STRUCTURAL DEGRADATION OF PUDDLE IRONS AND STEELS FROM OLD RIVETED METALLIC STRUCTURES

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Abstract. In repairing and strengthening operations of ancient riveted steel bridges is important to estimate and assess the structural degradation of the old metals in order to guaranty the structural safety. Long-time operated metallic materials (mild, rimmed low carbon steels <0.1%C, puddle irons) subjected to cyclic loading show tendency to the microstructural degradation processes. In this paper, the study of the structural degradation of puddle irons and steels from old riveted metallic bridges with long-term operation is proposed. The case-studies were performed for the materials from: ancient Portuguese steel bridges (Fão, Trezói, Pinhao, Viana and D. Luís I bridges) and Main Railway Station in Wrocław, Poland. Additionally, for the mentioned materials basic mechanical strength tests were performed (static tensile tests, hardness measurements). An analysis of the materials chemical composition and microstructures in several directions was performed.

1. Introduction

The maintenance and safety of existing bridges is a major concern of governmental agencies. In particular, the safety of old metallic riveted road and railway bridges fabricated and put into service at the end of the 19th century and beginning of 20th century deserve particular attention, since they were designed taking into account traffic conditions, both in terms of vehicle gross weight and frequency, completely different from those arising nowadays. 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 [1-7]. The maintenance of old steel structures, in full usefulness and reliability requires the use of precise diagnostic methods and evaluation of condition using procedures present in normative regulations for the modern structures [8-10]. The old structures steels present a tendency to microstructure degradation processes [11].

This paper aims at the characterization of the monotonic tensile strength properties characterization of different materials from a representative group of Portuguese old metallic riveted bridges, namely the Eiffel, Luiz I, Fão, Pinhão and Trezói bridges. Additionally, material fragments removed from the ''Wroclaw Glówny'' Main Railway Station in Wroclaw (1855– 1857) was also characterized. Besides the microstructures, the chemical composition and hardness measurements of the materials under consideration were also characterized. A review of data derived by the author and other data dispersed in the literature is gathered and compiled in this paper.

2. Monotonic tensile strength properties characterization

2.1 Ancient Portuguese steel bridges

Original members were removed and replaced by new ones. A diagonal 1500 mm in length and a bracing 1400 mm in length were removed from the Pinhão bridge. A diagonal member 1600 mm in length was removed from the Luiz I bridge. Also, a bracing 3000 mm in length was removed from the Trezói bridge. Regarding the Viana bridge, the highway Darque viaduct was removed and replaced by a new one. The required material for the experimental work was extracted from a viaduct girder. Several types of specimens were prepared using the material samples removed from the bridge.

All materials from the referred structures were characterized using monotonic tensile tests. According to the Portuguese NP 10002-1 Standard, round specimens machined from original members removed from the five bridges under investigation, exhibiting the dimensions listed in the Table 1 and Fig. 1, were subjected to monotonic increasing loading. Distinct diameters were selected since the materials samples extracted from the bridges showed distinct sizes. Besides the strength properties, the elastic properties of the materials were estimated, in particular the Young modulus and Poisson ratio.

The elastic properties, represented by the Young modulus, E, and Poisson ratio, μ, of the materials from the Luiz I and Fão bridges were computed directly from strain gauge measurements (see Fig. 2). The elastic properties of the materials from the Eiffel and Trezói bridges were computed indirectly from cyclic elastoplastic analysis. For the material of the Trezói bridge, the elastic properties were computed indirectly from analysis of the monotonic tensile tests. Table 2 summarizes the estimates of the monotonic tensile and elastic properties for all materials from old Portuguese metallic bridges.

The materials from the Pinhão and Trezói bridges have a monotonic tensile strength behavior similar with mild steels, on the other hand, the materials from the Eiffel, Luiz I and Fão are similar with puddled steel, as can be confirmed in Table 2.

Table 1: Cross-sections of the specimens used in the monotonic tensile tests of the materials

Bridge Material		Diameter mm	Cross-section mm^2
Eiffel	Viaduct	4	12.57
	Viaduct	5	19.63
	Viaduct	6	28.27
Luiz I	Diagonal	6	28.27
	Diagonal	8	50.27
Fão	Diagonal	6	28.27
Pinhão	Diagonal	5	19.63
	Bracing	8	50.27
Trezói	Bracing	8	50.27

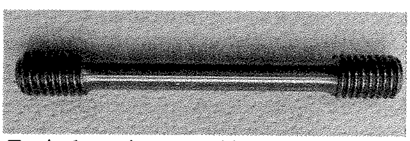


Fig. 1: Typical specimen used in monotonic tensile tests

Table 2: Monotonic tensile and elastic properties of the materials

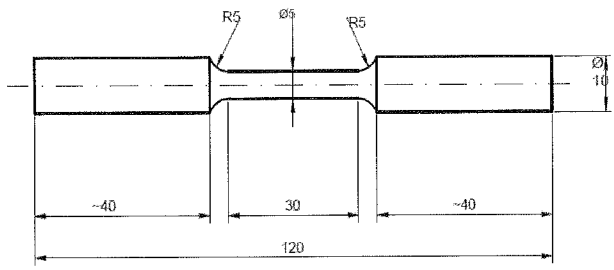
Bridge Material	f_u MPa	f_y MPa	A %	Z %	E GPa	ν -
Eiffel	341.75	292.38	8.14	11.60	193.10	0.30
Luiz I	396.60	302.60	21.20	27.18	192.70	0.26
Fão	359.33	219.90	23.13	13.06	198.70	0.26
Pinhão	361.06	305.89	33.19	70.97	210.68	–
Trezói	473.33	398.33	23.00	66.33	198.49	0.32
Puddled steel	330 – 400	220 – 280	< 25	–	170 – 220	–
Mild steel	340 – 450	250 – 300	23 – 25	–	200 – 220	–

2.2 Main railway station in Wrocław (Poland)

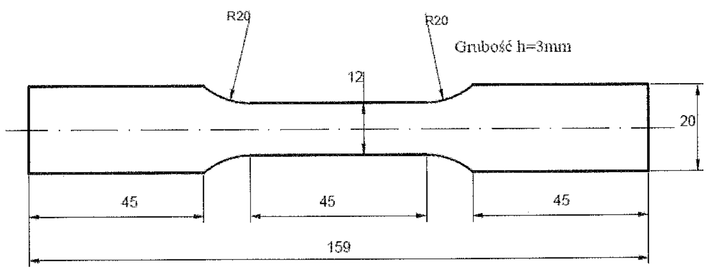
The material fragments removed from the ''Wroclaw Glówny'' Main Railway Station in Wroclaw (1855– 1857) were used to obtain the monotonic tensile strength. The samples C, K and W were extracted from the I220 – beam (B) and rail shaped beam (RS).

The specimens shown in Figure 2 a) and b) were used to perform the monotonic tensile strength tests. For the materials called by C and W was used the geometry presented in Figure 2a) and for K material was used the geometry presented in Figure 2b).

In Table 3 is presented the monotonic tensile and elastic properties of the materials C, K and W. The monotonic tensile strength obtained for the material W is similar with mild steel and for other materials (C and K) can be verified that is more similar with puddled steel.



a)



b)

Fig. 2: Typical specimen used in monotonic tensile tests

Table 3: Monotonic tensile and elastic properties of the materials

Material	f_u MPa	f_y MPa	A %	Z %	E GPa
C	282.00	245.00	6.00	5.60	193.00
K	325.00	273.00	4.80	6.80	172.00
W	418.00	255.00	30.20	64.50	193.00
Puddled steel	330 – 400	220 – 280	< 25	–	170 – 220
Mild steel	340 – 450	250 – 300	23 – 35	–	

3. Metallographic analysis and chemical composition of the materials

The metallographic analysis and chemical composition were carried out with materials extracted from the old Portuguese bridges and main railway station located in Wrocław, Poland. All materials present a homogeneous ferrite microstructure of regular grains, excluding the material from the Eiffel bridge that exhibits a ferrite microstructure with a high level of inclusions and different grain sizes. The chemical composition revealed a relative good homogeneity in the chemical composition of the materials.

3.1 Microscope observations

3.1.1 Ancient Portuguese steel bridges
Typical microstructures of the materials from the ancient Portuguese steel bridges are showed in Figures 3 to 7. In general, the materials are mainly composed of a ferrite microstructure. For some cases, namely the material from Pinhão and Trezói bridges, perlite is observed. These materials show a more homogeneous microstructure of regular grains than the other materials.

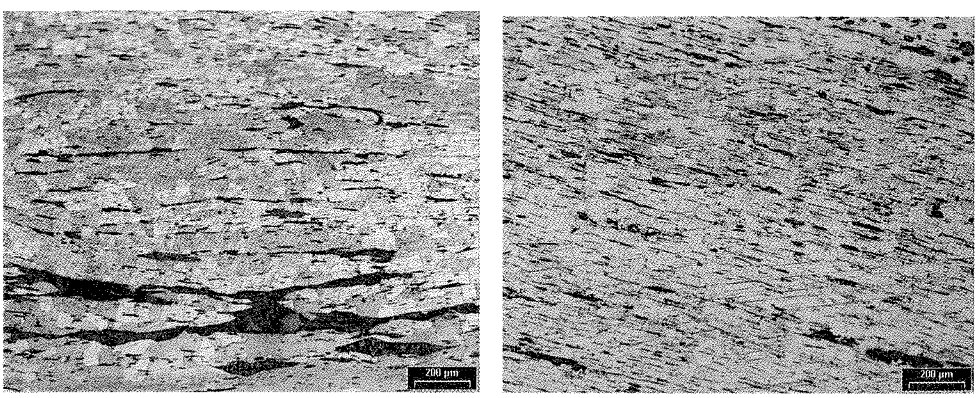
In Figures 3a) and 3b) can be observed the microstructure of the material from the Darque viaduct from Eiffel bridge. A ferrite microstructure with a high level of inclusions and different grain sizes is observed. For the material from the web of the longitudinal member of girder exhibits a high level of inclusions and greater grain sizes when compared with the material from the bracing member.

The material from Luiz I bridge is composed by ferrite, as expected due to the low carbon and manganese contents, with low volume fraction of perlite (see Figure 4).

Figure 5 shows microstructure of the original material from the Fão bridge. A significant amount of inclusions/heterogeneities are observed, which are typical of puddle irons, precursors of modern construction steels. The material shows a ferrite structure and inhomogeneous grain size.

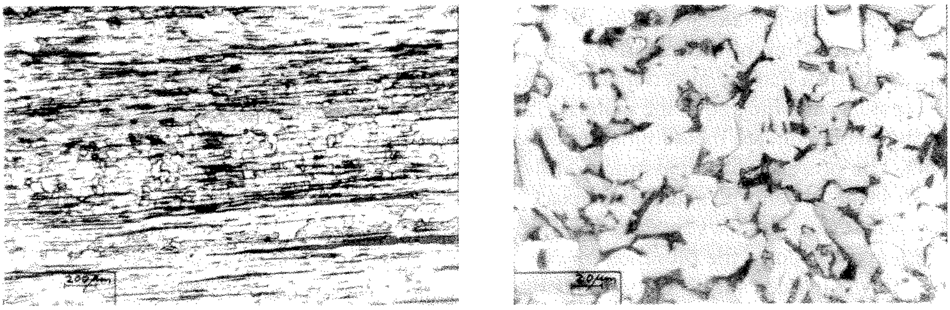
Figures 6a) and 6b) exhibit the microstructure of the diagonal and bracing members extracted from the Pinhão bridge, respectively, which is a ferrite microstructure with low content of perlite and some aligned inclusions.

Finally, the Figure 7 show the microstructure for the material from the Trezói bridge. This material presents essentially a ferrite microstructure, which is expectable due to the low carbon content. Figure 7a) illustrates the microstructure of the material in the parallel to the rolling direction composed of grains of ferrite, some lined up inclusions and small amounts of perlite.



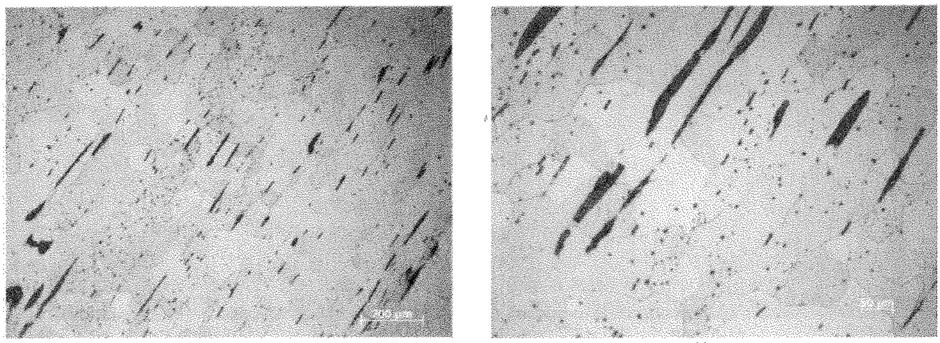
a) Web of the longitudinal member of girder b) Bracing member

Fig. 3: Microstructures of the material from the Eiffel bridge



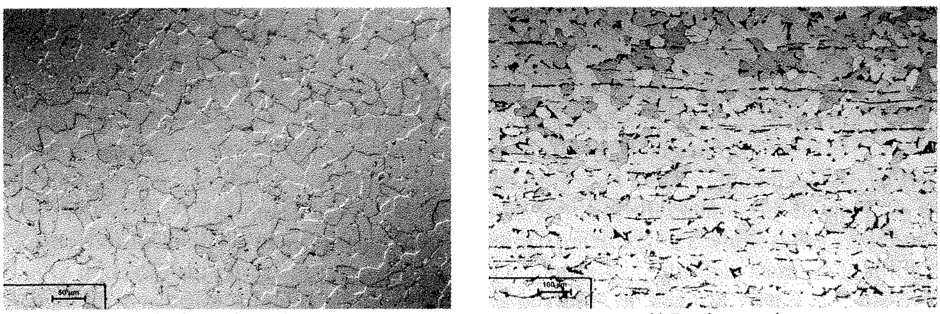
a) 200μm b) 20μm

Fig. 4: Microstructures of the material from the Luiz I bridge



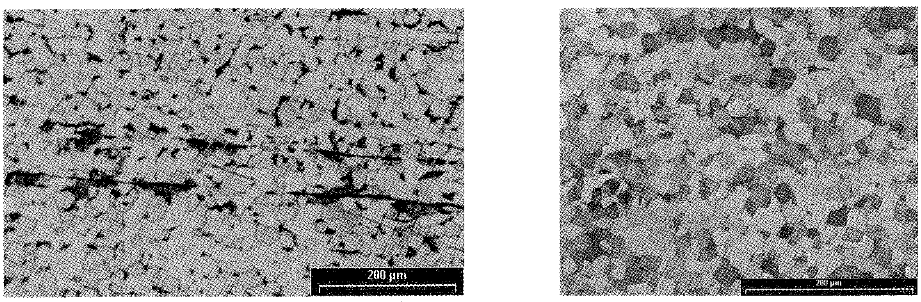
a) 200μm b) 50μm

Fig. 5: Microstructures of the material from the Fão bridge



a) Diagonal member b) Bracing member

Fig. 6: Microstructures of the material from the Pinhão bridge



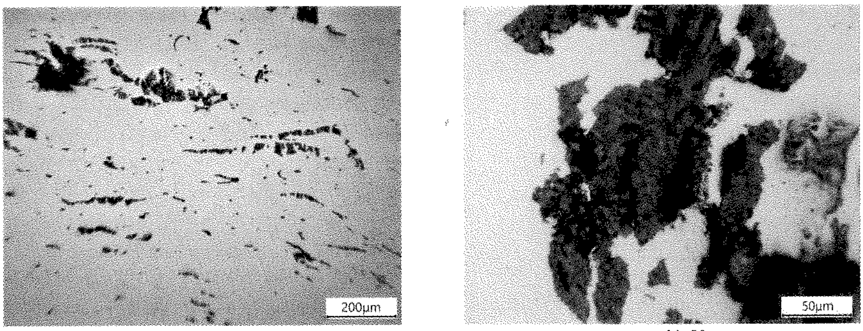
a) Parallel to the rolling direction (bracing member) b) transverse to the rolling direction (bracing member)

Fig. 7: Microstructures of the material from the Trezói bridge

3.1.2 Main railway station in Wrocław (Poland)

The microstructure of the material C showed in Figure 8 as well as the high content of phosphorus confirm that the material is an ancient puddled steel, produced in the second half of the 19th century, and the age of the material from which the material originates should be assessed. During the conducted metallographic observations significant presence of non-metallic inclusions. The presence of microstructural degradation processes (among others fragile carbides, nitrides and carbonitrides) has also been observed. In the context of analysis of the whole sample, their severity and severity are assessed as moderate.

Figure 8a) shows the presence of a large number of non-metallic inclusions of polyphase (probably sulphides and silicates) was observed in the cross-section of the sheet, staggered according to the direction of plastic processing. In the Figure 8b) is exhibited a typical multiphase non-metallic inclusions for sealing steel.



a) 200μm b) 50μm

Fig. 8: Material C from the main railway station in Wrocław (Poland)

The microstructure of the material K is presented in Figure 9. The microstructure and the high phosphorus content confirm that the material is a puddled steel, such as material C. In the course of conducted metallographic observations, significant presence of non-metallic inclusions was observed. Their volume ratio is extremely high - relatively higher than the material C. The presence of microstructural degradation processes has also been observed (as well as in C), which is well documented in Figure 9. Overall assessment of the cross section of the analysed laboratory sample should indicate a significant degree of microstructural degradation of this steel and in this context the material should be considered degenerate.

In Figure 8a) is showed a significant number of non-metallic multi-phase inclusions mainly in the form of silicates and sulphides arranged in strips in accordance with the direction of plastic processing. In Figure 8b) can be observed a structure of ferrite grains together with numerous fragile phase fragments in their interiors and significant contribution of non-metallic inclusions.

a) b)

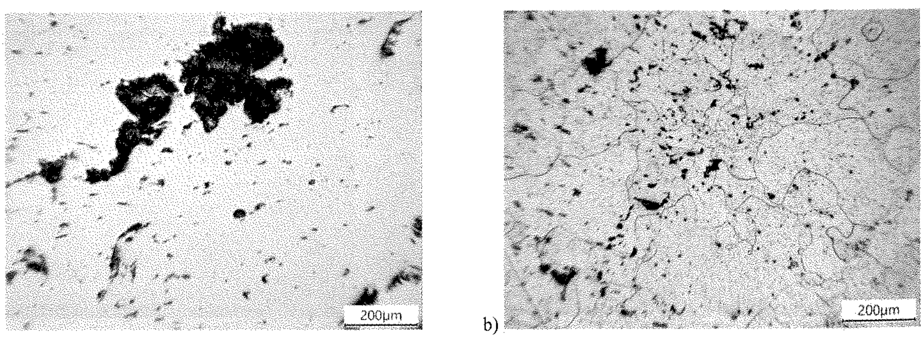
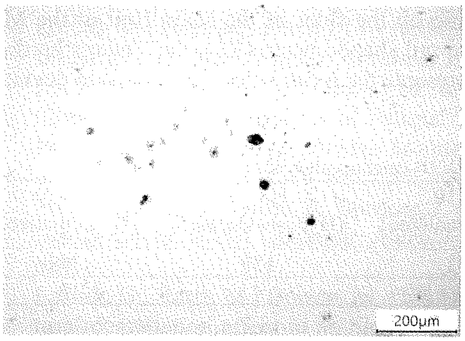


Fig. 9: Material K from the main railway station in Wrocław (Poland)

In Figure 10 is presented the microscopic observations of the material W. The microstructure of this steels in the undigested state revealed the presence of non-metallic inclusions occurring in the average amount of mainly sulphides arranged in the band according to the direction of plastic processing (Figure 10a)). In the context of the research results of C and K materials, this material is characterized by a significantly lower proportion of non-metallic inclusions. After etching, a fine-grained ferritic structure with a small amount of perlite was disclosed (Figure 10b)). The proportion of perlite in the microscopic images corresponds to the proportion of the chemical composition of the steel. No degradation was observed, and microscopic images of microstructures allowed to classify a given steel into a group of catchment steels or others - closer to modern low carbon steel.

a) 

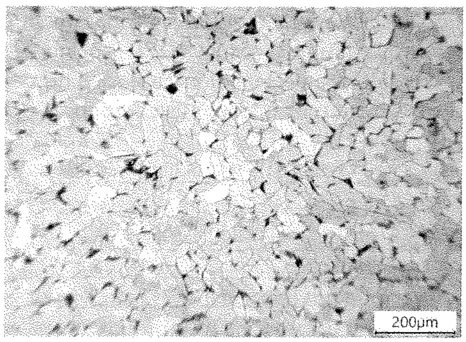
b) 

Fig. 10: Material W from the main railway station in Wrocław (Poland)

3.2 Chemical composition

Table 4 summarizes the chemical composition of some samples of materials from the old Portuguese steel bridges and main railway station in Wrocław (Poland), under investigation. The chemical compositions were assessed using the spark emission spectrometry technique.

In general, the chemical analyses revealed a relative 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 materials from the Eiffel, Luiz I and Fão bridges and C and K materials from the main railway station in Wrocław (Poland) are more similar with puddled steel while the materials from the Pinhão and Trezói bridges and W material from railway station are more similar with current mild steels.

Table 4: Chemical composition of the materials (wt.%)

Bridge/Station	Material	% *C*	% *Si*	% *Mn*	% *P*	% *S*
Eiffel (Portugal)	Darque Viaduct bridge*	0.23	0.39	1.78	> 0.15	> 0.15
		0.81	0.24	2.71	> 0.15	> 0.15
Luiz I (Portugal)	Diagonal	0.72	0.34	2.09	> 0.15	> 0.15
Fão (Portugal)	Diagonal	0.09	0.06	0.13	0.14	0.07
Pinhão (Portugal)	Diagonal	0.06	< 0.01	0.04	0.04	0.03
	Bracing	0.05	< 0.01	0.34	0.04	0.04
Trezói (Portugal)	Bracing	0.06	0.03	0.34	0.02	0.02
Main railway station in Wrocław (Poland)	C	0.01	0.12	0.01	0.28	0.012
	K	< 0.01	0.12	0.01	0.19	0.035
	W	0.12	0.08	0.49	0.017	0.055
Characteristic values	Puddled steel	Max. 0.08	–	0.4	0.6	0.04
	Mild steel	0.02 – 0.15	Variable	0.2 – 0.5	0.03 – 0.06	0.02 – 0.15

* determined with a portable emission spectrometry.

4. Hardness measurements

Vickers hardness were measured accordingly the procedures of the NP711-1 standard. Six samples of material from the Pinhão bridge were analysed, 3 from the diagonal and 3 from the bracing resulting, respectively, the average hardness of 108 HV40 and 116 HV40. For the Luiz I bridge, 3 samples of material from the diagonal were analysed resulting an average hardness of 158 HV50. Three samples of a bracing from the Trezói bridge were tested, exhibiting an average hardness of 136 HV40. In general, the measured hardness presented small scatter. For the Viana bridge no data is available [1-5].

Hardness measurements for the Fão bridge were also performed. An average hardness of 63.1 HV resulted from 22 measurements, with a standard deviation of 4.7 HV [12].
For the material extracted from basement ceiling on the floor of the Main Hall of the Main Railway Station Wrocław, I220 – beam (B) and rail shaped beam (RS), the Vickers hardness test results are presented in Table 5. This table presente the mean values and standard deviation for two materials under consideration.

Table 5: Vickers hardness test results HV10 (mean value of six measurements)

	HV10 (RS post-operated)	HV10 (RS_normalized)	HV10 (B_post-operated)	HV10 (B_normalized)
mean value	157	131	159	141
Std. dev.	24	4	4	8

5. Conclusions

Materials from the Eiffel, Luiz I, Fão and Pinhão bridges are very likely puddle iron due to their age, the high microstructural heterogeneities and the low ductility properties. The material from the Trezói bridge is a low carbon structural steel. In general, there is a significant correlation between the mechanical performance and the age of the materials.

For the materials extracted from the Main Hall of the Main Railway Station Wrocław is verified that the material called by W is more similar with current mild steels while the materials named by C and K are more similar with puddled steels.

The study of the structural degradation of the old steels is of great importance for the intervention and repairing operations in old steel structures.

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