Effect of hot dip galvanization on the fatigue strength of steel bolted connections

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ABSTRACT. Hot dip galvanized steel bolted joints has been tested under fatigue loading to evaluate the effect of galvanizing coating on the fatigue strength of S355 structural steel. The experimental results showed that the decrease of the fatigue life of coated specimens in comparison with that of uncoated joints is very limited and the results are in good agreement with Eurocode detail category, without substantial reductions. The procedure for coating and preparation of the bolted joints is described in detail in this paper providing a useful tool for engineers involved in similar practical applications. The experimental results are compared with the previously published data on central hole notched galvanized and not treated specimens characterized by the same geometry.

KEYWORDS. High cycle fatigue; Galvanized steel; Notch effect; Bolted joints.

Citation: Razavi, S.M.J., Peron, M., Torgersen, J., Berto, F., Mutignani, F., Effect of hot dip galvanization on the fatigue strength of steel bolted connections, Frattura ed Integrità Strutturale, 41 (2017) 432-439.

Received: 15.05.2017
Accepted: 24.05.2017
Published: 01.07.2017

INTRODUCTION

Majority of mechanical structures are made of various components which are connected using various kinds of joining methods such as welding, bolting, riveting and bonding. However, according to specific geometry of these joints, they are mostly considered as the critical components in structures. [1-6]. Due to their versatility and reliability, bolted connections are one of the most widely used methods for joining structural steel members. Among the numerous advantages of bolting as a joining method compared to the other methods of joining the following can be summarised: affordable process with less required time and cost, ease of assembly and inspection, reliability of service and good performance under variable applied loads [7].
The durability of structural components is significantly influenced by the environmental factors such as degree of corrosion encountered in service operative conditions [8-11]. Deterioration due to corrosion usually leads to the seizure of fasteners and premature failures, in the form of corrosion fatigue. Therefore, proper protections of the bolted joints from corrosion should be considered as the key parameter in design of the components. As a surface treatment, hot dip galvanizing protect the core material from corrosion and environmental aggressive agents and can be used in a wide range of materials and applications [12-17].
As the surface condition may directly effects the fatigue initiation of the materials, some authors correlated the fatigue strength to the coating thickness of the zinc layer [18]. On the other hand, other authors did not support any specific

correlation of loss in the fatigue properties due to the coating thickness [19,20]. By employing the Kitagawa–Takahashi diagram, Vogt et al. [21] specified a threshold value of the coating thickness that could not affect the fatigue behaviour of unnotched components made of structural steels. Valtinat and Huhn [22] published a preliminary study on hot dip galvanized bolted connections. Due to the available gap between the recent and past literature and also limited available data on this topic, the present technical note is aimed to partially fill this gap by presenting a clear explanation for the preparation and final assembly methods of the specimens.
In the current paper, the geometry and the procedure for fabrication and assembly of the specimens is described in details. Additionally, the fatigue data are summarized and compared with those taken from the standard in force for the same detail category followed by a comparison between the present data and some recent data by the same authors Berto et al. [23] from notched galvanized specimens weakened by a central hole.

MATERIAL AND GEOMETRY OF THE SPECIMENS

The test specimens, made of S355 structural steel, for the bolted connection are shown in Fig. 1. Preloaded M12 bolts of class 10.9, system HR, were used in drilled holes. Hot dip galvanized coatings of fasteners according to UNI EN ISO 10684. The dimensions of the test samples were designed primarily to produce a net section fatigue failure of the middle main plate, and not in the bolts or cover plates (EN 1993-1-8). All the samples were hot-dip galvanized for an immersion time of 14 minutes which is typical in the application. The result was a zinc layer of about 400 μm. This layer is commonly employed in practise in large structures.
Subsequently, the joint surfaces were treated according to a light sandblasting process (sweep blasting). In the absence of precise information by the national and European regulations it is proposed a specific procedure which relates to indications in the literature (ISO 8503). In fact, the hot-dip galvanized surface of structural steels requires special handling. The aim was to remove the outer layer consisting of pure zinc notoriously soft and malleable thereby making the surface rough. Moreover, this type of blasting does not severely damage the existing coating obtained by hot dip galvanizing. A specified torque was applied to the nut in two steps using a calibrated wrench capable of an accuracy of ± 4 % according to ISO 6789. Most of these connections are used in steel structures frequently submitted to cyclic loading such as splice joints used in steel and composite bridges.

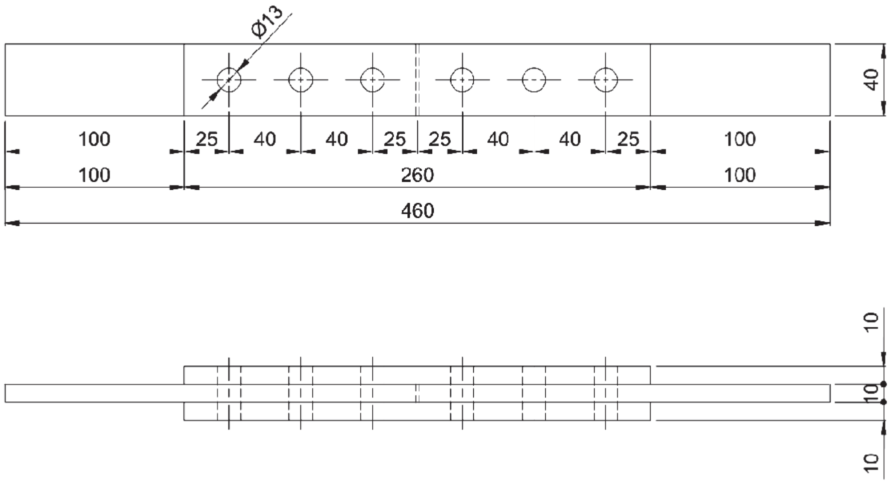

Figure 1: Geometry of the test specimen employed in the research program.

DETAILED PROCEDURE FOR SPECIMEN FABRICATION

After the hot dip galvanization process of steel plates, an adequate surface preparation was performed. The features of the sweep blasting procedure utilized are shown in Tab. 1. All above mentioned data were certified by the sand blaster firm inspection procedure. The results were a roughness equal to 32 μm and a reduction of the zinc layer measured in 12 μm (max. value). The surface preparation grade corresponded to SA1 (light blast cleaning). Fig. 2

illustrates hot-dip galvanized bolted connection before the test. A comparison before and after sweep blasting procedure has been shown in Fig. 3.
According to prescriptions of UNI EN 1090-2 the assembly of the joints were carried out: the high strength bolts, class 10.9, system HR (UNI EN 14399-3) were tightened by the torque control method in two steps. The final torque applied to the fasteners (equal to 1.1 Mr.2) corresponded to 91 Nm as defined and declared by the fastener manufacturer in the box label. Before the fatigue tests all the joint bolt torques were checked.

		Adopted values	Suggested values (*)
	Abrasive	garnet	garnet or ilmenite
	Mesh	80	80-100
Venturi nozzle	Orifice diameter (mm)	10	10÷13
	Distance from the surface (mm)	400	350÷400
	Angle to the surface	45°	≤45°
	Blast pressure(kPa)	200	≤275

Table 1: Sweep blasting procedure.
(*) with reference to well established international specifications relating to surface treatment for paintings (ISO 8503).

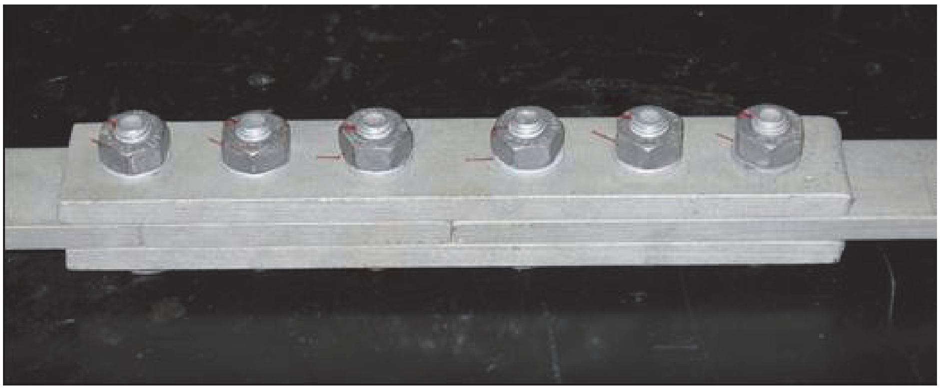

Figure 2: Hot-dip galvanized bolted connection before the test.

Figure 3: Comparison between specimens before and after sweep blasting.

RESULTS FROM FATIGUE TESTS

The fatigue tests were performed by using a servo-hydraulic MTS810 test system with a load cell capacity of 250 kN. All tensile stress-controlled fatigue tests were carried out over a range frequency varying from 5 to 10 Hz depending on the level of the applied load. A constant value of the load ratio, R=0, was employed in all tests.

After the tests the specimens were examined and the fracture surfaces were analysed to get information about the crack initiation and propagation. Failure always happened, as expected, in correspondence of the first bolt of the connection, as visible in Fig. 4. In particular Fig. 4a shows a lateral view and Fig. 4b an upper view of the specimen. Fig. 5 shows two broken parts of a specimen. In particular Fig. 5a shows the holed plate and Fig. 5b the fracture surface in proximity of the bolted connection. The representative failures shown in the figure always started from the net section in correspondence of the hole. From there the crack propagated through the material until the net section was so much weakened that finally a static crack caused the final failure. Multiple initiation points are well visible with a regular propagation until the final failure. This is in agreement with [22] which shows that in members with drilled holes a surface crack at the wall of hole was found always predominant. According to the fracture surfaces it can be observed that the crack has not a constant configuration in thickness. Thus, it is verified that the preloading applied to bolts influence crack initiation phase. Fig. 6 shows an example of the zinc layer from a SEM image.

Fig. 7 summarizes the results from fatigue tests of hot-dip galvanized bolted connections subjected to a nominal load ratio R=0. The stress range over load cycles N is plotted in a log-log diagram. The unbroken specimens (run-out samples), over three million cycles, were not considered in the statistical analysis. They are marked with an arrow in Fig. 7. The mean curve corresponding to a probability of survival, Ps, equal to 50% is reported in the figure as well as the scatter band defined by lines with Ps 10%-90%. The dashed line refers, instead to a Ps of 97.7% for a direct comparison with the Eurocode detail (EN 1993-1-9). The typical expression for the S-N curve in EC3 is reported below:

$$\Delta\sigma_R^k N_R = \Delta\sigma_c^k 2\times10^6 \quad (1)$$

The inverse slope k value of the S–N curve and the scatter index T referred to Ps 10%-90% are also shown. The complete list of data related to hot-dip galvanized bolted connections is summarised in Tab. 2 properly marking the run-out specimens. The results from the statistical re-analysis is provided in Tab. 3. From the re-analyses of the data it is clear that considering a Ps of 97.7% at two million cycles Δσ is equal to 100 MPa which is slightly lower than the corresponding classified category Δσc=112 MPa derived from EC3 for the considered uncoated bearing-type connection. In contrast to [22], the inverse slope of the curve, k, is very close to that suggested by EC3. The data from hot dip galvanized specimens are plotted together with data from uncoated specimens characterized by the same geometry and tested in this research program. It is possible to observe that all data fall inside a narrow scatterband and that the reference value at two million of cycles and corresponding to a Ps of 97.7% remains almost the same (101 MPa) with almost no significant differences between galvanized and not-galvanized specimens (see Fig. 8). This result is in agreement with that reported in [22] where it was shown that the use of preloaded high strength bolts gave a remarkable positive influence on the achieved fatigue life and that the detrimental effect of hot dip galvanizing can be easily neutralized. The advantage of this method is the easiness of handling with the maximum of efficiency of the bolted connection under fatigue loading. In this optic the accurate procedure described in section 3 for specimens preparation and assembly is surely necessary to guarantee a good repeatability of the connections in the different specimens. This procedure permits to allow beneficial compressive stresses in the neighbouring of the holes which are advantageous for the fatigue behaviour.

In fact, as described in [23], the difference between galvanized and non-galvanized simple plates weakened by a central hole is much higher than that reported in the present paper for bolted connections. In the research conducted by Berto et al. [23] a non-negligible deviation approximately equal to 30% has been found between coated and uncoated specimens with an insignificant reduction of the fatigue life due to influence of galvanization process. In that case two well different scatter bands were given without the possibility of providing a unified band for coated and uncoated specimens which is instead possible in the present investigation dealing with bolted connections. Some creep analyses are also planned [24].

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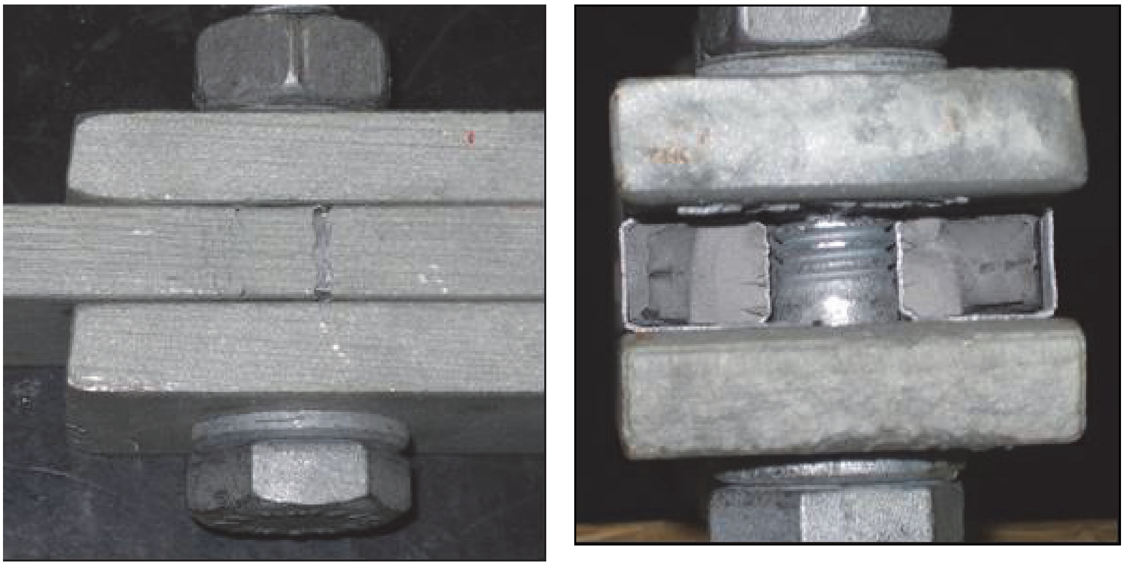

Figure 4: Typical failure from the hole corresponding to the first bolt of the connection. (a) lateral view and (b) upper view.

a b

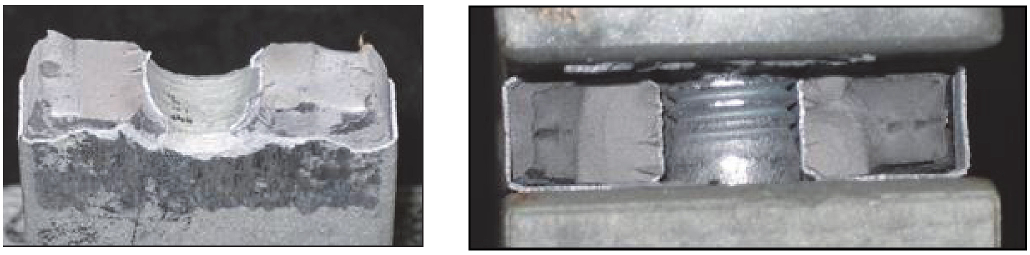

Figure 5: Typical fracture surface after cyclic loading. (a) Plate and (b) bolted part.

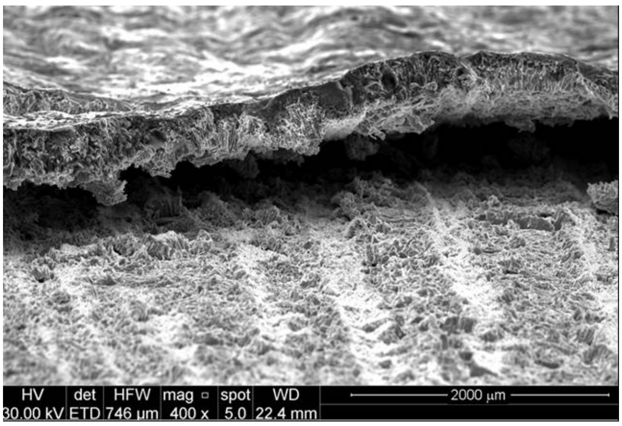

Figure 6: Layer thickness from a SEM image.

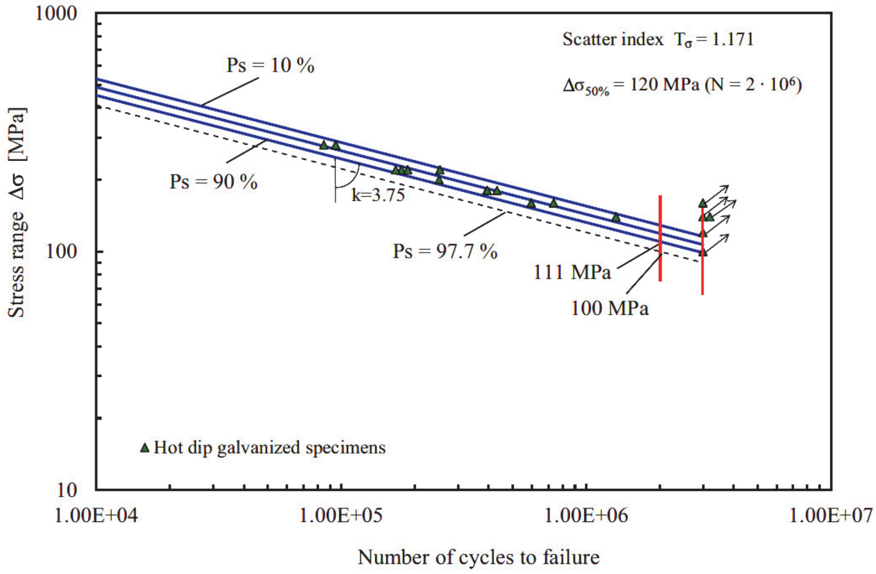

Figure 7: S-N-curves of hot dip galvanized connections.

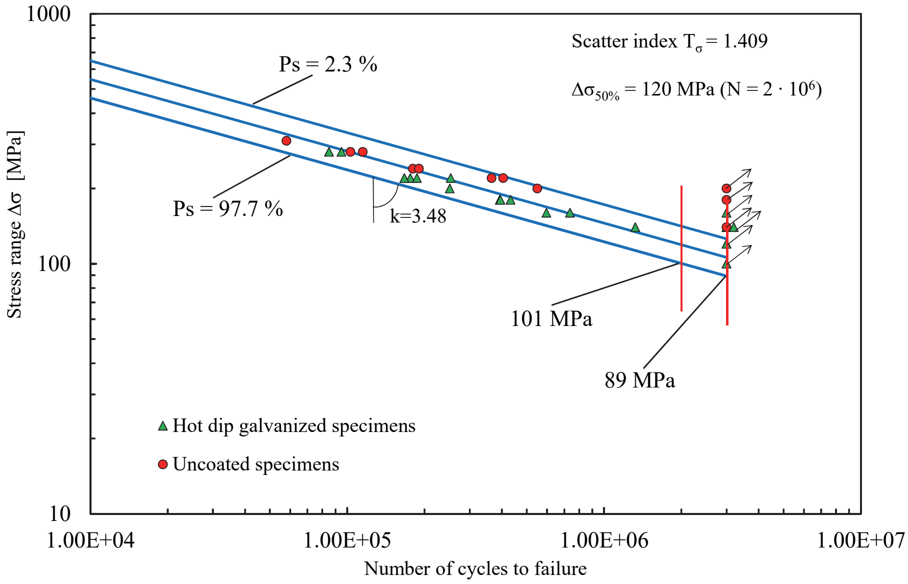

Figure 8: Unified scatterband considering uncoated and hot dip galvanized connections.

CONCLUSIONS

This short technical note reports some new data from hot dip galvanized steel bolted connections under fatigue loading. In particular the effect of a galvanizing coating on the fatigue strength of S355 structural steel has been accurately investigated showing that the reduction in the fatigue life is very limited if compared with that of uncoated joints. A detailed procedure for the accurate preparation of the specimens has been also systematically provided, showing a good repeatability in the assembly of the specimens and then in the final fatigue behavior.

$\Delta\sigma$ [MPa]	N	Notes
220	176000	
120	3000000	Run-out
160	736700	
160	597000	
280	85000	
100	3000000	Run-out
280	95000	
140	3000000	Run-out
140	3200000	Run-out
160	3000000	Run-out
220	253000	
220	167000	
220	187000	
200	251000	
180	432807	
180	393000	
180	395000	
140	1324000	

Table 2: Summary of all fatigue data from hot-dip galvanized bolted joints.

Ps	$\Delta\sigma$	N
10%	529	10000
10%	130	2000000
50%	489	10000
50%	120	2000000
90%	452	10000
90%	111	2000000
97.70%	100	2000000

Table 3: Summary of the statistical re-analysis for the hot-dip galvanized series.

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