ANALYSIS OF LOW-CYCLE FATIGUE DATA OF MATERIALS FROM SEVERAL PORTUGUESE RIVETED METALLIC BRIDGES

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ABSTRACT

Fatigue failures are a concern for metallic bridges due to the likelihood of metal to deteriorate under variable stresses. Residual life calculations of existing old metallic riveted 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 materials. This paper presents an analysis of low-cycle fatigue data from four representative ancient Portuguese riveted metallic bridges. This data can be used within the local approaches framework to assess the number of cycles to crack initiation. In particular, samples from the Luiz I, Eiffel, Fão and Trezói bridges are analysed. Strain-life relations are derived based on the classical deterministic Morrow proposition, as well as using a probabilistic strain-life regression model. Furthermore, the cyclic elastoplastic behaviour of the materials are characterized, namely the cyclic hardening/softening behaviours and the cyclic stress-strain curves of the materials.

KEY WORDS: Riveted bridges, puddled iron, construction steel, low-cycle fatigue, cyclic elastoplastic behaviour.

1. INTRODUCTION

The maintenance and safety of existing bridges is a major concern of governmental agencies. In particular, the safety of old riveted road and railway bridges fabricated and placed into service at the end of the 19th century/ beginning of 20th century deserve a particular attention, since they were designed taking into account traffic conditions, both in terms of vehicle gross weight and frequency, completely different from those observed nowadays. Also, the current design procedures were not yet fully developed or even did not exist in the 19th century and design engineers were not aware of some important phenomena, such as fatigue. Fatigue was only intensively studied in the 20th century. In order to assure high safety levels in old riveted metallic bridges, road and railway authorities have to invest heavily in their maintenance and retrofitting.

The approach widely used to assess the fatigue damage of riveted connections is the S-N approach, which is included in design codes of practice (ex: EC3 [1], AASTHO [2]). This approach is based on detail category S-N curves, which relates the total number of cycles to failure with the applied stress range. Alternatively, Fracture Mechanics has been applied to assess the residual fatigue life of damaged riveted connections [3]. This approach requires the knowledge of the initial defect, which may be assessed by inspection. In order to make Fracture Mechanics a truly design alternative to the S-N approach, it must be complemented by another approach for assessing crack initiation [3]. Local approaches, based on local or notch stresses or strains, are frequently used to assess the fatigue crack initiation [4].

This paper presents strain-life fatigue data obtained for original materials from four ancient Portuguese riveted metallic bridges, namely the Eiffel (Viana), Luiz I, Fão and Trezói bridges, using smooth specimens. Figure 1 gives a global overview of the four bridges. The Eiffel bridge, a piece of iron architecture, was designed by Eiffel and inaugurated on 30th of June, 1878. This bridge, crossing the Lima river between Darque and Viana, serves both road and railway traffic. The bridge has total length of 573 meters and a width of 6 meters, made of a continuous deck composed by nine spans. The Luiz I bridge links the cities of Porto and Gaia. It was designed by Eiffel and commissioned in 31st October 1886. The construction was initiated in the 1st December 1881. The bridge shows a double deck, supported by an arch with a radius of 45 meters. The lengths of upper and lower decks are respectively 391.25 and 174 meters. At present, the lower deck serves road traffic; the upper deck serves the metro. The Fão bridge is a road bridge that was designed by Abel Maria Mota, under the supervision of the engineer Reynau, at the end of 19th century. It was inaugurated at 7th of August 1892. This bridge is representative of the architecture of the iron. The bridge shows eight spans of 33.5 meters each. Finally, the Trezói bridge is a railway bridge that makes part of the Beira Alta railway line. It was inaugurated on 20th of August 1956. The deck is composed by three continuous spans, of 39, 48 and 39 meters, totalizing a bridge length of 126 meters. While the first three bridges were probability built using puddle or wrought iron, materials predecessors of modern steels, the Trezói bridge was built using modern construction steel.

Besides the basic characterization of the materials, the low-cycle fatigue and cyclic elastoplastic behaviour of the materials is presented. The low-cycle fatigue data of the materials is correlated using the deterministic relation proposed by Morrow [5]:

$$\frac{\Delta\varepsilon}{2}=\frac{\Delta\varepsilon^{E}}{2}+\frac{\Delta\varepsilon^{P}}{2}=\frac{\sigma_f^{'}}{E}(2N_f)^{b}+\varepsilon_f^{'}(2N_f)^{c} \qquad (1)$$

where: $\Delta\varepsilon$, $\Delta\varepsilon^{E}$ and $\Delta\varepsilon^{P}$ are, respectively, the total, elastic and plastic strain ranges; $\sigma_f^{'}$ and b are the fatigue strength coefficient and exponent; $\varepsilon_f^{'}$ and c are de fatigue ductility coefficient and exponent; $2N_f$ is the number of reversals and E is the Young modulus.
Furthermore, a Weibull-based probabilistic relation, as proposed by Castillo and Fernández-Canteli [6] is adopted to describe the strain-life data:

$$N_f=\exp\left[B+\frac{\lambda+\delta\left(-\log(1-p)\right)^{1/\beta}}{\log(\varepsilon_a)-C}\right] \qquad (2)$$

The previous equation defines strain-life curves associated to a certain probability of failure, p (percentile curves). Specifying the probability of failure, p, and the strain amplitude, ε_a, the number of cycles to failure, N_f, may be assessed. Therefore, Equation (2) defines the complete P-ε-N field. In Equation (2) B, C, λ, δ and β are constants to be evaluated for each material. Reference [6] gives the details concerning the identification of the constants of this model.

The stabilized cyclic elastoplastic behaviour of the materials is correlated using the well known Ramberg-Osgood relation [7]:

$$\frac{\Delta\varepsilon}{2}=\frac{\Delta\sigma}{2E}+\left(\frac{\Delta\sigma}{2K'}\right)^{1/n'} \qquad (3)$$

where: $\Delta\varepsilon$ and $\Delta\sigma$ are the strain and stress ranges; K' and n' are the cyclic strain hardening coefficient and exponent and E is the Young modulus.

Figure 1: Investigated bridges: a) Eiffel bridge; b) Luiz I bridge; c) Fão bridge and d) Trezói bridge.

2. EXPERIMENTAL DETAILS

This paper reports low-cycle fatigue data from four materials, derived from strain-controlled fatigue tests of smooth specimens, machined from original members that were removed and replaced in the four referred bridges. Flat specimens, with rectangular cross section, were manufactured in accordance with the ASTM E606 standard [8]. Specimens were manufactured from the Fão and Trezói bridges with a nominal cross section of 7.5x8 mm^2; specimens from the Eiffel and Luiz I bridges were prepared with a nominal cross section of 5x6 mm^2. The surfaces of the specimens in the gauge length were polished. All experiments were carried out in a close-loop servo hydraulic machine, rated to 100 KN. The fatigue tests were conducted under fully reversible 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 with a base length equal to 25 mm and limit displacements of ±2.5 mm.

Additionally to the fatigue tests, monotonic tensile tests were carried out according the NP 10002-1 standard [9], using round specimens. Also, chemical analyses of the materials were carried out.

3. BASIC CHARACTERIZATION OF THE MATERIALS

Table 1 shows the average tensile properties of the materials, namely the yield strength, tensile strength, elongation at fracture and the reduction in the cross section. The analysis of the results shows that the material from the Trezói bridge – similar to modern steels - shows simultaneously the highest strength and ductility values. The other materials, which are very likely puddle/wrought iron, exhibit lower strength and ductility properties. The material from the Fão shows the lowest yield strength; the material from the Eiffel bridge shows very low ductility.

Table 1. Tensile properties of the steels.

Material	Yield strength (MPa)	Tensile strength (MPa)	Elongation at fracture (%)	Reduction in cross section (%)
Eiffel	292	342	8	12
Luiz I	297	397	21	27
Fão	220	359	23	13
Trezói	401	464	23	66

Table 2. Chemical composition (weight, %).

Material	C	Si	P	Mn
Eiffel	0.03	0.15	0.49	0.02
Luiz I	0.42	2.09	>0.15	0.34
Fão	0.09	0.06	0.14	0.13
Trezói	0.06	0.03	0.02	0.34

Table 2 summarizes the average values of the chemical composition, which were assessed using the spark emission spectrometry technique. The material from the Trezói bridge exhibits the lowest contents of silicon and phosphorus, which is consistent with the age of the material. The Trezói material is a ferritic steel (structural steel), since it has a very small amount of carbon. The materials from the centenary bridges show variable chemical composition, due to the typical heterogeneous microstructures of these materials. The material from the Luiz I bridge shows a very high carbon and silicon content. The material from the Eiffel bridge exhibits a very high phosphorus content.

4. STRAIN-LIFE DATA

4.1. Deterministic assessment

This section shows the main results from the strain-controled fatigue tests. In particular, the experimental strain-life data was correlated using Equation (1) – the Morrow's relation. Table 1 summaraizes the constants of the Morrow's relation as well as the number of reversals of transition between the plastic strain governed behaviour to the elastic strain governed behaviour. Figure 2 compares the strain-life relations obtained for the materials from the four bridges. The analysis of the results shows that the material from the Eiffel, Luiz I and Fão bridges (the centenay brides) have a strain-life behaviour governed essentially by the elastic strain amplitude. The number of reversals of transition are very low when compared with the value obtained for the Trezói bridge – the youngest material. The elastic strain – life curves are very similair for the four materials. The major diferences were found in the plastic strain-life curves. The material from the Trezói bridge exhibits the higher fatigue resistance in the low cycle fatigue regimes (significantly higher fatigue ductility coeficient). The older materials – materials from Eiffel and Luiz I bridges - show the lower fatigue resistances.

Table 3. Strain-life data: Morrow's constants.

Material	σ'_f MPa	b	ε'_f -	c	$2N_t$
Eiffel	531.6	-0.0610	0.0362	-0.5380	222
Luiz I	469.6	-0.0540	0.0461	-0.6437	154
Fão	592.4	-0.0781	0.0809	-0.5747	771
Trezói	609.7	-0.0920	1.4733	-0.8137	5193

4.2. Probabilistic assessment

Since the fatigue data is usually characterized by significant scatter, the probabilistic models are preferable to correlate the experimental data. The probabilistic strain-life model defined by Equation (2) is used in this section to correlate the strain-life data obtained for the investigated materials. Figure 3 shows the P-ε-N field obtained for each material. Five percentil curves are represented, corresponding to the following probabilities of failure: p=1, 10, 50, 90 and 99%. Each graph includes the derived constants of the model. It is worth noting that this model does not requires the split of the total strain into elastic and plastic components. Figure 4 compares the P-ε-N fields between each material. Only the percentil curves corresponding to probabilities of failure p=1%, p=50% and p=99% are shown. The material from the Eiffel bridge shows the lowest P-ε-N field.

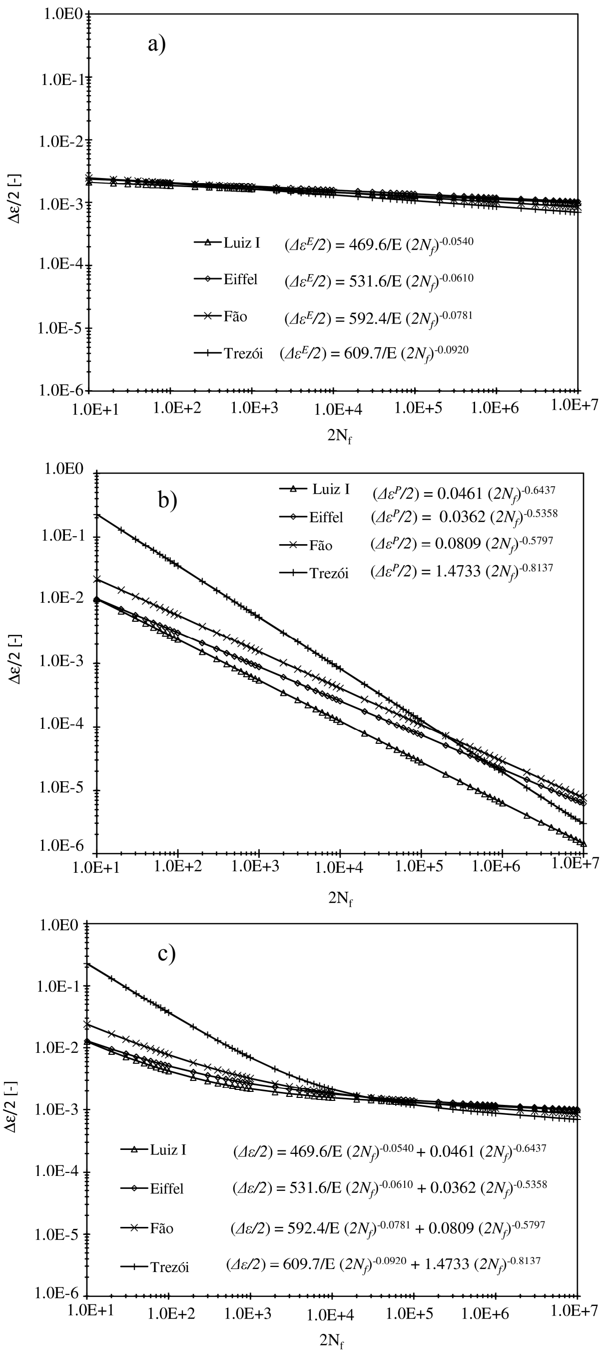

Figure 2: Comparison of strain-life relations: a) elastic behaviour; b) plastic behaviour; c) elastic plus plastic behaviour.

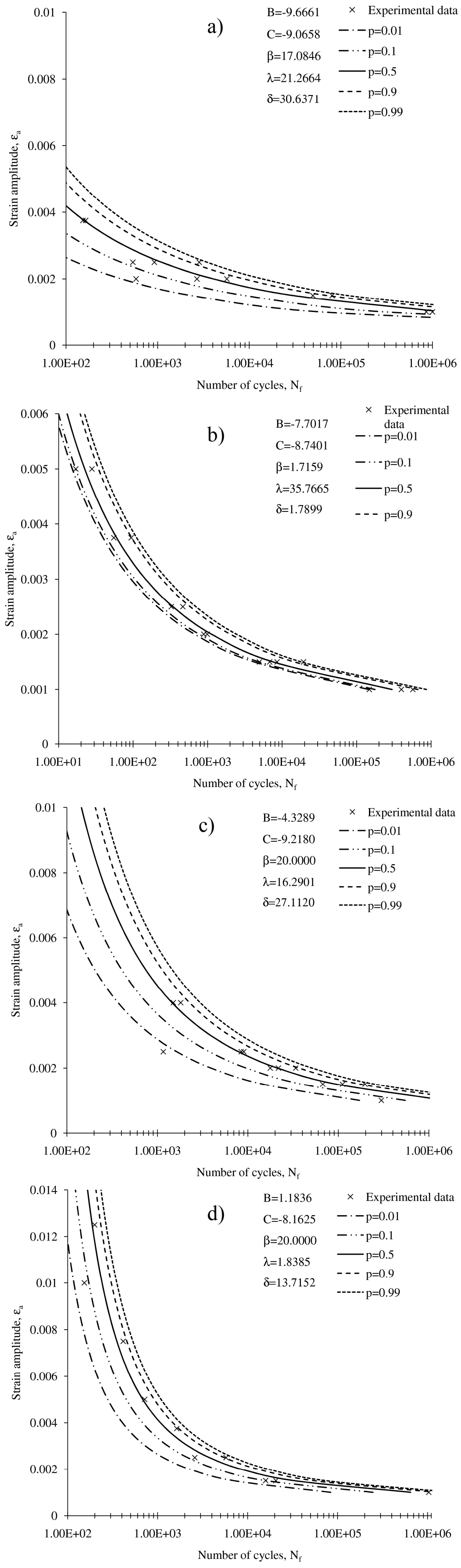

Figure 3: P-ε-N fields: a) Eiffel bridge; b) Luiz I bridge; c) Fão bridge and d) Trezói bridge.

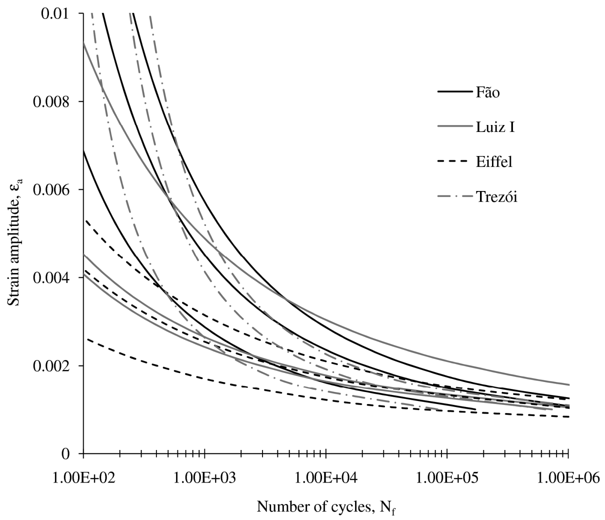

Figure 4: Comparison of the P-ε-N fields.

5. CICLIC ELASTOPLASTIC BEHAVIOUR

The strain-controlled fatigue tests, additionally to the strain-life data, they allow the evaluation of the cyclic plastic behaviour of the materials. Figure 5 shows the evolution of the stress amplitude with the number of cycles. The analysis of the results shows that materials from the centenary bridges show some hardening for higher strain ranges. The material from the Trezói bridge shows softening. For some tested series, this latter material exhibits stabilized behaviour. Therefore, a distinctive behaviour clearly exists between the centenary materials and the construction steel from the Trezói bridge.

Using the stabilized or pseudo-stabilized (half-life) behaviour of the materials, the respective cyclic curves were identified, resulting the constants presented in Table 4. The Young moduli were assessed using strain gauges for the materials from Luiz I and Fão bridges. For the other two materials, indirect estimates were obtained from the analysis of the hysteresis loops. Figure 6 shows the stabilized hysteresis loops as well as the cyclic curve and the cyclic curve scaled by a factor of two. Due to scatter in the cyclic behaviours, none of the materials shows a pure Masing behaviour. However, materials from Eiffel and Luiz I bridges shows a reasonable Masing behaviour. Due to scatter, the material from the Fão bridge shows two hysteresis loops that deviates significantly from the twice cyclic curve, making the material essentially a non-Masing material. Material from the Trezói bridge, which typically exhibits low scatter in its cyclic behaviour, have a consistent non-Masing behaviour.

6. CONCLUSIONS

Low-cycle fatigue data was derived for samples of materials from four riveted metallic bridges, namely the Eiffel, Luiz I, Fão and Trezói bridges. The following

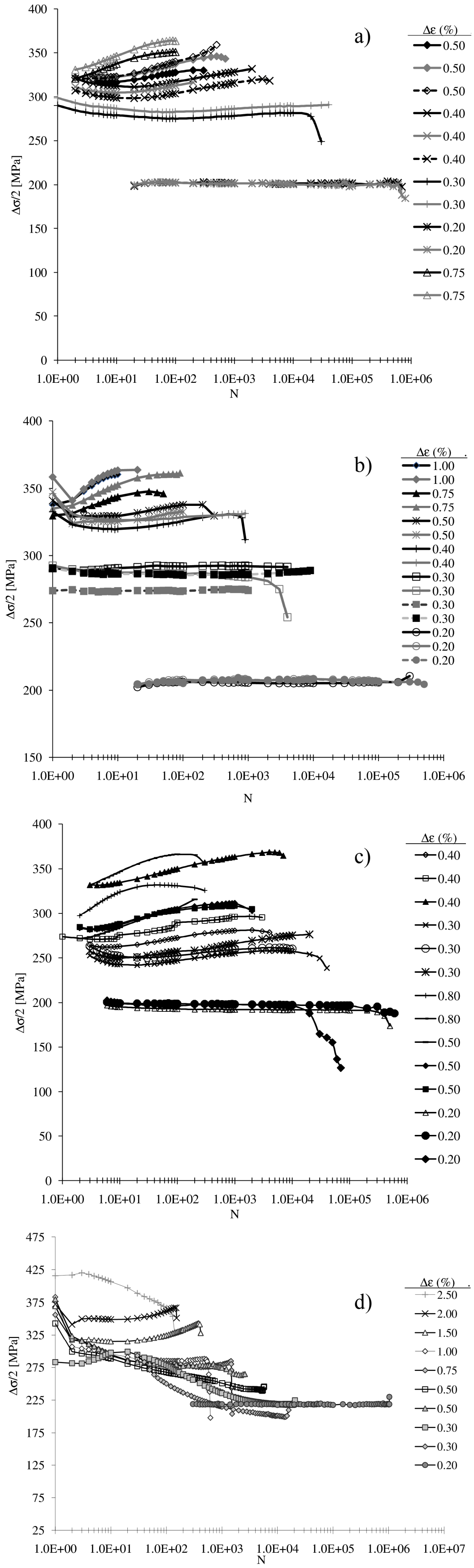

Figure 5: Cyclic behaviour of the materials: a) Eiffel bridge; b) Luiz I bridge; c) Fão bridge and d) Trezói bridge.

conclusions are formulated:

- The fatigue and cyclic elastoplastic behaviour observed for the centenary bridges are clearly distinct from the behaviour of the Trezói bridge. While the material from the Trezói bridge is a structural steel, materials from the centenary bridges are very likely puddle or wrought irons. These latter materials are characterized by higher scatter in properties due to characteristic microstructural heterogeneities.
- Materials from the centenary bridges show low-cycle fatigue behaviours with a very limited plastic behaviour, i.e., a very small number of transition reversals, $2N_t$.
- While the materials from the centenary bridges show trends of cyclic strain hardening, the material from the Trezói bridge exhibits cyclic strain softening. The older materials agree better with Masing behaviour than the material from the Trezói bridge.

Table 4. Cyclic elasto-plastic constants.

Material	E GPa	K' MPa	n'
Eiffel	193.1	458.1	0.115
Luiz I	192.7	604.2	0.083
Fão	198.7	852.1	0.139
Trezói	198.6	821.3	0.177

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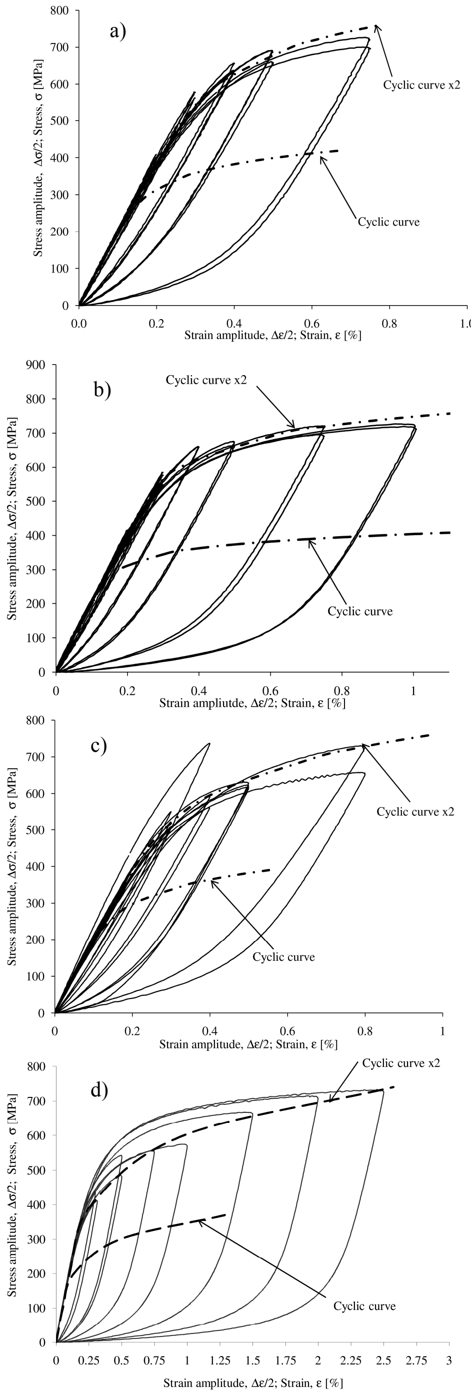

Figure 6: Stabilized hysteresis loops: a) Eiffel bridge; b) Luiz I bridge; c) Fão bridge and d) Trezói bridge.