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SUPER-BOLT AND SCREW FIXATION AN OPTIMIZED METHODOLOGY BASED ON TRIBOLOGICAL FUNDAMENTALS

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Abstract*. The aim of this study is to identify the best way to apply torque on a screw to have the lowest loss of power to the system, looking for to increase the efficiency use of the super-bolt and decreasing the possibility of a catastrophic failure in this form of fixation. Given the large applications of gaskets and clamping devices found in industry, especially screwed surfaces, is necessary the study and the understanding of the applied tightening conditions influences and the actual grip generated on the screw threads, as well as inadequate pre loads conditions, which is the main cause of the loosening bolted joints. Issues about inadequate pre loads are associated with the clamping method used, including the friction conditions between materials in the thread. For both tests were performed tribological study contact between the surfaces of AISI 4140 (super-bolt) and AISI 4140 (screw) in a real application by super-bolt fixation, considering different situations. Moreover, mathematical calculations for checking the tension torque x balanced strength in thread and the screw head are performed. Thus, the results show that there is wide variation between the application load and the outcome of torque, making it possible to identify the best grip method and surface characteristics for the use of super-bolt.*

Keywords*: Super-bolt, Tribology, Screw, Torque, AISI 4140*

1. INTRODUCTION

There are several ways to fix parts and components mechanically, but screw joints are the most commonly used today. Its great application is mainly due to its simplicity, ease of disassembly, productivity and cost. According to Hermano (2003), the bolts and their tensile forces have the objective of keeping the joint together in accordance with the functions assigned to it, supporting the work forces present. In observing the tightening of the screws, the torque applied to the screw head does not reflect the actual torque applied to the thread as described by Zou et. Al. (2007) and Eccles et. Al. (2010). Influences such as preload applied, screw lubrication and friction were approached to verify the best condition for the application of the super-bolt screws.

From the characterization of the super bolt, its operation and applications, presentation of the tribological aspects of the interaction of thread threads and indication of the tensions in threads and preload obtained in the literature, an experimental procedure was established, in which the interaction of the screw and the thread, both of AISI 4140 steel, through the test in a tribometer.

The aim of this study is to identify the best way to torque a screw with the lowest possible loss of power in the system, thus increasing the efficiency of super bolt use and reducing the possibility of catastrophic failures in this form of fixation.

2. THE SUPER BOLT

When designing a bolted joint, it is important to minimize the cyclic loads applied to the bolt to avoid fracture and consequently joint failure. Fatigue of a material occurs when a component is subjected to cyclic loads and, if the cyclic loads applied are too high, microscopic cracks will form. When they reach a critical size, the nucleation of a crack will propagate until total collapse. The basic principle to minimize or mitigate this is the use of screws to fasten the rigid members with a high preload, according to Norton (2000).

One of the key features of the screw is its elasticity and it can be improved by the use of a long screw or by reducing the stem diameter thereof. Generally, it is preferable to use several smaller screws instead of one with a larger diameter for better load distribution and increasing the number of back-ups for failures. A large diameter bolt can not be properly preloaded since the tools available in the industry do not have sufficient torque capacity. In this way the super bolt (Fig. 1) appears as the solution for many fixing problems for large diameters and high loads.

According to the Nord-Lock Group (2016) website information, Superbolt tensioners are designed as direct replacements for conventional nuts and bolts. These devices can be threaded onto a new or existing bolt, stud, threaded rod or shaft. The main thread serves to position the tensioner on the bolt or stud against the hardened washer and the load bearing surface. Once it is positioned, actual tensioning of the bolt or stud is accomplished with simple hand tools by torquing the jackbolts which encircle the main thread. The jackbolts transfer the preload evenly into the main thread and, consequently, onto the joint. The main thread is tightened in pure tension.

Figure 1: Super bolt.
Source: http://www.jeysons.com/nutstyle.asp in 05/11/2016

The super bolt great advantage is prevention of loss of preload. However, the preload applied to the super bolt must reach the required preload first. This is because, the fulfillment of the necessary preload on the workload is what keeps the bolts tight.

The torque required to tighten a super bolt is kept low, and a large preloading actuator is divided over many smaller bolts known as jack bolts, which are tightened with simple hand tools and / or torque wrench. In addition, lubrication must be performed in such a way that friction losses are minimized. The super bolt achieves high preloads with excellent accuracy and repeatability, which helps to maintain them mainly in thermal or dynamic applications.

Thus, in order to achieve the efficiency of the fastening process, it is necessary to understand the tribological aspects, of thread tension and preload of the super bolt.

2.1. Tribological Aspects

Tribology is defined by Hutchings (1995) as being "the science and technology of surfaces that interact in relative motion". This is the definition given by some authors and covers the study contents of friction, wear and lubrication. When contacting two surfaces, they will come into contact only at some points in areas that touch because they are more protruding, but when there is an increase in load there will be more contact points that will withstand the normal load on the surface and generate the frictional force between them.

The stability level of the preload on a screw or in this case of a super bolt is usually controlled by the torque applied on each of the jack bolts. The sum of individual loads results in the required preload; That is, in the total preload applied to the superbolt. These are some of the factors that have been described in the literature, that affect the torque-preload results (Nassar and Zaki, 2009).

As described by Zhu et. al. (2016) in general, about 90% of the input torque in threaded fasteners is converted to heat, thanks to overcoming the two friction torque components that are the underhead friction torque and the thread friction torque. The first component overcomes the friction between the face of bolt and the surface of joint and the second one resists the friction between male and female thread. Only 10% typically ends up contributing to the achieved preload in fastener.

In order to do this, the preloading of bolted joints requires a knowledge of the friction conditions so that the joint conditions are met and that the screws do not loosen.

There are several studies investigating the mechanical behavior of screw joints under various tightening and loosening cycles. The torque required for screw tightening is divided into three parts according to Zou et. Al. (2007),(a) the torque required to elastically deform the screw, (b) the torque required to overcome the friction between the threads and (c) the torque required to overcome the friction between the screw head and the Surface of the joint. Describing these variables in terms of an equation we have:

$$T = F_i\left(\pm \frac{P}{2\pi} + \frac{\mu_t r_t}{\cos\beta} + \mu_n r_n \right) \tag{1}$$

Where T is the torque applied to the screw, F_i is the preload generated on the screw due to the applied torque, P is the thread pitch (in this term we consider positive for tightening and negative for the loosening), μ_t is the coefficient of friction between the thread fillets, r_t is the effective contact radius of the threads, β is half the thread angle (30°), μ_n is the coefficient of friction between the screw head and the joint surface, and r_n is the contact radius between the screw head and the joint surface.

It is possible to note, then, that the coefficient of friction directly influences the result of the torque T applied to the screw, as well as in the preload Fi, which is the main result for the fixation of a screw joint. Therefore, it will be better explored in the next item.

2.2. Tensile in Threads and Preload

Theoretically, the screw-nut load interaction is applied in all the threaded threads. However, due to inaccuracies in fillet spacings, the fillers are concentrated almost entirely in the first pair of fillets. Tension calculations on more conservative threads take this into account, while less conservative calculations condition the load on all fillets (Norton, 2000).

Bolts in high fixation applications such as jackbolts suffer only tensile loads, and the traction area (A_t) is calculated with the formula below (Norton, 2000).

$$A_t = \frac{\pi}{4}\left(\frac{d_p + d_r}{2}\right)^2 \tag{2}$$

Where, for UNS threads

$$d_p = d - \frac{0{,}649519}{N} \qquad d_r = d - \frac{1{,}299038}{N} \tag{3,4}$$

And for ISO threads

$$d_p = d - 0{,}649519\,p \qquad d_r = d - 1{,}226869\,p \tag{5,6}$$

With d = outer diameter, N = number of fillets per inch and p = pitch in millimeters. Then, according to Norton (2000) the tension (σ_t) in a threaded rod due to an axial tensile force F under a cross-sectional area (A_t) is;

$$\sigma_t = \frac{F}{A_t} \tag{7}$$

As is often the case, ignoring the preload to be used in the joint can generate fatigue which is one of the most common problems in screw joints. An appropriate preload in a screw joint is essential for satisfactory performance of the joint in service. Insufficient preloading forces can cause serious damage to components, such as loosening of component vibration, joint separation, static failure, or screw fatigue. On the other hand, excessive pre-loading can induce the flow or fracture of the screw during tightening or in service (Yanyao, 2001).

The reuse of the screws several times is not advisable, due to the deformations that occur in the same, generated by the acting loads. According to Eccles et.al (2010), the friction increase resulting from re-use could have an adverse effect on a joint’s structural integrity due to the corresponding decrease in the generated clamp force that occurs.

Bolted joints have been widely used in mechanical framework designs in joint joints of parts that need to be dismantled. Examples are the space industry, nuclear, naval, automotive, pipelines, pressure vessels, among others. In this context, torque application needs to be well controlled. However, controlling the preload applied is extremely complicated due to the dispersion of the torque-preload ratio (Yan Yao, 2001 & Croccolo et al., 2011 & Zhu et al., 2016).

The preload has a fundamental role in unions subjected to dynamic loads as in the case of superbolt. As Norton (2000) explains from Fig. 2, the force acting on the material and the screw is the same when in contact. Once a load Fi is inserted by tightening the bolt, the deflections of the material and the bolt are controlled by their spring constants and reach the points A and B in their respective curves.

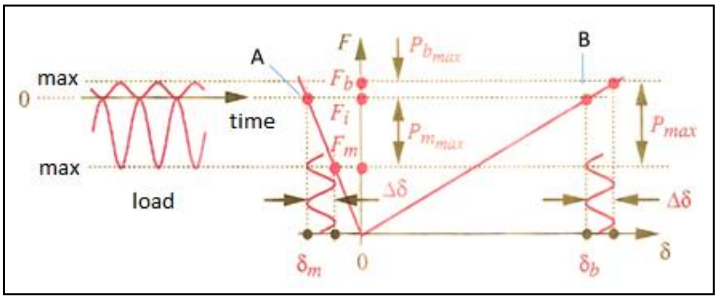

Figure 2: Dynamic load condition applied to screw joints
Source: Norton, 2000

In Figure 2, when the force P is applied, the bolt receives only part of this force due to the presence of the preload, which causes the joint material to absorb most of the load oscillations. This greatly reduces the alternating tensile stresses on the screw. When it comes to fatigue, the compressive forces are not so important, therefore, the preload reduces the tensile forces benefiting the joint in relation to the cyclic loads.

The alternating (F_a) and average (F_m) forces on the bolts are:

$$F_a = \frac{F_b - F_i}{2} \qquad\qquad F_m = \frac{F_b + F_i}{2} \tag{8,9}$$

Being F_b:

$$F_b = F_i + CP \tag{10}$$

Where Fi is the preload, P the load applied on the screw and C is the stiffness constant of the joint, calculated by:

$$C = \frac{k_b}{k_m + k_b} \tag{11}$$

With k_b being the bolt stiffness constant and k_m the stiffness constant of the joint material.

$$k_b = \frac{\pi d^2 E}{4l} \tag{12}$$

Where d is the diameter of the screw, l is the length of the screw and E is the Modulus of elasticity of the same. The alternating and average tensiles on the screw are:

$$\sigma_a = k_f \frac{F_a}{A_t} \qquad\qquad \sigma_m = k_{fm} \frac{F_m}{A_t} \tag{13, 14}$$

If At the area under tensile stress of the screw, kf is the tensile concentration factor obtained in Tab. 1, and k_{fm} which is the concentration factor for medium stresses and is generally 1.0 for preloaded bolts.

Table 1: Fatigue stress concentration factors for screws - adapted from Norton (2000)

Brinell Hardness	SAE Grade (UNS)	Metric Class (ISO)	Kf Rolled Threads	Kf Cut Threads	Kf Fillet
< 200 (annealed)	≤ 2	≤ 5.8	2.2	2.8	2.1
> 200 (hardened)	≥ 4	≥ 6.6	3.0	3.8	2.3

The tensile stress resulting from the pre-load Fi is,

$$\sigma_i = k_{fm} \frac{F_i}{A_t} \tag{15}$$

Thus, as Norton (2000) presents, the equation below computes the fatigue safety coefficient (N_f):

$$N_f = \frac{S_e(S_{ut} - \sigma_i)}{S_e(\sigma_m - \sigma_i) + S_{ut}\sigma_a} \tag{16}$$

Where S_e is the limit of fatigue resistance and S_{ut} the maximum tensile strength:

$$S_e = k_a k_b k_f S'_e \tag{17}$$

The factor k_a refers to the surface finish, kb corresponds to the size of the part and k_f is found in Tab. 1 above, and the corresponding value of S'_e indicates the reliability.

Understanding the functioning system and the influences on the super bolt, follows the experiment carried out and its results and analyzes.

3. METODOLOGY

From the super bolt characterization, operation and applications, a tribological aspect presentation of the interaction of thread, an tensions in threads indication and preload obtained in the literature, an experimental procedure was established, in which the interaction of the screw And the thread, both of AISI 4140 steel, through the test in a tribometer.

The objective of this study is to identify the best way to torque a screw generating the least possible energy loss to the system, thus increasing the efficiency of super bolt use and reducing the possibility of catastrophic failures in this form of fixation.

3.1. Experimental Procedures

The purpose of this experiment is to measure the coefficients of friction between the surfaces of the AISI 4140 steels belonging to the jackbolt and the superbolt thread under some specific conditions. The equipment used for this experiment is the pin-on-disk tribometer, Microtest, model SMT-A / 0100 (Fig. 3).

The standard used to carry out the tests was the ASTM STANDARD G99-05. Thus, test pins were machined with the jackbolts and disc material itself according to the recommendations of the standard used for this test.

Figure 3: Tribometer pin on disc Microtest. Source: The authors' collection

As a superbolt is used in industrial environments, under the most diverse contour conditions, based on practical observations of its field use related to a hydraulic press, the following boundary conditions were considered for the contact surfaces between the jackbolt thread and the superbolt itself, for this experiment.

Ambient temperature equal to 25ºC, tangential velocity of the pin on the disk equal to 0.1 m/s, load applied on pin 3 N.

a) Non-lubricating contact surfaces
b) Contact surfaces with de-oiling oil lubrication WD-40
c) Contact surfaces with white grease lubrication (Fig. 4)
d) Contact surfaces with metal conditioner lubrication Militec.

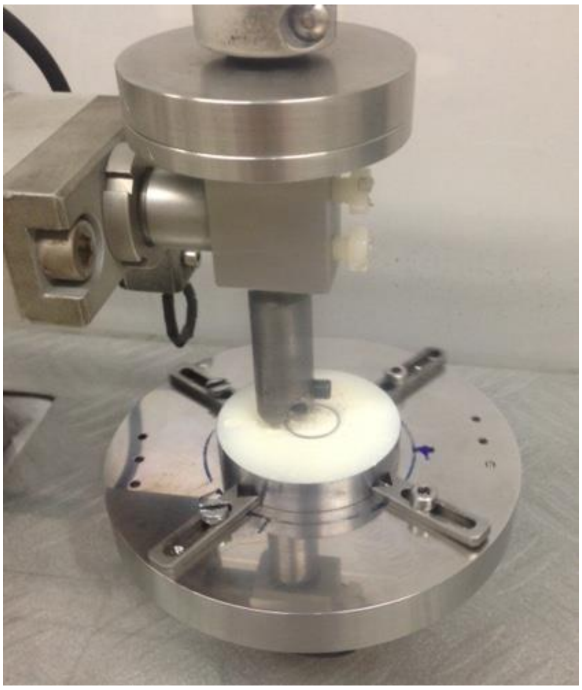

Figure 4: Pin on disc test with white grease. Source: The authors' collection

4. RESULTS AND DISCUSSION

The graphs and results obtained in the tribometer for each experiment are presented below.

a) Non-lubricating contact surfaces (Fig. 5).

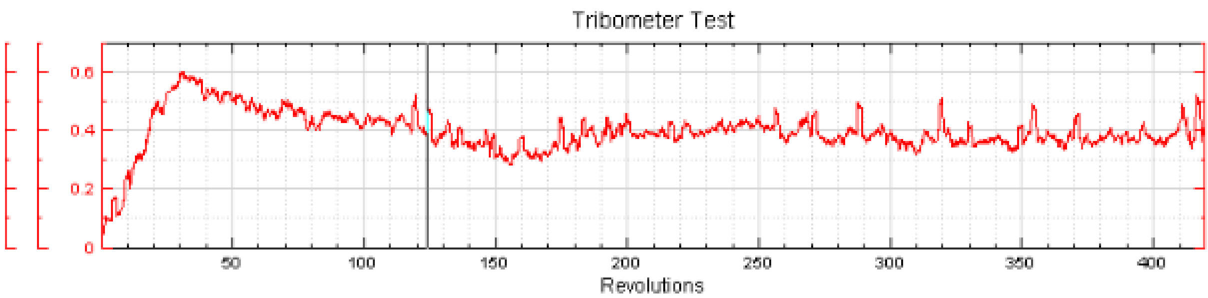

Figure 5: Non-lubricating contact surfaces. Source: The authors' collection

As it was the first test for the contour conditions presented, 200 disk revolutions were generated to wait for the friction coefficient stabilization obtained in the graph. As it can see, from revolution number 200 to 400, the conditions became more stable and the average result obtained was generated from this data region.

Friction coefficient result of 0.38.

b) Contact surfaces with de-oiling oil lubrication WD-40 (Fig. 6).

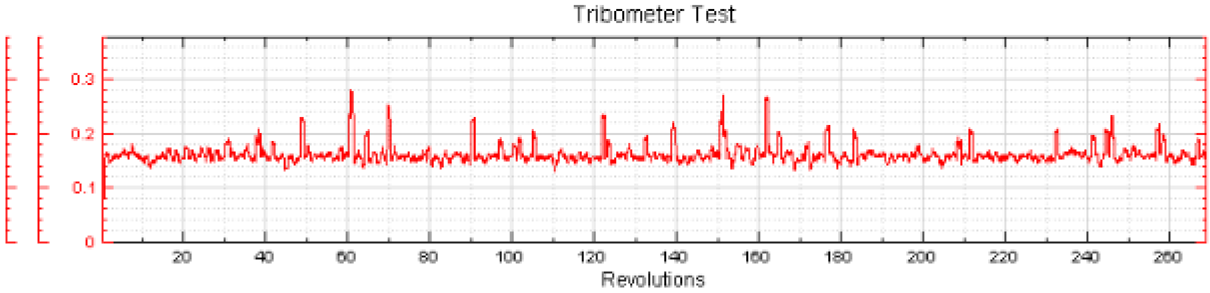

Figure 6: Contact surfaces with de-oiling oil lubrication WD-40. Source: The authors' collection

Figure 6 shows a results curve much more stable, in this way all the data were used to generate the final result. Friction coefficient result of 0.16.

c) Contact surfaces with white grease lubrication (Fig. 7).

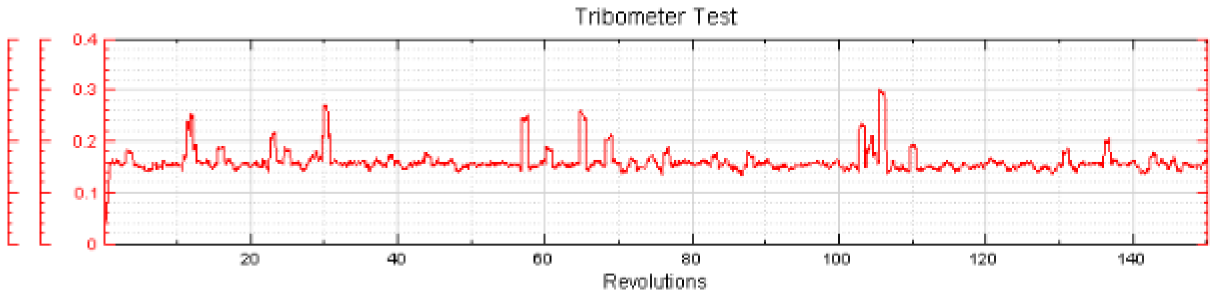

Figure 7: Contact surfaces with white grease lubrication. Source: The authors' collection

The graph shows a stable results curve with the exception of the first 3 revolutions that were discarded. So almost of all data was used to generate the final result.
Friction coefficient result of 0.17.

d) Contact surfaces with metal conditioner lubrication Militec (Fig. 8).

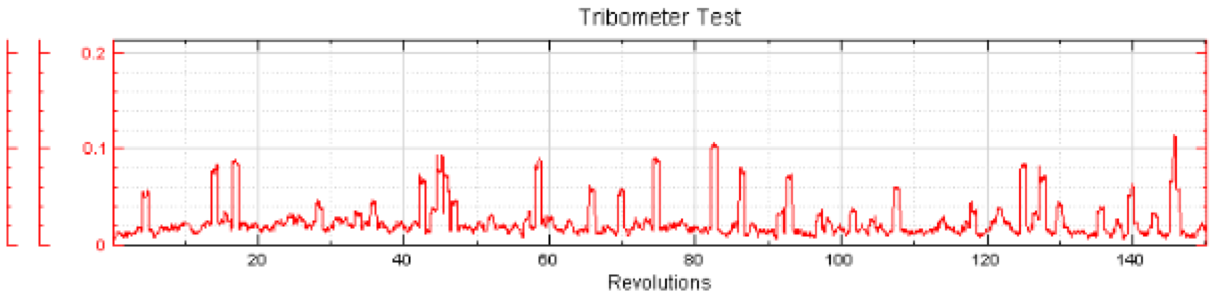

Figure 8: Contact surfaces with metal conditioner lubrication Militec. Source: The authors' collection

The graph shows a stable result curve with an exception until revolution number 20. So all data starting from revolution 21 was used to generate the final result.
The friction coefficient result in this case was 0.03.

4.1. Calculation of Preload-to-Fricition Ratio

Considering the application of a superbolt in a hydraulic press, which must withstand the load of 2500 tons, and with distribution of this load in 4 columns of its structure, the resultant load in each superbolt is 6125×10^3 N. The super bolt chosen for this use is fixed by a main nut with 32 units of jackbolts of size M24 that tighten the superbolt and ensure that it does not come loose. Using the proposed equation, we can calculate the tensile in each screw:

$$A_t = \frac{\pi}{4}\left(\frac{d_p + d_r}{2}\right)^2 \qquad (2)$$

Where:

$$d_p = d - 0{,}649519\,p \qquad d_r = d - 1{,}226869\,p \qquad (3,4)$$

Being:

$$\sigma_t = \frac{F}{A_t} \qquad (7)$$

We then find the stress σt = 543 MPa which is lower than the reference value of the tensile stress of the material found in the tensile test (σe 4140 = 1138 MPa), taking into account the mechanical strength requirement.
The friction coefficients values according to the results obtained in the tests in the tribometer were:

a) Non-lubricating contact surfaces – μt = 0.38
b) Contact surfaces with de-oiling oil lubrication WD-40– μ_t = 0.16
c) Contact surfaces with white grease lubrication – μ_t = 0.17
d) Surfaces with metal conditioner lubrification Militec – μ_t = 0.03

The preload calculation, using the friction values, is obtained by the equation below, preload values implemented for each contact condition and for a torque of 288 Nm, related to a hydraulic press column.

$$T = F_i\left(\pm\frac{P}{2\pi} + \frac{\mu_t r_t}{\cos\beta} + \mu_n r_n\right) \qquad (1)$$

Where T has been assigned value 288 Nm, P is the pitch of the thread which is 3 for screw M24, μ_t is the coefficient of friction between the threads for each tightening situation, r_t is considered a value of 180°. Coefficient β is half of the thread angle (30°), μ_n was considered for friction between non-lubricated surfaces (0.38), and r_n also considered a value of 180°, for these assignments are the values of the preload generated in the screw (Fi), shown in Tab. 2.

Table 2: Results of the preload generated on the screw (Fi), for a same torque of 288Nm, in each condition of surface contour

Surface Contour Condition	Preload (N)	Increase in relation to non-lubricated surface (%)
Non-lubricating contact surfaces	30.61 N	0%
Contact surfaces with de-oiling oil lubrication WD-40	58.42 N	91%
Contact surfaces with white grease lubrication	56.1 N	83%
Surfaces with metal conditioner lubrification Militec	126.21 N	312%

Using the same torque load for each
jackbolt at 288 Nm, the high preload value inserted in the hydraulic press column is shown when we have a very low coefficient of friction. The high efficiency is thus characterized, in relation to the loss of energy by friction, using a suitable lubrication.

4.2. Fatigue Calculation on Jackbolts

From the preload found in the tribometer by the application of the metal conditioner, the fatigue safety coefficient was calculated. By the equation below:

$$N_f = \frac{S_e\left(S_{ut} - \sigma_i\right)}{S_e\left(\sigma_m - \sigma_i\right) + S_{ut}\sigma_a} \qquad (16)$$

A value of kb was used to perform the fatigue calculations as found in formula (12) with Elasticity modulus according to Norton (2000) of E = 206.8 GPa and screw data M24x220 mm. Km which is the stiffness constant of the joint material was considered 8 times greater than the stiffness of the bolt because it had the same type of material. For the calculation of formula (16) the tightening condition of the screw was considered using the Militec metal conditioner, with a preload of 126.21 N, according to the preload calculations. Fatigue concentration factors K_f, was considered according to table 1, as value 3. And the fatigue limiting factors in the formula (17) k_a, k_b and k_f referring to the limit of fatigue resistance were considered as 0.73, 0.85 and 0.76 respectively. Where the value found for the fatigue safety coefficient was 5.07, which is considered high when considering the safety coefficient, however, due to the importance of its function in the machine, the result is adequate.

5. CONCLUSIONS

Method of use and tightening for a Superbolt:

- Use of jackbolts, only 1 time, thus guaranteeing the maximum load capacity for the same and the dimensional integrity for the entire fastening system between the superbolt and the column.
- Use of a dry and clean surface just for the bolt underhead surface, so its coefficient of friction will be higher, and as a consequence, it will have greater difficulty to failure by loosening performance.
- Militec friction oil reducer only on fastener threads, reducing the coefficient of friction between the surfaces in this region and increasing the actual preload implemented in the press column , in relation to the same jackbolt, without lubrication, by 312%. With a higher preload, the equipment fatigue life is increased.
- Cross-tightening condition, generating a better distribution of loads between jack bolts during total tightening.

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7. RESPONSIBILITY NOTICE

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