Design of computational experiments for fatigue assessment in steel bridges

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Abstract. Bridges are among the most important structures in a country's road network. Despite being an asset with enormous geopolitical value, the financial crisis of 2008 made it mandatory to implement strict financial management actions by the national governmental entities, resulting in a reduction of the resources available for bridge management. This reality is transversal to several countries and creates the conditions that may enable the occurrence of catastrophic results, such as the collapse of the Morandi bridge in the summer of 2018. This study proposes a design of computational experiments for fatigue assessment of the longitudinal beams of the Várzeas bridge, located in the Mealhada municipality and built in 2009 by the VESAM Group. The proposed design of computational experiments deals with these components' structural response to static load solicitations from two vehicles of the same type and with the same characteristics, with geometric centers coinciding with the mid-span section of the Várzeas bridge, as well as the own weight of the bridge's components .The resulting stress values at mid-span were obtained using an optimized computational model of the structure with the software Autodesk ROBOT Structural Analysis and compared with the stress value deemed as the limit state in the original design of the Várzeas bridge. The probability of failure for the aforementioned conditions was obtained using the Monte Carlo Simulation methodology. Through the stress values obtained by computational simulations, in order to verify the fatigue behavior of the longitudinal beams, a daily stress spectrum was created and extrapolated the respective yearly stress curves were extrapolated, considering the traffic of each year and the cumulative traffic effects over the years. The obtained results were compared with the results obtained from a fatigue curve for the material S355 in order to assess the expected time until fatigue failure occurs. In this regard, the proposed design of computational experiments aims at evaluating the structural response of the Várzeas bridge with a high level of precision and can be considered a useful tool for future studies.

Keywords. Design of Experiments, Monte Carlo Simulation, Fatigue assessment, Structural reliability, Bridge condition assessment, Fatigue curve

1. Introduction

1.1. Importance of bridge safety

First used to settle unexplored areas, bridges are currently a key component of a country's road network and its continuous use, along with the normal aging of the structure, the increase of traffic flows and the environmental conditions to which a bridge is exposed needs to be addressed in order to mitigate the possibility that damage can result in failure or, in critical situations, collapse. In this regard, it is important that the high investments made in a bridge's construction are maximized so the structure can perform in a safe way.

Since the turn of the century, maintenance and structural integrity assessment of public infrastructures has been a main goal of governments throughout the world. Although its importance, the 2008 economic crisis forced the national governments to apply several budget restrictions, limiting the resources available for bridge maintenance and inspection. This situation needs to be addressed in the near future in order to avoid other situations such as the Morandi bridge collapse, which occurred on the14th August, 2018. In Portugal, the most severe situation regarding a bridge failure that resulted in collapse occurred on the 4th March, 2001, when a portion of the deck of the Hintze-Ribeiro bridge collapsed, causing the death of 59 people.

In order to mitigate these consequences, it is important to create an optimized maintenance plan, as well as extending the bridge's life span in order to avoid its demolition and the construction of a new structure. This is achieved through the bridge's structural assessment, comprised by both simplified structural models (developed through material testing applied to several components, as well as the original documentation) and the structure's intrinsic load carrying capacity (in order to determine a bridge's structural response). Having in mind that such analyzes can be very complex when analyzing an entire bridge, an alternate approach is determining which components can be deemed as *critical*. This is a very conservative approach but can be deemed as useful when the resources and computational power available are not enough.

1.2. Problem statement

The main purpose of this Master dissertation is to develop a design of computational experiments to assess the fatigue behavior and detect the probability of failure of the Várzeas bridge, a girder (beam) bridge located in the Mealhada municipality, when subjected to certain traffic solicitations adapted from the literature. For the purpose of this study, the components analyzed were the longitudinal beams, considered as the critical components of the Várzeas bridge, which were subjected to the own weight of the bridge's components and to static loading solicitations, considering two vehicles of the same type at mid span.

The static load solicitations were obtained for six different types of vehicles, whose characteristics regarding the axle loads and distance between axles were obtained through random numbers generated and the different variable's inverse cumulative distribution and the Monte Carlo Simulation methodology was implemented to analyze these sample points. The correspondent stress values were obtained through an optimized computational model of the structure with the software Autodesk ROBOT Structural Analysis. The obtained value was compared to the value deemed as a *limit state* for static load solicitations.

The final step of this Master dissertation was to assess the fatigue behavior of the structure for different years. The daily traffic spectrum was set as a constant and obtained by achieving the requirements of the literature and the yearly traffic solicitations were then extrapolated, considering a traffic increase of 3 percent per year. These solicitations were analyzed for both the traffic solicitations of the years analyzed and the cumulative traffic solicitations up to the year analyzed. These values allowed to develop the fatigue curve for each case, which was then compared with a stress curve of the longitudinal beam's material obtained from the literature.

These analyzes allowed to not only correctly assess the behavior of the longitudinal beams when subjected to static load solicitations, but also to assess the degree of conservatism from the original design of the Várzeas bridge.

1.3. Document structure

This document is comprised in the following manner. In Section 1, an introduction to the study made is presented. Section 2 presents a literature of former approaches to bridge failure assessment. Section 3 presents the research methods and techniques applied for the purpose of this study. Section 4 presents a description of the case study. Section 5 presents the analysis of the case study. In Section 6, the conclusions of this study are presented and suggestions for further research are referred.

2. Literature review

2.1. Bridge types

When dealing with a bridge, it is important to first determine the type of structure to analyze in order to correctly access the kind of behavior it will present. Several categories have been presented in order to characterize a bridge by its type, with the most common ones dealing with its structural configuration (e.g. girder, truss, cantilever), the materials used (e.g. steel, iron, stone) and its end-use (e.g. road, railway, pedestrian or a combination of those).

2.2. Bridge failure assessment

In order to correctly assess the conditions of bridge failures, it is important define the concept of bridge *failure* and *collapse*. In this regard, bridge collapse can be defined as when one or more structural elements fell down from a bridge as a result of the failure rendering the structure incapable of remaining in service and classified as total or partial collapse[1]. Meanwhile, bridge failure can be defined as when a situation occurs that will result in loss of function (e.g. fatigue cracking that can result in collapse if left unchecked, stress values that violate the value defined as a limit state), that could result in bridge total or partial closures, repairs or strengthening works[1].

When a bridge failure occurs, a report is usually made in order to identify the principal causes of failure, which can be classified as *enabling causes* (causes of internal nature, design errors, limited knowledge, construction errors, lack of maintenance) or as *triggering causes* (causes of external nature, such as corrosion, natural hazards, collisions and overloads)[1]. These failures, if not addressed in time, will result in impacts from human (e.g. fatalities, injuries), economic (e.g. repair actions, traffic disruptions), environmental (e.g. pollution from congestion traffic) and social nature (e.g. loss of confidence in public entities).

2.3. Previous statistical studies

When observing the results of previous statistical studies regarding bridge failures, the wndks of Tarisçka[1] and Iman and Chryssanthopoulos[2] provide a value insight in not only in terms of quantifying bridge failures, but also addressing the effects of the way these failures are viewed by the public entities.

Figure 1 illustrates the results obtained by [2] for failure modes on collapsed and non-collapsed metallic bridges.

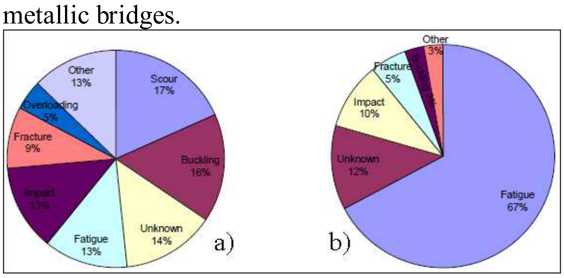


Figure 1- Failure modes for metallic bridges. a) collapsed, b) non-collapsed [2]

Figure 1a) shows that there is no single failure mode that can be considered as dominant in metallic bridge collapses, with fatigue and fracture combined being the most accounted for, reaching for a combined 22% of bridge collapses observed, followed by buckling (16%). Meanwhile, Figure 1b) shows that fatigue alone is responsible for about two thirds of every non-collapsed bridges observed. This led the authors to conclude that the high fatigue related issues in non-collapsed metallic bridges is a result of the attention paid to this specific failure mode by bridge engineers, resulting in detecting fatigue related problem in early stages through inspections in order to avoid its collapse. Another conclusion achieved by these authors relates to the satisfactory redundancy level regarding fatigue detailed failures. Figure 2 illustrates the results obtained by [1] for bridge failure occurrences in the period 2000-2012 in the United States of America.

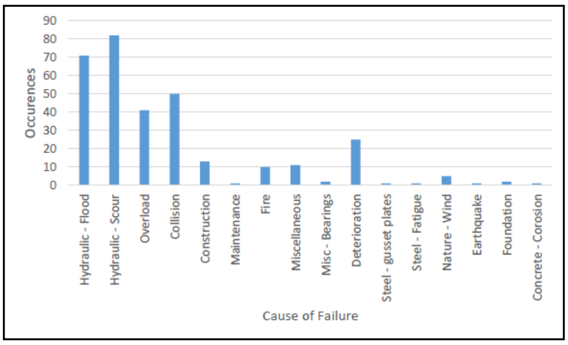


Figure 2- Bridge failure occurrences by failure mode in the period 2000-2012 in the USA [1]

From Figure 2 it is possible to observe that the number of occurrences caused by fatigue related issues (including steel fatigue, failure in steel-gusset plates, maintenance and several miscellaneous issues) had a weak role to play in the overall database, corroborating the conclusions of [2].

3. Research methods and techniques

3.1. Design of Experiments

Knowing that the data analyzed in an experiment is often corrupted by experimental errors, also referred to as ‘noise’, and that the output results will be also affected by these errors, it is important to adopt an adequate statistical model to the experiment and to determine the conditions in which an experiment will be performed.
This process is referred as ‘Design of Experiments’ (DoE), which can be defined as a procedure to plan and define the conditions for performing controlled experimental trials. In order to correctly implement the DoE methodology and obtain accurate results, several steps need to be addressed [3]:

- Set the objectives.
- Select the process variables.
- Select an experimental design.
- Execute the design.
- Check that the data obtained are consistent with the experimental assumptions.
- Analyze and interpret the results.

If well addressed, DoE will obtain a precise estimation value with fewer systematic errors.

Experiments, whether physical or computational, involve the use of design/input variables, which can be defined as elements, features and attributes that vary to study the response of the system. In this regard, considering that [7]:

$$x = \{x_n | n = 1, 2, \dots, N\} \in \mathbb{R}^N \qquad (1)$$

Denotes a N-dimensional vector of design variables. These design variables are comprised in a specified limit defined by the user inside an upper and a lower bound. This space is referred as ‘domain’, and can be denoted as [4]:

$$D: x^L \leq x \leq x^U \qquad (2)$$

Where D represents the domain, usually scaled as $[0,1]^N$ to avoid numerical ill-conditioning, and x^L and x^U represent the domain’s lower and upper bounds, respectively.
In this regard, a *sample point* can be defined as a specific instance of $x \in D$ and, a set of these points of a size K can be defined as a *sample set* [4]:

$$X_N^{(K)} = \{x^{(k)} | k = 1, 2, \dots, K\} \qquad (3)$$

Let the system response at $x^{(k)}$ be described by S output variables [4]:

$$y = \{y_s | s = 1, 2, \dots, S\} \in \mathbb{R}^S \qquad (4)$$

The collection of all responses obtained is a system ‘response set’, defined by [4]:

$$Y_S^{(K)} = \{y^{(k)} | k = 1, 2, \dots, K\} \qquad (5)$$

From the sample sets and the respective responses, it is possible to build an approximation for the system response surface, also known as a ‘surrogate model’ or ‘meta model’ [4]:

$$\tilde{f}^{(K)}(x), \tilde{f}^{(K)}: D \rightarrow \mathbb{R}^S \qquad (6)$$

This approximation model is needed because most variables considered in experiments are of ‘stochastic’ nature due to having a variety of unknown (hidden) and/or uncontrolled factors resulting in random errors [4]. In this regard, the measured response in an experiment can be modeled as [4]:

$$y(x) = y_t(x) + \varepsilon \qquad (7)$$

Where y is the measured response, y_t is the true response and ε represents a random error.
In this regard, the primary goal of DoE is to define the best sample points where $y(x)$ is simulated, and to derive the best possible approximation $\hat{y}(x)$ for

$y_t(x)$, in spite of the random error [4]. The way classical and modern DoE address this issue defines its impact in experimental design. In classical DoE, the system response typically assumes a linear/quadratic approximation, where the vertices or points on the boundaries of D are considered the best sample points, while in modern DoE this approximation is not considered, and the best sample points are the ones distributed within D [4].

3.2. Structural Reliability

One of the most important steps of a bridge maintenance scheme involves the safety assessment of the structure. A bridge is considered safe when its capacity to resist loading solicitation exceeds these solicitations. In other words, a bridge is considered safe when there is a low probability of loading solicitations, S, to exceed the structure's resistance, R, with structural reliability aiming to calculate and predict the possibility of this event happening.

In general, R can be described as a function of material properties and element or structure dimensions, while S is a function of the applied loads, material densities and, sometimes, element or structure dimensions [5].

In this regard, structural reliability can be described as the calculation of the probability of failure of a random system subjected to random conditions. A structure's response is considered satisfactory regarding if its requirements are satisfied, with each requirement corresponding to a limit state. The most common limit states are presented in Table 1.

Table 1- Typical limit states for structures [5]

Limit state	Description	Requirements
Ultimate (safety)	Collapse of all or part of the structure	Tipping or sliding, rupture, progressive collapse, plastic mechanism, instability, corrosion, fatigue, deterioration, fire.
Damage (often included above)		Excessive or premature cracking, deformation or permanent inelastic deformation.
Serviceability	Disruption of normal use	Excessive deflections, vibrations, local damage.

The simplest structural reliability problem consists on one load effect resisted by one resistance effect from the structure. The inherent probabilistic nature of design parameters, material properties and loading conditions in structural analysis is an important factor that influences structural safety. These effects are obtained through structural analysis procedures from loads and material strength properties (i.e. steel's yield stress), respectively, and translate in a structure's limit state function:

$$G(x) = R(x) - S(x) = 0 \tag{8}$$

Where $G(x)$ is the limit state function, $R(x)$ is the resistance effect, $S(x)$ is the load effect and x represents a stochastic variable of the structural reliability problem. The structure's limit state function will be violated when [5]:

$$R(x) - S(x) \leq 0 \tag{9}$$

In order to assess the probability of failure, Figure 3 shows a schematic representation of a basic structural reliability problem.

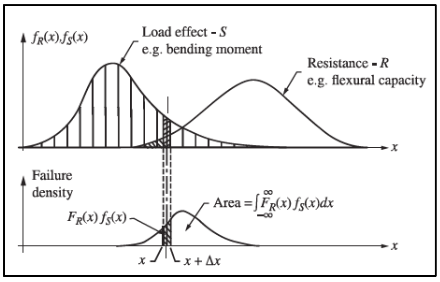


Figure 3- Basic structural reliability problem [5]

In this regard, for any given point, the probability of failure can be formulated as [6]:

$$p_f = P[R(x) - S(x) \leq 0] \tag{10}$$

$$p_f = \int_{G(X)\leq 0} f_{RS}(x)\, dx \tag{11}$$

Where $f_{RS}(x)$ is the joint probability function.

3.3. Monte Carlo Simulation

In structural reliability analysis, Monte Carlo Simulation can be used when an analytical solution cannot be achieved and the failure domain cannot be expressed or approximated by an analytical form (e.g. problems with an inherent level of complexity, where R and S are not independent or with a large number of basic variables where analytical reliability assessment methods are not applicable) [7].

The probability of failure through Monte Carlo Simulation is obtained through:

$$p_f = \int I(\boldsymbol{X}).f(\boldsymbol{X})\, d\boldsymbol{X} \tag{12}$$

From Equation 12, following the law of large numbers, Monte Carlo Simulation allows to determine the probability of failure through an unbiased estimator [7]:

$$p_f \approx \bar{p}_f = \frac{1}{N}\sum_{i=1}^{N} I(X_i) \qquad (13)$$

Where X_i represents each computational sample with density $f(X)$ and $I(X_i)$ is a failure indicator, defined as:

$$I(X_i) = \begin{cases} 1, & G(X_i) \le 0 \\ 0, & G(X_i) > 0 \end{cases} \qquad (14)$$

From Equation 13, it can be seen that N independent random samples of a specific probability density function of the vector $\boldsymbol{X}$ are prepared and the failure function is computed for every value of X_i. This makes it possible for Monte Carlo Simulation to determine the probability of failure in terms of sample mean as [7]:

$$\bar{p}_f \cong \frac{N_H}{N_S} \qquad (15)$$

Where N_H is the number of successful simulations where failure occur and N_S the number of total simulations made.

3.4. *Fatigue assessment in steel components*

A structure or component may fracture and fail if a certain load solicitation is cyclically applied many times. This is defined as a *fatigue failure*, resulting from a progressive propagation of flaws when the material is subjected to static loading [8]. In this regard, fatigue failure can be defined as the number of cycles taken to reach a predefined threshold failure criterion [8].

A fatigue failure occurs after the development of four different stages: crack initiation, crack propagation, crack growth and final rupture [8]. When dealing with fatigue-life methods, the three major methods are the stress-life method, strain-life method and linear-elastic fracture mechanics method. For the purpose of this study, the fatigue assessment that is made is based on the stress-life method.

The common form of presenting fatigue data from a stress-life analysis it through a fatigue curve, also known as a *S-N curve*. Originally developed by Wöhler in the 19th century, the S-N curve can be obtained through experimental testing with test specimens of a certain material in a laboratory and can be defined as a plot of the magnitude of an alternating stress versus the number of cycles to failure of a given material subjected to the load solicitations [8]. Figure 4 presents a schematic representation of a S-N curve.

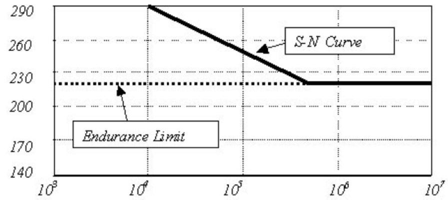


Figure 4- Schematic representation of a S-N curve[8]

From Figure 4, it is possible to observe that the fatigue life of a component reduces when the stress range applied increases. When this stress range is lower than a value deemed as *endurance limit* (usually defined at several 10^6 applied cycles), the S-N curve "flattens", and the component is considered safe for infinite life. In this regard:

$$\begin{cases} \Delta\sigma \ge \sigma_e, & finite\ life \\ \Delta\sigma < \sigma_e, & infinite\ life \end{cases} \qquad (16)$$

Where $\Delta\sigma$ is the stress range and σ_e is the endurance limit of the material.

In terms of $\Delta\sigma$, it is defined as the difference between the maximum and minimum value of stress applied in a cycle. For the purpose of this study, the cyclic loading is considered as a pulsating cycle, characterized by a minimum stress of zero and a maximum stress referring to the load applied, so that:

$$R_\sigma = \frac{\sigma_{min}}{\sigma_{max}} = 0 \qquad (17)$$

Where R_σ is the stress ratio, σ_{min} the minimum cyclic stress and σ_{max} the maximum cyclic stress.

To carry out fatigue life predictions in finite life, the relation between the stress range and the number of cycles to failure can be written as:

$$\log(N) = \log(C) - m * \log(\Delta\sigma) \qquad (18)$$

Where C is a constant dependent on the detailing category, N is the number of cycles to failure and m the slope of the S-N curve.

It is important to refer that, when a fatigue test is made in a laboratory, the conditions in which the test is made (e.g. environmental conditions) will influence the results obtained. Also, the frequency at which the cycles are applied is not considered to be a factor in the number of cycles to failure.

When dealing with a structure such as a bridge, it is imperative to determine the cumulative effects of cyclic loading in order to correctly assess its structural condition. A widely accepted approach to assess damage accumulation is the *Miner's rule* [8]:

$$Damage = \sum \frac{n_i}{N_i} \qquad (19)$$

Where n_i is the number of cycles at $\Delta\sigma$ and N_i the number of cycles to failure at $\Delta\sigma$. In this regard:

$$\begin{cases} Damage < 1, & safe \\ Damage \geq 1, & failure \end{cases} \quad (20)$$

From Equation 19, it is possible to understand the importance of the cumulative effects of cyclic loading on the life of a component.

4. Case study

4.1. Case study description

The test subject will be the Várzeas bridge, located in the Mealhada municipality in the central region of Portugal. This is a short-span girder bridge built in 2009 by VESAM Group, located over an embankment with a small creek flowing by.

The Várzeas bridge is a short-span, steel beam (girder) bridge composed by four simply supported longitudinal beams, each with a span of 19 meters [9]. In order to increase the bridge's stiffness to torsion when assembling and stabilizing the compressed flanges, a cross girder system was installed through the width of the bridge [9]. To increase the bridge stiffness when subjected to dynamic loads, a bracing system with angles was adopted [9]. Its original design was based on the Eurocode standards, in particularly those who deal with load solicitations[EC 1991] and steel assessment to fatigue [EC 1993].
This bridge belongs to a secondary path, making it a good test subject because:

- It is located in a remote area, resulting in a small possibility of vandalism.
- The embankment under the bridge means that sensors installation and maintenance and repair actions can be done easily.
- The pathway allows that maintenance, repair and monitoring actions to take place safely and with relative easiness.
- The tight curves that vehicles need to make both entering and exiting the bridge translates in vehicles crossing the bridge slower than usual, which makes the static assessment more thorough.

In terms of constraints, the deck of the Várzeas Bridge is supported by eight supports (four on each side), located on the ends of each longitudinal beam. For the purpose of this study, as the longitudinal strain will occur in the longitudinal direction, it will be considered that the critical components of this bridge will be the longitudinal beams, namely the center longitudinal beams. These components are made of S355 steel, a widely used structural steel characterized by a yield stress of 280 MPa for these range of dimensions.

4.2. Case study description

Although well instrumented, the MIRA system has the disadvantage of not recording the traffic load solicitations and rating them by vehicle types. To overcome this constraint, it will be considered load solicitations made in the study conducted by Guo et al.[10]. These authors divided the vehicles obtained from their study into six categories, which are described in Table 2. For the purpose of this study, it will be considered that the axle loads are equally distributed by the respective wheels. For each sample point generated, two vehicles of the same type are placed with its geometric centers coincident with the mid span section of the bridge and resulting stress is obtained through a computational model of the Várzeas bridge, comprised by isoparametric finite elements and developed by VESAM Group. The values of the variables that characterize a vehicle are obtained through generating random numbers in Microsoft Excel and inserted in the several distributions of each variable in order to obtain the value from the respective inverse cumulative function, with a set of random points created for each of the variables, ensuring that they are independent from one another.
With these values, it is possible to determine the daily traffic spectrum through the recommendations of [10,11] and extrapolate the yearly stress spectrums, accounting for an increase of 3 percent per year. The obtained fatigue curves will be compared to a curve obtained for the material S355 for a stress ratio $R_\sigma = 0$, resulting in $\Delta\sigma = \sigma_{max}$. This fatigue curve was developed by Stranghoner & Jungbluth[12], which analyzed ten specimens with a thickness of 40 mm, tested with an applied force of 1.4 MN at a frequency of 9 Hz.

5. Results

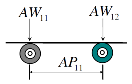
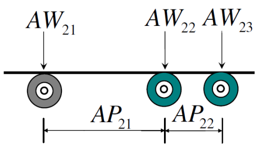
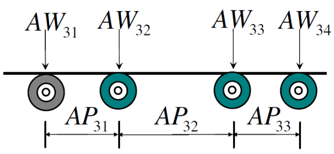
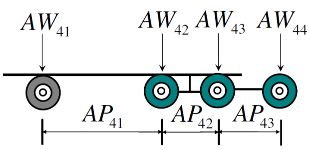
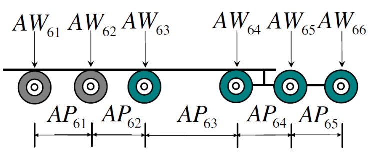
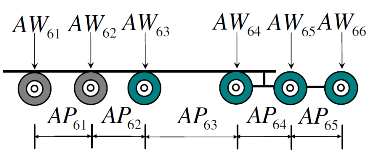
5.1. Static load solicitations

For each type of vehicle, 3000 sample points were generated. After generating these sample point, all the ones who produced negative values or a total vehicle length superior than the total span of the Várzeas bridge were eliminated. When determining if a certain situation will result in failure of the critical components (longitudinal beams), it will be considered that the limit state is defined by the limit state stress, σ_{LS}, and that the Várzeas bridge will not fail when:

$$\sigma_{sim} \leq \sigma_{LS} = 280\ MPa$$

Where σ_{sim} is the stress obtained from each simulation. In this regard, a failure occurrence will result from a value of σ_{sim} higher than 280 MPa.

Table 2 - Random variables for axle weights and axle spacing [10]

Vehicle type	Variable designation	Distribution type	Mean value	Standard deviation
	$AW_{11}[kN]$	Normal	38.22	9.74
	$AW_{12}[kN]$	Normal	62.08	20.92
	$AP_{11}[m]$	Lognormal	6.036	1.044
	$AW_{21}[kN]$	Lognormal	48.06	8.51
	$AW_{22}[kN]$	Lognormal	62.02	24.43
	$AW_{23}[kN]$	Lognormal	56.92	21.99
	$AP_{21}[m]$	Lognormal	4.864	1.388
	$AP_{22}[m]$	Lognormal	1.310	0.052
	$AW_{31}[kN]$	Normal	44.46	8.73
	$AW_{32}[kN]$	Normal	68.06	23.56
	$AW_{33}[kN]$	Lognormal	63.96	25.04
	$AW_{34}[kN]$	Lognormal	61.44	28.22
	$AP_{31}[m]$	Lognormal	4.497	1.044
	$AP_{32}[m]$	Normal	1.325	0.058
	$AP_{33}[m]$	Normal	7.724	2.200
	$AW_{41}[kN]$	Normal	44.46	8.73
	$AW_{42}[kN]$	Normal	68.06	23.56
	$AW_{43}[kN]$	Lognormal	63.96	25.04
	$AW_{44}[kN]$	Lognormal	61.44	28.22
	$AP_{41}[m]$	Lognormal	3.929	0.298
	$AP_{42}[m]$	Normal	10.114	1.317
	$AP_{43}[m]$	Normal	1.230	0.034
	$AW_{51}[kN]$	Normal	47.31	6.68
	$AW_{52}[kN]$	Lognormal	63.19	21.05
	$AW_{53}[kN]$	Lognormal	59.70	20.44
	$AW_{54}[kN]$	Lognormal	61.04	23.13
	$AW_{55}[kN]$	Lognormal	59.37	27.24
	$AP_{51}[m]$	Normal	4.609	1.073
	$AP_{52}[m]$	Normal	1.323	0.033
	$AP_{53}[m]$	Normal	9.839	1.136
	$AP_{54}[m]$	Normal	1.258	0.049
	$AW_{61}[kN]$	Normal	48.48	8.06
	$AW_{62}[kN]$	Normal	88.94	25.72
	$AW_{63}[kN]$	Normal	82.61	25.49
	$AW_{64}[kN]$	Normal	80.89	32.91
	$AW_{65}[kN]$	Normal	84.88	30.65
	$AW_{66}[kN]$	Normal	80.65	30.84
	$AP_{61}[m]$	Normal	4.996	0.421
	$AP_{62}[m]$	Normal	1.342	0.051
	$AP_{63}[m]$	Lognormal	4.487	1.418
	$AP_{64}[m]$	Lognormal	1.288	0.105
	$AP_{65}[m]$	Lognormal	1.283	0.088

For the static loading solicitations, it was possible to observe that there were no failure occurrences. Therefore:

$$p_f = 0$$

The stress values obtained through computational simulation will have a higher dispersion with the increase of variables needed to define a vehicle type. Figure 6 shows a graphic representation of the frequency density of the σ_{sim} results obtained.

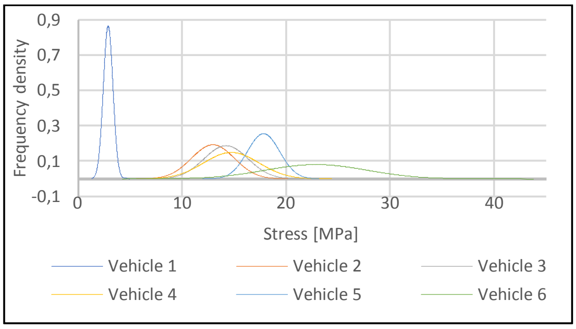


Figure 5- Frequency density of the σ_{sim} results obtained for each vehicle type

5.2. Fatigue assessment

In terms of fatigue assessment, through the information pertaining [11], it was possible to determine the number of vehicles expected to cross the Várzeas bridge in one day, considering that one cycle corresponds to two vehicles of the same type crossing the mid span section simultaneously. Table 3 shows the number of cycles needed to develop the daily stress spectrum.

Table 3- Daily stress cycles of the Várzeas bridge

Vehicle type	Traffic volume [%] [10]	Daily vehicles	Daily cycles
1	22.59	88	44
2	39.56	154	77
3	4.62	18	9
4	3.08	12	6
5	28.14	108	54
6	2.01	8	4
Total	**100**	**388**	**194**

To create a daily stress spectrum, it was selected from the σ_{sim} results obtained for each type of vehicle the amount of cycles required. This was achieved through generating random numbers in Microsoft Excel in order to determine which sample point would be included.
From the former JAE documentation [11], it is possible to see that for a bridge such as the Várzeas bridge (a T6 type bridge, as determined by the original designers), the yearly traffic increase to be considered is of 3 percent a year. In this regard, it is possible to use the constant daily stress spectrum to determine the several yearly spectrums, both for the cyclic load solicitations of a certain year and the cumulative cyclic load solicitations up until that year through, respectively:

$$N(t) = ADC * 365 * (1+\alpha)^{t-1} \qquad (21)$$

and

$$N(t) = ADC * 365 * \int_0^{t-1} (1+\alpha)^t \, .dt \qquad (22)$$

Where ADC represents the average daily cycles on the bridge (the number of vehicles crossing a bridge), α is the factor of traffic increase and t the year to analyze. For a stress ratio $R_\sigma = 0$, the stress range is $\Delta\sigma = \sigma_{max} = \sigma_{sim}$. In this regard, Figures 6 and 7 shows the S-N curves for the yearly cyclic load solicitations and the cumulative cyclic load solicitations for years 1, 2, 5, 10, 25, 50, 75 and 100, respectively.

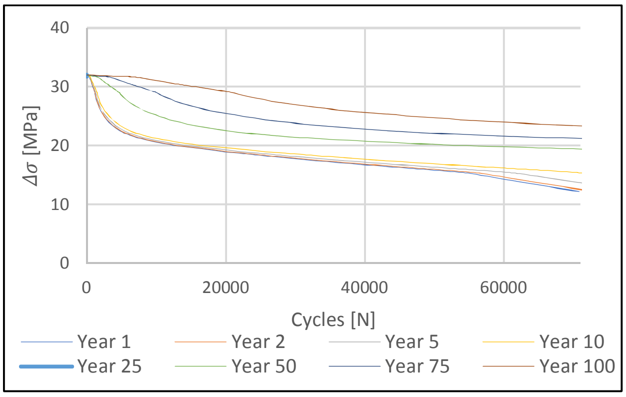


Figure 6- Yearly S-N curve, considering a traffic increase of 3% per year

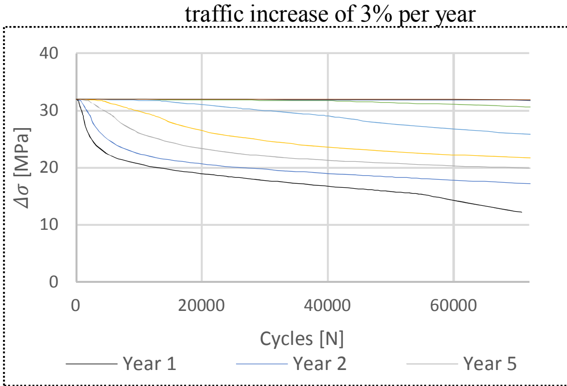


Figure 7- Yearly cumulative fatigue curves, considering a traffic increase of 3% per year

Comparing the results from Figures 6 and 7, it is possible to observe that the cumulative effect of cyclic load solicitations has. For the purpose of assessing the fatigue behavior of the longitudinal beams to cyclic loads, the fatigue curve representing the cumulative effect of cyclic loading has on the components on the 100th year will be compared to a theoretical fatigue curve for the material S355 at $R_\sigma = 0$. This fatigue curve was developed by Stranghoner & Jungbluth[12], which analyzed ten specimens with a thickness of 40 mm, tested with an applied force of 1.4 MN at a frequency of 9 Hz and the experiments were stopped at $2*10^6$ cycles or at the moment where failure occurred. These authors then established the following equation to characterize the obtained fatigue curve.

$$\log(N) = 15.133 - 4 * \log(\Delta\sigma)$$

This curve is characterized by a σ_e of 192 MPa. Therefore, if a fatigue failure were to occur, this value had to be surpassed, otherwise the longitudinal beams of the Várzeas bridge can be considered safe. In this regard, Figure X shows a representation comparing the values obtained from the theoretical fatigue curve for the material S355 and the fatigue curve for a cumulative effect of cyclic loading for the 100th year.

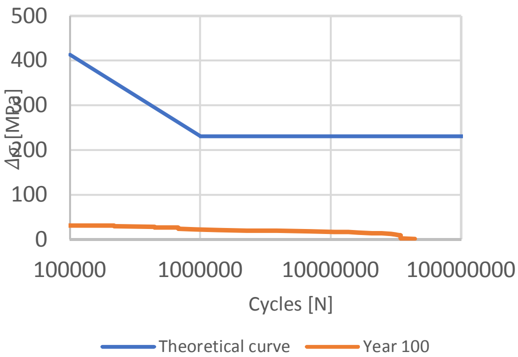


Figure 8- Theoretical S355 fatigue curve compared to the cumulative cyclic load solicitation curve for year 100

From Figure 8, it is possible to see that the value of σ_e from [12] is not surpassed by the cumulative cyclic load solicitations up until the 100th year. Therefore, the longitudinal beams of the Várzeas bridge are considered safe to cyclic load solicitations of this sort for an infinite life span. From Equation 19:

$$N_f = \infty$$

$$Damage = 0$$

Although an important assessment parameter, it is important to refer that this consideration is only valid when dealing with this type of solicitations. Phenomena such as corrosion will inevitably influence this assumption and need to be addressed by designers in future works.

6. Conclusion and future work

6.1. Conclusion

When researching about past bridge failures and collapses, as well as both possible causes and consequences of these events, it was important to realize the level of importance such as asset has in a country's road network and the impact of such an event on both the responsible entities and the society as a whole. This translates in a level of conservatism in the design phase of a bridge, aiming to develop a safe structure to all kinds of analyzed solicitations. Although structural safety, maintenance and reliability are important fields, the effects of the economic crisis of 2008 still affect the way several countries look at the current structural condition of its bridges, making it imperative to address these issues as soon as possible in order to avoid another collapse, such as the Morandi bridge collapse in 2018.

The main goal of this study was to create a design of computational experiments for fatigue assessment of the four longitudinal beams of the Várzea bridge, made from a S355 steel, when subjected to static load solicitations from two vehicles of the same type, both placed with its geometric center coincident with the midspan section of the bridge, as well as to the weight of every component of the Várzeas bridge. The stress values for each sample case were obtained through computational simulation using a computational model of the Várzeas bridge and then compared with a stress value deemed as *limit state*. This computational model was previously optimized by VESAM Group and is widely used by the company, enabling it to reproduce static load occurrences in a timely manner and without allocating resources to the location of the actual structure.

As initially expected, no failure occurrences were detected, which could be explained by the level of conservatism adopted in the original design of the Várzeas bridge, as well as due to several other structural assessment analyzes made in the original design of the structure in order to meet the requirements established by the Eurocode standards. With the stress values obtained from the simulations, along with several criteria obtained from the literature, it was possible to determine a daily traffic spectrum, which was set as a constant and enabled to extrapolate the yearly traffic spectrums for several years, both in terms of cumulative effects and only for the yearly traffic. This made it possible to determine the fatigue curve for the loading solicitations and, when compared to the fatigue curve of the material S355 obtained from the literature and created for a pulsating cyclic loading, it was possible to conclude that the longitudinal beams are designed for infinite life when subjected to the static load solicitations of the several traffic spectrums analyzed.

In conclusion, the design of a structure with the importance of a bridge must take into consideration a certain degree of conservatism in order to avoid any situation that could result in a performance deterioration and can result in failure and/or collapse. In terms of EU member-states, these structures must meet the requirements of the Eurocode standards, which in turn can be considered as conservative in its analyzes. These approaches must be complemented by a well-planned public investment strategy in order to assess the actual structural condition of a country's bridges and enabling the responsible entities to act in time, preventing situations that can result in large repercussions in the future.

6.2. Limitations

For the purpose of this study, several limitations need to be addressed. The first one is the assumption made regarding traffic loads solicitations, which needed to be adapted from the literature due to the absence of a Bridge Weigh-in-Motion system that enables to create a database of this sort of parameters.
Regarding the behavior of the longitudinal beams of the Várzeas bridge, it was established that the limit state for static load solicitations was a constant stress value of 280 MPa, as established by VESAM Group in the original design of the structure. Although its value from an academical perspective is important, the material's parameters may suffer alterations throughout time.
The subject of this study were the longitudinal beams of the Várzeas bridge, considered as the critical components of the structure. This can represent the basic effects of structural reliability of the structure but does not represent the structure as a whole. To overcome this limitation, it is important to address all the components of the Várzeas bridge.
Due to the use of a finite element model to simulate the response of the vehicle load solicitations on the bridge, it is important to take into consideration the differences between the computational model and the actual Várzeas bridge
In terms of solicitations, the bridge will only be subjected to the dead loads of the weights of its components and the static traffic loads, with the effects of temperature and wind on the structure being omitted. This was considered correct after analyzing the public available data from the Portuguese Institute of Sea and Atmosphere.
In terms of fatigue assessment of the longitudinal beams of the Várzeas bridge for a period up to 100 years, the daily stress spectrum was set as a constant, which can result in value discrepancies when compared to the actual cyclic load solicitations.
Finally, this study only deals with static loads and the dead load from the structure's weight, as well as the fatigue assessment of the longitudinal beams throughout the years. Other effects need to be addressed (e.g. vehicle collision with the side of the bridge) to assess the safety level of the structure.

6.3. Future work

In order to proceed with further research on the topic of bridge structural reliability, several methodologies have been proposed in order to address the limitations of current approaches. One of the most important one it to try to by-pass the complexity of analyzing a structure as a whole. A widely accepted way to do this is to analyze several components individually, followed by analyzing them together through series and parallel combinations. This approach is proved to provide thorough results, better than analyzing only the critical components.
In terms of simulation, a widely accepted alternative to Monte Carlo Simulation is the Importance Sampling methodology. Importance Sampling is considered a variance reduction technique, able to optimize the computational power available by using fewer sample points selected from the region where the probability of failure is higher.
Throughout the next years, it is expected that new approaches will be proposed, making the field of structural reliability even more wide.

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