CIÊNCIA e NATURA

ISSN 2179-460X
OPEN ACCESS

Ci.e Nat., Santa Maria, v. 45, spe. n. 3,P. 01-16, e73885, 2023 • https://doi.org/10.5902/2179460X73885
Submitted: 01/25/2023 • Approved: 04/10/2023 • Published: 12/01/2023

Special Edition

Verification of structural reliability of a highway bridge in the state of Rio Grande do Sul

Verificação da confiabilidade estrutural de uma ponte rodoviária no estado do Rio Grande do Sul

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ABSTRACT

This study deals with the evaluation of the reliability index of prestressed girders members of road bridges in relation to the ultimate limit state (ULS) of bending failure. In a wide bibliographic review of scientific works that deal with structural reliability, prestressed structural elements and road bridges, it is observed that few of these deals specifically with the reliability of girders considering the codes NBR 7188 of 2013 and NBR 7187 of 2021. A mechanical model was developed for the calculation of the beam resistant moment and the Monte Carlo Method was used to obtain a data set that represents the statistics of the structure in the ULS. To obtain the reliability index β the first order reliability method (FORM) was used. The values obtained by the analytical method are validated using the Monte Carlo simulation method. For all evaluated cases, the value of the reliability index was higher than 4.0, which is higher than the minimum required value of 3.5, showing that the national normative recommendations for the design of beam members guarantee a very conservative level of safety.

Keywords: Reliability; Prestressed concrete; Bridges; FORM; Monte Carlo

RESUMO

Este estudo trata da avaliação do índice de confiabilidade de elementos protendidos de pontes rodoviárias em relação ao estado limite último (ELU) de ruptura por flexão. Em uma ampla revisão bibliográfica de trabalhos científicos que tratam de confiabilidade estrutural de elementos estruturais protendidos de pontes rodoviárias, observa-se que poucos deles tratam especificamente da confiabilidade de vigas considerando as normas NBR 7188 de 2013 e NBR 7187 de 2021. Um modelo mecânico foi desenvolvido para o cálculo do momento resistente da viga e o Método de Monte Carlo foi utilizado para obter um conjunto de dados que representa as estatísticas da estrutura no ELU. Para obter o índice de confiabilidade β foi utilizado o método de confiabilidade de primeira ordem (FORM). Os valores obtidos pelo método analítico são validados usando o método de simulação de Monte Carlo. Para todos os casos avaliados, o valor do índice de confiabilidade foi superior a 4.0, que é superior ao valor mínimo exigido de 3.5, mostrando que as recomendações normativas nacionais para dimensionamento de elementos de vigas garantem um nível de segurança bastante conservador

Palavras-chave: Confiabilidade; Concreto protendido; Pontes; FORM; Monte Carlo

1 INTRODUCTION

Bridge failures can cause great losses and inconvenience to people around them and the economy. Therefore, it is of great importance to study the safety of these structures in order to avoid such adversities.

The most frequently used method for assessing the safety of bridges is structural reliability. Its main objective is to determine the probability of occurrence of structural failures that are related to the reliability index.

The structural reliability method requires the statistical definition of the parameters included in the model, which depends on the quality of the statistical data referring to the problem and the precision of the mathematical model used to verify the limit state equations.

In Brazil, road bridges are designed based on the design codes NBR 7188 of 2013 and NBR 7187 of 2021, entitled “Carga móvel rodoviária e de pedestres em pontes, viadutos, passarelas e outras estruturas” and “Projeto de pontes de concreto armado e de concreto protendido - Procedimentos”, respectively.

It becomes feasible to assess the structural safety of these types of structural elements since most of the works that make up the Brazilian roads were designed before the changes in NBR 7188 of 2013 and NBR 7187 of 2021.

This study aims to evaluate the structural reliability of the prestressed concrete stringer beams of a bridge designed before the changes in the codes and to verify if such a structure still guarantees a satisfactory level of safety and within the requirements of current codes.

2 METHODOLOGY

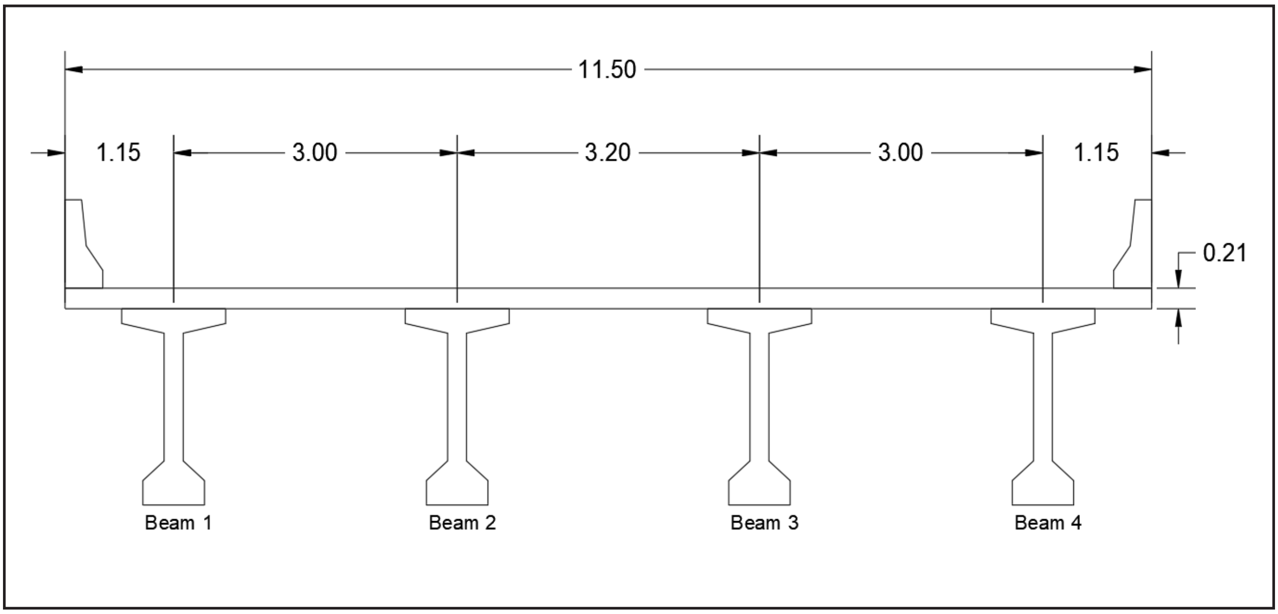
2.1 Structural internal forces

The bridge studied, shown in Figure 1, was designed in 2007 and is located on BR-392/RS at Km 59, close to port terminals, it is a bi-supported bridge with 4 prestressed precast beams and slab molded “in loco”, has a of 27.4 m, two lanes of traffic. The slab is cast “in loco” with a thickness of 21 cm and the asphalt layer is 7 cm thick. The dimensions of the prestressed precast beam and the guardrail are shown in Figure 2. For the analysis, Beam 1 was considered.

Table 1 shows the values of the main properties of the bridge materials.

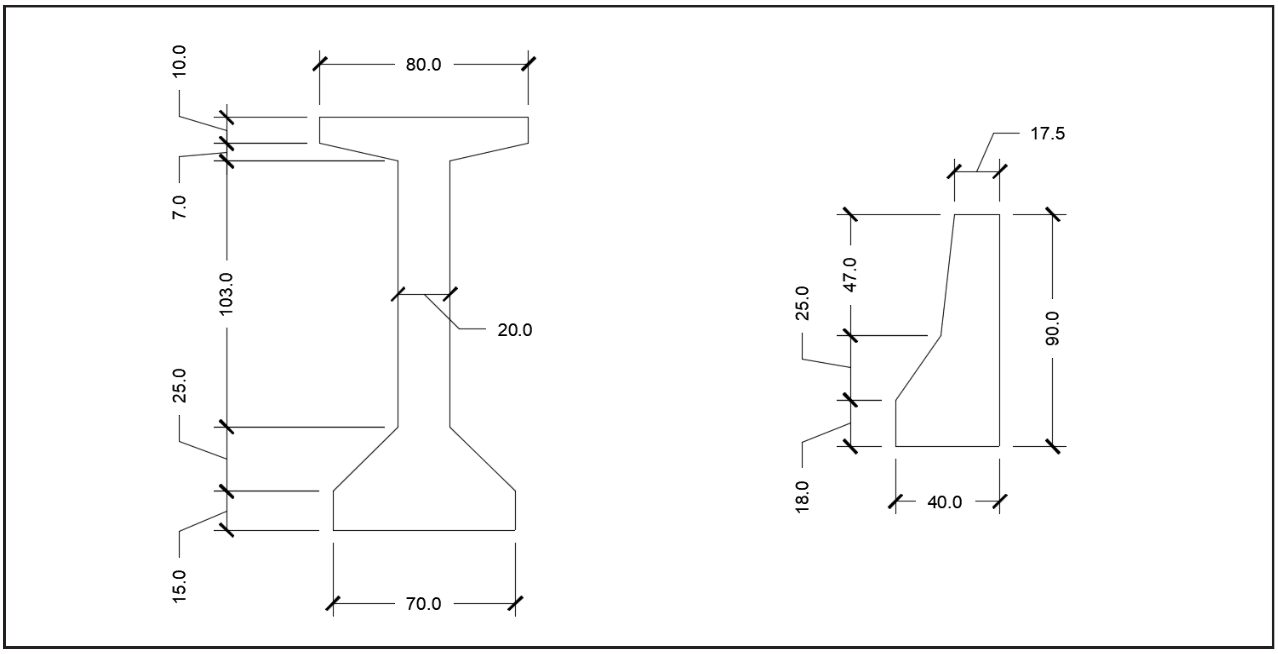
The analysis of transverse load distribution is performed using the Fauchart Method, used for bridges without intermediate transvers. This method provides a simple modeling and results very close to those obtained by a method with greater precision, such as the Finite Element Method, according to Ferreira *et al.* (2016).

Figure 1 – Cross section of the bridge (dimensions in meters)



Source: Authors, 2022

Figure 2 – Cross section of the bridge spars and railing (dimensions in centimeters)



Source: Authors, 2022

Table 1 – Bridge material properties

Properties	Value adopted	Unity
Specific Mass of Concrete	2500	kg/m³
Asphalt Specific Mass	2400	kg/m³
Compressive strength of the concrete of the beams	35	MPa
Compression Strength of the Slab Concrete	30	MPa

Source: Authors, 2022

Fauchart's method suggests the calculation of a flat structure that corresponds to one meter in width of the slab's cross section. The beams are replaced by springs which have resistance to vertical displacement and rotation. The spring constants are obtained by applying the Euler-Bernoulli theory to beams and elastic torsions, and their resolution is given by the Fourier series, resulting in Eqs. (1) and (2):

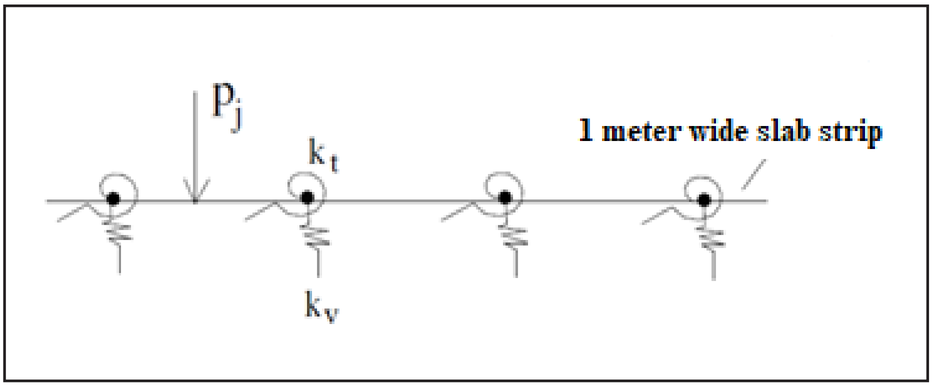
$$k_v = \left(\frac{\pi}{L}\right)^4 . EI \quad (1)$$

$$k_t = \left(\frac{\pi}{L}\right)^2 . GJ \quad (2)$$

where *L* is the span length in meters, *I* is the inertia of the beam section at , *J* is the torsion constant of the beam at , *E* is the secant modulus of elasticity of the material that makes up the beam in kPa, *G* is the modulus of transverse elasticity of the material that makes up the beam in kPa, is the coefficient of the vertical spring in kN/m and is the coefficient of the transverse spring in kN.m/rad (Stucchi, 2006).

In order to obtain the lines of influence that represent the loads on the beams, and to obtain the stresses on the slab, the beam is resolved on elastic supports for different positions of a unit load, as shown in Figure 3 (Heinen, 2016).

Figure 3 – Transverse structural scheme for a unitary strip



Source: Heinen, 2016

2.2 Resistant moment

A mechanical model was developed, based on Moura (2018), which calculates the resistant moment of cross-sections of prestressed concrete beams.

As this model was used in reliability analyses, with respect to the Ultimate Limit State (ULS) of flexural failure, the objective is to represent only the failure moment or the resistant moment.

Tables 2 and 3 show the model input data and their respective values used in this study to determine the resistant moment.

Table 2 – Properties of bridge materials

Data	Symbol	Value	Unity
Characteristic compressive strength of concrete (slab)	f_{ck}	30	MPa
Characteristic compressive strength of concrete (girder)	f_{ck}	35	MPa
Characteristic tensile strength of prestressing steel	f_{ptk}	1900	MPa
Characteristic resistance to yielding of prestressing steel	f_{pyk}	1710	MPa
Active steel modulus of elasticity	E_p	195	GPa
Breadth of Web	b_w	20	cm
Effective Width of the Flange	b_f	21	cm
Thickness of the Flange	h_f	265	cm

Source: Authors, 2022

Table 3 – Bridge material properties

Data	Symbol	Tier	Value	Unity
Cross-sectional area of active reinforcement	A_p	1°	36.36	cm²
		2°	12.12	
Useful height of the cross section, distance from the active reinforcement to the top of the beam	d_p	1°	171	cm
		2°	151	

Source: Authors, 2022

2.3 Live load model

The development of a live load model is essential in assessing the reliability of road bridges. This analysis demands an understanding of the real circumstances of truck traffic and is used to assess the structural reliability of bridges.

The data referring to truck weighing are those developed and used in Portela (2018). The author used data from two Weight in Motion (WIM) stations, one is in the state of Rio Grande do Sul, on the BR-290, and has 78 days of data collected, being the data from this station used in the present study. The other station is in the state of São Paulo.

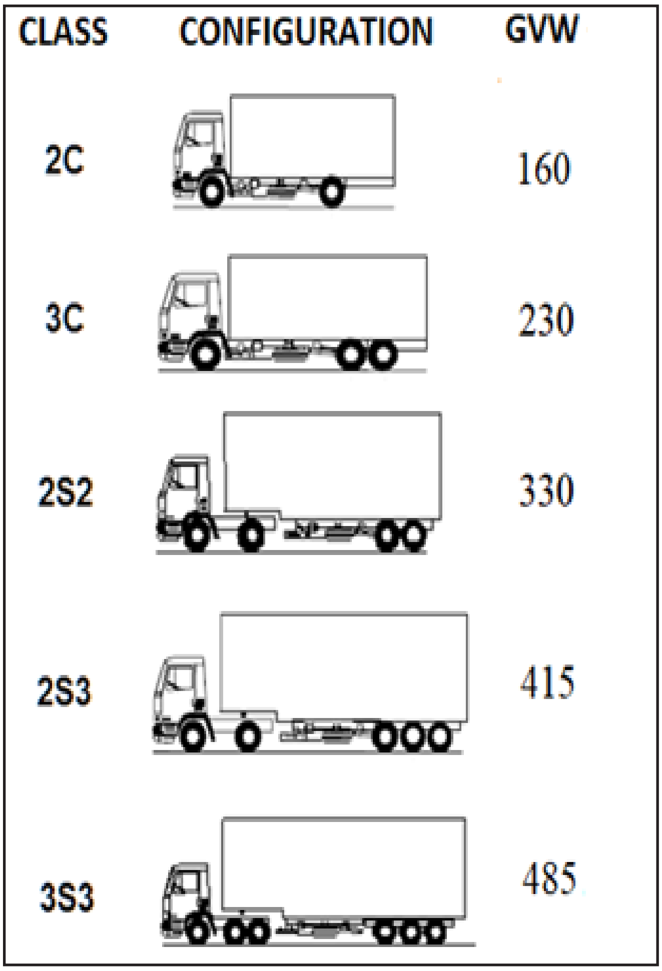
The silhouette of the five most frequent classes obtained in the WIM is shown in the Figure 4.

The present Study uses as deterministic values, for the wheelbase of the selected vehicles, the averages of the data obtained in a statistical study of the axle spacing carried out by Portela (2018). Table 4 shows the average for each of the five most frequent truck classes at the BR-290 WIM station.

Based on Ferreira *et al*. (2008), the maximum gross weights for each truck were extrapolated considering the useful life of the structures (100 years).

Table 5 presents the mean and standard deviation for the studied trucks.

Figure 4 – Frequent classes with the respective legal weights in kN



Source: Adapted from Carneiro *et al.*, 2020

Table 4 – Average for each of the five most frequent truck classes at the BR-290 WIM station

Truck Classes (DNIT)	First axis spacing (cm)	Second axis spacing (cm)	Third axis spacing (cm)	Fourth axis spacing (cm)	Fifth axis spacing (cm)
2C	562.3	-	-	-	-
3C	561.0	129.2	-	-	-
2S2	366.6	887.5	126.9	-	-
2S3	379.2	668.5	124.2	124.3	-
3S3	364.8	128.6	602.3	125.3	125.5

Source: adapted from Portela, 2018

Table 5 – Statistical parameters of vehicles evaluated for 100 years

Truck	Mean (kN)	S.D. (kN)
2C	392.49	65.38
3C	654.45	108.75
2S2	666.97	111.07
2S3	889.69	123.51
3S3	951.95	116.34

Source: Authors, 2022

2.4 Reliability

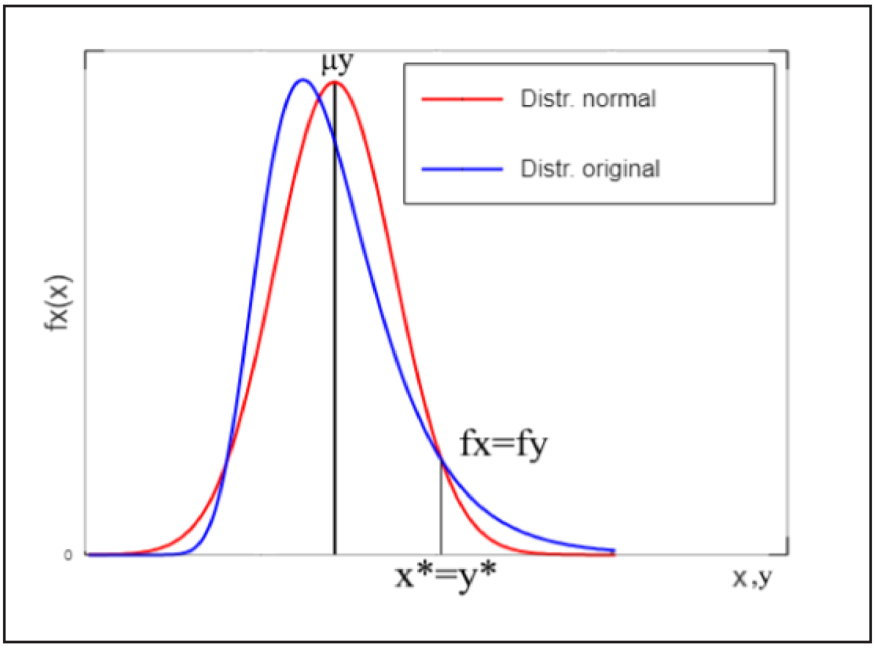
The design based on design codes applies the limit state format, which approximates uncertainties in design variables. In fact, the effects of materials, geometries and load are random in nature and can be specified through probability distributions. A structure is considered reliable if it performs its intended function during the lifetime of the project. A reliability analysis provides the probability of failure (p_f) and the reliability index (β), which are related according to Eq. (3):

$$\beta = \Phi^{-1}(1 - p_f) \tag{3}$$

where Φ^{-1} is the inverse standard normal distribution function. In this study, the reliability index (β) is calculated using the first-order reliability method (FORM) and validated using the Monte Carlo simulation method.

According to Beck (2019), the FORM method is a method of calculating the reliability index β through the first-order approximation of the performance function and converting all non-normal distributions into equivalent normal distributions at the point of failure x*, as shown in Figure 5.

Figure 5 – FORM method for non-normally distributed variables



Source: Silva Júnior, 2019

The FORM procedure consists of: defining the limit state equation G(x); assume an initial point of failure x*; calculate, as a function of x*, the corresponding mean ($\mu^N_{X_i}$) and standard deviation ($\sigma^N_{X_i}$) of each variable not normally distributed, calculate the partial derivatives at point x*; calculate the director cosines α_i; get the new failure point, according to Eq. (4):

$$x_i^* = \mu^N_{Xi} - \alpha_i . \beta . \sigma^N_{Xi} \tag{4}$$

calculate the updated β value; repeat the previous steps until convergence between β and x* is reached.

The FORM requires the analysis to be carried out in the standard space, and it is essential that the statistical parameters of random variables with the most diverse probability distributions are transformed into their normal equivalents (Beck, 2019).

The Monte Carlo method boils down to obtaining an estimate of the probability distribution of the response of a system by randomly generating the input parameters according to their probability distributions and performing N simulations for the resulting statistical analysis (Moura *et al.*, 2019).

The reliability study for engineering structural systems basically consists of three possible responses of the performance function G(x): in safety (G(x) > 0), limit state (G(x) = 0) and failure (G(x)) < 0).

The probability of failure can be determined by Eqs. (5) and (6):

$$p_f = \frac{1}{N} . \sum_{i=1}^{N} I_g(x_i) \quad (5)$$

$$I_g(x) = \begin{cases} 1, if \ g(x) \leq 0 \\ 0, if \ g(x) > 0 \end{cases} \quad (6)$$

The limit state equation, G(x), used in the study is given by Eq. (7):

$$G(x) = \theta_r . M_r - \theta_s . \left(\frac{g . l^2}{8} + M_{tt} \right) \quad (7)$$

where θ_r is the estimation of the model error, is the Resistant Moment of the prestressed concrete beam, is a factor due to the uncertainties of the actions, *g* is the permanent load, *l* is the design span and the moment due to the moving load.

The mean, standard deviation or coefficient of variation (COV) and the probability distribution curve of the variables considered are contained in Table 6.

Table 6 – Distribution and values of random variables

Variable	Mean μ	S.D. σ	COV = σ / μ	Type of distribution	Source
f_c	$1.22 \cdot f_{ck}$	-	0.15	Normal	Santiago *et al.* (2019)
f_{pt}	$1.07 \cdot f_{ptk}$	-	0.015	Normal	Santiago *et al.* (2019)
A_p	$1.03 \cdot A_{p,nom}$	-	0.01	Log-Normal	Santiago *et al.* (2019)
d_p	$d_{p,nom}$	1.00	-	Normal	JCSS (2001)
θ_r	1.053	0.081	-	Normal	Adapted from Moura (2018)
θ_s	1.00	-	0.10	Log-Normal	JCSS (2001)
g	$1.06 \cdot g_{nom}$	-	0.12	Normal	Santiago (2019)
M_{tt}	$M_{tt,nom}$	Nowak method	-	Normal	Nowak (1999)

Source: Authors, 2022

3 RESULTS

3.1 Reliability index

The reliability methods used in this study, FORM and Monte Carlo simulation, were both implemented using the PYTHON programming language.

For the Monte Carlo analysis, the importance sampling method was used, in order to accelerate the simulation convergence, adopting the probable failure points of each random variable provided by the FORM method. In this study, the accuracy of the Monte Carlo method was considered satisfactory when the COV of reached the value of 5%. (Beck, 2019).

Table 7 show the results of the reliability index using the first order reliability method (FORM) and the Monte Carlo simulation method.

From the results achieved, it can be observed that the values of the reliability indices calculated using the FORM method and the Monte Carlo simulation method are close, which confirms the validation of the models.

Table 7 – Bridge reliability index for isolated truck cases

Truck	Beta	
	FORM	Monte Carlo
2C	6.14	6.10
2S2	5.60	5.56
2S3	4.50	4.48
3C	4.83	4.81
3S3	4.50	4.48

Source: Authors, 2022

For all evaluated cases, the value of the reliability index was higher than 4.0, which is higher than the minimum required values of 3.5 or 3.8, according to ACI-318 (2011) and CEB-FIP (2010), respectively.

3.2 Sensitivity analysis

A sensitivity analysis was performed by calculating the Importance Index , which is a function of the sensitivity factor and is defined by Eq. (8) (Nova and Silva, 2017):

$$I_i = \alpha_i^2 \tag{8}$$

Sensitivity analysis makes it possible to determine the uncertainties that influence the failure event under analysis, and then locate those variables that present greater sensitivity in the response.

The sensitivity factor was obtained in the implementation of the FORM method and is shown in Table 8.

The sensitivity analysis showed that the random variables of the model error estimate (θ_r) and the uncertainty factor of the actions (θ_s) have a greater contribution to the probability of failure.

Table 8 – Importance index for each random variable

Random variable	Importance index (%)				
	2C	*2S2*	*2S3*	*3C*	*3S3*
f_c	0.10	0.10	0.11	0.10	0.11
f_{pt}	0.65	0.68	0.72	0.70	0.73
A_p	0.29	0.30	0.32	0.31	0.32
d_p	0.12	0.13	0.13	0.13	0.14
θ_r	47.05	43.21	37.30	38.28	37.93
θ_s	30.92	32.27	34.16	33.32	34.56
g	11.57	10.12	7.79	8.26	7.95
M_{tt}	9.30	13.20	19.47	18.89	18.26

Source: Authors, 2022

4 CONCLUSIONS

This study deals with the evaluation of the reliability index of road girders with regard to the ULS of failure by bending.

The reliability study of concrete stringer beams is justified by the increasing use of this type of structural element in bridge constructions, associated with the need to discover and achieve a certain level of safety in projects carried out in accordance with Brazilian codes NBR 7187 of 2021 and NBR 7188 of 2013. Using the first order reliability method (FORM), the reliability index was determined and the degree of safety of a prestressed concrete bridge designed before the changes of the Brazilian codes was verified. The values obtained by the analytical method are validated through the Monte Carlo simulation method, since they presented similar results.

It was possible to verify that the analyzed structure provides adequate levels of security. Taking as an expected reliability index, the value of 3.5, according to ACI-318 (2011), or the value of 3.8, according to CEB-FIP (2010), all cases analyzed exceeded this value, in fact all values greater than 4.0, thus showing that the previous codes remain conservative when compared with the current parameters of NBR 7187 of 2021 and NBR 7188 of 2013.

Through the sensitivity analysis, it was shown that the random variables of the moment due to the estimation of the model error (θ_r) and the factor due to the uncertainties of the actions (θ_s) have a greater contribution to the probability of failure. On the other hand, the permanent load (*g*) and the load due to the mobile load model (M_{tt}) have a smaller contribution to the probability of failure and the other variables have almost zero contributions.

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Contribution: Data Curation, Supervision, Writing – review & editing

How to quote this article

AVILA, V. H.; REAL, M. V. Verification of structural reliability of a highway bridge in the state of Rio Grande do Sul. **Ciência e Natura**, Santa Maria, v. 45, spe. n. 3, e73885, 2023. DOI 10.5902/2179460X73885. Available from: https://doi.org/10.5902/2179460X73885. Accessed in: day month abbr. year.