Dynamic structural analysis of steel-concrete composite highway bridges based on Monte Carlo simulations

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Abstract. The highway bridges are subjected to several random dynamic loadings of different intensities, among which the vehicles traffic is one of the most present. This type of loading generates displacements and stresses amplitudes that vary in intensity along the time, causing stress cycles on the bridge structural elements. When a structural element is subjected to these stress ranges, serious problems related to the fatigue phenomenon can occur. It is well known that an efficient analysis methodology to assess the fatigue service life caused by the road traffic is based on a dynamic analysis considering a coupled vehicle-pavement-bridge system. This way, this research work proposes an analysis methodology based on Monte Carlo simulations aiming to determine the fatigue service life of steel-concrete composite high way bridges. The main characteristics of the bridge and the vehicle are defined as random variables and the vehicle-pavement-bridge dynamic interaction effect is considered. Furthermore, the simulations are carried out considering two levels associated to the pavement degradation. The dynamic response of a typical simply supported steel-concrete composite highway bridge with straight axis and spanning 40 m is investigated. After that, the results calculated through the proposed analysis methodology, considering a large sample of the vehicle-pavement-bridge combinations, make it possible to assess which parameters of the vehicle-pavement-bridge system presented the most relevant influence on the fatigue service life of the investigated highway bridge.

Keywords: highway bridges, dynamic structural analysis, Monte Carlo simulations.

1 Introduction

Highway bridge decks are subjected to a variety of random dynamic loads, primarily vehicular traffic. The stochastic nature of traffic, with characteristics that vary over time and space, makes it challenging to accurately model the loads on the structures. This variability is influenced by several factors, such as vehicle characteristics, speed, vehicle spacing, and pavement conditions [1].

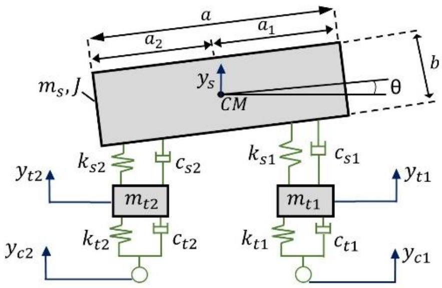
The passage of vehicles over the deck of bridges induces repetitive stress cycles that can promote the initiation and propagation of cracks in the bridge structure due to the phenomenon of fatigue. Coupled with this condition, the deterioration of the road surface caused by wear and tear and weathering, generates irregularities in the surface, further intensifying the load and unload cycles on the structural components [2].

The proposed analysis methodology implements Monte Carlo Simulations (MCS) to perform the dynamic analysis of a highway bridge. This approach accounts for the non-deterministic nature of vehicular loads and bridge structural parameters. The irregular pavement surface is generated using a random model based on the spectral density of pavement irregularities. The analysis aims to identify which of the main parameters of the vehicle-bridge system, modeled as random variables, have the greatest influence on the results of vertical displacement, flexural stress, and fatigue life.

2 Mathematical modelling of the vehicle

The truck employed in this study is depicted in Fig. 1(a), being one of the most common vehicles on local roads in Brazil. The structural-mechanical model of the two-axle truck is shown in Fig. 1(b), where the front axle features single wheels and the rear axle features dual wheels. This model exhibits four degrees of freedom. The geometry, mass distribution, damping, and stiffness are summarized in Tab. 1.

a) Truck geometry: 2C vehicle



b) Modelling of the rigid body, springs and dampers

Figure 1. Model of the two-axle truck prototype

Table 1. Dynamic properties of the vehicle (2 axles)

Parameter	1st Axle		2st Axle	Units
Suspension spring stiffness (k_s)	250		700	kN/m
Tire spring stiffness (k_t)	1,960		3,920	kN/m
Suspension damping (c_s)	15		30	kNm/s
Tire damping (c_t)	2		4	kNm/s
Unsprung mass (m_t)	570		735	Kg
Sprung mass (m_s)		16,695		Kg
Wheelbase (a)		5		m
Height (b)		2.4		m
Pitch inertia (*J*)		43,476.6		Kgm^2

3 Modelling of the progressive deterioration for road surface

The Road surface roughness, characterized by the irregularities present in the pavement, constitutes a critical factor influencing the dynamic response of vehicles and bridges. Based on the studies carried out by Dodds and Robson [3], the road surface roughness was assumed as a zero-mean stationary Gaussian random process and it could be generated through an inverse Fourier transformation as shown in eq. (1):

$$r(x) = \sum_{i=1}^{N} \sqrt{2 \times \Delta\Omega \times G_d(\Omega_i)} \times \cos(2\pi \times \Omega_i x + \theta_i) \quad (1)$$

Where θ_i = random phase-angle uniformly distributed from 0 to 2π; $G_d(\Omega)$ = power spectral density (PSD) function (cm^3/cycle) for the road surface elevation; and Ω_i = wave number (cycles/m). The PSD function for road surface roughness was developed by Dodds and Robson [3], as presented in eq. (2):

$$G_d(\Omega_i) = G_d(\Omega_0) \times \left[\frac{\Omega}{\Omega_0}\right]^{-2} \quad (2)$$

Where Ω = spatial frequency of the pavement harmonic i (cycles/m); Ω_0 = discontinuity frequency of $1/2\pi$; and $G_d(\Omega_0)$ = road roughness coefficient (m^3/cycle), called RRC, used by the International Organization for Standardization [4] to define the road-roughness classification based on pavement quality (see Tab. 2).

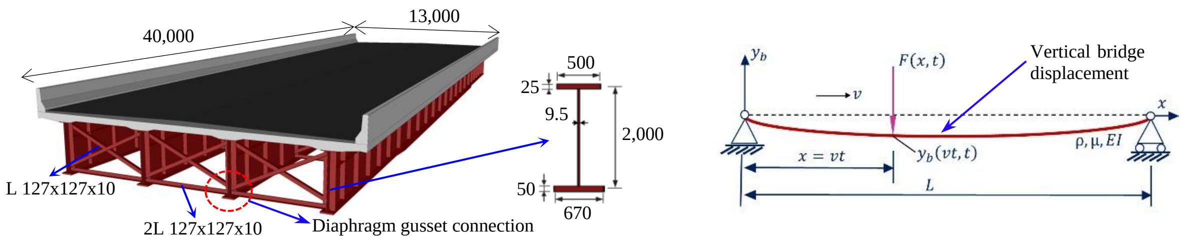
Table 2. Average values of $G_d(\Omega_0)$ for different levels of road quality (in cm^3) [4]

Road Quality Level	$G_d(\Omega_0)$: Lower	$G_d(\Omega_0)$: Mean	$G_d(\Omega_0)$: Upper
Excellent	-	1	2
Good	2	4	8
Average	8	16	32
Poor	32	64	128
Very poor	128	256	512

4 Investigated highway bridge and mathematical model

The bridge structural model corresponds to a simply supported steel-concrete bridge deck with straight axis, spanning 13 m by 40 m and with a 0.225 m thick concrete slab (see Fig. 2). The steel sections are composed by welded wide flanges made with A588 steel with 350 MPa yield strength and 485 MPa ultimate tensile strength. A 2.0×10^5 MPa Young's modulus with 0.3 Poisson's ratio was adopted. The concrete slab has 25 MPa compression strength with 3.05×10^4 MPa of Young's modulus and 0.2 Poisson's ratio.

The mathematical model of the bridge is idealized as a bi-supported planar Euler-Bernoulli beam, exhibiting constant linear mass (ρ), damping (μ), and flexural rigidity (EI) properties along its length. Considering the mixed nature of the bridge, composed of steel and concrete, an equivalent homogeneous steel section was adopted. Table 3 presents the parameters employed in the two-dimensional bridge model.



a) Structure design (units in millimetres) b) Two-dimensional bridge model

Figure 2. Investigated simply supported steel-concrete highway bridge

Table 3. Bridge properties adopted in the model

Dynamic characteristic	Value	Physical Unit
Mass per meter	13,446.27	kg/m
Flexural rigidity	$1{,}03 \times 10^{11}$	Nm^2
Damping coefficient	0,02	-

5 Vehicle-bridge dynamic interaction simulation

The mathematical model simulates the bridge deck and the vehicle as a single system, the vehicle-bridge system. The equations that describe the system's motion, consisting of four equations for the vehicle and one for the bridge are presented in eq. (3), representing the dynamic equilibrium equation of the system's behaviour.

$$[M]\{\ddot{Y}\}+[C]\{\dot{Y}\}+[K]\{Y\}=\{Q\} \quad (3)$$

In eq. (3), [M] represents the system's mass matrix, [C] the damping matrix, and [K] the stiffness matrix. The force vector {F} is composed of the vehicle's weight and the contact forces between the wheels and the bridge surface. The interaction between the two systems is ensured by the compatibility of displacements at the contact point between the wheels of the rear and front axles with the pavement (y_{c1} and y_{c2}, respectively) [5]. The eq. (4) guarantees the coupling of the systems, where y_b represents the vertical displacement of the bridge, r is the road surface roughness, and "i" is the index representing the front and rear wheels, 1 and 2, respectively.

$$y_{ci} = y_{bi} + r_i \quad (4)$$

6 Dynamic structural analysis

Monte Carlo Simulation (MCS) is a computational technique that employs random sampling to approximate the behavior of complex systems. By generating a large number of random values from a known probability distribution, MCS can represent the uncertainties inherent in various parameters that influence the outcome of an analysis. In this context, eleven parameters of the vehicle-bridge system were defined as random variables for the dynamic analysis. The types of probability distributions used for the parameters are described in details in Tab. 4.

In this analysis methodology, initially, a dynamic structural analysis is performed using deterministic and stochastic parameters, the latter being generated by Monte Carlo simulations. In each numerical simulation, 1,000 values of the random variable were generated. For each value, a new vehicle-bridge-pavement system was created and the corresponding dynamic problem was solved [see eqs. (3) and (4)].

Considering that the stress cycles generated by vehicular traffic can lead to serious problems related to the fatigue phenomenon [2], the next step in the methodology utilises the stress histories from the dynamic analysis to estimate the fatigue life of the lower diaphragm gusset connection at the mid-span, see Fig. 2(a). The Rainflow algorithm is used to count stress cycles, from which the accumulated damage (D) and fatigue life (T) are calculated according to Palmgren-Miner rule.

Based on the accumulated damage value, the failure condition presented in eq. (5), determines whether the failure occurred and counts the number of occurrences. After all simulation analyses, the probability of failure is calculated based on the ratio between the total number of analyses and the number of failures identified. Aiming for a better understanding the Fig. 3 presents a flowchart of the proposed analysis methodology.

$$1 - \sum D_i \leq 0 \tag{5}$$

The bridge dynamic response simulations were performed following the developed analysis methodology, using the random variables presented in Tab. 4, where eleven with only one random variable and one with all variables simultaneously present. The pavement roughness level considered in the analysis was medium.

In sequence, Fig. 4 presents the bridge displacement and stress results determined based on a generic analysis where the simulated random variable was the vehicle sprung mass (m_s). The assessment of the dynamic structural response illustrated in Fig. 4 reveals that the bridge maximum displacement and stress values occur when the excitation frequency, related to the vehicle traffic on the deck, approaches the first and third bridge natural frequencies, respectively, as presented in Figs.4 and 5.

Table 4. Probabilistic models adopted for random variables

Random variable	Distribution type	Mean value / Standard deviation	Physical units	References
Sprung mass (m_s)	Gamma	16,695/3,672.9	Kg	[6]
Velocity (v)	Normal	77/13.5	km/h	[6]
Bridge mass (ρ)	Normal	13,446/1,075.7	Kg/m	[7]
1^{st} axle suspension spring stiffness (k_{s1})	Normal	217.78/134.61	kN/m	[8]
2^{st} axle suspension spring stiffness (k_{s2})	Normal	441/299.92	kN/m	[8]
1^{st} axle suspension damping (c_{s1})	Normal	15/4.18	kNm/s	[8]
2^{st} axle suspension damping (c_{s2})	Normal	26.43/7.07	kNm/s	[8]
1^{st} axle tires stiffness (k_{t1})	Normal	2,026.68/927	kN/m	[8]
2^{st} axle tires stiffness (k_{t2})	Normal	3,402.2/1,490.5	kN/m	[8]
1^{st} axle tires damping (c_{t1})	Normal	2/0.9	kNm/s	[9]
2^{st} axle tires damping (c_{t2})	Normal	4/1.8	kNm/s	[9]

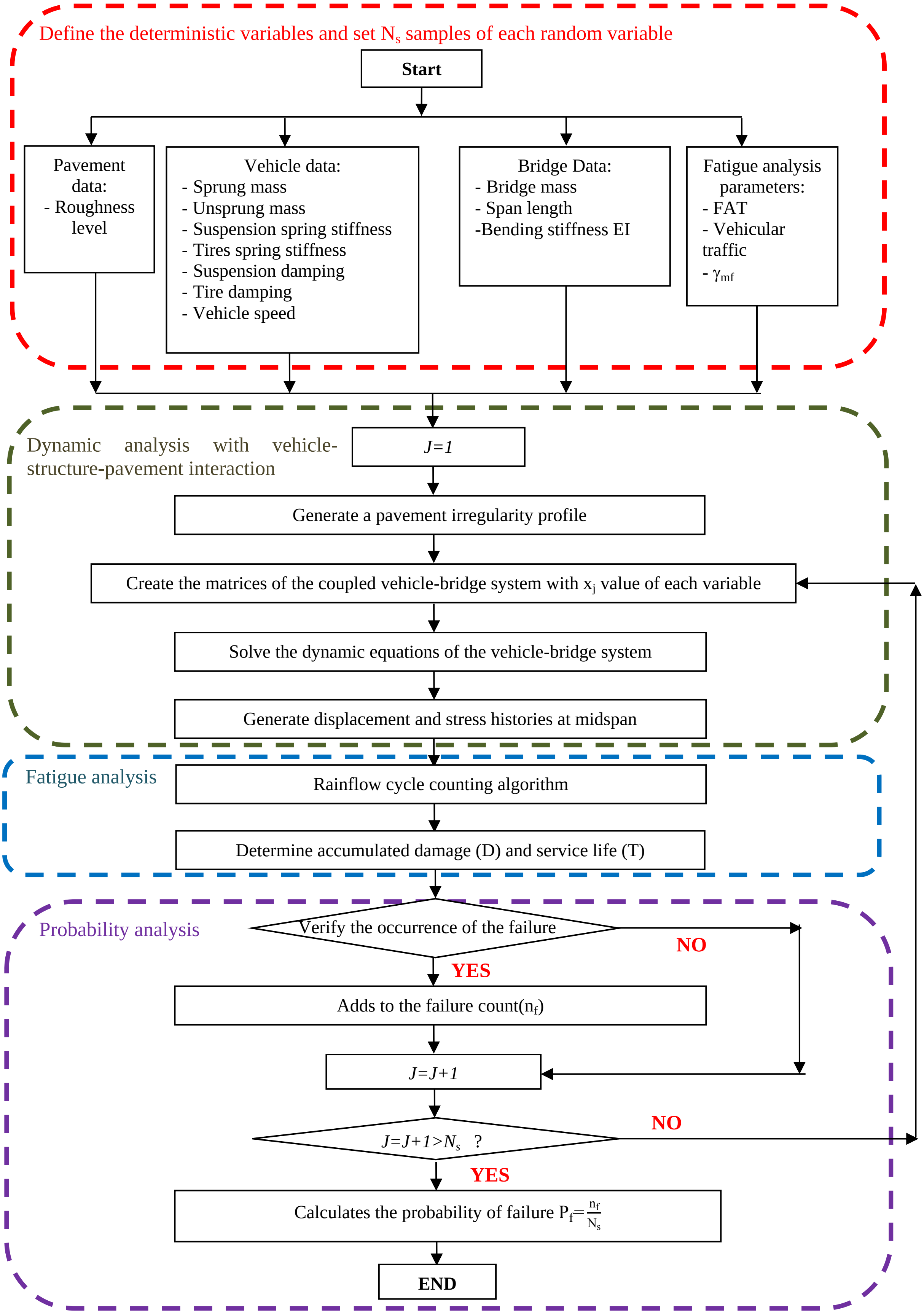
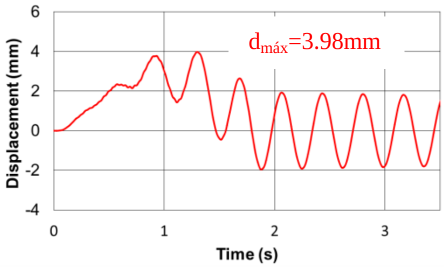
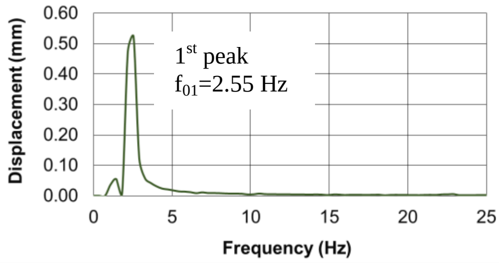


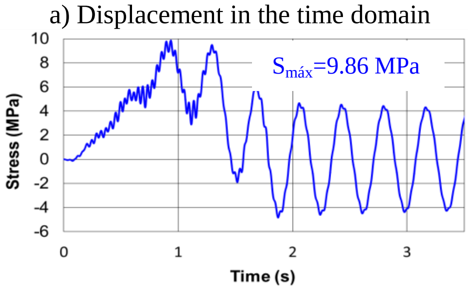
Figure 3. Flowchart of the developed analysis methodology



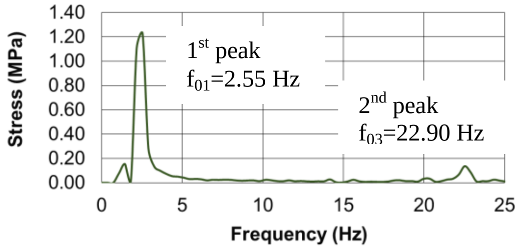
a) Displacement in the time domain



b) Displacement in the frequency domain



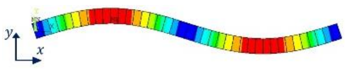
c) Stress in the time domain



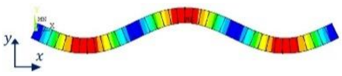
d) Stress in the frequency domain

Figure 4: Generic results for sprung mass: medium roughness pavement ($G_d(\Omega_0) = 16$ cm^3)

a) First vibration mode
f_{01}: 2.70 Hz



b) Second vibration mode
f_{02}: 10.85Hz



c) Third vibration mode
f_{03}: 24.20 Hz

Figure 5: Vibration modes of the investigated bridge determined based on the use of ANSYS software [10]

Aiming to determine in which simulations the use of the random variable in dynamic structural analysis influenced the dynamic behavior of the bridge, statistical analysis of the maximum displacement and stress values and service life was carried out in each simulation. This allowed identifying the cases where the evaluated quantities followed the changes in values assumed by the random variable, indicating a significant influence of the variable on dynamic behavior.

Similarly, simulations were identified in which, despite the variable values changing in each analysis, the results of maximum displacement and stress and service life tended to a common value, indicating a lesser influence of the random variable. In this context, Tab. 5 organizes the vehicle-bridge system parameters that most impacted the maximum displacement and stress values, and service life, listing them from most to least influential. Additionally, the Tab. 6 presents the estimated fatigue failure probability of the diaphragm connections in the mid-span (see Fig. 2), calculated based on the failure cases identified in the 1,000 analyses of each simulation.

Table 5. Influence of each parameter of the vehicle-bridge system

Maximum displacement	Maximum stress	Fatigue life
Velocity	Velocity	Bridge mass
Sprung mass	Bridge mass	Velocity
2st axle suspension spring stiffness	Sprung mass	2st axle suspension spring stiffness
Bridge mass	2st axle suspension spring stiffness	Sprung mass
2st axle tires stiffness	2st axle tires stiffness	1st axle suspension damping
1st axle suspension damping	1st axle suspension damping	2st axle suspension damping
1st axle suspension spring stiffness	1st axle suspension spring stiffness	1st axle suspension spring stiffness
2st axle suspension damping	2st axle suspension damping	2st axle tires stiffness
1st axle tires stiffness	2st axle tires damping	1st axle tires stiffness
2st axle tires damping	1st axle tires stiffness	1st axle tires damping
1st axle tires damping	1st axle tires damping	2st axle tires damping

Table 6. Probability of failure (P_f)

Random variable	P_f	Random variable	P_f
Sprung mass	93%	2st axle suspension damping	100%
Velocity	41%	1st axle tires stiffness	100%
Bridge mass	89%	2st axle tires stiffness	76%
1st axle suspension spring stiffness	84%	1st axle tires damping	100%
2st axle suspension spring stiffness	21%	2st axle tires damping	100%
1st axle suspension damping	99%	Set of all variables	15%

7 Conclusions

In this investigation, the dynamic structural analysis of steel-concrete composite highway bridge was conducted using Monte Carlo simulation (MCS). In this context, eleven parameters of the vehicle-bridge system were defined as random variables, each with a sample of 1000 values. Based on the presented results, the following conclusions can be drawn.

1. It is observed that the largest amplitudes of the dynamic response in the frequency domain occur near the first and third natural frequencies, f_{01} = 2.55 Hz and f_{03} = 22.90 Hz, respectively. This conclusion is consistent, considering that the dynamic response was calculated at the span central section, where the first and third bridge vibration modes present the maximum amplitudes.

2. The statistical analysis of the simulations, focusing on the influence of each parameter on the variability of maximum displacement, maximum stress, and service life results, have identified that the four parameters that most influence the bridge structural behavior and the fatigue assessment the vehicle velocity, vehicle sprung mass, bridge mass, and second axle suspension spring stiffness of the vehicle.

3. It is observed that parameters of great influence, such as velocity, in some cases, reached values at which the vehicle-bridge system did not fail during its service life, resulting in P_f = 41%. On the other hand, parameters such as the first axle tires damping, which had little influence on the dynamic behaviour of the system failed in all simulation analyses, resulting in P_f =100%. However, this result suggests that, in this case, the failure was more impacted by the deterministic values than by the first axle tires damping. Therefore, the analysis highlighted the importance of individually evaluating the influence of each parameter on the failure probability.

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References

[1] Y. Shao, C. Miao, J.M.W. Brownjohn, Y. Ding, "Vehicle-bridge interaction system for long-span suspension bridge under random traffic distribution". *Structures*, vol. 44, pp. 1070-1080, 2022.
[2] A. C. S. Silva, G. S. Alencar, J. G. S. Silva, "Advances in Methodology for Fatigue Assessment of Composite Steel-Concrete Highway Bridges Based on the Vehicle-Bridge Dynamic Interaction and Pavement Deterioration Model". *Metals*, vol. 13, n. 8, pp. 1343-1368, 2023.
[3] C. J. Dodds and J.D Robson, "The description of road surface roughness". Journal of Sound and Vibration, vol. 31, n. 2, pp. 175-183, 1973.
[4] EUROCODE 1. *Actions on Structures-Part 2: Traffic Loads on Bridges*. European Committe for Standardization, 2003.
[5] T. L Wang and D. Huang, "Cable-stayed bridge vibration due to road surface roughness". *Journal of Structural Engineering*, vol.118, n. 5, pp. 1354-1374, 1992.
[6] C.E. Rossigalli. Atualização do modelo de cargas móveis para pontes rodoviárias de pequenos vãos no Brasil. DSc Thesis, Federal University of Rio de Janeiro (UERJ). Rio de Janeiro/RJ, Brazil, 2013.
[7] A.S. Nowak and K. R. Collins. *Reliability of structures.* CRC Press, 2012.
[8] CarSim/TruckSim Mechanical Simulation Corporation Inc. Theory Reference (2016.1), 2016.
[9] AASHTO. Bridge Design Specifications. American Association of State Highway and Transportation Officials, 2012.
[10] ANSYS Swanson Analysis Systems Inc. Theory Reference (R-12.1), 2009.