



Fatigue strength of corroded bolted connection

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ABSTRACT. This note summarizes some recent investigation results on the behavior of corroded steel bolted joints under uniaxial fatigue loading. Fatigue test specimens, were made up using S355 structural steel plates joined together with preloaded M12 bolts of class 10.9 with a geometry that corresponds to the $\Delta\sigma = 112$ MPa EC3 detail category.

The accelerated corrosion process was accomplished using an electrolyte consisting of an aqueous 5% NaCl solution whereby the specimens were treated. In particular, during the corrosion process specimens were repeatedly immersed for 2 minutes in the electrolyte and then removed keeping them 60 minutes long in free air at 35 °C.

An atmospheric corrosion in marine-industrial environment is well-represented through corrosion test. Fatigue loading tests and surface morphology measurement of uncorroded and corroded specimens were performed and the results were compared.

KEYWORDS. Fatigue strength; Corrosion; Bolted connections; Steel bridge.



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INTRODUCTION

In civil engineering, the structures most affected by mechanical fatigue are steel railway bridges that are subjected to a large number of traffic load cycles during their service life. In this type of structures, the most critical elements from the point of view of fatigue strength are the connections between the members; the irregularity of the connections geometry is one of the factors that affect the fatigue life of these structural elements. The fatigue life assessment of structural details is widely studied in the recent years [1, 2].

Another important factor of great influence on the fatigue strength of bridge structure is the material degradation [3-5]. In particular, corrosion phenomenon is perhaps one of the problems that most affects the integrity of metal structures in all countries. In this context, understanding the corrosion effects on the fatigue life of steel structures is becoming a topic on which research is investing.

Many studies were conducted on the corrosion and fatigue phenomena, however there are few publications regarding their interaction in steel bridges. Researches are carried out in fields different than the civil sector, e.g. structures working in the



seawater like offshore structures and pipelines [6]. Typically to study the interaction of corrosion and fatigue, it is used a model of pre-corroded samples and then the cyclic loads are applied to them. There are few cases where electrochemical and mechanical stresses act at the same time. Fatigue crack initiation and growth from artificial pits was modelled by Rokhlin et al. [7]. The authors find good agreement with the experimental data: they described fatigue crack initiation and growth from pits and obtained the relationship between reduction of fatigue life and artificial pits size. Other studies focused the attention on the pits shape characterization [8, 9]. Shan-hua Xu et al. [10] estimated the effects of corrosion pits on the fatigue life of steel plates. They defined three different pit shapes and concluded that corrosion causes a significant decrease in fatigue life as the pit depth increases and the surface roughness is a crucial factor to assess the fatigue strength. They also found that the start of the crack could trigger from a single pit or by the interaction and coalescence of multiple pits. Similar studies were conducted also by Acuna et al. [11] and by Kondo et al. [12]. Some researches were proposed as regards the fatigue corrosion interactions in steel bridges. The proposed approaches for corrosion fatigue life assessment are based on the use of S-N curves and cumulative damage laws. Sharifi et al. [13] studied the notch factor in steel bridges due to corrosion and proposed two functions which could represent fatigue notch factor in terms of average corrosion penetration and time of weathering exposure to compare it with the one obtained for various classes of structural detail as classified in BS 5400. They concluded that the fatigue notch factor could well quantified the effect of corrosion on the fatigue life of steel bridge members.

Aim of this paper is to investigate the influence of the corrosive phenomenon on the fatigue strength of a friction type joint made of high strength preloaded bolts (M12 class 10.9). To work out these analyses the fatigue behavior of virgin bolted joints (without any degradation effect) and the behavior of the same joints, (having the same geometric and material properties) after corrosion effects were compared.

To make so, an accelerated corrosion process was carried out on a lot of n. 10 specimens. At the end of the procedure, it was possible to perform fatigue tests ($R=0$) to plot the S-N fatigue curve of uncorroded and corroded specimens.

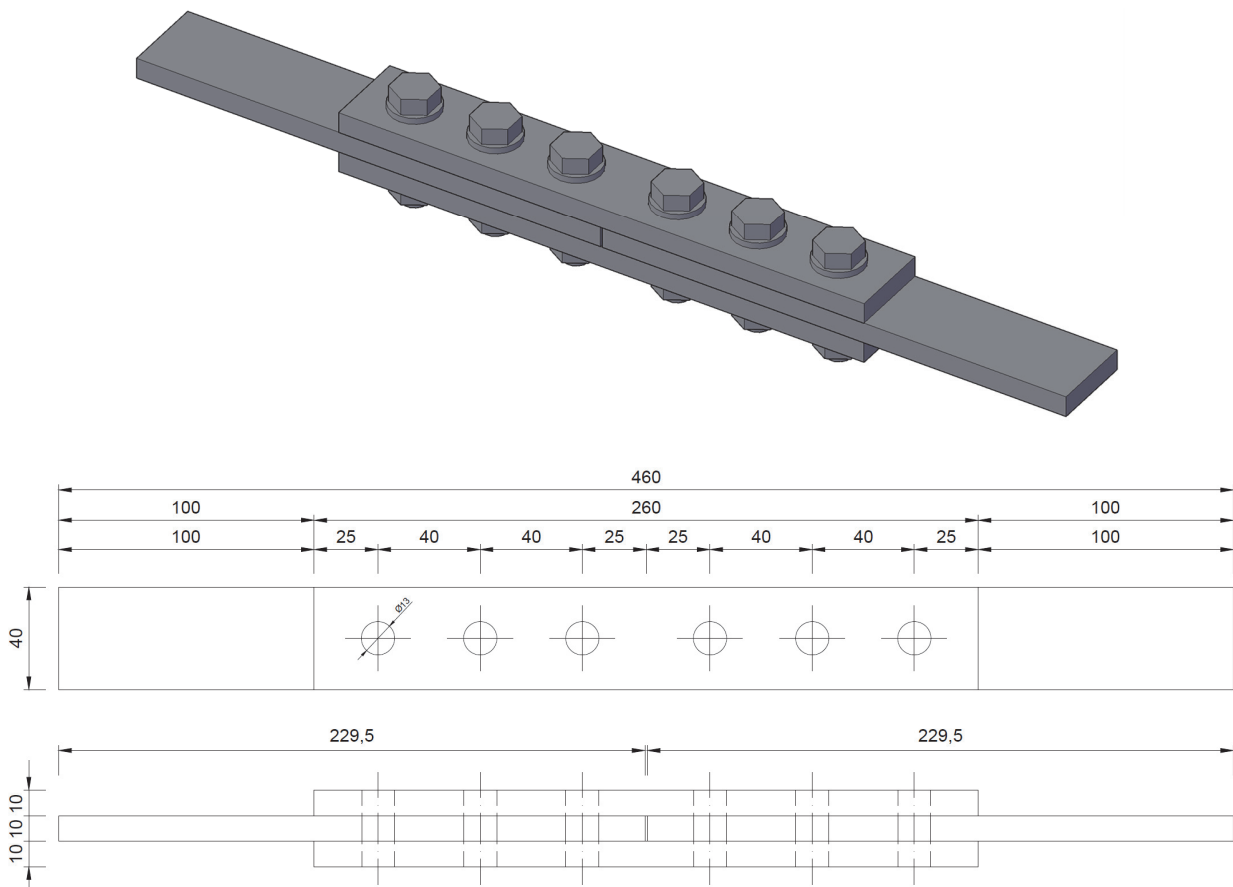


Figure 1: Geometry of the bolted joints.

ACCELERATED CORROSION PROCESS

Material and geometric properties of the specimens

The structural detail under investigation is a slip resistant bolted joint made with high strength preloaded bolts (with geometry carried out from Berto et al 2016) [3-4]. In particular, two plates of 10mm thickness, 40mm width and 229.5mm length are longitudinally joined by means of two cover plates and n.6 M12 class 10.9 bolts tightened with a torque of 91Nm (Fig. 1). The plates are made of S355 structural steel with drilled holes. All the plates were treated with a SA3+ sandblasting process that guarantees a white metal cleaning and consequently a quite uniform friction coefficient equal to 0.5. In regard the friction, between the bolt shank, the nut and the bolt washers, the manufacturer's technical data sheet was considered, which provides a friction coefficient value equal to 0.128.

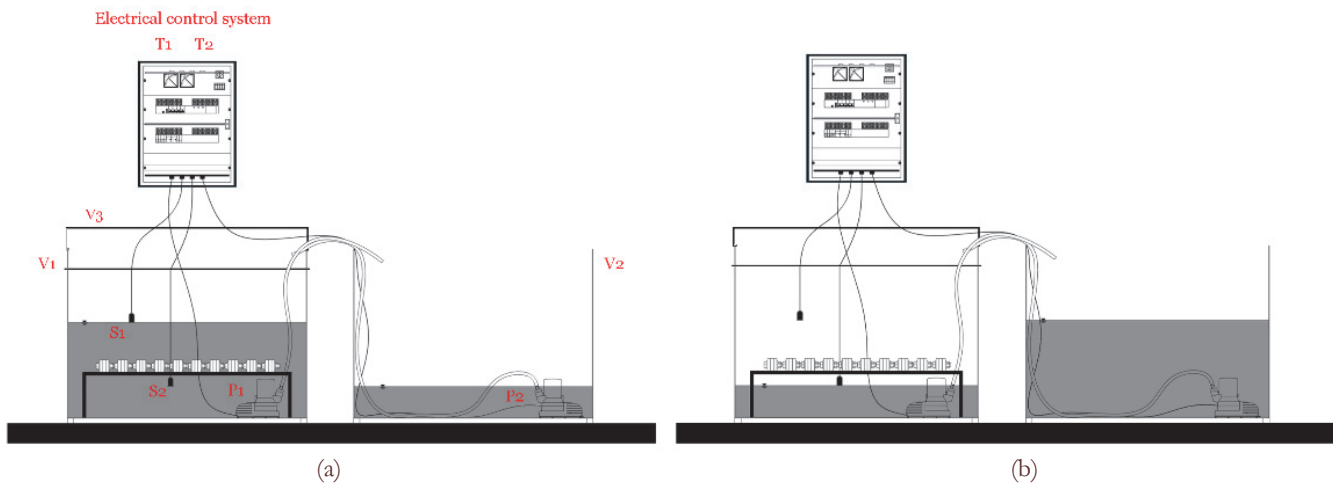


Figure 2: Equipment used for the corrosion process: (a) phase of samples immersion; (b) phase of samples exposure on air.

Accelerated corrosion treatment

The accelerated corrosion process was applied on n. 10 specimens. The procedure was set up by referring to ISO 11130 norm. The process consists in submitting samples to a sequence of immersion and drying cycles, without interruption for the duration of 672h (corresponding to 4 weeks). Every cycle is made up of two minutes long immersion step in a distilled water solution with 5% NaCl followed by a sixty minutes long drying step made with dry air at a temperature of about 35°C. The equipment used to carry out the corrosion cycles consists of the following parts:

- Two tanks for the specimens immersion named V1 and V2: samples are completely immersed in saline solution in V1 tank; V2 tank allows to empty the V1 volume and to let samples on air at the controlled temperature of 35°C for the drying phase;
- Two immersion pumps named P1 and P2: P1 pump, located inside V1 tank, allows to empty the tank to expose specimens to the air during the drying phase; the P2 pump, located inside the V2 tank, allows to move the solution from V2 to V1 and to immerse the specimens;
- Two electromagnetic sensors called S1 and S2: both inside V1 tank. The S1 sensor is positioned at a higher level than that of the samples; it has the function of detecting the maximum level of the solution in the V1 tank and therefore sending the pumping interruption signal to P2 pump (which was transferring the solution from V2 to V1 tank). The S2 sensor, positioned at a lower level than that of the samples, sends to P1 pump the pumping signal (it allows to transfer the solution from V1 to V2 tank).
- An electric panel to power to the pumps and sensors, and a simple control system (made by a couple of timers) having the function of managing the tanks filling and emptying steps;
- A third tank V3 placed above the V1 and used as an hermetic closure; an heating device positioned on the top of the V3 tank has the purpose to keep the air temperature at a constant value of 35°C.

The outline of the equipment is shown in Fig. 2. Prior to initiating the accelerated corrosion process, samples were weighed with an electronic scale to be able to estimate the mass drop caused by the oxidative phenomenon. Every 168 hours of



treatment mass drop measurements were conducted taking off the specimens from the tank and performing the following steps:

- Cleaning of the tanks and replacing the solution with a new one; this operation was carried out to ensure that the corrosive liquid was as untouched as possible by external agents and to restore the quantities of water and NaCl lost due to evaporation;
- Samples surface cleaning;
- Samples weighing to measure mass losses.

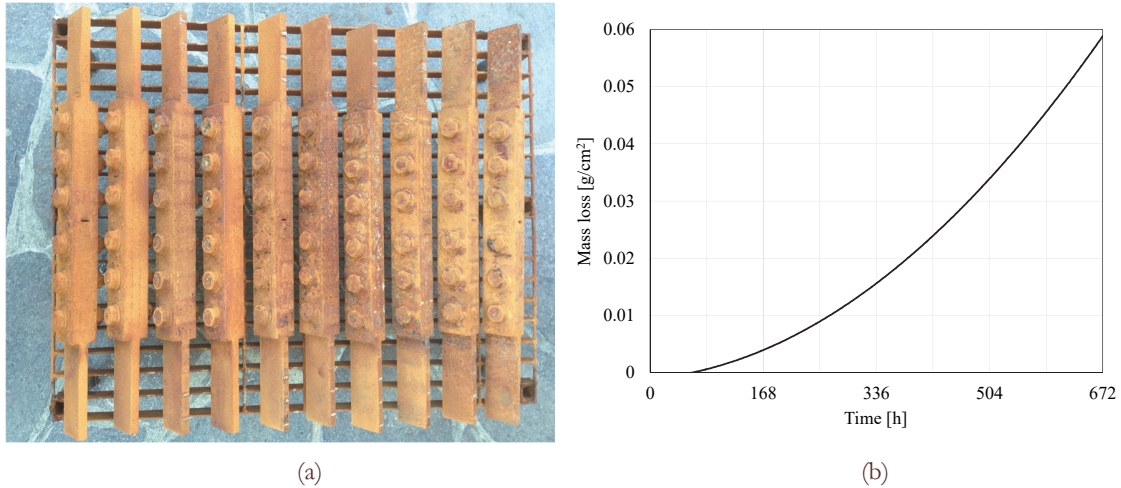


Figure 3: a) Corroded specimens (672h); b) Mean mass losses interpolation of the corroded specimens (g/cm²).

In Fig. 3, the curve resulting from the interpolation of the mean mass losses (g/cm²) measured every 168 hours is reported. As can be seen from the chart, the maximum mass loss at the end of the corrosion process is approximately equal to 0.06g/cm².

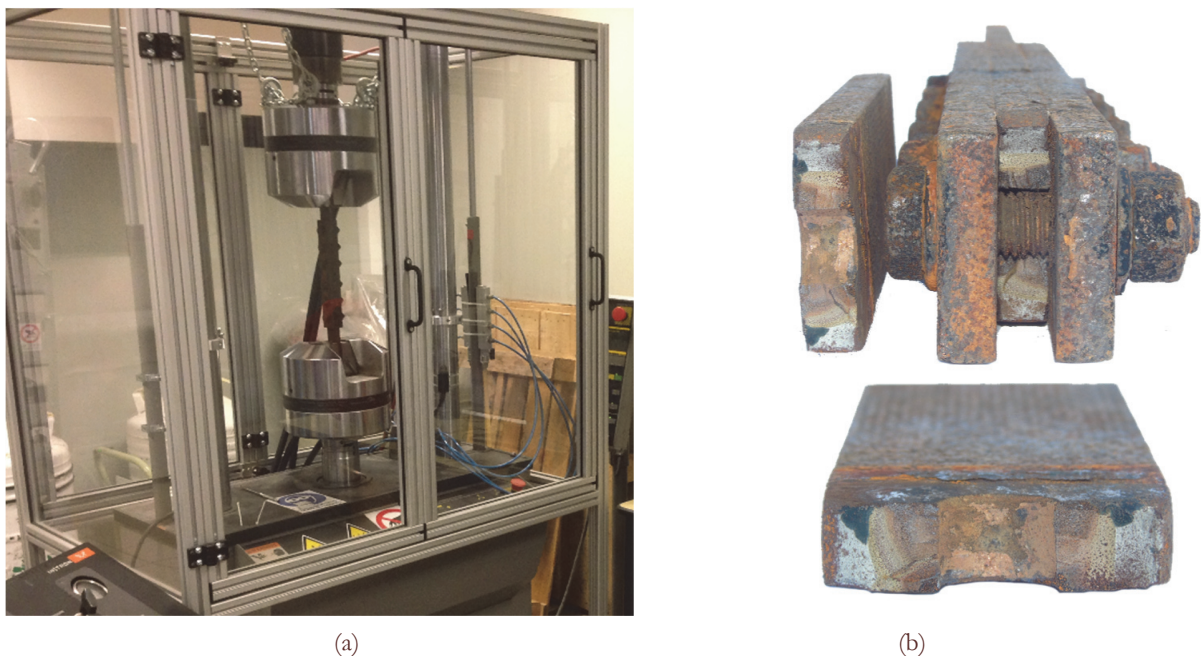


Figure 4: a) Fatigue test Setup with MTS810; b) Failure section of the specimen n. 2 set B.

FATIGUE TESTS

Fatigue tests were conducted using a MTS810 hydraulic test system with a load capacity of 250kN (Fig. 4 a). Stress cycles were performed setting a sinusoidal load control signal (constant amplitude, R=0, 5 Hz frequency). All fatigue tests were made at room temperature. Two sets of samples were tested: set A composed of 8 uncorroded specimens and set B composed of 10 corroded specimens (Fig. 4 b).

The results obtained from fatigue tests for both sets in terms of stress range $\Delta\sigma$ and number of cycles to failure N were reported in a bi-logarithmic chart and interpolated by a regression curve calculated by the least squares method. In addition, the S-N curve with Ps (probability of survival) 97.7%, 10% and 90% were computed by Student's distribution. The expression used for the S-N curve provided by the EC3 [15] is shown below:

$$\Delta\sigma_R^k N_R^k = \Delta\sigma_C^R \cdot 2 \cdot 10^6 \quad (1)$$

where k is the inverse slope of the S-N curve, $\Delta\sigma_C$ is the stress range at 2 million cycles of the detail category, $\Delta\sigma_R$ is the stress range (independent variable) and N_R is the number of cycles (dependent variable).

In Fig. 5 the data obtained from fatigue tests on uncorroded specimens and the corresponding S-N curves with Ps = 10%, 50%, 90% e 97.7% are reported. In Fig. 6 the data obtained from fatigue tests on corroded specimens and the corresponding S-N curves with Ps = 10%, 50%, 90% e 97.7% are shown. The two different S-N curves (Ps 97.7%) obtained from the experimental tests presented in this paper have about the same slope but the curve representative of corroded specimens moves downward respect to the curve of virgin samples.

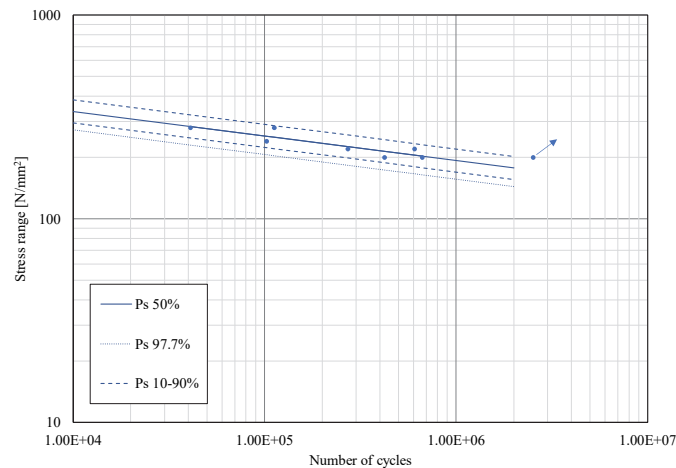


Figure 5: Test results with Ps 10-50-90-97.7% of not corroded joints.

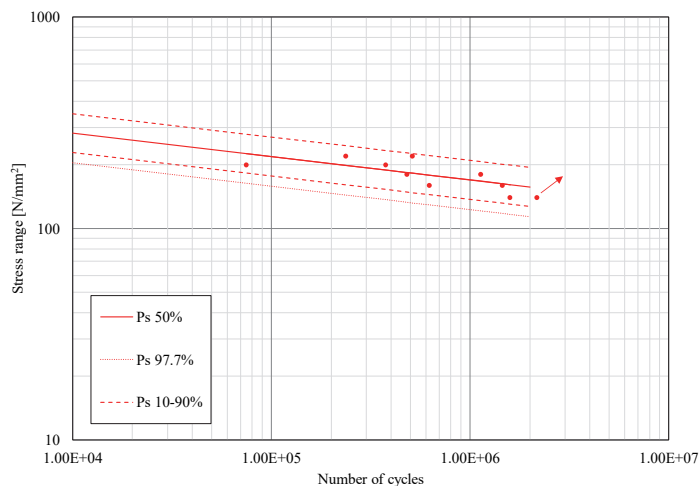


Figure 6: Test results with Ps 10-50-90-97.7% of corroded joints.



Moreover, as already noted by other researchers [14], the inverse slope k of the S-N curve obtained from experimental tests is substantially greater (between 8 and 9) than the one proposed by the EC3 standard for the detail category 112. The inverse slopes and $\Delta\sigma$ at 2 million cycles with $P_s = 90\%$ and 97.7% are reported in Tab. 1.

Specimens	k	$\Delta\sigma_{90}$ [N/mm ²]	$\Delta\sigma_{97.7}$ [N/mm ²]
Not corroded	8.29	155.9	144.0
Corroded	9.05	127.7	113.7
Difference [%]	8.00	22.0	27.0

Table 1: Summary of fatigue tests.

CONCLUSIONS

In this paper, experimental tests were performed on a bolted joint (category 112 of the EC3 standard) by fatigue cyclic tests on virgin samples and on degraded samples obtained by an accelerated corrosion process. From the test results statistical reanalysis, the S-N curve (with $P_s 97.7\%$) obtained from uncorroded samples has an inverse slope of 8.29, approximately equal to 9.05 that is the one relative to the S-N curve derived from corroded tests results, however the last curve (of corroded specimens) is moved down with respect to the not corroded curve. The results confirm that the accelerated corrosion process applied to the specimens caused a not negligible reduction of the fatigue strength of this kind of joints.

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