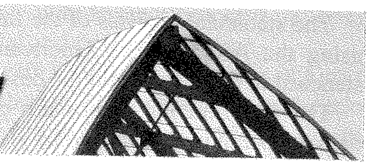
XI CONGRESSO DE
CONSTRUÇÃO
METÁLICA E MISTA
23 e 24 de novembro de 2017
iParque Coimbra - PORTUGAL



FATIGUE DESIGN CURVES OF MATERIALS COLLECTED FROM OLD PORTUGUESES METALLIC BRIDGES

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Abstract. This paper aims to extend the interpretation of data collected from experimental tests developed to analyze the fatigue phenomena on the material obtained from old Portuguese metallic bridges. The metallic bridges addressed were built in the late nineteenth and early twentieth centuries and have now become important historical heritage. The main materials used at that time were steel and puddle iron. The design fatigue curves were obtained for several fatigue damage parameters based on fatigue results and using the statistical models proposed in actual codes.

1. Introduction

In this paper, a probabilistic interpretation of experimental data for the materials obtained from old Portuguese metallic bridges is made.

The ancient metallic bridges under consideration were built in the late nineteenth and early twentieth centuries and have now become important historical heritage. The main materials used at that time were old steels and puddle irons.

There is an increasing interest of governmental agencies for their conservation and maintenance, not only for their historical value, but also for being structures that are still in use. These bridges were designed for a very different scenario of cars and trains flow than the one that is being used nowadays. Due to this situation, the old materials and riveted connections of these bridges can accumulate significant fatigue damage.

Fatigue design philosophy has evolved from fatigue limit and infinite life criteria to approaches based on finite life behaviour. The local approaches use fatigue damage parameters to correlate fatigue test results, especially for crack initiation life.

In order to predict the fatigue life under a specified condition, different fatigue damage parameters have been proposed to correlate fatigue life. The local approaches are generally divided into three categories, i.e., stress-based, strain-based and energy-based methods, when stress, strain or energy are respectively used as the fatigue damage parameter.

The statistical analysis of the fatigue results for several fatigue damage parameters is made using the ASTM E739 American standard [1]. Several authors have used this American standard in order to obtain the design curves for fatigue and fracture mechanics [2-9].

The experimental results are compared to the fatigue design curves for several fatigue damage parameters obtained by statistical analysis. These design curves based on stress-based, strain-based and energy-based fatigue parameters can be used in fatigue local approaches of structural details of these bridges [3,10,11].

2. Overview of the fatigue tests developed

This section addresses the fatigue data obtained from materials collected in old metallic bridges. Smooth specimens were machined from original material removed from the bridges (Fig. **1**, Fig.2 and Fig. **3**). These specimens were then tested in order to evaluate the crack initiation, in the scope of a local approach analysis on fatigue.

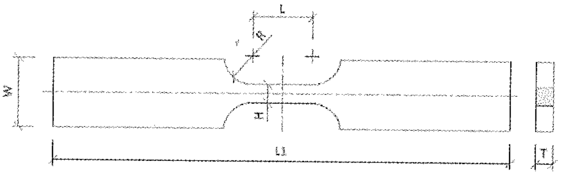


Fig. 1: Geometry of the specimen used in the fatigue tests [2]

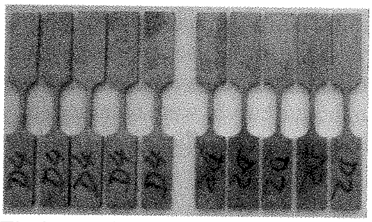


Fig.2: Specimens of material extracted from Fão bridge [3]

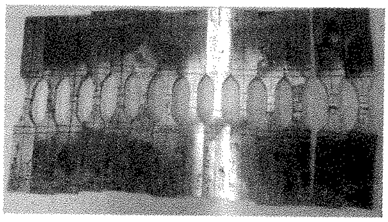


Fig. 3: Specimens of material extracted from Eiffel bridge [3]

The dispositions of ASTM E606 standard were followed, in order to obtain smooth specimens. The specimens, collected from Eiffel bridge, Fão bridge, Trezói bridge and Luiz I bridge, were shaped into rectangular cross sections. The choice to use rectangular section specimens instead of circular cross section specimens resulted from the the fact that the specimens' withdrawals from the bridges were small and the reduced thicknesses did not allow the preparation of round specimens. The dimensions of the specimens were varied for each material, since the material thicknesses were not constant. A base length of 12.5 mm specimens was adopted for Viana and Luiz I bridges. A base length of 25 mm was adopted for some specimens of Viana bridge and specimens from Trezói and Fão bridges. The dimensions of the specimens can be observed in Table 1 [3].

Table 1: Nominal dimensions of specimens used in fatigue tests [3]

Bridge	No. of specimens	W (mm)	T (mm)	L (mm)	L1 (mm)	R (mm)	H (mm)
Eiffel	27	22.0	6.0	20.0	150.0	15.0	7.0
Fão	32	30.0	7.5	26.0	200.0	12.5	8.0
Trezói	10	30.0	7.5	26.0	200.0	12.5	8.0
Luiz I	15	20.0	5.0	15.0	150.0	10.0	6.0

Several specimens were tested for stress, strain and SWT with strain ratios of 0 or -1, in order to characterize the elastoplastic behavior of the material and fatigue resistance.

The experimental tests were performed on 27 specimens of Eiffel bridge, 15 specimens of Luiz I bridge, 10 specimens of Trezói bridge and 32 specimens of Fão bridge. The tests with the strain ratio equals to -1 were performed on Eiffel, Luiz I and Trezói bridge specimens and also in 14 specimens of Fão bridge. The remaining 18 specimens of Fão bridge were tested with a strain ratio equal to 0.

3. Stress-Life Method or S-N Curve

The stress-life method or S-N curve is used to study high-cycle fatigue and long-life prediction when the stress and the strain loads possess elastic characteristics. It is aimed to study the life of a structure and does not distinguish between the beginning and the propagation of the crack.

The method establishes the relation between the stress range and the number of cycles up to failure, represented in a S-N curve. The stress variation can be the difference between the maximum and the minimum stress or the stress amplitude [12].

3.1 ASTM E739-91 standard

The statistical analysis based on ASTM E739 American standard, adopts a linear model for the mean S-N curve, which is given by the Equation (1),

$$Y = A + B \cdot X \tag{1}$$

with dependent variable Y, and independent variable X, defined by Equation (2),

$$X = \log \Delta\sigma \, ; \; Y = \log N_f \tag{2}$$

where $\Delta\sigma$ is the stress range and N_f is the number of cycles to failure.

Based on Equations (1) and (2), it is possible to write the S-N curves in the following alternative forms (Equations (3) and (4)).

$$\log N_f = A + B \cdot \log \Delta\sigma \tag{3}$$

or

$$\log \Delta\sigma = -\frac{A}{B} + \frac{1}{B} \cdot \log N_f \tag{4}$$

This representation of the S-N curve, can also be written according to Equation (5),

$$\Delta\sigma^m \cdot N_f = C \tag{5}$$

where m and C are constants which can be determined from the parameters A and B of the linear regression.

$$C = 10^A ; m = -B \tag{6}$$

Estimates for the parameters A and B are determined based on Equations (7) and (8),

$$A = \bar{Y} - B \cdot \bar{X} \tag{7}$$

$$B = \frac{\sum_{i=1}^{k} (X_i - \bar{X})(Y_i - \bar{Y})}{\sum_{i=1}^{k} (X_i - \bar{X})^2} \tag{8}$$

where X and Y are the average values of the experimental values $X_i = \log \Delta\sigma_i$ and $Y_i = \log N_i$, respectively, and k is the number of samples that conducted the specimen to failure. Rectilinear confidence intervals are then defined through Equation (9),

$$Y = A + B \cdot X \pm \alpha \cdot S = (A \pm \alpha \cdot S) + B \cdot X \tag{9}$$

where α is an integer number and S is the standard deviation of the residuals.

The advantage of the linear model lies in its easy implementation. On the other hand, due to its inherent simplicity, it is not necessarily well suited to represent transitions between low, high and very-high cycled fatigue.

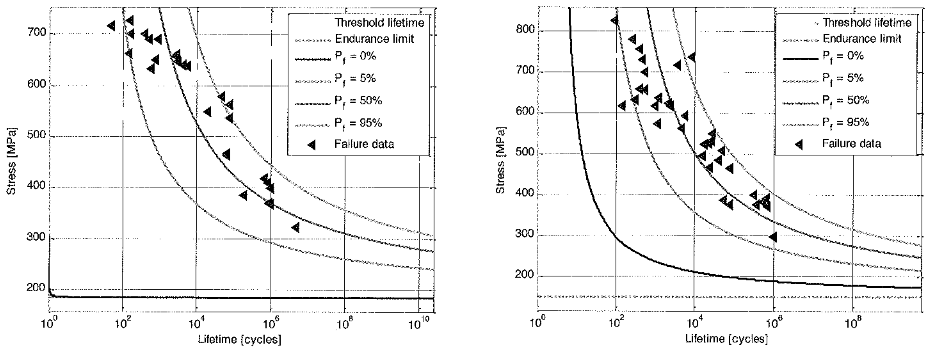
This linear model is also applied for local fatigue damage parameters, such as, strain, SWT, energy and others.

4. Analysis of results obtained in stress-life tests

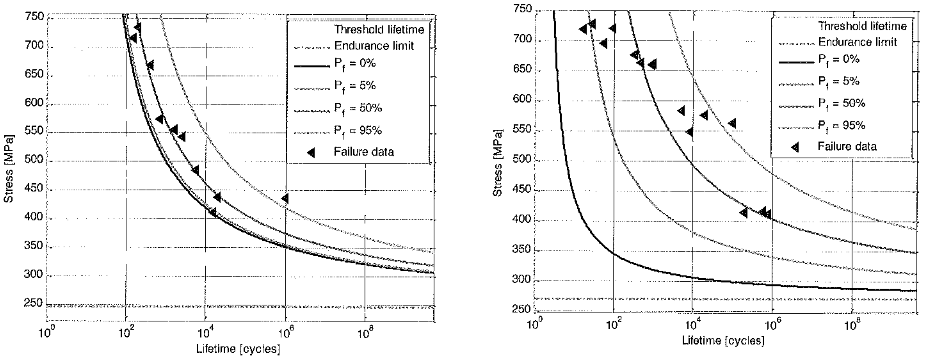
The stress-life method relays on the stress amplitude to evaluate the number of cycles to failure.

Fig. **4** shows the results on the fatigue life of the bridge specimens collected in each of the analyzed bridges, following the log-normal distribution and the log-normal distribution parameters (i.e. the logarithmic values and standard deviation of fatigue lives at each equivalent stress amplitude) [13].

The graphics presented in **Fig. 4** were developed with the software ProFatigue® [14].



a) Eiffel bridge b) Fão bridge



c) Trezói bridge d) Luiz I bridge

Fig. 4: S-N curves of the bridges' material stress test (R_ε= 0 and -1)

The data obtained with the study of the local approach involved the parameter of stress range, corresponding with the lifetime of each bridge material, are compared in order to demonstrate the accuracy of the probabilistic approach.

The results obtained were compared following a statistical analysis based on the ASTM E739-91 standard. These results show a good behavior, because the mean experimental data is contained in the band between p=5% and p=95%.

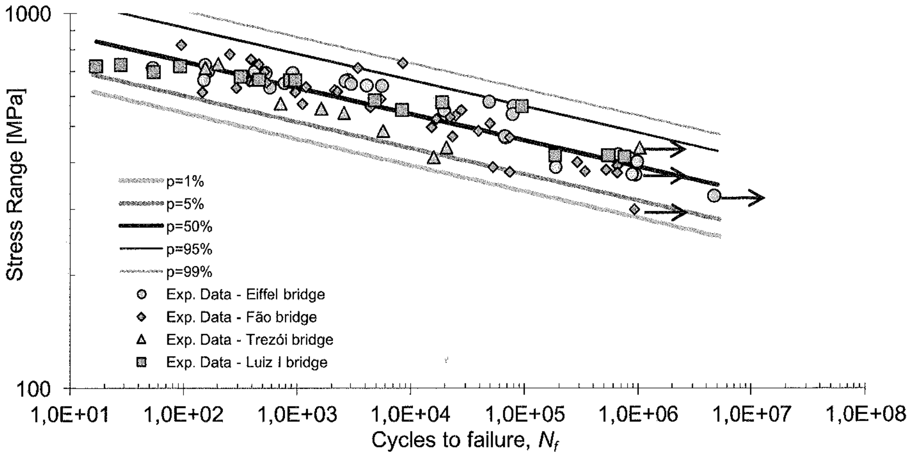


Fig. 5: Statistical analysis on the stress-life of all bridge materials, based on ASTM E739-91 standard

In the study of the stress-life (Table 2), the constants β, B, C, Δ and λ are important in the normalizing process. The parameters obtained are: β - the shape parameter of the Weibull model, B - the linear regression parameter (related to the lifetime), C - the material constant (related to endurance limit) and λ - the threshold parameter of the Weibull model.

Table 2: Material parameters estimated from the stress-life test results

	β	B	C	Δ	λ
Eiffel bridge (R_ε= 0)	6.29	0 (1 cycle)	5.22	9.89	0.01
Fão bridge (R_ε= 0 and R_ε= -1)	5.25	0 (1 cycle)	5.01 (150.23 MPa)	8.51	3.13
Trezói bridge (R_ε= -1)	1.45	0 (1 cycle)	5.51 (247.41 MPa)	1.15	4.87
Luiz I bridge (R_ε= -1)	3.39	0 (1 cycle)	5.60 (271.48 MPa)	4.86	1.12

The parameters from the statistical analysis for linear model based on ASTM E739 standard are presented in Table 3. The *C* and *m* fatigue parameters were obtained taking into account the mean S-N curve considering the lower linear boundary defined by *2S*, using Equation (9).

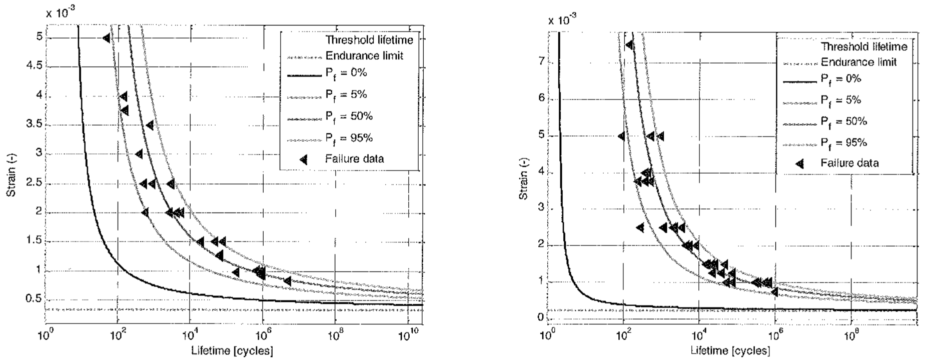
Table 3: Statistical linear regression and fatigue parameters for materials from all the bridges in analysis

	Eiffel	Fão	Trezói	Luiz I
Number of test specimens, *k (*)*	27	32	10	15
Average value of the independent variable, $\bar{X}$ (*)	4.079	3.915	3.487	3.423
Average value of the dependent variable, $\bar{Y}$ (*)	2.739	2.733	2.737	2.772
A (*)	3.0268	3.0694	2.9754	2.9565
B (*)	-0.0706	-0.0857	-0.0685	-0.05399
Variance, S^2 *(*)*	0.001453	0.0022	0.0023	0.00097
Standard deviation, *S (*)*	0.03811	0.04699	0.0475	0.0312
C in MPa ($\alpha = 2$)	892.60	945.05	759.18	783.51
Slope, *m*	14.17	11.66	14.60	18.52

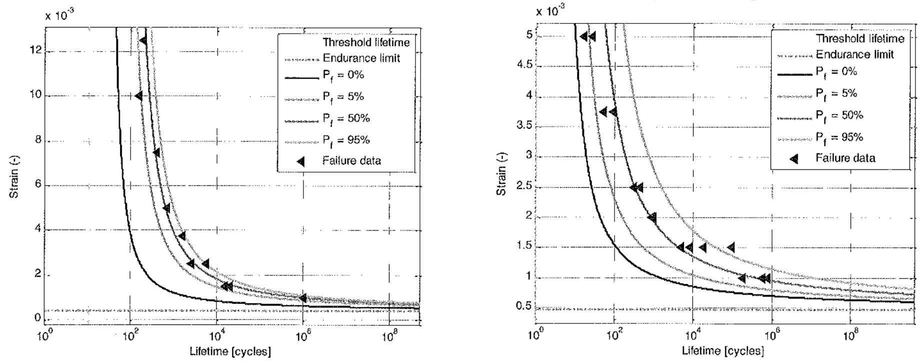
* parameters of the statistical linear regression analysis in the logarithmic scale.

5. Analysis of results obtained in strain-life tests

Fig. **6** shows the results on the fatigue life of the bridge specimens collected in each of the analyzed bridges, following the log-normal distribution and the log-normal distribution parameters (i.e. the logarithmic values and standard deviation of fatigue lives at each equivalent strain amplitude).



a) Eiffel bridge b) Fão bridge



c) Trezói bridge d) Luiz I bridge

Fig. 6: Strain-N curves of the bridges' material stress test (R_ε= 0 and -1)

In the study of the strain-life (**Table 4**), the constants β, B, C, Δ and λ are used in the normalizing process. The parameters obtained are: β - the shape parameter of the Weibull model, B - the linear regression parameter (related to the lifetime), C - the material constant (related to endurance limit) and λ - the threshold parameter of the Weibull model.

Table 4: Material parameters estimated from the strain-life test results

	β	B	C	Δ	λ
Eiffel bridge (R_ε= -1)	6.40	0 (1 cycle)	-7.99 (0.0 MPa)	9.26	5.59
Fão bridge (R_ε= 0 and R_ε= -1)	11.52	0 (1 cycle)	-8.38 (0,0 MPa)	16.25	2.40
Trezói bridge (R_ε= -1)	7.90	2,38 (10 cycle)	-7.82 (0.0 MPa)	5.58	5.0
Luiz I bridge (R_ε= -1)	3.12	0,0 (1 cycle)	-7.66 (0.0 MPa)	4.78	5.50

The data obtained with the study of the local approach involving the parameters of strain amplitude, corresponding with the lifetime of each bridge material, are compared in order to demonstrate the accuracy of the probabilistic approach.

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The results obtained were compared following a statistical analysis based on the ASTM E739-91 standard. These results show a good behavior, because the mean experimental data is contained in the band between p=5% and p=95%, as observed in Fig. 7.

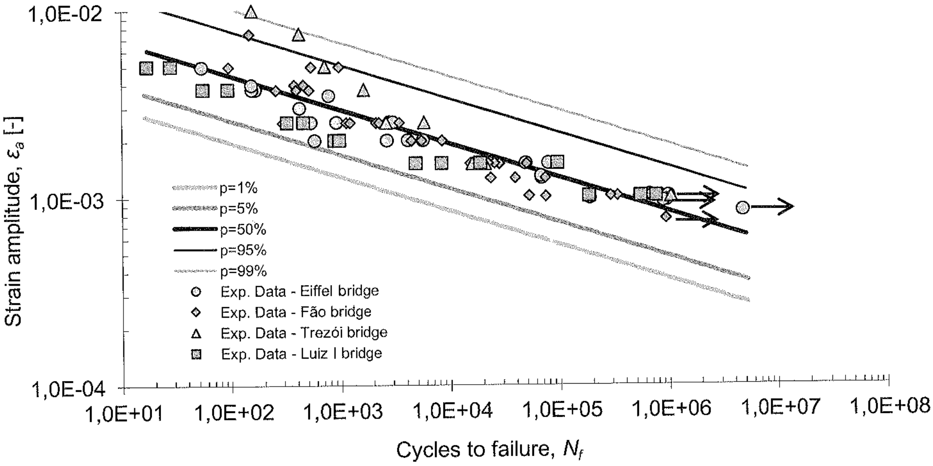


Fig. 7: Statistical analysis on the strain-life of all bridge materials, based on ASTM E739-91 standard

The parameters from the statistical analysis for linear model based on ASTM E739 standard are presented in Table 5. The C and m fatigue parameters were obtained taking into account the mean ε-N curve considering the lower linear boundary defined by $2S$, using Equation (9).

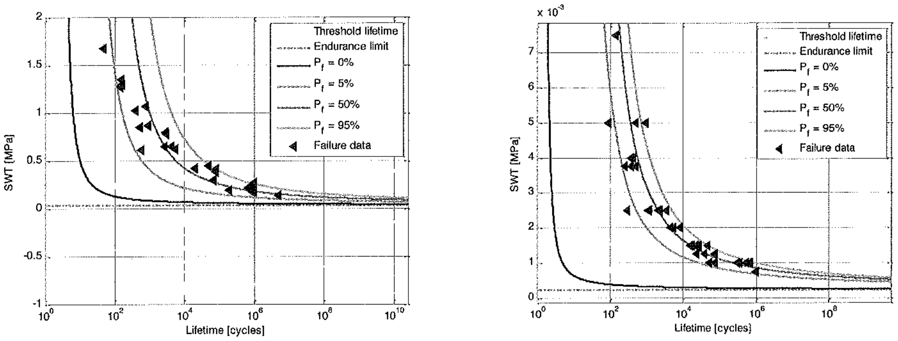
Table 5: Statistical linear regression and fatigue parameters for materials from all the bridges in analysis

	Eiffel	Fão	Trezói	Luiz I
Number of test specimens, *k (*)*	27	32	10	15
Average value of the independent variable, $\bar{X}$ (*)	4.0788	3.916	3.487	3.423
Average value of the dependent variable, $\bar{Y}$ (*)	-2.7394	-2.703	-2.461	-2.690
A (*)	-2.1199	-1.889	-1.4099	-2.178
B (*)	-0.1519	-0.2077	-0.3014	-0.1495
Variance, S^2 *(*)*	0.00328	0.00768	0.0209	0.0044
Standard deviation, *S (*)*	0.05724	0.0877	0.1448	0.0667
C in MPa ($\alpha = 2$)	0.00583	0.00862	0.01997	0.00488
Slope, *m*	6.583	4.810	3.318	6.689

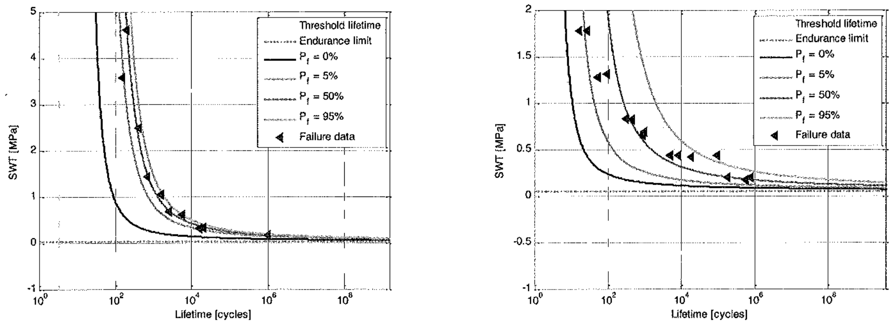
* parameters of the statistical linear regression analysis in the logarithmic scale.

6. Analysis of results obtained in SWT-life tests

Fig. 6 shows the results on the fatigue life of the bridge specimens collected in each of the analyzed bridges, following the log-normal distribution and the log-normal distribution parameters (i.e. the logarithmic values and standard deviation of fatigue lives at each equivalent SWT amplitude).



a) Eiffel bridge b) Fão bridge



c) Trezói bridge d) Luiz I bridge

Fig. 8: SWT-N curves of the bridges' material stress test (R_ε= 0 and -1)

In the study of the SWT-life (Table 6), the constants β, B, C, Δ and λ are used in the normalizing process. The parameters obtained are: β - the shape parameter of the Weibull model, B - the linear regression parameter (related to the lifetime), C - the material constant (related to endurance limit) and λ - the threshold parameter of the Weibull model.

Table 6: Material parameters estimated from the SWT-life test results

	β	B	C	Δ	λ
Eiffel bridge (R_ε= -1)	5.38	0.0 (1 cycle)	-3.44 (0,03 MPa)	18.51	6.39
Fão bridge (R_ε= 0)	11.52	0.0 (1 cycle)	-8.38 (0,0 MPa)	16.25	2.40
Trezói bridge (R_ε= -1)	10.52	1.19 (1 cycle)	-3.40 (0,03 MPa)	9.37	11.25
Luiz I bridge (R_ε= -1)	3.07	0.0 (1 cycle)	-2.98 (0,05 MPa)	10.90	7.09

The data obtained with the study of the local approach involving the parameters of SWT, corresponding with the lifetime of each bridge material, are compared in order to demonstrate the accuracy of the probabilistic approach.

The results obtained were compared following a statistical analysis based on the ASTM E739-91 standard. These results show a good behavior, because the mean experimental data is contained in the band between p=5% and p=95%, as observed in Fig. **9**.

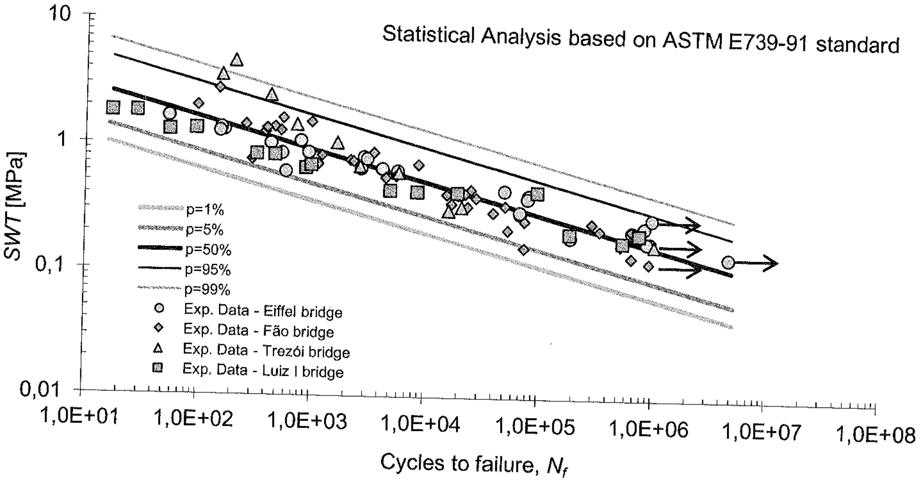


Fig. 9: Statistical analysis on the SWT-life of all bridge materials, based on ASTM E739-91 standard

The parameters from the statistical analysis for linear model based on ASTM E739 standard are presented in **Table** 7. The C and m fatigue parameters were obtained taking into account the mean SWT-N curve considering the lower linear boundary defined by $2S$, using Equation (9).

Table 7: Statistical linear regression and fatigue parameters materials from all the bridges in analysis

	Eiffel	Fão	Trezói	Luiz I
Number of test specimens, k *(*)*	27	32	10	15
Average value of the independent variable, $\bar{X}$ (*)	4.0788	3.916	3.487	3.423
Average value of the dependent variable, $\bar{Y}$ (*)	-0.3022	-0.273	-0.0367	-0.2277
A *(*)*	0.5633	0.8835	1.3369	0.48305
B *(*)*	-0.2122	-0.2953	-0.3939	-0.2076
Variance, S^2 *(*)*	0.00576	0.01205	0.02789	0.005325
Standard deviation, S *(*)*	0.0759	0.1098	0.1670	0.0729
C in MPa ($\alpha = 2$)	2.5795	4.613	10.07	2.173
Slope, m	4.712	3.386	2.538	4.816

* parameters of the statistical linear regression analysis in the logarithmic scale.

7. Results from the fatigue damage parameters

The S-N curve is used to calculate the long-life time prediction of the material. The graphics included in Fig. 10, Fig. 11 and Fig. 1are used to express the influence of the mean stress on the fatigue limit, as well as the fatigue strength for a prescribed fatigue life. The obtained data results appear to possess good behavior, since the experimental data is mostly located above the proposed line (it can be observed in the graphics as the solid black line), hence the involved parameters stress, strain and SWT.

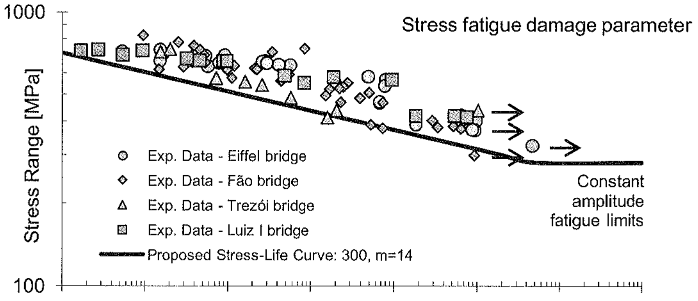


Fig. 10: Proposed Stress-life curve of all bridge materials

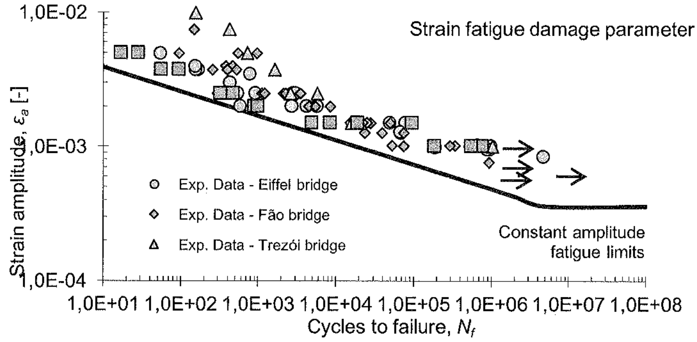


Fig. 11: Proposed Strain-life curve of all bridge materials

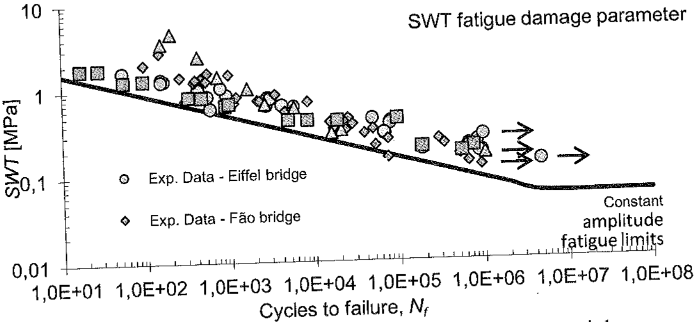


Fig. 12: Proposed SWT-life curve of all bridge materials

8. Conclusions

Fatigue failures are a concern for steel bridges due to the likelihood of the steel to deteriorate under variable stresses, being recognized as the major cause of failure in metallic bridges. Residual life calculations of existing bridges in operation should take into account fatigue as a progressive damaging mechanism. A consistent residual life prediction should be based on actual fatigue data from bridge members being assessed.

The following steps involved the preparation and validation of a probabilistic approach on the design fatigue of materials. The study developed is based on experimental data obtained in experimental tests performed in specimens collected from old Portuguese metallic bridges. Subsequently, with the assistance of the software ProFatigue®, probabilistic curves for several fatigue damage parameters were obtained. This specific software follows the mathematical method known as Weibull distribution, providing results as the design fatigue curve, probabilistic curves, which represents the Weibull distribution and the parameters obtained from the resulting graphics.

The statistical analysis based on ASTM E739-91 standard aimed at the design fatigue curves for several fatigue damage parameters (stress, strain and SWT) using the experimental data of the materials from the different bridges. In the all resulting graphics the data is contained within the zone between the 5% curve and the 95% curve. These design fatigue curves for different fatigue damage parameters can be used with local fatigue approaches with aims to study the fatigue lifetime of critical details in bridges.

Aknowledgements

The authors of this paper thank the SciTech-Science and Technology for Competitive and Sustainable Industries, R&D project NORTE-01-0145-FEDER-000022 co-financed by Programme Operational Regional do Norte ("NORTE2020") through Fundo Europe de Desenvolvimento Regional (FEDER) and the Portuguese Science Foundation (FCT) through the post-doctoral grant SFRH/BPD/107825/2015 the for their collaboration, financial and technical support during this research works.

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