Available online at www.sciencedirect.com
ScienceDirect
Procedia Engineering 160 (2016) 77 – 84
Procedia Engineering
www.elsevier.com/locate/procedia

XVIII International Colloquium on Mechanical Fatigue of Metals (ICMFM XVIII)

Design S-N curves for old Portuguese and French riveted bridges connection based on statistical analyses

L. Gallegos Mayorga[a,b], S. Sire[a], J.A.F.O Correia[c,*], A. M. P. De Jesus[c], I. Valente[d], C. Rebelo[e], A. Fernández-Canteli[f], M. Ragueneau[b], B. Plu[b]

[a]*Universiy of Brest, Dupuy de Lôme Research Institute - IRDL CNRS FRE 3744, 29238 Brest, France.*
[b]*National Society of French Railways – SNCF, Civil Engineering Structures Department, 93574 La Plane Saint-Denis, France.*
[c]*University of Porto, INEGI, Engineering Faculty, Rua Dr. Roberto Frias, 4200-465 Porto, Portugal.*
[d]*ISISE, Department of Civil Engineering, University of Minho, Campos d'Azurém, 4800-058 Guimarães, Portugal.*
[e]*ISISE, Department of Civil Engineering, University of Coimbra, Rue Luis Reis Santos, Pólo II, 3030-788 Coimbra, Portugal.*
[f]*University of Oviedo, Department of Construction and Manufacturing Engineering, Campus de Viesques, 33203 Gijón, Spain.*

Abstract

Maintenance of ancient road and railway metallic bridges has become a major concern for governmental agencies in the past few decades. Indeed, since the construction of these structures, between the end of the 19th century and the beginning of the 20th century, traffic conditions have evolved, both in weight and frequency. In the purpose to assess the remaining life of old metallic bridges, some critical structural details have been identified and associated to S-N curves in order to be used in damage estimation (using Palmgren-Miner's rule for cumulative damage, for example). These constructional details are described by design rules of several European and North American standards, such as the Eurocode 3, BS 5400 and AASHTO standards. The particularity of ancient bridges is that hot riveted assemblies, commonly used for their construction, are not represented in most construction standards. Further experiences on the matter by numerous research teams have suggested detail category C71 from the Eurocode 3 as appropriate. In this paper, experimental data from double shear assemblies manufactures from three different metallic ancient bridges is used to identify, through a statistical analysis, the S-N curves that best fit this constructional detail. Portuguese and French puddled iron bridges were considered.

Peer-review under responsibility of the University of Oviedo
Keywords: Fatigue; S-N Curves; Statistical Analysis; Old Bridge; Riveted Connections.

* Corresponding author. Tel.: +351225082151; fax: +351225081584.
E-mail address: jacorreia@inegi.up.pt

Peer-review under responsibility of the University of Oviedo
doi:10.1016/j.proeng.2016.08.865

1. Introduction

The phenomenon known today as materials fatigue, most specifically in metals, has accompanied the railway industry since its beginnings. Indeed, its observation and study was (in no negligible part) encouraged by the incidents during the first decades of railway exploitation. The Meudon accident in 1842 is a tragic example of this.

Fatigue as a failure mechanism is observed in pieces (or structures) subjected to cyclic loadings. Railway infrastructure, particularly metallic bridges, is no exception. Indeed, this phenomenon is a cause of major concern for railway industry managers. This can be explained in part by the sustained growth in railway networks, both in traffic and infrastructure, across Europe for the past 150 years.

In this paper, we will focus exclusively in the fatigue behavior of metallic structures, most precisely in the ones built in Europe using the hot riveting technique (Portuguese and French bridges were considered for this study). To this purpose, fatigue tests were carried out for double shear riveted specimens. A statistical analysis of the obtained data is given and a comparison with the current literature and construction norms is proposed.

2. Context

The understating of fatigue behavior of a structure is accompanied with numerous difficulties. Indeed, this failure mechanism is known for its intrinsic scatter and sensitivity to numerous parameters (*e.g.* material, stress ratio R). In the case of riveted assemblies, commonly found in ancient railway bridges, we must also take into account other sources of uncertainty:

- The loading history of the structures (traffic archives) is not necessarily available for the entire period of existence of the bridge. The true loading history of the structure might be incomplete or unknown.
- The hypothesis considered in stress estimations models (used in fatigue damage calculations) might underestimate local stresses (*e.g.* parasite loadings in stringer to floor-beam connections) [1,2].
- Built during the second half of the 19th century, the majority of these metallic structures were made in puddled iron. This metal (no longer produced today at an industrial scale) is known for its scattered, anisotropic and brittle behavior. Indeed, given the circumstances of its fabrication during a period of large technological evolution in Europe, the finished product contained numerous non-metallic inclusions randomly distributed [3].
- In addition to the variability found in material properties for puddled irons, the geometrical configurations for this type of bridges is quite diverse. The second half of the 19th century was a period of innovation and technological exploration. Construction norms could change significantly in the span of a few years and no unique approach was considered in a European scale. The development of Eurocodes, for example, is rather recent (started in the 1970s).

The estimation of fatigue damage in ancient metallic structures is therefore a delicate and complex matter.

It must also be taken into account that no unique, or standard, experimental procedure exists to characterize the fatigue behavior of this type of assemblies. The databases found in the literature are therefore particularly difficult to compare to one another.

However, as concluded in multiple experimental campaigns the use of constructional detail C71 from de Eurocode 3 [4] seems to be an appropriate conservative criterion for fatigue resistance for riveted assemblies [5,6]. Nevertheless, if used indistinctively for any type of assembly, this will imply that all fatigue damage in riveted assemblies would be calculated without taking into account the geometrical configuration nor the type of applied loads. Moreover, fatigue curves proposed in the Eurocode 3 (conceived for the construction of new metallic structures, mostly welded) would be somehow applicable for riveted connections as well. This is strongly debatable as shown by Taras and Greiner in their extensive study on experimental results for riveted structures found in current literature [7].

In order to minimize the number of parameters in a given joint, fatigue testing data available from experimental campaigns carried out in the Engineering Faculty of the University of Porto and University of Trás-os-Montes and

Alto Douro in Portugal, and the University of Brest in France were analyzed. Three similar configurations of riveted assemblies were chosen (all of them double shear connections). Each geometry is described in section 4.1.1.

The experimental strategy will therefore be divided in two main stages: the material and the structure. First, the characterization of the mechanical properties of puddled irons found in the studied bridges is presented, and then, the fatigue behavior of the double shear constructional details is studied.

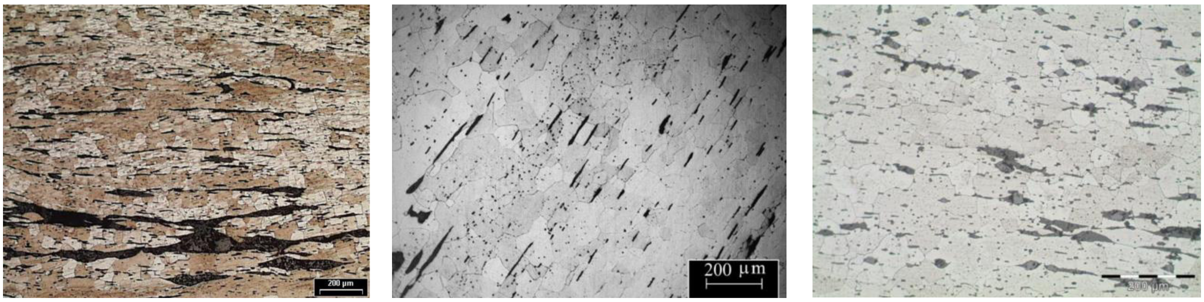
3. Material characterization

As mentioned in the precedent section, puddled iron is no longer produced at an industrial scale, therefore, it is necessary to recover the material for specimens from already existing structures. Three different bridges were used for this purpose: The Fão Bridge, built in Portugal in 1892, the Eiffel Bridge also built in Portugal in 1878 and the Bridge over the Adour River built in France in 1864. These three structures are shown in Figure 1.

(a) (b) (c)

Fig. 1. Presentation of the studied bridges; (a) Eiffel Bridge (Viana do Castelo, Portugal); (b) Fão Bridge (Esposende, Portugal); (c) Bridge over the Adour river (Bayonne, France).

In order to validate that the materials from these structures belong to the same family of metals (puddled irons), micrographic observations were performed. As shown in figure 2, the three metals showed elongated and randomly distributed non-metallic inclusions. This characteristic is a consequence of the puddling process which uses slags in order to decarburize cast irons.



(a) (b) (c)

Fig. 2. Micrographs of the studied puddled irons; (a) Eiffel Bridge (Viana do Castelo, Portugal); (b) Fão Bridge (Esposende, Portugal); (c) Bridge over the Adour river (Bayonne, France).

Moreover, tensile tests were also carried out. The mean values of the mechanical properties of the studied materials are shown the following table.

Table 1. Mechanical properties measured during monotonic tensile tests for the studied puddled irons.

Material	$R_{p0,2}$ (yield stress)	A (elongation)
Eiffel Bridge (Portugal)	292,4 MPa	8,1 %
Fão Bridge (Portugal)	219,9 MPa	23,1 %
Bridge over the Adour Bridge (France)	292,2 MPa	9 %

As shown in Table 1, the mechanical properties of the puddled iron from the Eiffel Bridge and the Bridge over the Adour River are very close. However, the puddled iron from the Fão Bridge shows a lower yield stress and a higher elongation at failure.

4. Constructional detail characterization

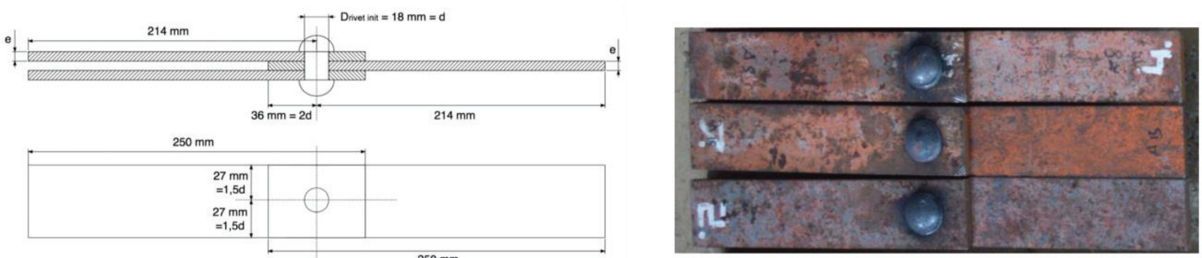
Once the main mechanical properties of the materials were obtained, and their classification as puddled irons confirmed, constructional detail specimens were studied.

4.1. Fatigue tests

4.1.1. Geometries considered

Numerous fatigue test campaigns might be found in the literature for riveted constructional details (see [5-17]). However, and as shown by Taras and Greiner in [7], the absence of a common experimental procedure results in a very rich, very diverse data base. The proposal of a common fatigue curve for all riveted assemblies seems neither plausible nor useful. It is after all possible to over-estimate the resistance of certain details and to under-estimate the resistance of others.

In order to compare riveted assemblies in similar loading configuration (double shear in our case), the following geometrical configurations were studied: singe riveted double lap joints (see figure 3, also characterized under monotonic loads in [18], single riveted double butt joints (see figure 4) and double riveted double butt joints (see figure 5).



(a) (b)

Fig. 3. Riveted specimens fabricated from puddled iron pieces recovered from the Bridge over the Adour river (France); (a) layout of the specimens; (b) some examples of the fabricated specimens.

(a) (b)

Fig. 4. Riveted specimens fabricated from puddled iron pieces from the Fão Bridge (Portugal) [10-13]; (a) layout of the specimens; (b) some examples of the fabricated specimens (plate surfaces were machined and holes drilled).

(a) (b)

Fig. 5. Riveted specimens from the Eiffel Bridge (Portugal) (original joints sliced from girders web) [10-13].

4.1.2. Results

The following figure shows the data obtained from classical fatigue testing for the assemblies shown in the previous section.

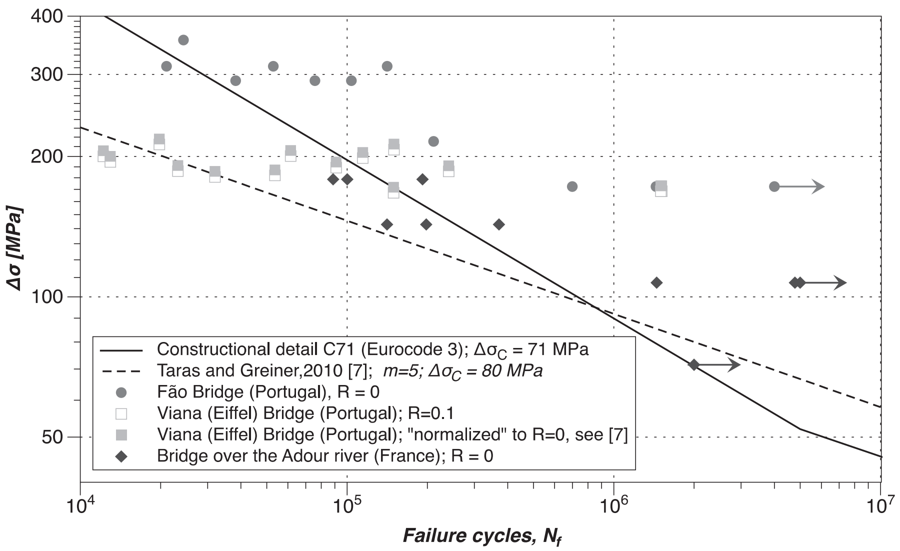


Fig. 6. Fatigue tests performed for double shear specimens fabricated from Portuguese and French ancient metallic bridges.

Several conclusions can be proposed from the figure 6:

- C71 constructional detail does not represent a conservative lower boundary for range stresses over 150 MPa.
- The fatigue curve proposed by Taras and Greiner ($\Delta\sigma_C$=80 MPa, m=5) seems to be more suitable, however it still under-estimates high cycle fatigue resistance.
- There is no unique fatigue behavior for the tested specimens.
- The re-manufactured specimens showed less scatter behavior that the original riveted assemblies. However, stress ranges are significantly different.

4.2. Statistical analysis

The results of the fatigue tests are generally presented in the form of S-N curves illustrating the relationship between a given applied stress range, $\Delta\sigma$, and the corresponding number of cycles to failure, N_f.

In order to represent this behavior, we adopted a linear model for the mean S-N curve, given by the following equation:

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

with the dependent variable Y, and independent X, defined as follows:

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

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 rewrite the S-N curves in the following alternative forms:

$$\log N_f = A + B \cdot \log \Delta\sigma$$

or (3)

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

This representation of the S-N curve, can also be written as follows:

$$\Delta\sigma^m \cdot N_f = C \tag{4}$$

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

$$C = 10^A; m = -B \tag{5}$$

Estimates for the parameters A and B are determined based on the following equations:

$$A = \bar{Y} - B \cdot \bar{X} \tag{6}$$

$$B = \frac{\sum_{i=1}^{k}(X_i - \bar{X})(Y_i - \bar{Y})}{\sum_{i=1}^{k}(X_i - \bar{X})^2} \tag{7}$$

where X and Y are the average values of the experimental values $X_i = \log \Delta\sigma_i$ and $Y_i = \log \Delta\sigma_i$, respectively, and k is the number of samples conducted to the rupture.

Also confidence bands were defined for the S-N curves. Rectilinear confidence bands were adopted since they are commonly found in literature particularly in design codes.

These rectilinear confidence bands were defined as follows:

$$Y = A + B \cdot X \pm \alpha \cdot S = (A \pm \alpha \cdot S) + B \cdot X \quad (8)$$

Where α is an integer number and S the standard deviation of the residuals. In this analysis $\alpha = 1 \; and \; 2$.

Figure 7 shows the mean S-N curve and the rectilinear confidence bands for fatigue tests performed for double shear specimens from Portuguese and French bridges. Based on statistical analysis, a design S-N (mean S-N curve $\pm 2S$) is obtained ($m = 3.9$ and $\Delta\sigma_c = 51.7 \; MPa$). In comparison with Taras and Greiner proposal [7], $\Delta\sigma_c$ value is somewhat higher while the parameter m (linked to the slope of the curve) is lower.

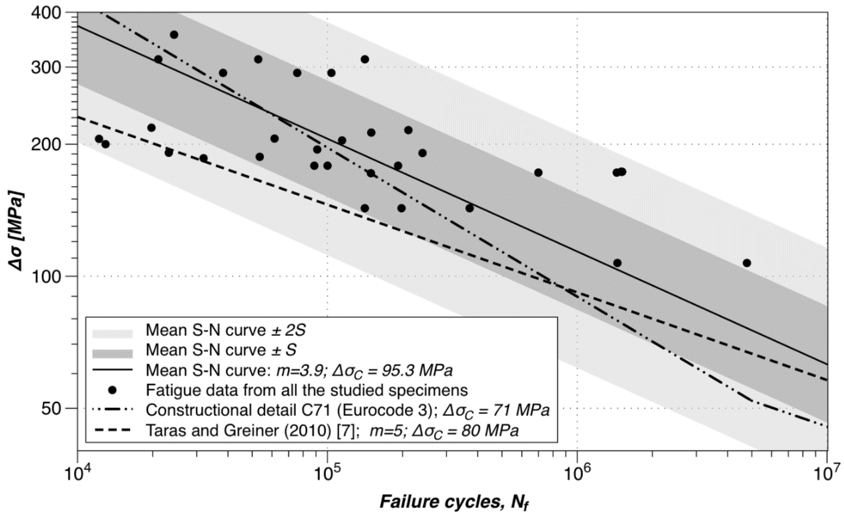


Fig. 7. Statistical analysis for fatigue tests performed for double shear riveted specimens from Portuguese and French bridges.

5. Conclusions

Fatigue of riveted railway bridges is today a major concern of railway network managers all across Europe. The evolution of traffic (speed, frequency and weight), as well as the long life service of many of these structures (over 100 years in many cases) makes their maintenance a delicate matter.

In this paper, double shear riveted assemblies fabricated from three existing ancient metallic bridges were submitted to constant stress amplitude fatigue tests.

Through a statistical analysis performed on the combined group of experimental tests (all of them double shear riveted specimens), a mean fatigue curve defined by $m = 3.9$ and $\Delta\sigma_c = 95.3MPa$ was obtained. Confidence bands of $\pm S$ (68%) and $\pm 2S$ (95%) were also calculated. For the 95% confidence band, the lower boundary is given by a fatigue curve defined by $m = 3.9$ and $\Delta\sigma_c = 51.7MPa$. The upper limit is given by $\Delta\sigma_c = 175.6 \; MPa$.

The results showed that current fatigue curves considered in design codes (such as the Eurocode 3) might not be well adapted to this type of constructional detail since the fatigue resistance seems to be underestimated in the high cycle fatigue domain of the curve. However, and since the data in this particular area of the obtained experimental curves (after 2×10^6cycles) is scarce, more tests are needed at lower stress. Indeed, most of ancient metallic riveted assemblies are subjected to stress range below $150MPa$.

Acknowledgements

The authors of this paper thank the National Society of French Railways and the SciTech - Science and Technology for Competitive and Sustainable Industries, R&D project NORTE-01-0145-FEDER-000022 cofinanced by Programa Operacional Regional do Norte ("NORTE2020"), through Fundo Europeu de Desenvolvimento Regional (FEDER) for their collaboration and support during this research works. The authors also acknowledge the Portuguese Science Foundation (FCT) for the financial support through the post-doctoral grant SFRH/BPD/107825/2015.

References

[1] Akesson, B. (1994). Fatigue life of riveted railway bridges. PhD Thesis, Chalmers University of Technology.

[2] Al-Emrani, M. (2002). Fatigue in riveted railway bridges: A study of the fatigue performance of riveted stringers and stringer to floor-beam connections. PhD Thesis, Chalmers University of Technology, Göteborg, Sweden.

[3] Gallegos Mayorga, L., Sire, S. and Plu, B. (2015). Understanding Fatigue Mechanisms in Ancient Metallic Railway Bridges : A Microscopic Study of Puddled Iron. Procedia Engineering, 114(0):422–429.

[4] Comité Européen de Normalisation (2005). Eurocode 3 EN 1993-1-9 : Calcul des structures en acier (fatigue).

[5] Brühwiler, E., Smith, I. F. C. and Hirt, M. A. (1990). Fatigue and Fracture of Riveted Bridge Members. Journal of Structural Engineering, 116(1):198–214.

[6] Di Battista, J., Adamson, D. E. J. and Kulak, G. (1998). Fatigue strength of riveted connections. Journal of Structural Engineering, 124(7):792–797.

[7] Taras, A. and Greiner, R. (2010). Development and Application of a Fatigue Class Cata- logue for Riveted Bridge Components. Structural engineering international, 1:91–103.

[8] De Jesus, A. M., Pinto, H., Fernández-Canteli, A., Castillo, E. and Correia, J. A. F. O. (2010). Fatigue assessment of a riveted shear splice based on a probabilistic model. International Journal of Fatigue, 32(2):453–462.

[9] De Jesus, A. M. P., Da Silva, A. L. L. and Correia, J. A. F. O. (2015). Fatigue of riveted and bolted joints made of puddle iron—An experimental approach. Journal of Constructional Steel Research, 104:81–90.

[10] Sanches, R.F., de Jesus, A.M.P., Correia, J.A.F.O., Silva, A.L.L., Fernandes, A.A. (2015). A Probabilistic Fatigue Approach for Riveted Joints Using Monte Carlo Simulation. Journal of Constructional Steel Research, Vol. 110, 149-162.

[11] de Jesus, A.M.P., Silva, A.L.L., Correia, J.A.F.O. (2014). Fatigue of riveted and bolted joints made of puddle iron - A numerical approach. Journal of Constructional Steel Research, Vol. 102, 164-177.

[12] de Jesus, A.M.P., da Silva, A.L.L., Figueiredo, M.V., Correia, J.A.F.O., Ribeiro, A.S., Fernandes, A.A. (2011). Strain-Life and Crack Propagation Fatigue Data From Several Portuguese Old Metallic Riveted Bridges. Engineering Failure Analysis, Issue I, Vol. 18, 148-163.

[13] Correia, J.A.F.O. (2014). An Integral Probabilistic Approach for Fatigue Lifetime Prediction of Mechanical and Structural Components. Ph.D. Thesis, University of Porto, Portugal (in English).

[14] Helmerich, R. (2012). Full scale fatigue testing of original truss members and connections. Bridge Maintenance, Safety, Management, Resilience and Sustainability, pages 1420– 1427.

[15] Kühn, B., Luckic, M., Nussbaumer, A., Günther, H. P., Helmerich, R., Herion, S., H., K. M., Walbridge, S., Androic, B., Dijkstra, O. and Buckak, O. (2008). Assessment of existing steel structures: Recommendations for estimation of remaining fatigue life. Sustainable Bridges.

[16] Larsson, T. (2009). Fatigue Assessment of Riveted Bridges. PhD Thesis, Lulea University of Technology.

[17] Pipinato, A., Pellegrino, C., Bursi, O. and Modena, C. (2009). High-cycle fatigue behavior of riveted connections for railway metal bridges. Journal of Constructional Steel Research, 65(12):2167–2175.

[18] Sire, S., Gallegos Mayorga, L. and Plu, B. (2015). Observation of Failure Scenarios in Riveted Assemblies: An Innovative Experimental Strategy. Procedia Engineering, 114(0):430–436.