

Analysis of Failure Paths in Steel Bolted Connections

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ABSTRACT. *This paper analyzes the tensile fatigue behaviour of bolted joints constituted by commercial steel bolts. They were tested under both monotonic and fatigue tensile loading, with different R-ratio. Results show that under increasing monotonic tensile loading the bolted joint is not the failure zone of the bolt, whereas such a bolted joint is the failure region under cyclic loading. The fatigue life decreases with the increase of the stress range and with the maximum stress, and pre-loading enlarges the fatigue life. Fatigue fracture surface shows a geometry of crescent moon in the case of short cracks and such a shape evolves towards a quasi-straight crack front in the case of long cracks. Fatigue fracture usually happens at the root of the first notch inside the bolted joint, although fracture initiation may happen in several consecutive notch roots, increasing the initiation angle of the fatigue crack as the applied stress diminishes.*

INTRODUCTION

In many cases bolted joints are the weakest elements in structures or mechanisms, so that understanding their mechanical behaviour turns out to be the key when they are subjected to an increasing monotonic load until fracture (for instance due to a bad design) or in presence of cyclic loads (fatigue). Although bolts may be subjected to multiple types of loads (torsion, bending), they always present a strong component of tension, loading condition studied in this paper.

Fatigue in bolts is usually characterized by Wöhler curves, where the increase of the R-ratio decreases fatigue life [1]. Calculation of the fatigue strength is usually a factor conditioned by time; however, it can be measured in shorter lapses of time by means of an accelerated method consisting of using the threshold stress to originate a fatigue fracture on the root thread [2]. A screw failure is shown until a certain number of cycles, after which fracture does not take place [3].

Coarse pitch bolts have a larger fatigue life compared to those with a fine pitch. Furthermore, the bolt undergoes a size effect regarding its fatigue life [4], this effect decreasing when the nominal diameter increases, due to the notch effect of the notch roots [5]. The friction coefficient of the threads decreases when the tightening speed increases and, therefore, the load on the bolted joint increases [6]. The preload level influences the fatigue life of the joint: an insufficient or null initial preload may generate a reduction in fatigue life [1].

Rolled bolts exhibit an increase in fatigue life compared to those machined, due to the compressive residual stresses generated upon notch roots [1,7]. The fatigue strength of machined bolted elements is influenced to the greatest degree by the wearing of the tool and the cutting speed, whereas the cutting method and the radial feed are of lesser importance [8]. In groove-rolled products, tools's high penetration rate increases the fatigue strength, due to the appearance of greater compression axial residual stresses and strain hardening [9].

The rolling of steel bolts after annealing, compared to most common procedure (machining) that is the usual one, increases the fatigue life remarkably for low minimum stresses [10,11]. On the contrary, for high minimum stresses there are barely any changes if the bolts are of normal pitch [10] and the increase is much lower if the bolts are of fine pitch [11].

EXPERIMENTAL PROCEDURE

The specimens were commercial M10x200 bolts with 8.8 grade (DIN 931), made of blue steel, and without head in a cylindrical piece (with machined inner thread) of 16 mm of diameter, 150 mm length and same material as the bolt (Fig. 1).

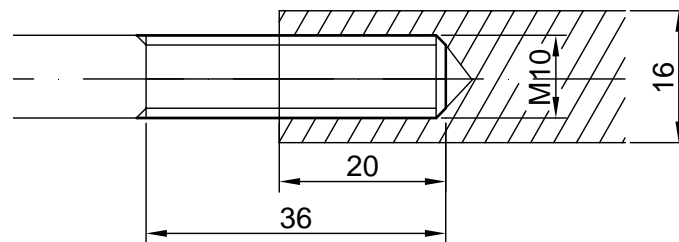


Figure 1. Bolted joint.

The mechanical behaviour of steel in bolts has been characterized by simple tension tests, with specimens obtained from the body of the bolts, using a crosshead speed of 2 mm/min.

Tests with axial monotonic stress controlling the displacement (crosshead speed of 2 mm/min) were carried out on the specimens with the bolted joint until fracture. For the fatigue characterization, load control tests were performed (constant stress range $\Delta\sigma$), with the form of a sinusoidal wave, frequency of 10 Hz and different values for the R -ratio (0, 0.25 and 0.50). These tests were carried out until fracture or until they reached 10^6 cycles. Some specimens were subjected to a tensile preload of 80% of the theoretical yield strength of the bolt material, in order to study how it affected the fatigue life.

EXPERIMENTAL RESULTS

Material Characterization

The steel used for this study, after its metallographic preparation and being etched with 4% Nital, presented a ferritic-pearlitic microstructure, as displayed in Fig. 2.

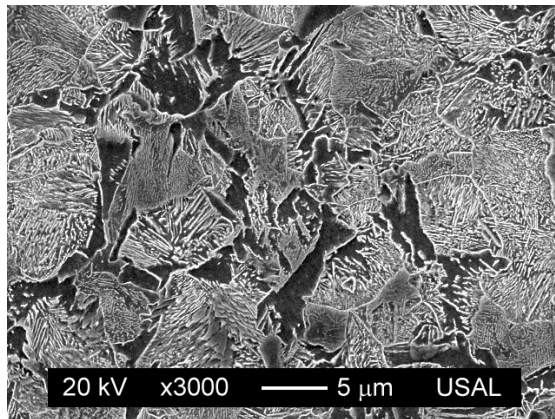


Figure 2. Microstructure of steel.

Three standard tension tests were carried out. The evaluated mechanical properties were as follows: Young modulus $E=199$ GPa, standard yield strength at 0.2% $\sigma_{0.2}=546$ MPa, tensile strength $\sigma_{\max}=715$ MPa and strain for maximum load $\varepsilon_{\max}=0.04$. The results obtained showed lower values than those corresponding to quality 8.8 of the bolts.

The fracture surface, which results from the standard tension test (Fig. 3), is the typical cup-cone fracture that appears in many metallic alloys (ductile). It shows a straight and fibrous central zone formed by irregular microvoids and an external ring that has 45° walls with elongated microvoids.

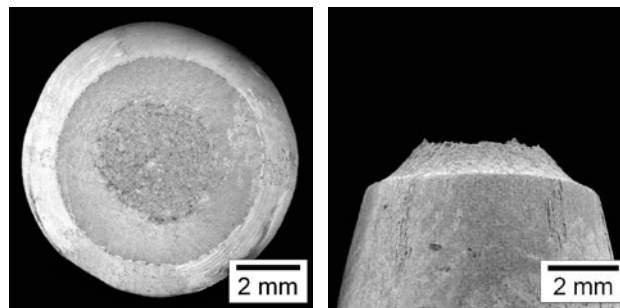


Figure 3. Fracture surface in standard tensile tests.

Tests under Increasing Monotonic Stress

When applying increasing monotonic stress on the specimens with bolted joints, the fracture occurred outside of such a joints. On those specimens where just some bolt thread was placed on the joint, the fracture occurred on the root of some of the outer threads and the failure stress was the same as the yield strength of the material. On the contrary, if all the threads were inside the joint (i.e., all had been bolted), the fracture occurred outside such a joint (on the body of the bolt or on the link with the thread) at a higher stress level than the material's yield strength.

The fracture resulting from the tests is the cup-cone type, with the special feature of the threads which generate a fracture surface more asymmetrical, where the one thread's height must be surpassed (Fig. 4). On such a surface, there emerged a fibrous zone, smaller than that in simple tension (compared to the total surface of the fracture), as well as a more irregularly shaped external ring.

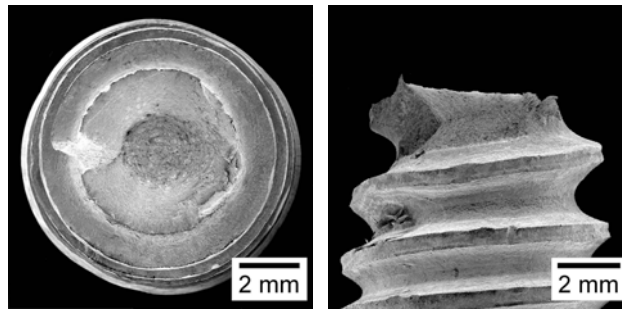


Figure 4. Fracture surface in bolt under monotonic loading.

Fatigue Tests

R-ratio

Wöhler curves were obtained ($\sigma_{\max}-N_f$ and $\Delta\sigma-N_f$) for specimens with bolted joints subjected to a cyclic load, for constant $\Delta\sigma$ and several values of the R -ratio (0, 0.25 and 0.50). They appear in Fig. 5.

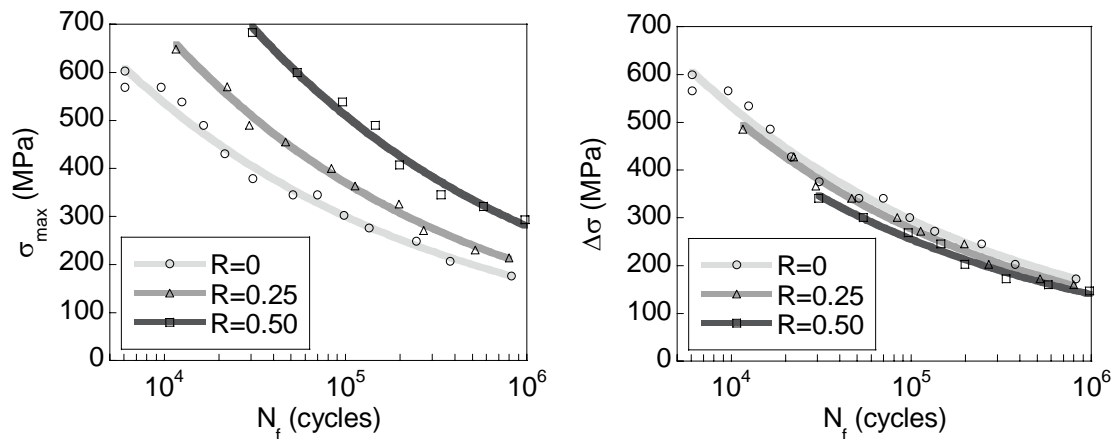


Figure 5. Wöhler curves: $\sigma_{\max}-N_f$ (left) and $\Delta\sigma-N_f$ (right).

It can be seen that $\sigma_{\max}-N_f$ curves move to the right when the R -ratio increases, whereas the $\Delta\sigma-N_f$ curves move to the left. Therefore, fatigue is a biparametric phenomenon, where the increase of σ_{\max} or $\Delta\sigma$ decreases fatigue life. Furthermore, a potential fit was obtained for the fatigue life, and was the same for all curves, considering both parameters,

$$N_f = 2.82 \cdot 10^{14} \sigma_{\max}^{-1} \Delta\sigma^{-2.82} \quad (1)$$

Preload effect

In some tests, the bolts were subjected to a preload in order to study its effect on fatigue (Fig. 6, where the value of preload is represented with a horizontal broken line). Wöhler curves show that fatigue life of bolts for $R=0$ and $R=0.50$ increases when applying a preload for stress ranges under ~ 220 MPa.

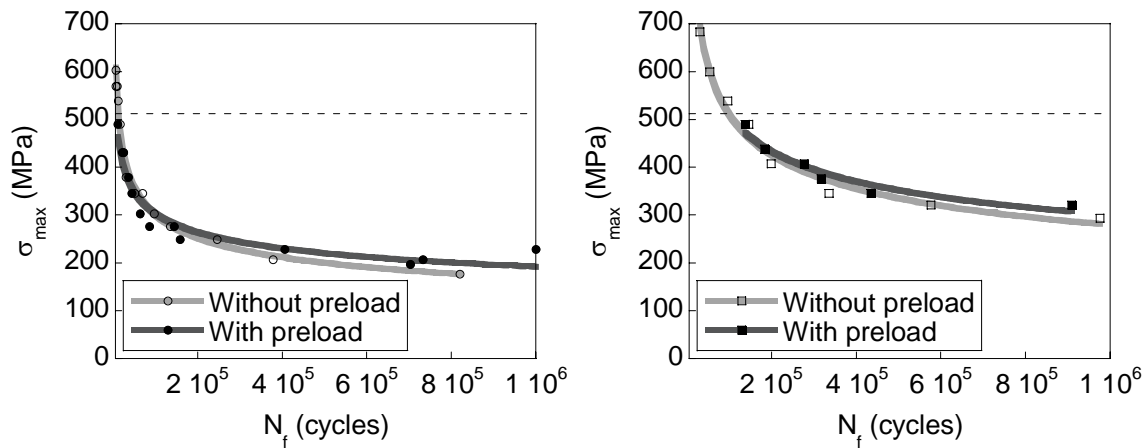


Figure 6. Wöhler curves, $R=0$ (left) and $R=0.50$ (right), with and without preload.

In bolts without residual stress, like those machined, tension preload is always beneficial due to the compressive stresses generated on the notch roots. On the other hand, in bolts machined by plastic strain (after the heat treatment) there are still residual stresses produced by the machining which will be redistributed, thus affecting the fatigue life [1].

Fracture surfaces

Fatigue fracture (Fig. 7) occurs on the first thread's root inside the bolted joint [3,4, 10-12], where the surface tension is the highest. The fracture surface first shows a fatigued region, then a zone with plane fracture and, finally, an inclined fracture or shear lip [10]. Shallow cracks (Fig. 7a) show a fatigue crack front shape of crescent moon, encircling the whole bolt edging. Intermediate depth cracks (Fig. 7b) close to the centre of the bolt have a crack front, which is still in the shape of crescent moon, but doesn't enclose the edging of the whole bolt. Finally, deeper long cracks (Fig. 7c) show a quasi-straight front.

The applied stress influences the fatigue behaviour of the bolted joints, but especially in the primary stages. A fatigue test was performed without breaking the specimen (with $\Delta\sigma=486$ MPa, $R=0$ and during $0.75N_f$ cycles) and then it was subjected to a high load in order to make the crack more visible, since this is how the rounding and increase of the crack opening displacement (COD) is produced. On the longitudinal section (Fig. 8), it is seen the beginnings of fracture on the roots of consecutive threads, the longest one being the crack on the first notch inside the joint, which is the most loaded, and so on. Furthermore, initially the fatigue-induced cracks propagation from the thread root with

certain slope regarding the cross section of the bolt in such a way that the angle formed increases when the applied load decreases (bottom of Fig. 7 and Fig. 8), due to the location and directionality of the maximum principal stresses [13].

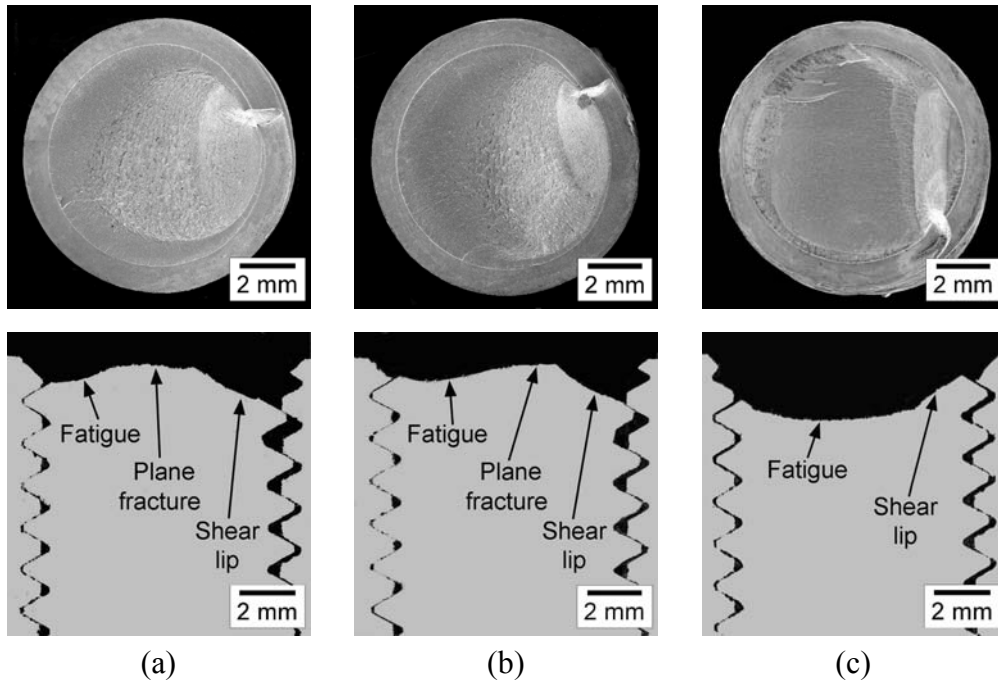


Figure 7. Fatigue fracture surface.

- (a) $\Delta\sigma=600$ MPa, $R=0$ and $N_f=6056$ cycles.
- (b) $\Delta\sigma=486$ MPa, $R=0$ and $N_f=16475$ cycles.
- (c) $\Delta\sigma=172$ MPa, $R=0$ and $N_f=820321$ cycles.

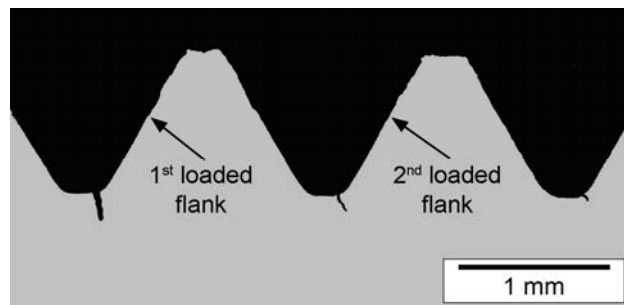


Figure 8. Initial propagation of the fatigue crack.

After the fatigue surface, the region associated with critical cracking (fracture regime) appears. It presents a quasi-plane shape whose size diminishes when the depth of the fatigue fracture increases, almost disappearing for small $\Delta\sigma$ (Fig. 7c), and a ductile edge which corresponds to the final fracture where the thread breaks longitudinally. This last region has a slope of 45° in its section located towards the first thread's loaded side.

On the longitudinal section of the specimens (bottom of Fig. 7), it is shown how there is barely any plastic strain on the fatigued zone, and that is a perfect adjustment between the inner and the outer screw; whereas in the inclined fractured zone (shear lip), it is seen an increase of the plastic strain while the applied stress becomes greater, mainly on the zone of the first thread inside the joint.

The fatigue fracture surface of the steel bolt is made up of ductile micro-tearings (Fig. 9 left), where fatigue striations can be seen correspond to the crack growth in a load cycle on Paris regime [12,14]. In steel subjected to low maximal stresses, with a great part of its surface fractured, fatigue marks are observed on the origin of the bolts' edges, which demonstrates the direction of fatigue advance. The longitudinal section of the fatigued specimen (without reaching total fracture), after revealing its microstructure (fracto-metallography), shows that the crack path presents frequent deflections and branches, which implies the existence of a strong local mixed mode of crack propagation. After the fatigue surface, the fracture mechanism is made up of micro-voids (Fig. 9 right), appearing on an intermediate zone between both surfaces, where both fractographies mix.

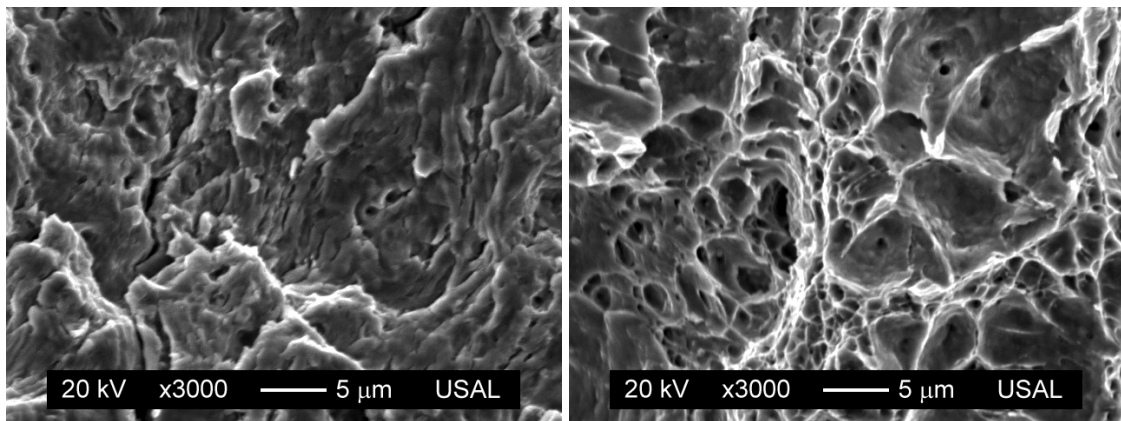


Figure 9. Ductile micro-tearings (left) and microvoids (right).

CONCLUSIONS

With increasing monotonic stress, the fracture of bolted joint specimens does not occur on the joint itself. If the bolt has not been completely screwed in, the fracture occurs on the notch of some of the threads outside the joint, with the corresponding stress to the yield strength of that material.

In fatigue, the $\sigma_{\max}-N_f$ curve for steel specimens with bolted joints moves to the right while the R -ratio increases; whereas the $\Delta\sigma-N_f$ curve moves to the left. Fatigue is, therefore, a biparametric phenomenon, where the increase of the σ_{\max} or the $\Delta\sigma$ diminishes fatigue life; furthermore, a unique power fit is obtained, which is a function for both parameters. The application of a tension preload (512 MPa) before the cyclic loading phase, with ratios $R=0$ and $R=0.50$, prolongs fatigue lives of the bolts for low stress ranges (~ 220 MPa).

The fatigue fracture surface is practically plane and almost perpendicular to the longitudinal axis of the wire. For shallow cracks, the crack front shows a crescent moon geometry that extends almost all over the bolt edge; for intermediate depth cracks, the geometry is the same, but covers a smaller outer surface; and for deeper cracks, the front is quasi-straight.

Fatigue fracture occurs on the notch of the loaded side corresponding to the first thread inside the bolted joint, where the surface tension is highest. The initial propagation of the fatigue crack shows a certain inclination, with an angle which increases when the applied stress diminishes. Furthermore, if the applied stress is high enough, cracking may appear on the notch of several consecutive threads.

ACKNOWLEDGEMENTS

The authors wish to express their gratitude to the University of Salamanca (USAL) for the financial support of this research work (Grant USAL2008A09), as well as to the Spanish Foundation *Samuel Solórzano Barruso* (Grant FS/16-2010).

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