FATIGUE BEHAVIOUR OF RIVETED AND BOLTED CONNECTIONS MADE OF PUDDLE IRON - PART I: EXPERIMENTAL INVESTIGATION

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Abstract. *In Europe and North America there are a number of old riveted highway/road and railway bridges, constructed during the second half of the 19th century up to the middle of the 20th century which, due to economic reasons, are still in operation. Since they have been subjected to increasing traffic intensity along their operational lives, both in terms of vehicle gross weights/axle loads as well as truck/train frequencies, their damage levels need to be assessed in order to decide about possible repairs. Thus, the maintenance and safety of these existing bridges is a major concern of governmental agencies. In order to assure high safety levels in old riveted steel bridges, highway and railway authorities have to invest heavily in their maintenance and retrofitting. Fatigue failures are a concern for riveted steel bridges since they were not originally designed taking into account fatigue. The fatigue phenomenon was only intensively investigated after the half of the 20th century, when the riveted construction was no longer applied in new bridge structures. Therefore, there is a lack of a comprehensive methodology for the fatigue assessment of riveted bridges motivated by limited knowledge on the fatigue behavior of this type of construction as well as a deficient understanding on the fatigue behavior of the old materials (wrought-iron, puddle iron or old steels) and riveted connections. This paper presents an experimental study concerning the fatigue characterization of a puddle iron from the centenary Portuguese Fão bridge. Also, the fatigue behavior of a type of riveted and bolted joints is investigated. The effect of the clamping stress on bolted joints is investigated. Furthermore, variable amplitude loading is investigated for the riveted joints.*

***Keywords**: Riveted Joints, Bolted joints, Fatigue Behavior, Ancient Riveted Bridge, Fatigue Testing*

1. INTRODUCTION

In Europe and North America there are a number of old riveted highway and railway bridges, constructed during the second half of the 19th century up to the middle of the 20th century which, due to economic reasons, are still in operation. Since they have been subjected to increasing traffic intensity along their operational lives, both in terms of vehicle gross weights/axle loads as well as truck/train frequencies, their damage levels need to be assessed in order to decide about possible repairs. Thus, the maintenance and safety of these existing bridges is a major concern of governmental agencies. In order to assure high safety levels in old riveted steel bridges, highway and railway authorities have to invest heavily in their maintenance and retrofitting. In particular, fatigue failures are a concern for riveted steel bridges since they were not originally designed taking into account fatigue. The fatigue phenomenon was only intensively investigated after the half of the 20th century, when the riveted construction was no longer applied in new bridge structures. Therefore, there is a lack of a comprehensive methodology for the fatigue assessment of riveted bridges motivated by limited knowledge on the fatigue behavior of this type of construction as well as a deficient understanding on the fatigue behavior of the old materials (wrought-iron, puddle iron or old steels).

In Portugal, similarly to what occurs across the Europe and North America, there is an important number of old riveted metallic bridges requiring maintenance and rehabilitation in order to increase the operational period of those structures. Their replacement in a short period of time is extremely expensive and therefore postponed. The old riveted metallic bridges are very susceptive to accumulated fatigue damages due to their long operational period under variable amplitude loading (Akesson, 1994)(Crocetti, 2001)(Mohammad, 2002). The fatigue damage assessment and the computation of the residual life should be preferably based on experimental fatigue data from original materials and typical details made from the original materials. The current fatigue design procedures (ex: EC3 (CEN-TC 250, 2003)) are based on experimental data resulted from modern steels, which are not fully adequate for old metallic bridges, some of them built more than 100 years ago with precursor materials of modern steels (ex: puddle or wrought iron).

This paper presents the results of an experimental program aiming at characterizing the fatigue resistance of a puddle iron original from the Portuguese Fão bridge, which is a centenary metallic riveted bridge located at Esposende. The bridge was recently rehabilitated and some original side diagonals were removed and used in the experimental program. The experimental program included monotonic tensile tests, hardness tests, Charpy impact tests, metallographic analysis, fatigue crack propagation tests and fatigue tests of riveted and bolted joints. The bolted joints were tested with distinct preloads on bolts. The riveted joints were tested under constant and variable amplitude loading.

2. THE FÃO BRIDGE

The Fão bridge, illustrated in Fig. 1, is a road bridge over the Cávado river, located at the City of Esposende. This bridge is a metallic riveted bridge that was inaugurated on August 7th, 1892. The length of the bridge is 267 meters, divided into 8 spans with 33.5 meters each. The bridge is supported by 7 masonry piers with 15 meters deep foundations. The design of the bridge was due to Abel Maria Mota. The construction of the bridge was led by the French Engineer Reynau. It is very likely that this project was influenced by Gustave Eiffel that lived in the nearby city of Barcelos at that time. This bridge is considered the unique peace of iron architecture of the region of Esposende.

Figure 1. Fão bridge (left) and diagonals removed from the bridge (rigth).

3. BASIC MATERIAL CHARACTERIZATION

The Fão bridge suffered a rehabilitation that was completed in the summer of 2007. Seven original side diagonals of bridge were removed and replaced by new ones. The removed material was used in the current investigation, namely in the preparation of the experimental program. The main objective of the experimental program was the fatigue characterization of the original material of the bridge as well as the fatigue characterization of riveted and bolted connections made of original material. The riveted joints are the original joining process used in the bridge. However, the rehabilitation requires very often the use of bolts to replace the rivets, since riveting may be not practicable due to space limitations. The base material was also subjected to preliminary mechanical tests, namely monotonic tensile tests, according the NP 1000/02-1 standard (IPQ, 2006). A total of 22 specimens were tested under monotonic tensile loading. Figure 2 illustrates the stress-strain curves and Tab. 1 summarizes the strength properties, namely the 0.2% proof stress (σ_y), the tensile strength (σ_{UTS}), the elongation at fracture (A) and the reduction in cross section (Z).

Some specific tensile tests were instrumented with electrical strain gauges in order to allow the determination of the elastic properties of the material. A Young modulus equal to 198.70 GPa and a Poisson coefficient equal to 0.26 were measured from the tests.

Table 1. Results from the monotonic tensile tests.

	σ_y [MPa]	σ_{UTS} [MPa]	**A** [%]	**Z** [%]
Average Value	219.9	359.3	23.1	13.2
Standard Deviation	36.6	28.5	7.4	4.0

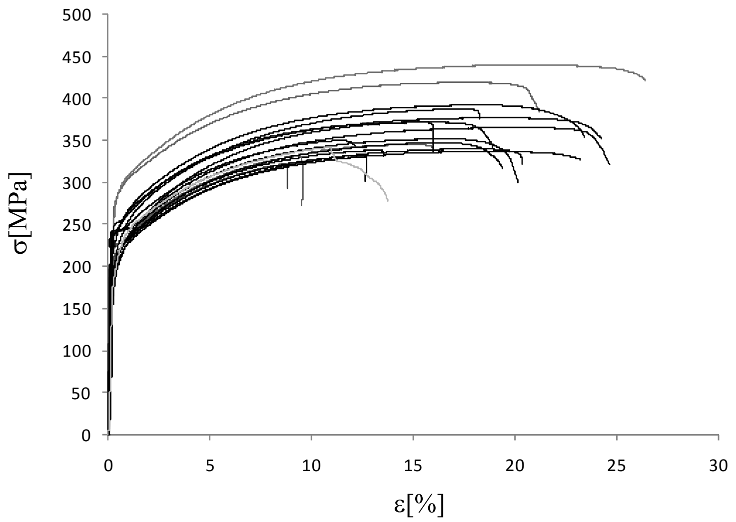


Figure 2. Monotonic stress-strain curves.

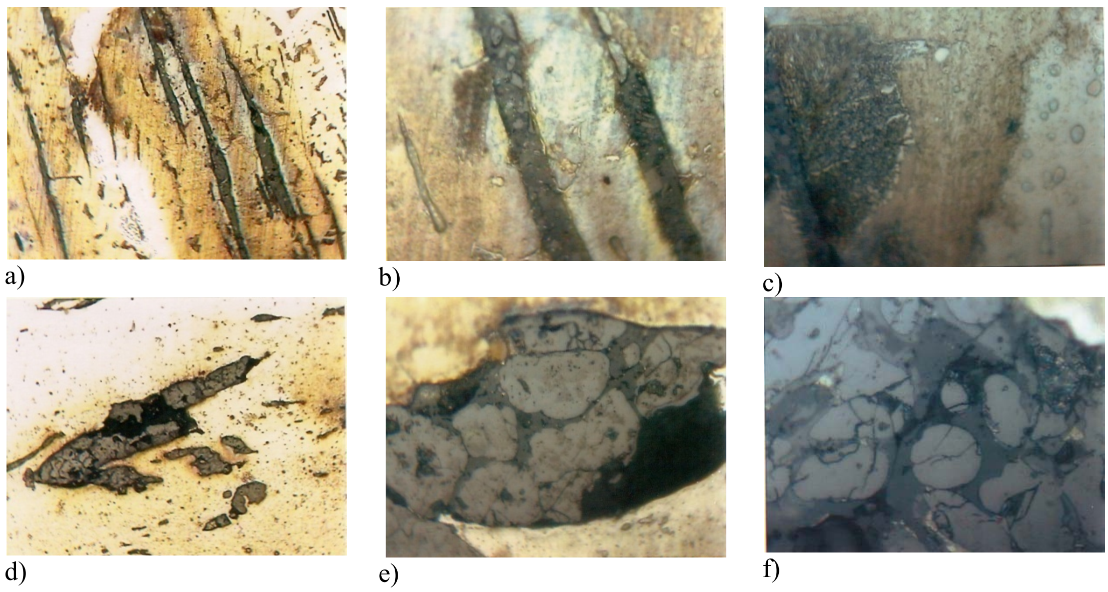


Figure 3. Optical observations of the material: a) and d) magnification of 100x, b) and e) magnification of 500x, c) and f) magnification of 1000x.

Table 2. Chemical composition of the material (weight,%)

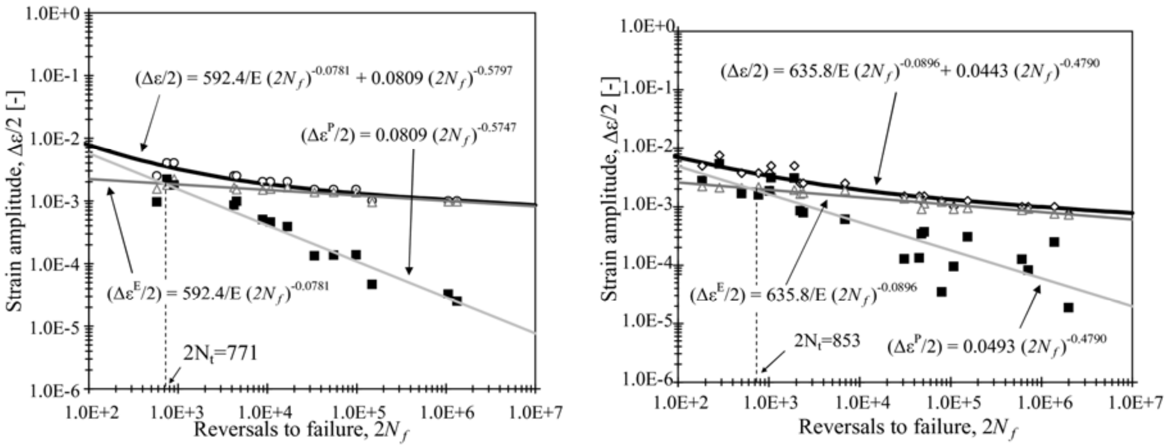
C	Si	Mn	P	S	Cr	Mo	Ni	Al	Cu	As	Zn	Fe
0.09	0.06	0.13	0.14	0.007	<0.01	0.013	0.03	0.008	0.13	0.04	0.005	99.3

Figure 3 shows some micrographs of the original material from the Fão bridge. A significant amount of inclusions/heterogeneities, typical of puddle irons, are observed. The puddle irons are precursors of modern construction steels. These heterogeneities may have a significant influence on fatigue behavior, constituting a major cause of scatter on experimental results. Table 2 shows the chemical composition of the material. The carbon and manganese content of the material is relative small, in comparison with current construction steels. The phosphorus content is significant.

Hardness measurements were performed. An average hardness of 61.1 HRC resulted from 25 measurements, with a standard deviation of 5.8 HRC. Furthermore, Charpy impact tests were performed according the NP10045-1 (IPQ, 1990) standard at the temperature T=21ºC. An average impact energy of 46.9J resulted from 15 tests carried out with specimens machined along the longitudinal direction. The standard deviation of 46.9J was obtained which corresponds to a very significant coefficient of variation (100%). This significant coefficient of variation observed on the Charpy impact energy is attributed to the high heterogeneities on the material microstructure.

4. STRAIN-LIFE FATIGUE DATA

Flat-sheet polished fatigue specimens with rectangular cross section were machined from the original diagonals removed from the Fão bridge. The dimensions of the specimens are specified according the ASTM E606 standard (ASTM, 1998). The specimens were machined according the rolling (longitudinal) direction of the members. Two test series were prepared with average cross sections of 5.4x7.3 mm^2 and 5.3x7.5 mm^2, which were tested under strain ratios equal to −1 (14 specimens) and 0 (18 specimens), respectively. All experiments were carried out in a close-loop servohydraulic machine, rated to 100 kN. The fatigue tests were conducted under constant strain amplitudes, at room-temperature in air and with a frequency adjusted to result an average strain rate of 0.008/s. The longitudinal strain was measured using a longitudinal extensometer (clip gauge) with limit displacements of ±2.5 mm and a base gauge length of 25 mm. Figure 4 illustrates the strain-life data for the two tested strain ratios. The experimental data is correlated using the Basquin (1910), Coffin-Manson (Coffin, 1954) (Manson, 1954) and Morrow (1965) equations. The analysis of the curves shows a very small number of transition reversals, which is a clear indication of a fatigue behavior dominated by the fatigue strength properties. Figure 5 compares the strain-life relations obtained for fully reversible and for repeated strain loading conditions. The strain ratio has a negligible effect on fatigue behavior, at least for the range of cycles to failure covered by the tests.



a) b)

Figure 4. Strain-life data of the material from the Fão bridge: a) strain ratio equal to -1, b) strain ratio equal to 0.

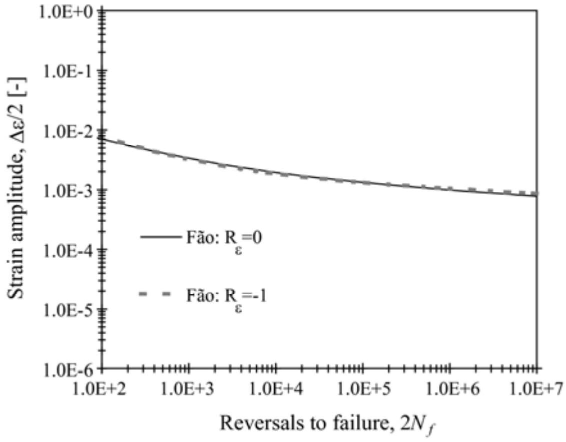


Figure 5. Comparison of the strain-life relations obtained for repeated and fully reversible strain control conditions.

5. FATIGUE CRACK PROPAGATION DATA

Fatigue crack growth tests were conducted according to the ASTM 647 standard (ASTM, 1999) in order to assess the fatigue crack propagation rates of the material from the Fão bridge. Compact tension specimens (CT geometry) were prepared with a width, W=50 mm, and a thickness, t=8 mm. All tests were performed in air, at room temperature, under a sinusoidal waveform with a maximum frequency of 20 Hz. The crack growth was measured on both faces of the specimens by visual inspection, using two travelling microscopes with accuracy of 0.001mm.

A total of 12 specimens from the Fão bridge were tested covering several stress ratios, namely R=0, R=0.25, R=0.5 and R=0.75. Figure 6 presents the fatigue crack propagation rates obtained for the Fao bridge. A slight increase of the crack propagation rate is observed with the increase in the stress ratio. The experimental crack propagation data was correlated using the power law between the crack propagation rate (da/dN) and the stress intensity factor range (ΔK), as proposed Paris and Erdogan (1963). Figure 6 also includes the constants of the Paris's law together with the respective determination coefficients. It is interesting to note that the exponent of the Paris's law, *m*, is higher than 3 (adopted value in design codes). Figure 7 presents a comparison of the crack growth rates between the material from the Fão bridge and materials from other ancient Portuguese bridges. It is clear a higher fatigue crack propagation rate for the material from the Fão bridge.

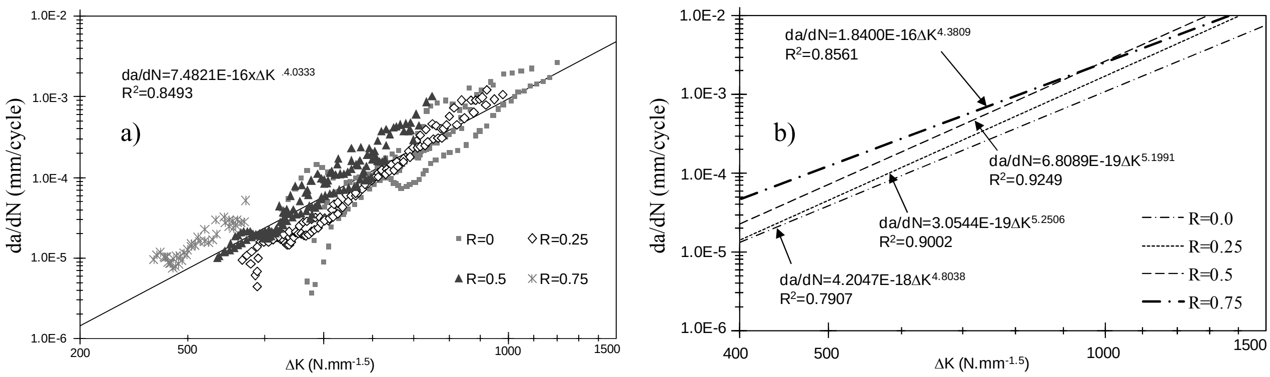


Figure 6. Fatigue crack propagation data obtained for the material from the Fão bridge: a) all experimental data; b) Paris's law for each stress R-ratio.

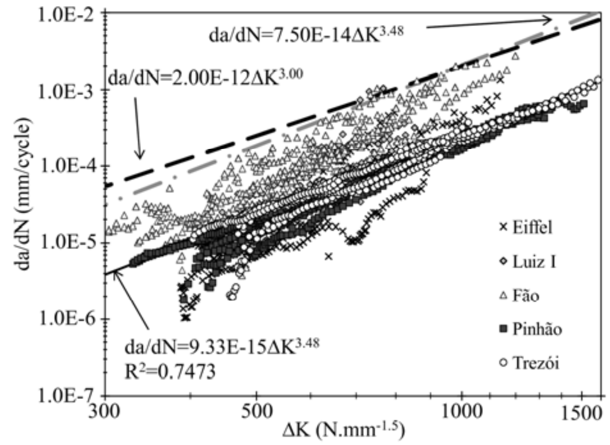
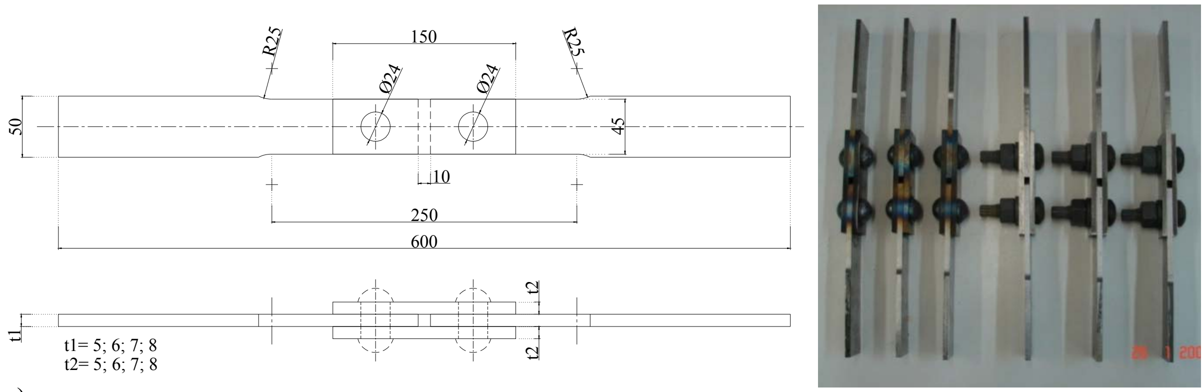


Figure 7. Comparison of the fatigue crack growth properties between the material from the Fão bridge and materials from other Portuguese bridges (Jesus *et al.*, 2010).

6. FATIGUE BEHAVIOUR OF RIVETED AND BOLTED CONNECTIONS

6.1. Constant amplitude data

The experimental program included fatigue tests of riveted and bolted connections built with original material from the Fão bridge, namely from the replaced side diagonals. The same rivets and bolts that were used in the last rehabilitation of the bridge were used to build the connections tested in the current experimental program. Figure 8a illustrates the geometry of the riveted joints; the bolted joints were obtained simply replacing the rivets by bolts. Figure 8b shows a photograph of some riveted and bolted joints prior testing. The required plates for the joints were machined from thicker members and new holes were drilled with a diameter of 24 mm. Bolts and rivets with a diameter of 22 mm were used in the joints. The clearance between rivets and holes were filled due to the expansion of the rivets. Three series of specimens were tested under constant amplitude loading: one series of riveted joints and two series of bolted joints. One series of bolted joints was tested with null preload on bolts; the other bolted series was tested with a preload on bolts generated by a torque of 70N.m, which corresponds approximately to a preload of 16kN or 52MPa in the bolt. All specimens were tested under load control (R=0.0), on a servo-hydraulic machine rated to 100kN. Test frequencies ranged between 2.5 and 12Hz.



a) b)

Figure 8. Riveted and bolted joint prepared with material from the Fão bridge: a) geometry of the riveted/bolted joint (dimensions in mm); b) photograph of riveted and bolted specimens.

Figure 9 presents the S-N data obtained for the riveted and bolted connections, with and without preload. The riveted connections show a fatigue strength that fits between the preloaded bolted connections and the non preloaded bolted connections. The riveted joints are characterized by some amount of clamping stresses. Furthermore, the rivet fits completely the holes due to expansion during application. These two effects justify the higher fatigue resistance of riveted joints with respect to the bolted joints without preload. The preloaded bolted joints exhibited significantly higher fatigue strength. On effect, high clamping stresses reduces the stress concentration around the holes of the plates due to the load transfer by friction on plate interfaces.

Figure 10 presents a comparison of the S-N data obtained for riveted joints from several bridges, namely from the Fão, Luiz I, Pinhão and Trezói bridges (Correia, 2008). The riveted joints from the Luiz I, Pinhão and Trezói bridges are single shear splices that were machined from riveted members, preserving the original rivets. Therefore, these riveted joints may present significant fatigue damage on rivet holes. Despite constructed using original material from the bridge, new rivet holes were machined, avoiding any initial flaws for riveted joints from the Fão bridge. Also, the riveted joints from the Fão bridge are symmetrical double shear connections, which eliminates bending stresses that appears in single shear splices. Finally, the riveting process used in the shear splices from the Fão bridge was conducted in laboratory, with controlled conditions, which is not the case for the riveted joints carried out one hundred years ago on construction site. The aforementioned arguments justify higher fatigue resistance of the riveted joints from the Fão bridge, despite the higher fatigue crack propagation rates, observed for this material. A comparison of the S-N data from the Fão bridge with the EC3 Class 71 S-N curve (CEN-TC 250, 2003) or AASHTO Class D S-N curve (AASHTO, 1994), shows that the code curves are conservative for high-cycle fatigue as would be expected. However, for low cycle fatigue ($N_f < 10\times10^5$ cycles) the code based curves are no longer conservative. The fatigue data from Luiz I and Pinhão bridges are distributed around the code based S-N curves, which may be justified by initial cracks on riveted joints, prior fatigue testing. The fatigue S-N data from the Trezói bridge is conservative with respect to the code based S-N curve, with one exception in the low-cycle fatigue region. Despite original rivets were tested for the Trezói bridge, the bridge has only half age of the other bridges and the removed member was a horizontal bracing with expected low significant stress levels during the bridge operation.

Figure 10 compares the S-N data obtained for the bolted joint from the Fão bridge, with and without preloaded bolts. A significant reduction in fatigue strength is observed, when the preload on bolts is removed. Figure 10 also shows the EC3 class 112 S-N curve, which recommended for double covered symmetrical joints with preloaded high strength bolts. The experimental data shows a very distinct slopes than the code based S-N curve. Also, the bolted joints, with null preload, shows very significant low fatigue strength when compared with the code based S-N curve. Some data points from the preloaded bolted joints are less conservative than code based S-N curves. The main reason should be the relative low preload applied to the bolts (52 MPa). The code base procedures should be based on preloads in the order of magnitude of at least half of the bolt tensile strength, which could be easily above 500MPa.

6.2. Variable amplitude data

Additional riveted specimens were tested under variable amplitude loading, namely under two-block loading for Low-High (L-H) and High-Low (H-L) stress ranges sequences and under spectrum loading. Concerning the two-block loading, a sequence of two constant blocks is applied until failure. The first block is applied for a predefined number of cycles followed by the second block which is applied until failure. A total of 8 specimens were tested, including one repetition for each test condition. Four specimens were tested for H-L sequences and four for L-H sequences. The stress range defining the higher stress range level was assumed equal to 355.47 MPa; the stress range defining the lower stress

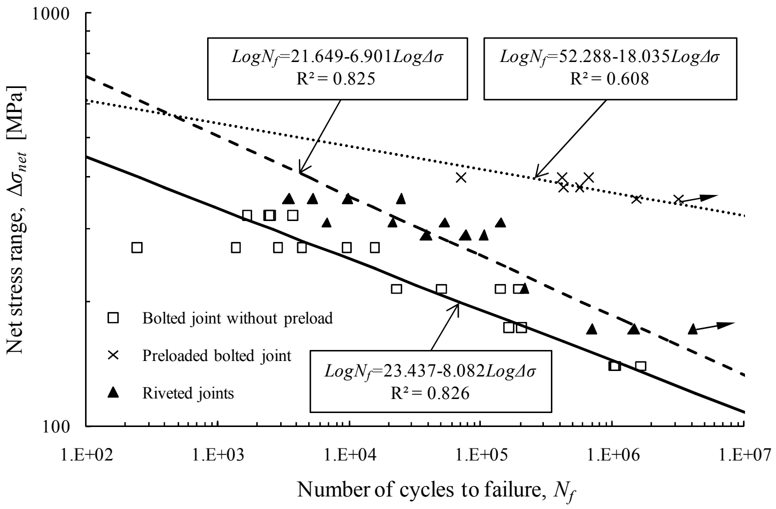


Figure 9. Comparison of constant amplitude S-N data between riveted and bolted joints.

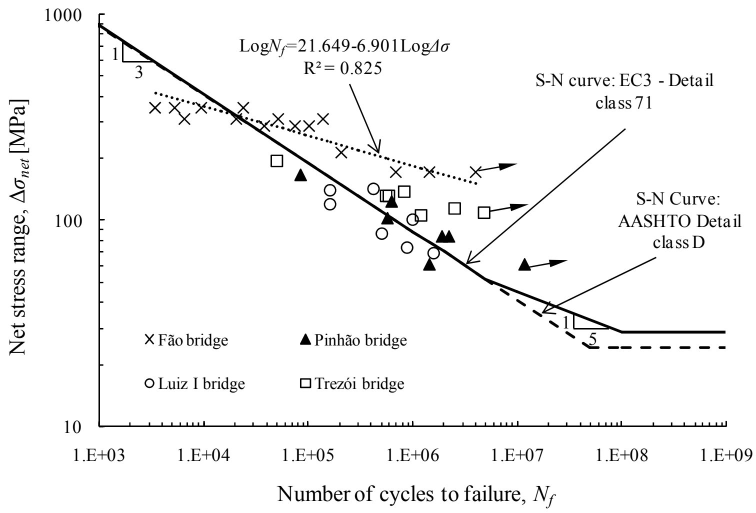


Figure 10. Comparison of S-N data from riveted joints from several Portuguese bridges.

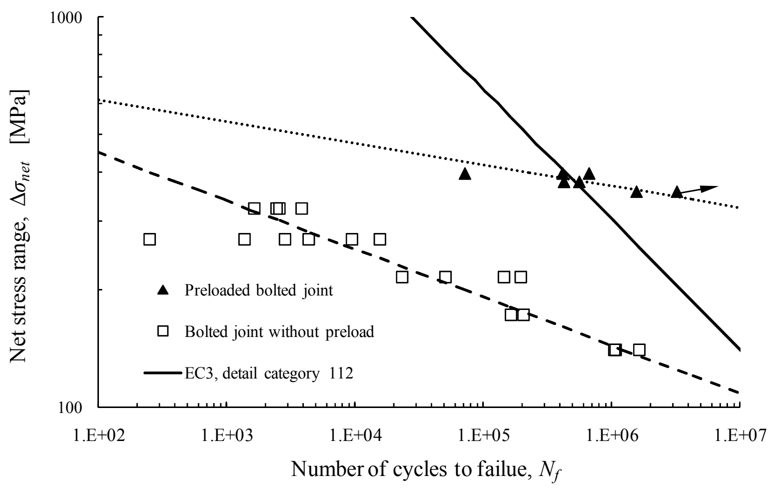


Figure 11. Comparison of S-N data of bolted joints from the Fão bridge: joints with and without preloaded bolts.

range was assumed equal to 290.84 MPa. The duration of the first blocks (n_H or n_L) was defined as a fraction of the average fatigue life determined with constant amplitude data, respectively for the high and low stress ranges (N_H or N_L). Half of the specimens were tested with a first block duration corresponding to 30% of the constant amplitude life and another half of the specimens were tested until 70% of the constant amplitude life. Figure 12a plots the fraction of life n_H/N_H versus against the fraction of life nL/NL. The sum of the two fractions of lives is always greater than unity, which is confirmed by the experimental data points always above the Miner's line. Therefore, the linear damage summation, as defined by the Miner's relation, may be considered conservative if used to assess the two-blocks loading data. Figure 12b compares the constant amplitude data obtained for the riveted joint with the variable two-blocks loading data. The latter data was transformed using the equivalent stress range concept. The equivalent stress range, when applied for the same duration of the variable amplitude data, produces the same fatigue damage according the Miner's relation. The variable amplitude data plotted in Fig. 12b fits always above the average S-N curve from the constant amplitude data, which confirms the conservatism of the Miner's rule.

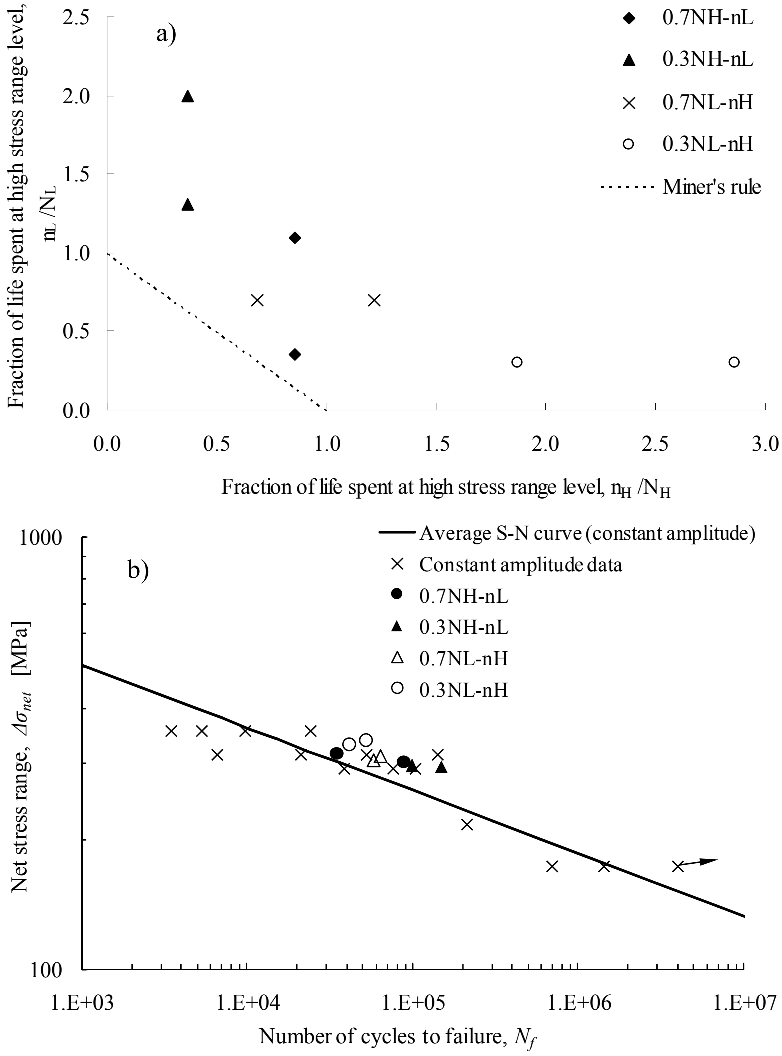


Figure 12. Variable amplitude data from two-blocks loading: a) fraction of lives at low and high stress levels; b) comparison of constant amplitude with variable amplitude data using the equivalent stress range concept.

The experimental program also included fatigue tests of riveted joints under spectrum block loading. Figure 13 shows three random stress spectra blocks. The first spectrum is composed of individual stress cycles with stress ranges in the interval of 170 and 360 MPa. The second spectrum is composed of individual stress cycles with stress ranges in the interval of 45 and 360MPa. The last spectrum shows a central region with higher stress concentration. In this stress spectrum, the stress ranges also varies between 170 and 360 MPa. Each block is formed by 100 cycles of null stress ratio. A total of 8 specimens were tested: 2 specimens under stress spectrum 1; 3 specimens under the stress spectrum 2; 3 specimens under the stress spectrum 3. Figure 13 shows the results of the fatigue tests of the riveted joints under spectrum loading. Figure 13a plots the number of blocks to failure against the number of blocks to failure computed using the Miner's relation. Two data points fall below the Miner's line, meaning unsafe predictions based on linear damage summation rule. However, in Fig. 13b the average experimental results are used instead of individual data points, resulting average safe predictions based on Mine's rule. Spectrum 2 resulted in higher number of blocks to failure than the other two spectra since it is composed of less damaging stress cycles.

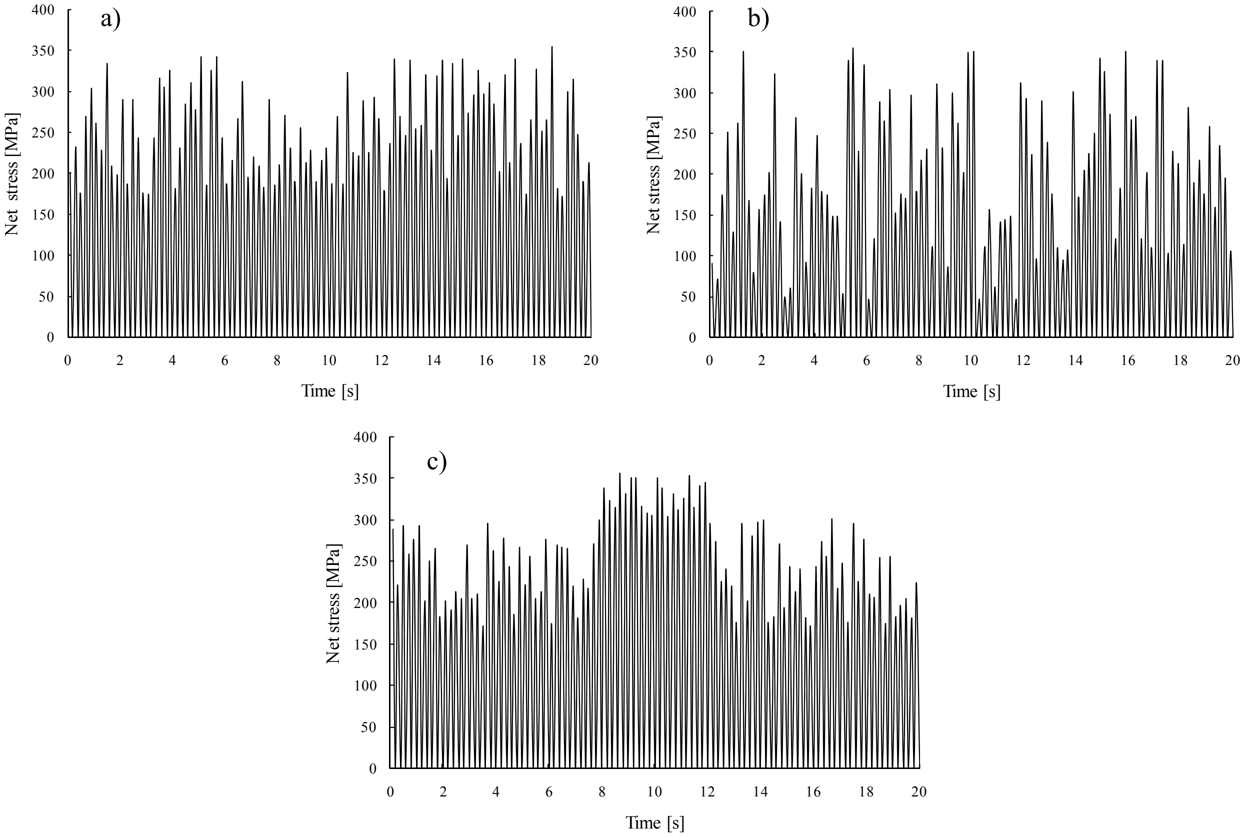


Figure 13. Spectrum block loading: a) spectrum 1; b) spectrum 2; c) spectrum 3.

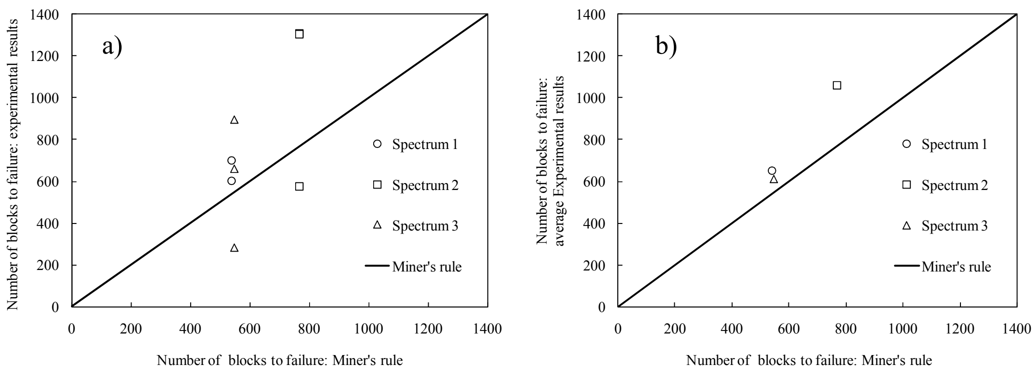


Figure 14. Spectrum block loading results – comparison with Miner's rule predictions: a) full results; b) average experimental results.

7. CONCLUSIONS

The results of a fatigue experimental program, based on material from an old riveted metallic bridge (Portuguese Fão bridge), was presented. Both plain material, riveted and bolted joints were tested. The following summary of conclusions is presented:

- The material is very likely a puddle iron, taking into account the high heterogeneity level, strength properties and age.
- The low-cycle fatigue results showed a very small number of transition reversals, which is a clear indication of a fatigue behavior dominated by the fatigue strength properties. The strain ratio has a negligible effect on fatigue behavior, at least for the range of cycles to failure covered by the tests.
- The crack propagation tests revealed a slight increase of the crack propagation rate with increasing stress ratio.

- It is clear a higher fatigue crack propagation rate for the material from the Fão bridge than other materials from other riveted metallic bridges.
- The fatigue tests of the riveted and bolted joints showed that riveted joints shows an intermediate fatigue resistance between the non preloaded bolted joints and the preloaded bolted joints. This is due to some clamping stress introduced by rivets.
- A significant effect of the preload on bolts on fatigue strength is verified.
- The riveted joints from the Fão bridge shows higher fatigue resistance than other riveted joints from other riveted metallic bridges., despite the higher fatigue crack propagation rates, observed for the material from the Fão bridge. A comparison of the S-N data from the Fão bridge with the EC3 Class 71 S-N curve or AASHTO Class D S-N curve, shows that the code curves are conservative for high-cycle fatigue as would be expected.
- The preloaded bolted joints exhibited moderate fatigue strength than class 110 of EC3, which is attributed to the low preload applied to the bolts.
- The Miner's rule yield safe predictions when applied to the data derived from the variable amplitude fatigue tests of riveted joints.

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