Overview of Recent Portuguese Research on Fatigue Behaviour of Ancient Portuguese Riveted Steel Bridges

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ABSTRACT

This paper reports experimental work that has been carried out by authors to characterize the fatigue behaviour of Portuguese ancient riveted steel bridges. Four riveted steel bridges have been analysed, namely the Luiz I, Viana, Pinhão and Trezói bridges. A basic material characterization is presented. The fatigue crack propagation behaviour is also characterized and finally the fatigue strength of original single-riveted connections is characterized.

1- INTRODUTION

In Portugal there is a number of steel riveted railway and highway bridges more than one hundred years old, still in operation, requiring rehabilitation. Fatigue failures are a concern for these riveted steel bridges due to the likelihood of the steel to deteriorate under variable stresses [Akesson (1994]. A consistent residual fatigue life prediction should be based on actual fatigue data from bridge members which is often limited, mostly for ancient steel riveted bridges.

The present paper reports research work carried out to characterize materials from ancient Portuguese riveted bridges, namely the Luiz I and Pinhão highway bridges, the Viana highway/railway bridge and the Trezói railway bridge (see figure 1). This paper gives an overview of the main experimental results, essentially on fatigue, which have been published by authors, in detail, in specific research reports and papers [Fernandes et al. (2004)], [Figueiredo et al. (2006)], [Jorge et al. (2006)], [Silva and Fernandes (2007)].

Fig 1a - Highway Luiz I bridge.

Fig 1b - Highway Pinhão bridge.

Fig 1c - Highway and railway Viana bridge.

Fig 1d - Railway Trezói bridge.

2 – MATERIALS CHARACTERIZATION

Materials characterization was carried out with materials extracted from the bridges. Original bridge members were removed and replaced by new ones. One piece 1500 mm in length was extracted from a diagonal member and another piece 1400 mm in length was removed from a bracing member of the Pinhão bridge. A diagonal member 1600 mm in length was removed from the Luiz I bridge. Also, a 3000 mm in length bracing was removed from the Trezói bridge. Regarding the Viana bridge, the highway Darque viaduct was removed and replaced by a new one.

The specimens were prepared using the materials samples removed from the bridge. Chemical and metallographic analyses, hardness measurements, tensile tests, notch toughness tests, fatigue crack propagation tests and fatigue strength of riveted connections were carried out. More details can be found in [Figueiredo et al (2004)], [Figueiredo et al (2006)], [Fernandes et al (2004)] and [Figueiredo et al (2007)].

2.1 - Chemical and Metallographic Analyses

Chemical and microstructural analyses were carried out for each material extracted from the bridges. The following numbers of samples were analyzed:

- Pinhão bridge: 6 samples, three from the diagonal member and three from the bracing member;
- Luiz I bridge: 3 samples from the diagonal member;
- Viana bridge: 2 samples from Darque viaduct;
- Trezói bridge: 1 sample from the bracing member.

In general, the chemical and metallographic analyses revealed a good homogeneity in the chemical composition of the materials. The phosphorus and sulphur contents are low and are within the acceptable values for modern steels. The analyzed steels are carbon steels with small amounts of Mn, Si and C. The average chemical composition is summarized in Table 1.

Table 1 – Chemical composition of the materials.

Brigde	Material	%C	%Si	%Mn	%P	%S
Pinhão	Diagonal	0.06	<0.01	0.04	0.04	0.03
	Bracing	0.05	<0.01	0.34	0.04	0.04
Luiz I	Diagonal	0.72	0.34	2.09	>0.15	>0.15
Viana	Darque Viaduct	0.23	0.39	1.78	>0.15	>0.15
	bridge*	0.81	0.24	2.71	>0.15	>0.15
Trezói	Bracing	0.06	0.03	0.34	0.02	0.02

* determined with a portable emission spectrometry

The microstructure of the materials is composed by ferrite with low content of perlite, as expected due to the low carbon and manganese contents. Figure 2 illustrates some typical microstructures of the materials from the bridges.

2.2 – Strength Properties

Tensile strength properties for the various materials under investigation were evaluated according to the NP 10002-1 standard. The following numbers of specimens were tested:

- Luiz I bridge: 5 specimens from the diagonal member;
- Pinhão bridge: 14 specimens, 7 from the diagonal and 7 from the bracing;
- Viana bridge: 4 specimens in the longitudinal and 4 in the transverse directions of the girder;
- Trezói bridge: 3 specimens from the bracing member.

2.3 – Hardness measurements

Vickers hardness were measured accordingly the procedures of the NP711-1 standard for the bridges materials. Samples of material of the bridges were analysed resulting the average hardness values summarized in Table 3. In general, the mea-

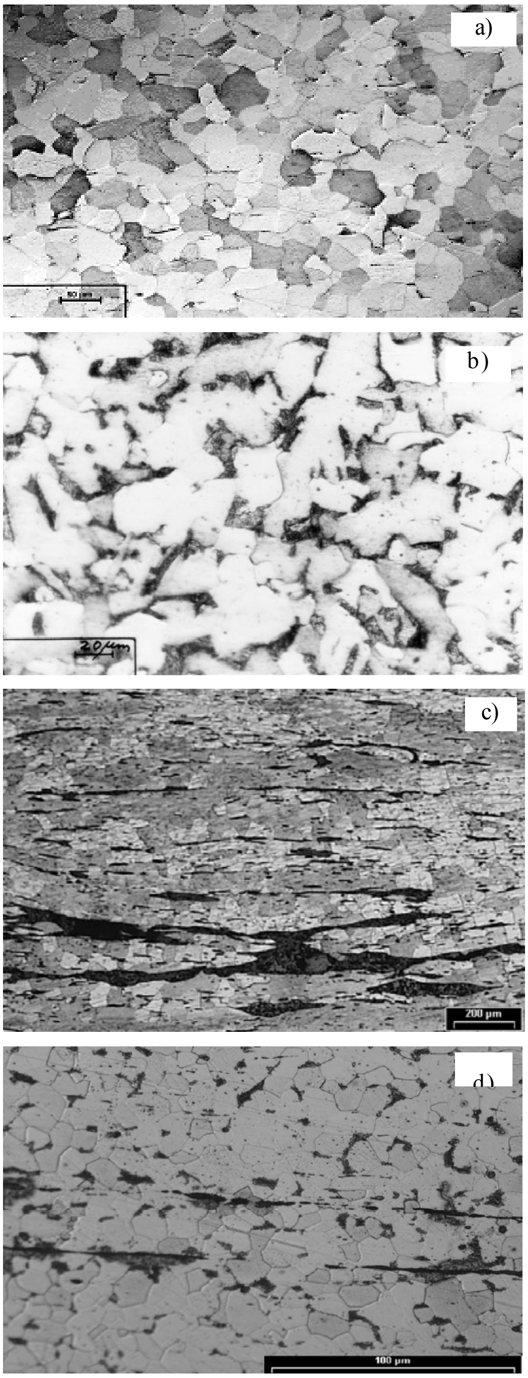

Fig 2 – Microstructures of the materials: a) Pinhão; b) Luiz I; c) Viana; d) Trezói.

sured hardness presented small scatter.The average values of the tensile strength properties are summarized in Table 2, namely the ultimate strength, f_u, the yield strength, f_y, the elongation at fracture, A, and the reduction in cross section at fracture, Z. In general, the materials exhibit a high ductility. A comparison between the ultimate and yield strengths allows to conclude that materials have a relative small strain hardening, if compared with actual steels. This behaviour is compatible with the observed microstructure of ferrite with low volumetric fraction of perlite.

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Table 2 – Tensile strength properties.

Brigde		f_u	f_y	A	Z
		MPa	MPa	%	%
Pinhão	Diagonal	367	284	33	70
	Bracing	355	328	33	70
Luiz I	Diagonal	397	303	21	27
Viana	Darque Viaduct	342	292	8	12
Trezói	Bracing	464	401	23	66

Table 3 – Average hardness values.

Brigde	Material	Samples	Result
Pinhão	Bracing	3	116 HV40
	Diagonal	3	108 HV40
Luiz I	Diagonal	3	158 HV50
Viana	Viaduct	*	*
Trezói	Bracing	3	136 HV40

* no data is available.

2.4 – Notch toughness testing

The notch toughness of the materials was measured using both Charpy V-notch impact and COD tests. The Charpy V-notch impact tests were conducted according to the NP10045-1 standard for several temperatures and the COD tests were carried out according to the BS 5762 standard. The notch toughness properties, although lower than those required by modern codes of practice, with the exception of the Pinhão bridge, are considered acceptable, given the heterogeneity of the material. Tables 4 and 5 summarize the Charpy V-notch and COD test results, respectively.

The measured Charpy V-notch energy was in the range 4-107 J for several temperatures and the COD in the range 0.017-0.343mm. According to the Eurocode, the minimum allowable Charpy V-notch energy should be 27 J at the service temperature. Taking into account this criterion, only the material from the Pinhão bridge revealed acceptable values.

Table 4 – Charpy V-notch test results.

Brigde	Material	Direction	Thickness	Specimens	Energy	Temperature
			mm	N.º	J	º C
Pinhão	Bracing	Longitudinal	7.5	4	89	19
		Transverse		4	26	19
	Diagonal	Longitudinal	7.5	4	107	19
		Transverse		4	20	19
Luiz I	Diagonal	Longitudinal	6	5	13	0
				11	14	22
Viana	Viaduct	Longitudinal	5	-	7	0
Trezói	Bracing	Longitudinal	10	5	24	26.5
				3	6	-10
		Transverse		4	16	26.5
				4	4	-10

Table 5 – COD test results.

Brigde	Material	Direction	Thickness	Specimens	COD "pop-in"	COD Fmax	Temperature
			mm	N.º	mm	mm	º C
Pinhão	Bracing	Longitudinal	7	3	0.017	0.765	24
	Diagonal	Longitudinal	9	2	0.030	0.972	22
		Longitudinal		1	0.022	0.905	19
Luiz I	Diagonal	Longitudinal	6	1	0.343	1.360	20
		Longitudinal		1	0.236	0.940	-1
		Longitudinal		2	0.173	0.950	18
Viana	Viaduct	not available	not available	not available	not available	not available	not available
Trezói	Bracing	Longitudinal	9	7	0.028	1.188	26.5
				4	0.030	0.720	-10

3 – CRACK PROPAGATION DATA

Crack growth tests were undertaken according to the ASTM E647 standard for all materials. A total of 30 specimens were tested, 13 from the Pinhão bridge (6 from the diagonal and 7 from the bracing), 4 from the Luiz I bridge, 5 from the Viana bridge (1 according the longitudinal direction and 4 according the transverse direction) and finally 8 specimens from the Trezói bridge.

Due to limitations in material availability, distinct dimensions for the specimens were adopted:

- Luiz I bridge: MT geometry; thickness=10 mm; width, *W*=40 mm;
- Pinhão and Viana bridges: CT geometry; thickness=4.35 mm; width, *W*=40 mm;
- Trezói bridge: CT geometry; thickness=8 mm; width, *W*=50 mm.

The following stress ratios were investigated for each material:

- Luiz I bridge: *R*=0.1;
- Pinhão: *R*=0.0, *R*=0.1 and *R*=0.5;
- Viana bridge: *R*=0.1 and *R*=0.5;
- Trezói bridge: *R*=0.0, *R*=0.25 and *R*=0.5.

All tests were performed in air, at room temperature, under a sinusoidal waveform with a frequency of 20 Hz for all materials with the exception of material from Luiz I bridge, which was tested under a frequency of 10 Hz.

The experimental results are presented in Figures 3, 4, 5 and 6, respectively for the Pinhão, Luiz I, Viana and Trezói bridges.

Results were correlated using the Paris's law:

$$da / dN = C \cdot \Delta K^m \tag{1}$$

where *da/dN* is the crack propagation rate, *ΔK* is the stress intensity factor range, *C* and *m* are material constants.

The greatest scatter in crack propagation data was found in materials from Luiz I and Viana bridges which is consistent with the fact that these bridges are the oldest ones and respective materials present important heterogeneities. The data from Pinhão bridge reveals a relative low scatter; this material is about 25 years younger than previous, revealing good homogeneity, similar to modern steels. Finally, the material from the Trezói bridge exhibits very low scatter which is expectable due to the relative low age of the material.

The two samples of material from the Pinhão bridge (bracing (B) and diagonal (D)) exhibit slightly distinct crack growth rates for R=0.0; however for the other stress ratios no differences in crack growth rates can be found between these two materials. The stress ratio influence seems to be more visible for the material from the Viana bridge. For this bridge, crack propagation rates were measured in the girder longitudinal (L) direction; only one test was carried out in the transverse direction (T). This last result suggests a lower crack propagation rate in the transverse direction of the material. The material from Trezói bridge is also sensitive to the stress ratio. The crack propagation rate slightly increases as the stress ratio increases.

A linear regression analysis is carried out for all data together, resulting a determination coefficient R^2=0.87, which is

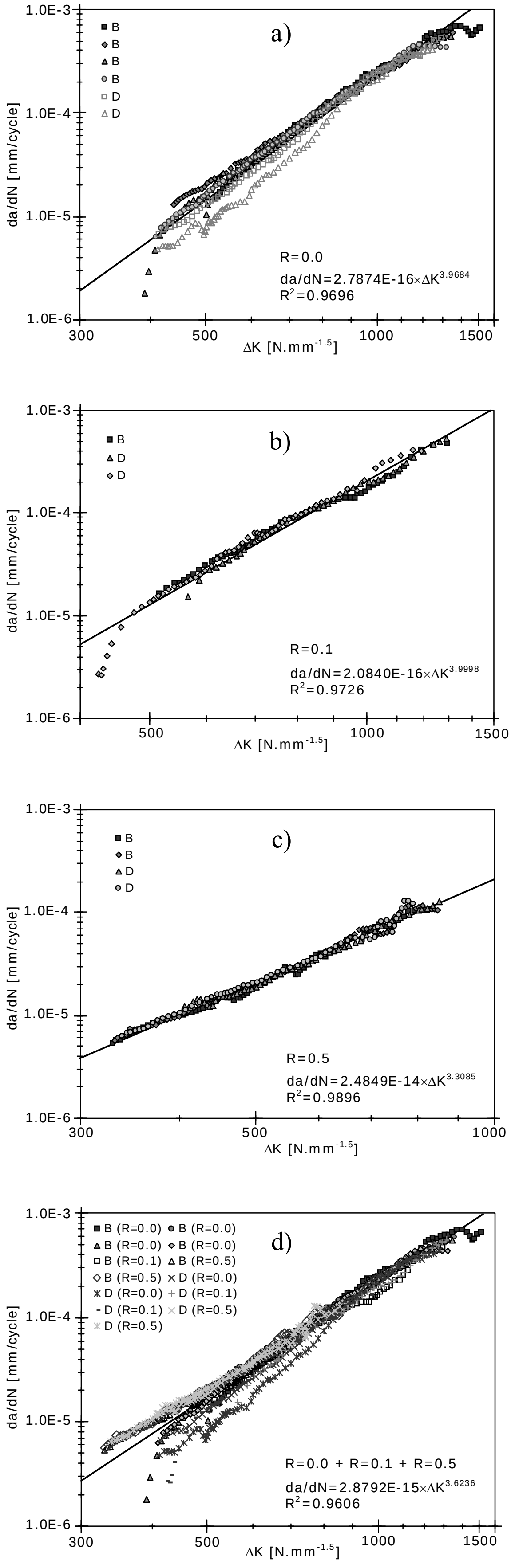

Fig 3. Fatigue crack growth data of the material from the Pinhão bridge: a) *R*=0.0; b) *R*=0.1; c) *R*=0.5; d) *R*=0.0+*R*=0.1+*R*=0.5.

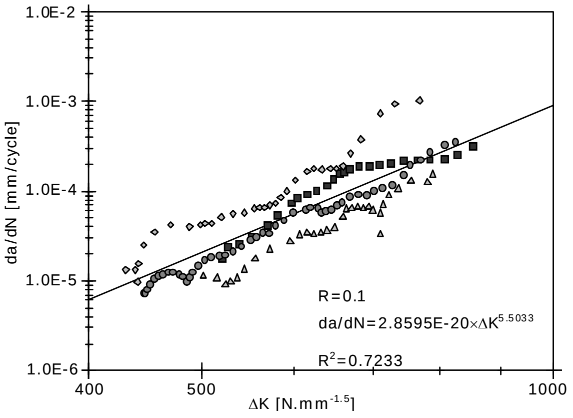

Fig 4. Fatigue crack growth data of the material from the Luiz I bridge: *R*=0.1.

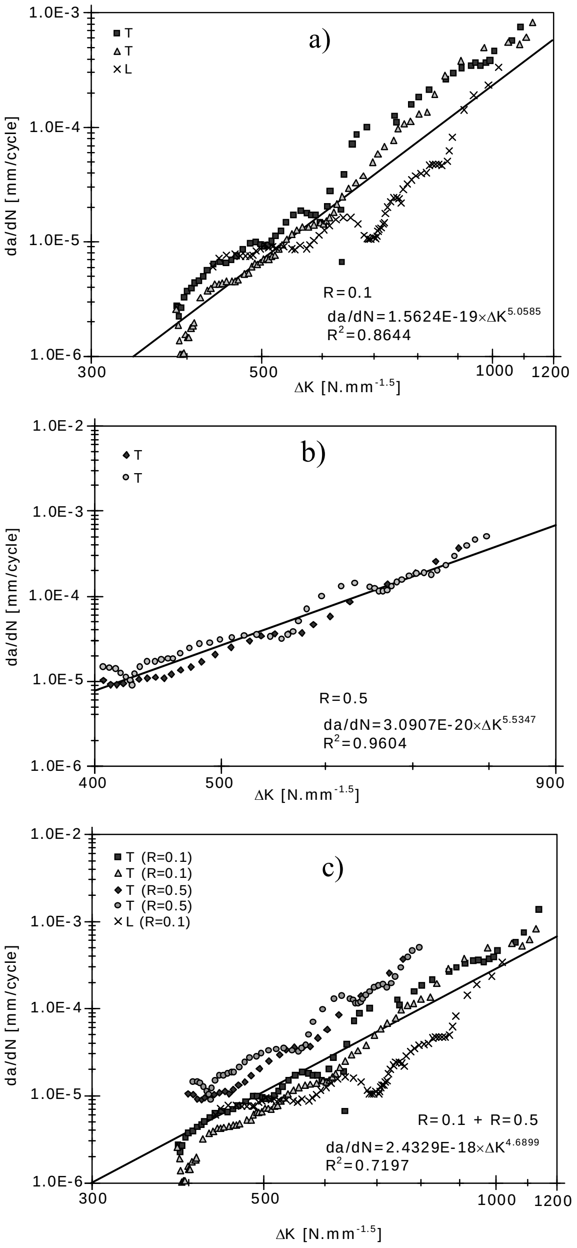

Fig 5. Fatigue crack growth data of the material from the Viana bridge: a) *R*=0.1; b) *R*=0.5; c) *R*=0.0+*R*=0.5.

relatively high, taking into account the different origins of the investigated materials. Constant m resulted higher than 3.0 and constant C resulted significantly lower than the usual range of $1.2\times10^{-13}\leq C\leq5\times10^{-13}$, referred in literature for modern steels [APK, 1996]. Clearly, a crack propagation curve based on a slope of 3 and $C=7\times10^{-13}$ will produce safe results for all analyzed materials (see figure 7).

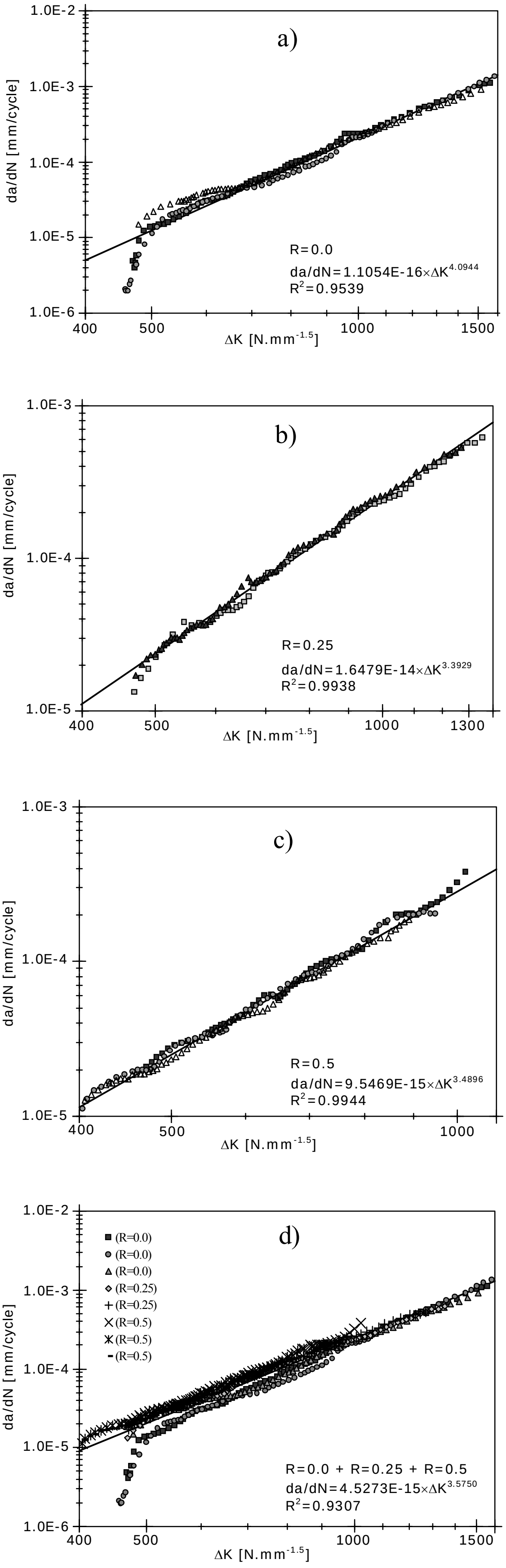

Fig 6. Fatigue crack growth data of the material from the Trezói bridge: a) R=0.0; b) R=0.25; c) R=0.5; d) R=0.0+R=0.25+R=0.5.

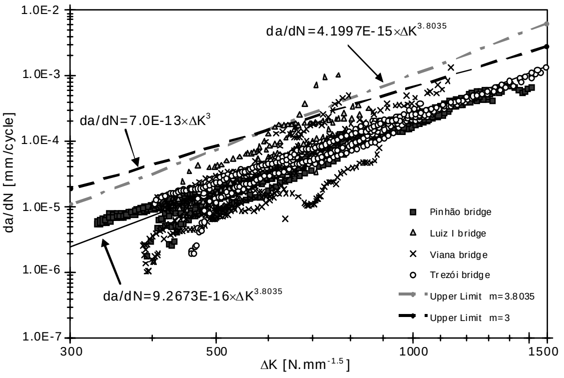

Fig 7. Fatigue crack growth for all materials.

4 - FATIGUE STRENGTH OF RIVETED CONNECTIONS

Original riveted joints were fatigue tested to derive a S-N curve. Due to limitations imposed by the available material only single lap joints with a unique rivet were tested. Figure 8 presents the results of the tests. For the Viana bridge no data is available. Based on author's results a global S-N curve is proposed. Its slope is slightly higher than 3.0.

Riveted connections are not specifically mentioned in Eurocode 3 (EC3). If it is assumed that a riveted connection behaves similarly to one sided bolted connection, then EC 3 prescribes the use of detail categories between 50 and 80. The authors plotted on figure 8 the detail category 71, which coincides with the AASHTO proposal. Taking into account the derived experimental S-N curve, author's results are very acceptable, since the S-N curve is above the ASSTHO and EC 3 – class 71 curves. Riveted connections from Trezói bridge revealed higher fatigue strength due to higher rivet clamping forces.

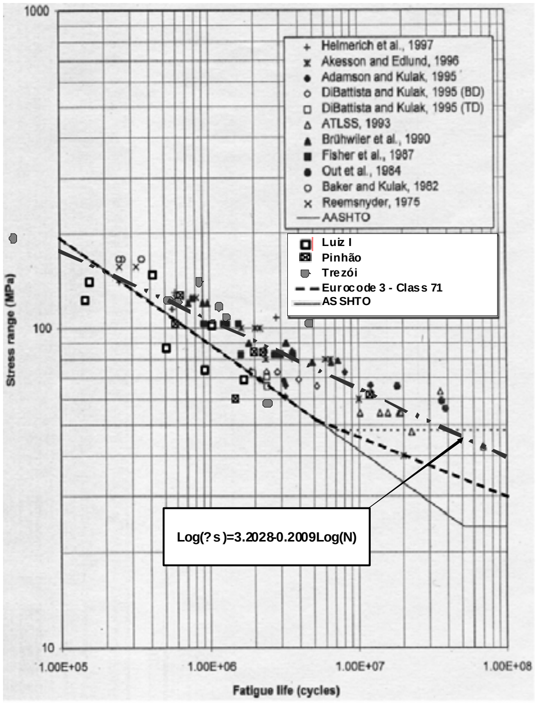

Fig 8 – S-N curve for riveted connections.

5 – CONCLUSIONS

The main conclusions of this study can be summarized as follows:

- Chemical and metallographic analyses revealed low carbon steels for all bridge materials.
- The Pinhão bridge revealed very acceptable toughness properties. However, the other materials exhibited toughness values in general lower than recommended in current design codes of practice (EC 3).
- The crack propagation tests allowed the determination of a global crack propagation law which can be used for design/assessment purposes.
- The fatigue resistances obtained for the single lap riveted joints are compatible with the recommendations of actual international codes of practice.

ACKNOWLEDGMENTS

This work was supported by the Portuguese Scientific Foundation (FCT) through the project PTDC/EME-PME/78833/2006.

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