, and boundary conditions.

Bridges are complex structures composed of various elements such as piers, abutments, main beams, and others. Each of these elements plays an essential role in ensuring the overall safety and reliability of the bridge system. However, due to the complexity of the structure, analysing every component would require extensive resources and time.

Main beams are critical components in transferring the load of the bridge's traffic to the supporting elements, such as piers and abutments. Therefore, any damage or failure in these components can have severe consequences for the overall safety and functionality of the bridge system.

Considering the importance of the main beams in the structural safety of bridges, this article prioritised the analysis of these elements. By focusing on the main beams, the article aimed to provide a more in-depth and detailed analysis of this critical component and its role in ensuring the overall safety and reliability of the bridge system. The article does not claim that other components, such as piers or abutments, are less critical, but rather that by prioritising the analysis of the main beams, it was possible to provide a more detailed and focused study of this critical element.

In this article, the analysis was conducted using the STRAP 2022 Software, based on the finite element method (FEM), with the focus on simulating the behaviour of the bridge deck, the primary load-carrying component. The piers and abutments were simplified as supports to provide necessary boundary conditions for the deck analysis, streamlining the process and reducing computational effort. A model representation is shown in *Fig. 6*.

For stress calculations, a linear analysis approach was adopted. The slab was modelled using Medellin shell elements, ensuring accuracy with a maximum size of 0.50 metres. Additionally, the longitudinal and transversal beams were modelled using the Euler-Bernoulli theory. The connection between the slabs and beams was established at the centroid of the beams. Moreover, the beam/slab interaction was independently calculated and considered in the beam section to account for their interaction effectively.

As just described, it was employed a FEM to calculate the internal forces. In the subsequent part of the analysis,

Bridge	Type	Length (m)	Span (m)	Year of construction	f_{ck}(*MPa*)
Joanes	Reinforced concrete	27	19	1975	18
Itapemirim		180	24	1977	17
Canindé		92	25/30	1973	18
Anhanguera	Prestressed concrete	36	17.5	1967	25
Iguape		32	32	1969	30
Corumbatai		75	25	1974	30

Table 2: Description of the bridges

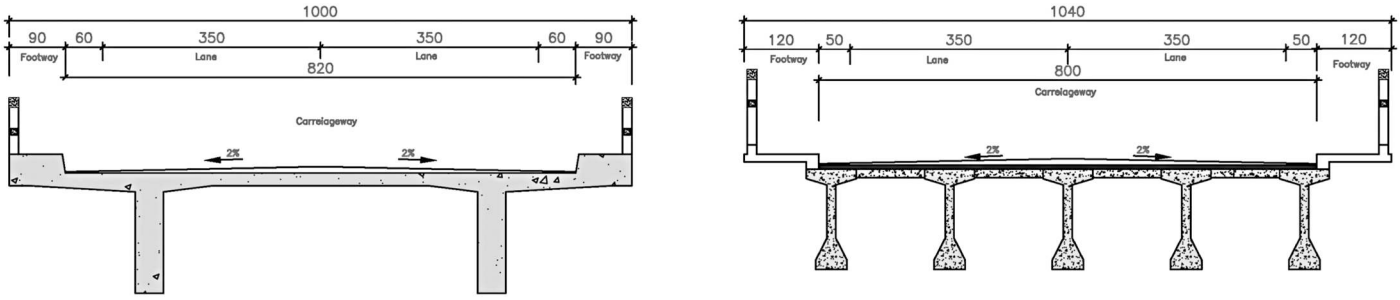


Fig. 5: Typical sections of concrete road bridges in Brazil. Measurement unit = cm

the estimation of the flexural capacity of the reinforced concrete beam cross-section was conducted using a non-linear 2D sectional analysis software[31]. This advanced analysis method involves modelling the concrete and reinforcing steel with appropriate constitutive models and dividing the cross-section into layer elements. The software applies load (or rotation) incrementally to the cross- section until failure occurs, allowing for the accurate estimation of the ultimate flexural capacity. Unlike the traditional binary equilibrium approach, this non-linear analysis provides a more precise estimate, particularly for complex cross-sections or those exhibiting significant non-linear behaviour. By adopting this approach, a more reliable assessment of the beam's flexural capacity can be ensured, enhancing the overall accuracy of the analysis and contributing to a deeper understanding of its structural behaviour.

Semi-Probabilistic Method

In the semi-probabilistic method, the resistance of the beam sections (R_d) is determined based on the designed resistance of the materials (f_{cd}, f_{yd}, and f_{ptd}) defined in the code[11], which means that the materials' variability is not directly considered.

For the semi-probabilistic approach, two criteria were used to determine the designed load effects (S_d). The first criterion is to adopt the partial factors defined for new structures according to NBR 8681[14]. The second criterion is to adopt reductions in the partial factors for existing structures according to Annex D of NBR 7187[12].

The rationale for using different partial factors for existing structures is based on the assumption that the existing structures have a higher level of reliability since they have already been in service and have proven their safety and also due to the high cost involved in strengthening an existing structure. However, it is essential to note that this hypothesis is only valid when the bridge is in good structural and durability conditions. If the bridge has any damage or degradation, the level of safety and reliability may be compromised, and additional measures may need to be taken to ensure the structural safety of the bridge.

Probabilistic Method

In the probabilistic method, the resistance and loading distribution curves are fundamental to calculating the probability of failure (p_f) and the reliability index (β), as described in *Equation 6*. The resistance curve (R) represents the structure's capacity, while the load curve (S) represents the expected load on the structure. The calculation of these curves is performed through different computational techniques.

To obtain the resistance curve, a variance reduction technique known as Latin hypercube sampling[32] was employed. This method allows for a more comprehensive exploration of parameter variability within the analysis. By generating a strategically designed set of samples, encompassing diverse combinations of factors such as material strength, dimensions, and other critical variables, it was ensured a robust representation of the system's behaviour. Subsequently, the obtained set of samples was seamlessly integrated into another specialised software[31], where each individual sample was evaluated to derive its unique contribution to the result. This process enables to derive a comprehensive resistance curve, showcasing the system's response under various conditions. Finally, it was performed a normal distribution fitting procedure based on the final resistance curve.

The load curve, on the other hand, was obtained by following a systematic approach. Firstly, individual unit loads representing permanent and traffic loads were added separately in the Finite Element software to acquire the corresponding internal bending moments. Next, these bending moments were scaled based on the actual load distribution (*Table 1*). With the final bending moment distributions for each load in hand, the final bending moment distribution was obtained using the PaCAL software package[33]. PaCAL allows calculating the probability distribution of random variables resulting from arithmetic operations, given the probability distributions of the input random variables. This enabled computing the load

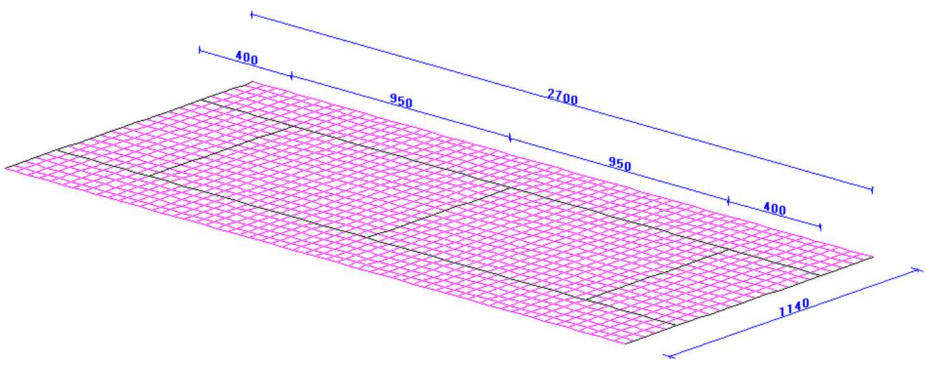


Fig. 6: Numerical model (Joanes' bridge). Measurement unit = cm

curve based on statistical parameters of the input load values, such as their means and standard deviations. This approach achieves high accuracy and allows computations with a broad range of probability distributions. By propagating the input loads through the arithmetic operations, PaCAL provided the probability distribution of the final bending moment curve.

Once the resistance and load curves have been obtained, the PaCAL software is invoked once more to conduct essential computations for reliability analysis.

Specifically, the PaCAL software efficiently calculates the performance function (*Equation 5*), which serves as a fundamental precursor in subsequent analyses. Building upon this, it was determined the probability of failure (*Equation 6*) and, subsequently, the corresponding reliability index (*Equation 8*). The probability of failure represents the likelihood of structural failure under the influence of specific load and resistance distributions.

Sensibility Analysis

Sensitivity analysis constitutes a vital component of reliability assessment, as it enables the identification of input parameters (*Table 1*) that exert significant influence on output variability. Through quantification of input-output relationships, sensitivity analysis elucidates the underlying behaviour of the numerical model under consideration. In the present study, this analysis was executed by leveraging the probability distributions derived from the codes[8,24].

A variance-based sensitivity analysis was performed using the Sobol method[32,34] to quantify how uncertainties in the inputs contribute to uncertainty in the structural response. This method decomposes the variance of the output into fractions attributable to each input or combinations of inputs. The Sobol method provides sensitivity indices that measure the main effect of each individual input, as well as the total effect including interactions with other inputs. These indices indicate the proportion of output variance explained by each input or combination of inputs.

The sensitivity analysis results (*Fig. 7*) for the reinforced concrete bridges indicate that steel's yield stress is the most critical parameter in determining the reliability of the main beams of the bridges. This is because, in most cases, failure is dominated by steel yielding, a crucial factor in designing the beams according to the NBR 6118[11]. On the other hand, the geometric parameters, such as the dimensions of the cross-section, had almost zero influence on the reliability of the beams. This can be attributed to the fact that the variances of these parameters are relatively low compared to the yield stress of steel.

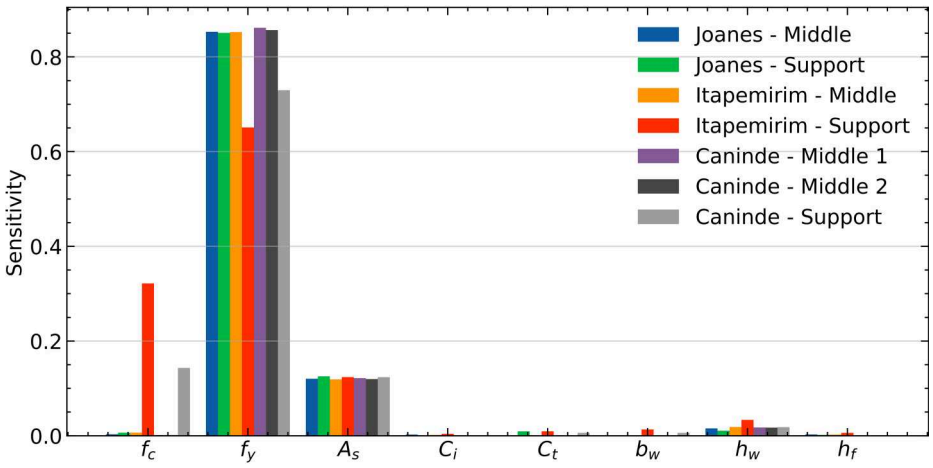


Fig. 7: Sensitivity analysis of the reinforced concrete bridges

Similar results were found when performing the sensitivity analysis of prestressed concrete bridges (*Fig. 8*). The most significant parameter is the tendon, namely its strength (f_{pt}) and area (A_p). Interestingly, concrete had a small influence, except for beam A of bridge 87.

By conducting the sensitivity analysis, the researchers could determine which input parameters had the most significant impact on the output results of the numerical model. This information is crucial in refining the model and making it more accurate. It also helps to identify areas where further research and data collection may be necessary to improve the model's reliability.

Results

In this chapter, the outcome of the study is presented. The results encompass a comparison of the resistance distribution under different material distributions and a comparison between the semi-probabilistic and probabilistic methods. These findings offer valuable insights into safety assessment and contribute to a deeper understanding of reliability analysis.

Comparison - Brazilian and Codes' Distributions

In order to perform a reliable analysis, it is essential to have an accurate representation of the material and geometry distribution. While codes and standards provide generic curves, it is essential to note that these distributions may not accurately represent the specific materials and geometries of the structure. Therefore, obtaining the actual distribution of the material and geometry is essential for a more accurate and reliable assessment.

The safety of the internal beam of bridge Anhanguera was assessed using two different sets of distributions to demonstrate the importance of having actual data for material and geometry. The first set of distributions was obtained from the codes[8,24]. The second set of distributions was suggested by Ref. [15] and was considered to be more accurate for this particular bridge. *Table 1* shows the distribution parameters.

The obtained resistance bending moment distributions (*Fig. 9*) diverge significantly. The curve obtained from the codes is more conservative, indicating that the actual safety level of the beam might be higher than predicted by the codes.

Comparing two approaches for reliability assessment has revealed the importance of using actual data for material and geometry distributions rather than relying solely on generic curves provided by codes and standards. This emphasises the need for

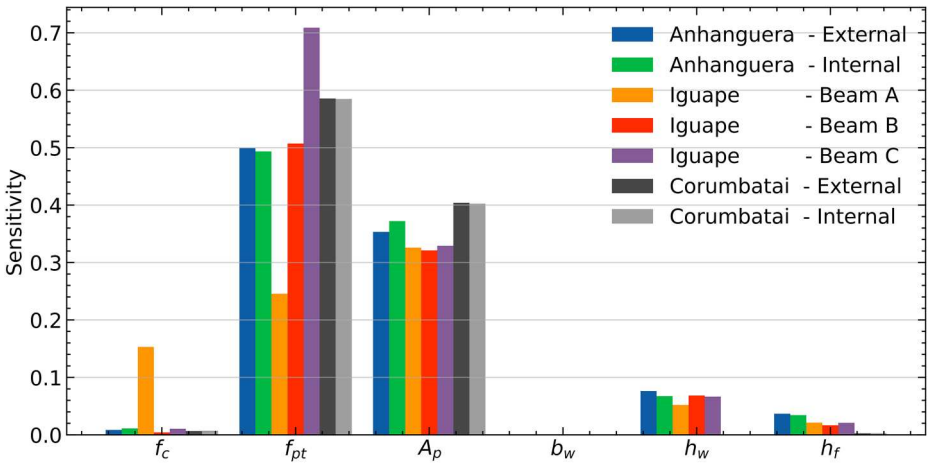


Fig. 8: Sensitivity analysis of the prestressed concrete bridges

more accurate and updated data to ensure a reliable and efficient analysis. The divergence between the two approaches highlights the potential consequences of using outdated or inaccurate information in the assessment of structures, which can result in costly errors and compromises in safety.

Comparison – Semi-Probabilistic and Probabilistic Methods

In this sub-chapter, the focus lies on a critical comparison between the two fundamental approaches discussed in this article: the semi-probabilistic and probabilistic methods. The results are presented in two distinct ways, namely through *Table 3* and *Fig. 10*, and are thoroughly discussed.

Table 3 provides a summary of the results obtained through the semi-probabilistic and probabilistic approaches. The table contains characteristic values of the load moments (S_{G1k}, S_{G2k}, S_{G3k}, S_{Qk}) obtained from the structural analysis, along with the corresponding designed values of the load moments, accounting for partial coefficients applicable to new structures ($S_{d,1}$)[14] and existing structures ($S_{d,2}$)[12]. Additionally, the table presents the design value of the section resistance (R_d) and the reliability indices (β_{50}), considering distributions sourced from the codes[8,24] as well as from Brazilian studies[15].

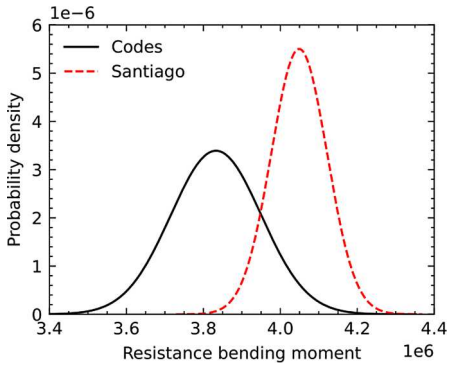


Fig. 9: Comparison of the resistance probability curve using material and geometrical distribution from codes[8,24] and Ref. [15]

As it can be seen, the cases of bridges Itapemirim (middle), Itapemirim (support) Canindé (middle 1), Anhanguera (External), Anhanguera (Internal), Iguape (B), Iguape (C), Corumbatai (External), and Corumbatai (Internal) showed adequate resistance for both analysis hypotheses. The cases of the Joanes (middle), Joanes (support), Canindé (middle 2) Canindé (support), and Iguape (A) showed adequate safety only when the reduced coefficients were considered.

The graphical representation in *Fig. 10* elucidates the findings obtained from *Table 3*. This visualisation entails the plotting of the distinct columns (namely, $S_{d,1}$, $S_{d,2}$, $\beta_{50}^{8,24}$, and β_{50}^{15}) for a comprehensive illustration of the results. The left graph corresponds to the outcomes based on the codes[8,24], while the right graph depicts results derived from Ref. [15].

The X-axis represents the ratio of the design resistance (R_d) to the design demand (S_d), where values above 1 indicate that the resistance exceeds the demand, inducing the structure safe. Meanwhile, the Y-axis represents

Bridge	S_{G1k}	S_{G2k}	S_{G3k}	S_{Qk}	$S_{d,1}$	$S_{d,2}$	R_d	β_{50}[8,25]	β_{50}[15]
Joanes - middle	1521	330	0	2453	7309	6550	7232	3.41	3.84
Joanes - support	1375	52	0	1068	4715	4222	4257	3.01	3.44
Itapemirim - middle	2323	780	−328	3075	9802	8780	13349	4.91	5.38
Itapemirim - support	4694	1428	−179	3133	14068	12572	16238	4.45	4.86
Canindé - middle 1	1379	685	0	2571	7729	6925	8182	3.67	4.16
Canindé - middle 2	2661	791	0	2816	10004	8952	9973	3.55	4.06
Canindé - support	3933	1393	0	2864	12700	11350	12162	3.40	3.81
Anhanguera - External	813	177	0	1501	3590	3215	3701	3.38	3.66
Anhanguera - Internal	820	156	0	1110	2982	2669	3199	3.65	3.97
Iguape - A	2410	542	0	2240	7333	6556	7029	3.44	3.80
Iguape - B	2404	541	0	2169	7229	6462	8209	4.11	4.45
Iguape - C	2410	536	0	1985	6954	6214	8620	4.82	5.15
Corumbatai - External	2551	227	0	2912	8129	7274	10548	4.64	4.89
Corumbatai - Internal	2185	200	0	2066	6319	5651	7461	4.25	4.59

Table 3: Results of analysis of bending moments (kN.m) and reliability index for selected bridges in Brazil

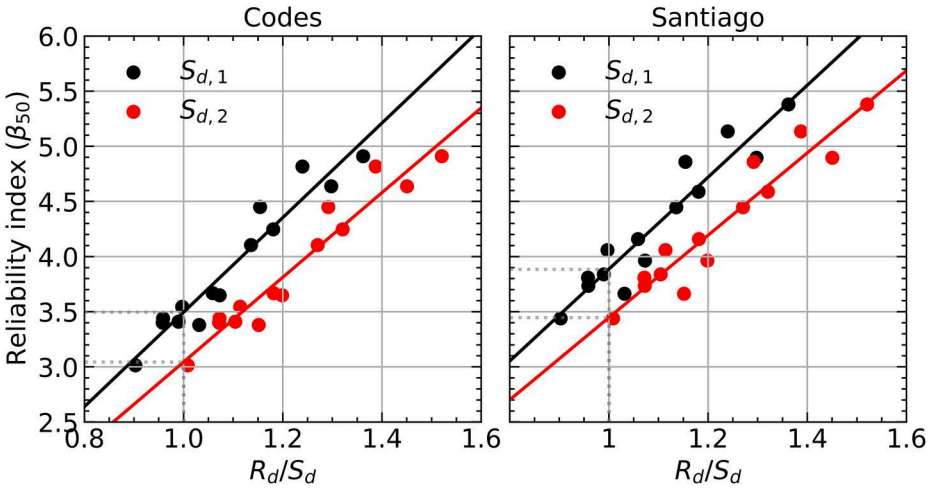


Fig. 10: Correlation between rating factors (R_d/F_d) and reliability index (β_{50})

the reliability index (β_{50}). Each data point on the graph corresponds to a specific bridge section, with black dots ($S_{d,1}$) representing demand values based on NBR 8681[14] and red dots ($S_{d,2}$) denoting demand values based on NBR 7187[12]. For each case scenario ($S_{d,1}$ and $S_{d,2}$), a fitted line is presented.

Through an examination of the intersection points where the fitted lines intersect the X-axis at a value of 1 (indicative of the bridge's safety status), noteworthy observations can be made. On the left graph, the Y-axis value for the black line is equal to 3.5, whereas for the red line, it approximates 3. This outcome implies that the calibration of Brazilian codes is oriented towards a beta target of 3.5 for new designs and a beta target of 3 for existing bridges. However, when analysing the right graph, Y-axis value for the black line is equal to 3.9, whereas for the red line, it approximates 3.5. Evidently, this observation suggests that, when using Ref. [15]'s distributions, the beta values are increased by 0.4.

Another observation arises in relation to the discrepancy of 0.5 in the beta targets represented by the black and red lines. This discrepancy harmoniously coincides with the guidance presented by fib80[23], which advocates for a 0.5 reduction in beta for existing bridges.

Conclusion

This study has provided a comprehensive analysis of the safety evaluation of reinforced and prestressed concrete bridges in Brazil, employing semi-probabilistic and probabilistic methodologies. Through the systematic examination of typical Brazilian bridges (3 reinforced concrete and 3 prestressed concrete) and by adopting two code- based criteria (new and existing bridges), this research has effectively highlighted the merits of adopting probability-based bridge assessment (PBBA) within the Brazilian context.

The reliability analysis results showed that the partial safety factors in Brazilian codes are consistent with international standards and seem to be calibrated for target reliability indices of 3.5 for new bridges and 3.0 for existing ones. Using actual statistical distributions for Brazilian materials resulted in higher reliability indices compared to those from standard codes, emphasising the need for accurate data. Thus, results obtained from material testing, or any other source of information, such as monitoring, should be used to calibrate and reduce statistical uncertainty. Nevertheless, this study focused only on main beams while a more comprehensive assessment involves other load-bearing components and considers other factors like deterioration, fatigue, and serviceability limit states (SLS).

It's vital to note that while rating factors (R_d/S_d) contribute to safety assessment, they fall short of offering a definitive measure. Instead, reliability emerges as a robust gauge of safety, accounting for intricate variables and uncertainties. Additionally, reliability analysis empowers engineers with heightened control in decision-making, enabling the identification of key analysis points and iterative result improvement. Moreover, for concessionaires overseeing bridge networks, reliability analysis offers a transformative approach, enabling risk-based prioritisation of maintenance and strengthening investments, optimising structural integrity and resource allocation.

Looking ahead, the successful integration of PBBA within Brazil's engineering landscape necessitates tailored implementation that considers national codes, practices, and context. As a forward step, comprehensive training and education for engineers are pivotal, urging academic institutions to include reliability analysis in curricula while encouraging practising engineers to participate in specialised professional development. Proper education will build the familiarity necessary for wide acceptance of PBBA. Codes and standards for bridge assessment in Brazil should formally incorporate PBBA within a tiered assessment framework as a higher-level method, as is increasingly done internationally, and establish target reliability levels for Brazilian highway bridges based on quantitative risk and cost–benefit analyses. This integration will promote the systematic use of PBBA in practice.

In essence, the transition of PBBA into mainstream practice in Brazil mandates concerted efforts across various fronts. While the journey towards full integration may demand diligence, the long-term benefits in terms of optimal infrastructure asset utilisation stand poised to outweigh the investment. This transition not only holds the potential to reshape bridge safety assessment but also promises a safer and more resilient bridge infrastructure.

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Data Availability Statement

Data sharing is not applicable to this article as no new data were created or analyzed in this study.

Disclosure Statement

No potential conflict of interest was reported by the author(s).

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