# POLITECNICO DI MILANO

Master of Science in

Mechanical Engineering

# Design and optimization of the tightening procedure used by the M10X60 Hexalobular flanged screws


*University Supervisor:* **Professor Barbara Rivolta**

*Company Supervisor:* **Ing. Massimiliano Testa**

*Thesis of:*

**Wei Jiming**

**767617**

# Abstract

Nowadays, a high accurate clamping load can be applied easily to a bolted joint, thanks to the proper tightening method and high sensitive and accurate driver unit. But the precise clamping force, actually, is not always guaranteed during the bolt's service life, especially when a dynamic load is applied to the joint or the bolt is employed for a high working temperature condition.

The aim of this study is to design a proper tightening procedure able to guarantee an accurate initial clamping load and minimize the clamping load lost due to the working conditions, thus optimizing the joint performance.

The mutual influence between bolt and clamped parts is somewhat of a complex situation and still lacking of study. Therefore the basic theory and practical experience are taken as the basics of this thesis to describe how and why some new tightening procedures have been designed.

Then experimental method has been defined for performing lab tests. And thanks to the ultrasonic method, the clamping force in the assembled bolt has been measured precisely.

In tests the M10X60 Agrati zinc flake coated bolt used for fixation of calipers in car's brake system is taken as a reference test-piece.

The new tightening procedures are performed firstly on the dummy joints to measure the trends of clamping load over time at room temperature and the fall in clamping load during a 5 steps repeated heating and cooling process. Secondly, the same tests are performed on the real calipers to enhance the reliability of the previous measurements.

At last, based on the test results the new tightening procedures are judged by three aspects: the resistance to embedding, accuracy and joint security. By this way the optimal tightening procedure is suggested.

***Keywords:*** *clamping load, embedding phenomenon, tightening procedure, self relaxation resistance.*

# List of Figures

# List of Tables

# Index

# CHAPTER 1: INTRODUCTION

## 1.1 Fastener Industry

AGRATI Group is one of the leading European manufacturers in bolt industry, it is composed by ten production units, has a surface area of 500,000 $m^2$ and a capacity of 150,000 tons per year, over 500 machines dedicated to the production of advanced fastening systems. The different specialties of the various units and the different production technologies offer AGRATI customers a complete and varied range of products. It includes over 5000 standard product codes and 9000 special ones. The actual production system of AGRATI Group allows AGRATI to make screws with thread diameters from M2.5 up to M33 and lengths up to 300 mm, while the diameters of nuts and ring-nuts can be from M2.5 up to M280.

## 1.2 The basic theory of fastening bolted joint

On the screws, a helical structure is used to convert the rotational movement back into an axial clamping force. After tightening, due to the friction the linear movement is prevented to convert to rotary, so that the screw does not slip even when axial force is applied.
For a bolted joint at least two threaded elements are required:

- One internal (female) thread (eg. Nut)
- One external (male) thread (eg. Bolt)

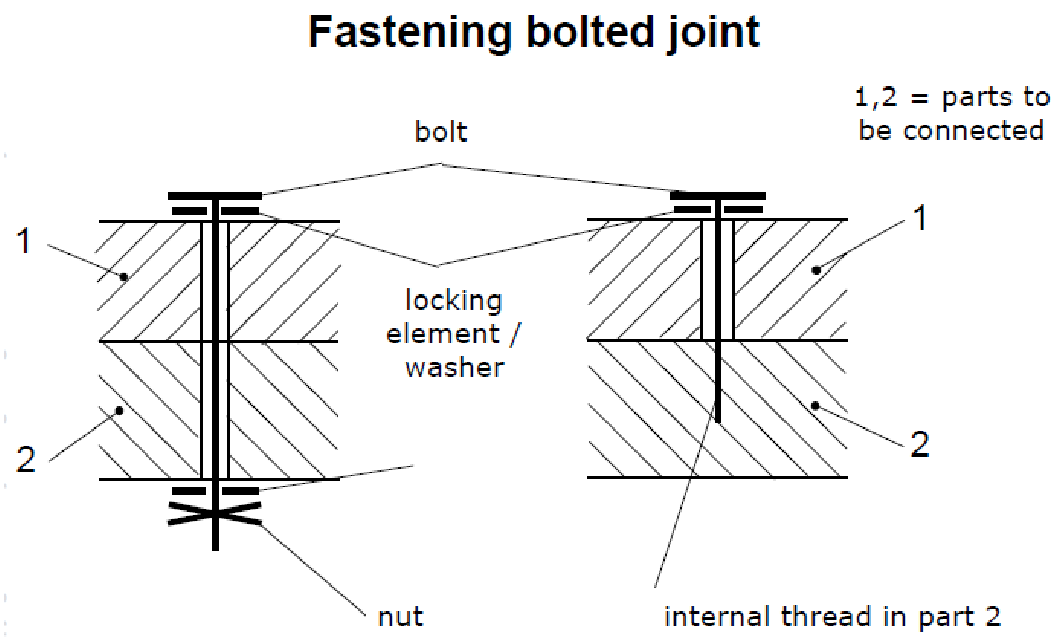



*Figure 1.1 Basic components in a bolt jointed system*

Theoretically, a bolt can be simplified to an one dimensional tensile test sample and equally the clamped parts to an one dimensional compress test sample; so according to the Hook's law, when the bolt is stressed in the elastic deformation domain, the tensile force in the bolt and clamped part is linearly proportional to the axial elongation:

$$F_B = K_B \Delta L \qquad\qquad F_P = K_P \Delta L$$

where $K_B$ and $K_P$ are the spring constants of bolts and clamped parts.

So a bolted joint system can be simulated as a parallel connection of two springs. And by this way the working principle of bolted joint can be introduced in the following 3 steps:

*Step 1:* Assembly before tightening.
In Fig. 1.2 the left black spring represent the clamped parts and red spring on the right side is the bolt. Before tightening, no load is applied both on the parts and on the bolt, so as spring they are in initial length

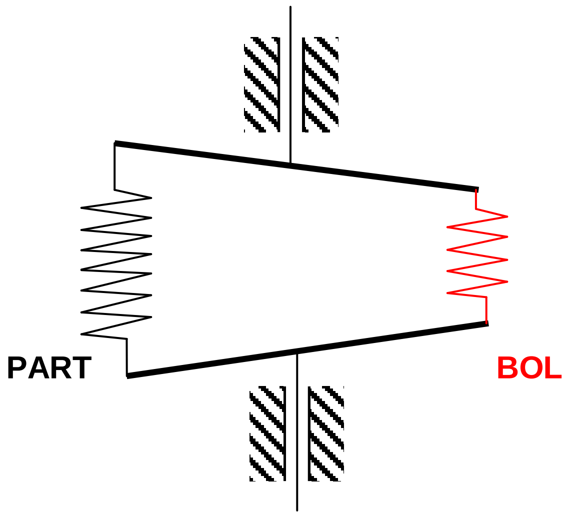



***Figure 1.2 Theoretical model of bolted joint before tightening***

*Step 2:* Application of the preload.
In this step the bolt is tightened with a pre-torque; the bolt is elongated (shown in the graph as $f_{b.p}$) and the parts are compressed ($f_{p.p}$). The parts are clamped with a designed preload, and the bolt is elongated to withstand this force.

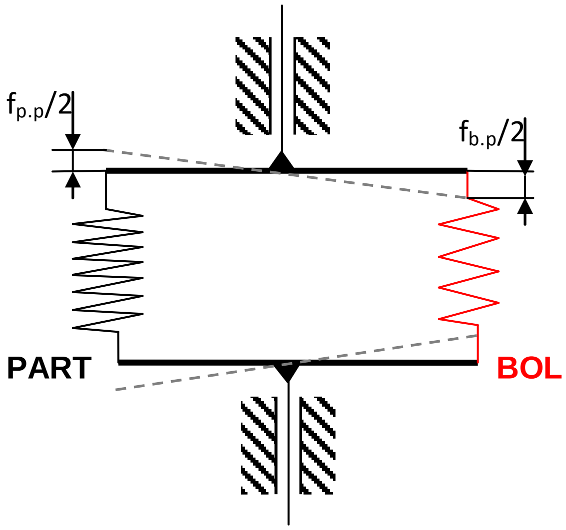



*Figure 1.3 Theoretical model of bolted joint after tightening*

*Step 3:* Application of the working load

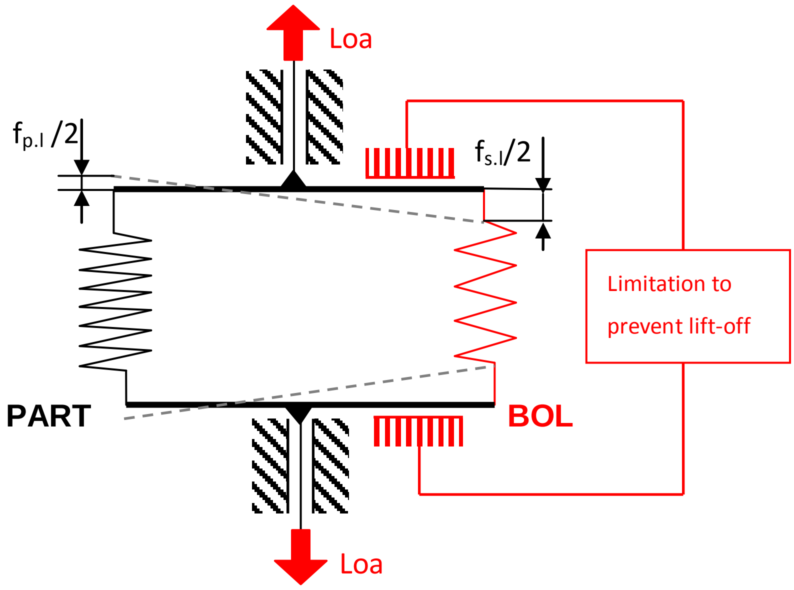



*Figure 1.4 theoretical model of a bolted joint after application of the working load*

As shown in the sketch, after the working load is applied to the system, the bolt, shown in the graph as the red spring, is elongated (fs.l) to generate more force to withstand the working load. On the other hand, the compression force applied on the parts is decreased (the decreased elongation is fp.l).

The amount of working load that the joint system can withstand is not only decided by the bolt and the assembled parts, but also determined by the preload value. The basic demand of a fastener system is joint two assembled parts, so the working load acting on the bolted joint is limited by the minimum clamping force demanded to avoid the lift-off.

To get a better understanding of how the load is distributed in a bolted system, a force/deformation curve can be studied.

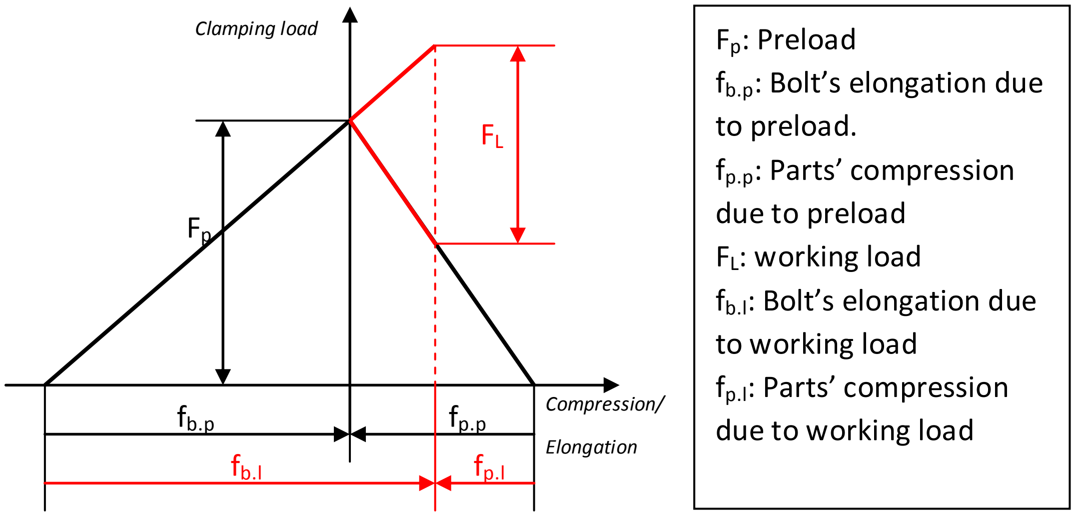



***Figure 1.5 Force/Deformation curve of a bolted system***

In the zero working load condition, the assembled components are clamped by a preload applied by tightened bolt, shown in the graph as Fp. In this situation, the elongation of the bolt is fb.p and compression of assembled components is fp.p.

*where*

$$f_{b.p} = \frac{F_p}{K_B} \qquad\qquad f_{p.p} = \frac{F_p}{K_P}$$

In which $K_B$ and $K_P$ are the spring constant of screw and clamped parts [N/mm]. When a working load Fl is applied, the elongation of the bolt increases to fb.l and compression of assembled components decreases to fp,l, the force generated by the elongated bolt is separated into two parts: one part is applied on assembled components to ensure the minimum clamping force, and the other part resist the working load.

*where*

$$f_{b.l} = \frac{F_p}{K_B} + \frac{F_l}{K_B + K_P} \qquad\qquad f_{p.l} = \frac{F_p}{K_P} - \frac{F_l}{K_B + K_P}$$

Another very important variable in bolted joint system is the "Friction coefficient" $K_{tot}$, what connects the tightening torque with clamping load.

$$M = K_{tot}F \quad wit \quad K_{tot} = f(\mu_{tot}, D_{z}, d_{m}, $$

In this equation the parameter $K_{tot}$ includes, from the mathematical points of view, all the factors that affect the relationship between torque and preload. In the real applications many "noise" like torsion, bending, plastic deformation of the threads can seriously influence the tribologic behavior

of a joint system. So sometimes a large number of tests need to be done to predict the resulting and desired clamping force by the application of torque.
The measurement of the friction coefficient is carried out on the torque/tension test machine. When the bolt is tightening, the torque applied by the machine will be recorded by a torque sensor and at the same time the corresponding clamping force is measured by a force sensor. Generally a specific point is chosen according to the standard, at this point the ratio between force and torque is calculated as the friction coefficient.
The knowledge of the friction coefficient makes possible to achieve a particular clamping load by applying a designed tightening method.

## 1.3 Traditional tightening methods

The tightening techniques in use today do not control the preload produced in the bolt directly, instead, the clamping load is sensed as a function of the tightening torque, of the elastic linear deformation, of the angle of rotation or by determining the yield point of the bolt. According to the parameter monitored and controlled by the tightening tool tightening methods can be divided into several types shown as follows.

### *1.3.1 Torque –controlled tightening*

This tightening procedure is based on the relationship, which is described by the $K_{tot}$, between clamping force and tightening torque:

$$M = K_{tot} F$$

As an experimental determined factor, $K_{tot}$ usually has an inevitable scatter of about ±35%, this brings a poor accuracy to the torque-controlled tightening system. And for most tightening tools used in the torque-controlled tightening, a high accuracy of input torque is hard to provide. As shown in the Fig. 1.6, the scatters of $K_{tot}$ and input torque lead to a large possible range in preload.

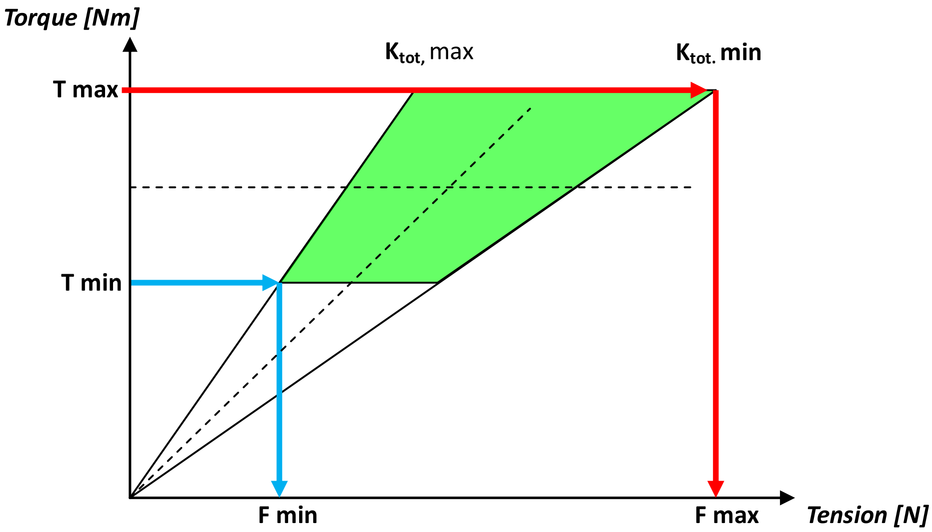



***Figure 1.6 The Load/Torque curve of a bolt when tightened by torque-control tightening.***

Experience shows that, for torque-controlled tightening the max scatter of the clamping load can reach to ±30%. But torque-controlled tightening is still the mostly used tightening method for standard assemblies on account of the simple handling and the cost-effective tightening tools.
The torque-controlled tightening is based on the experimental relationship between clamping load and tightening torque; this brings to a problem, even perfect input torque can give a ±25% variation in preload due to the possible range in $K_{tot}$. To fulfill the demand of high accuracy preload, angle-controlled tightening methods base on the Hook's law is designed. As mentioned above, a tightened bolt can be seen as an elongated spring. The spring factor $K_B$ can be measured as a more reliable connection between the clamping load and bolt's elongation, which can be monitored and controlled by tightening systems:

$$F_B = K_B \Delta L$$

Based on this function, angle-controlled tightening is designed.

### *1.3.2 Angle-controlled tightening*

Angle-controlled tightening method is an indirect method of the bolt elongation measurement. Theoretically the axial displacement of a bolt is directly linked to the angle of rotation by the equation:

$$\Delta L = P \times \frac{\Delta\theta}{2\pi}$$

where P is the pitch of the bolt, ΔL is its elongation when turned Δθ degrees. But in the real bolted joint system, as shown in Fig. 1.3 (section 1.2) when the bolt's under head surface mates the upper clamped part and then turned Δθ degrees, the bolt elongates $f_b$ [mm] and synchronously the clamped parts are compressed $f_p$ [mm]. So, actually, the axial displacement ΔL is the sum of $f_b$ and $f_p$.

$$\Delta L = f_b + f_p$$

where $f_b$ is the elongation of the bolt and $f_p$ is the compression of the clamped parts.
According to the test results, when tightening a bolt the relationship between preload and turned degrees can be introduced in following four stages:

1. The first few turns of the bolt produce no preload at all, because the bolt has not yet attached with joint members and they are therefore not yet involved. This situation is shown in Fig. 1.7A
2. Finally the bolt starts to pull clamped members together. There may be frictional restraint between joint members and surrounding structures. And clamped parts may not be perfectly flattened. As a result, although the bolt has been stressed, most of the input turn is absorbed by

the clamped members and the bolt sees only a small increase in preload, as shown in Fig 1.7B. This process is called snugging the joint, and the amount of turn required varies unpredictably.

3. After the joint has been sugged, all the bolt and clamped parts start to deform simultaneously, with individual deformations in inverse proportion to individual spring constants:

$$f_{b.p} = \frac{F_p}{K_B} \qquad\qquad f_{p.p} = \frac{F_p}{K_P}$$

   Preload now starts to build more rapidly in the bolt, following a straight line whose slope is equal to:

$$Slope = \frac{\Delta F_P}{\Delta \theta} = \left( \frac{K_B K_P}{K_B + K_P} \right) \frac{P}{2\pi}$$

   where $K_B$ and $K_P$ are the spring constants of bolt and clamped parts (N/mm), P is the pitch (mm), $F_P$ is the preload (N), and θ is the input turn in degrees.

4. With the increasing of tension in bolt and compression in clamped parts, the yielding situation of some components is reached, the further buildup of preload is limited.

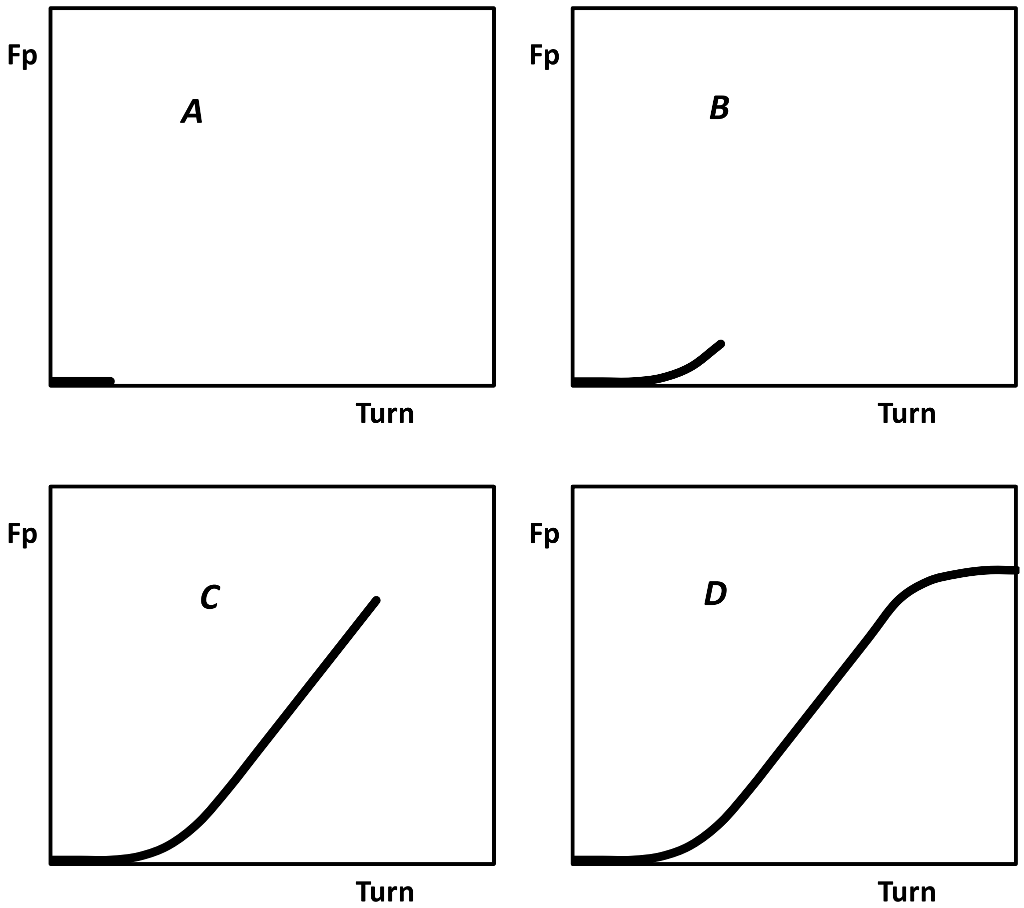



*Figure 1.7 Step-by-step the preload in a joint increases with degrees the bolt is turned.(A) bolt run-down process, no preload. (B) Snuggging process, the joint members are pulled together. (C) Bolt and clamped parts deforming elastically. (D) Yielding happens in the joint.*

According to the theory, the preload is linearly proportional to the turning degrees only after the snugging process shown in Fig. 1.7(C). So in angle-controlled tightening, a torque (shown in Fig. 1.8) is designed as a threshold. The angle of rotation is not measured until the threshold torque is exceeded.

The spring constants $K_B$ and $K_P$ can be affected by the irregularity of bolt geometry, different tightening condition and irregularity of clamped parts, etc. And also, errors may happen when the tightening angle is measured and controlled, so in Fig 1.8, the relationship between tightening angle and preload can be shown as:

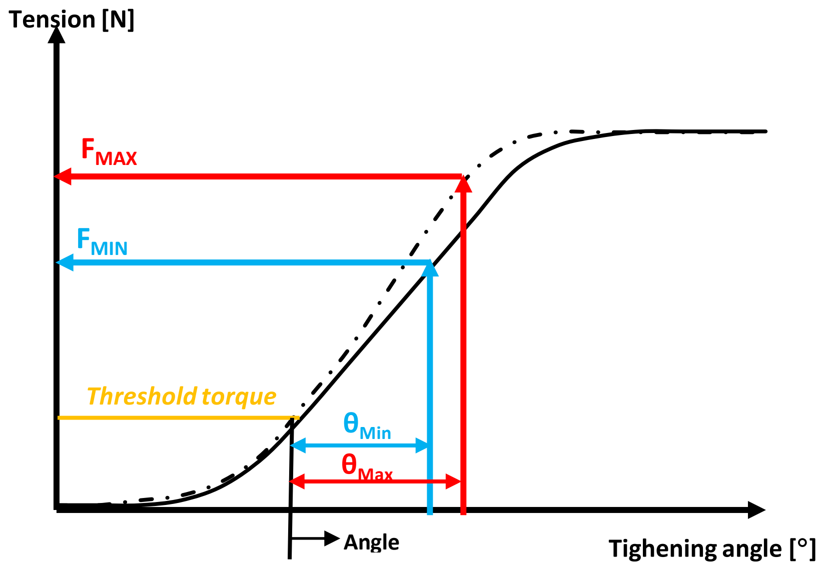



*Figure 1.8 Angle-controlled tightening (in elastic domain) with torque monitoring.*

Practice has shown that this technique only reaches its highest precision when the bolt is tightened into the plastic range, because angle errors have almost no effect on the clamping force scattering account of the approximately horizontal line of the deformation characteristic within the elastic-plastic domain (Fig. 1.9)

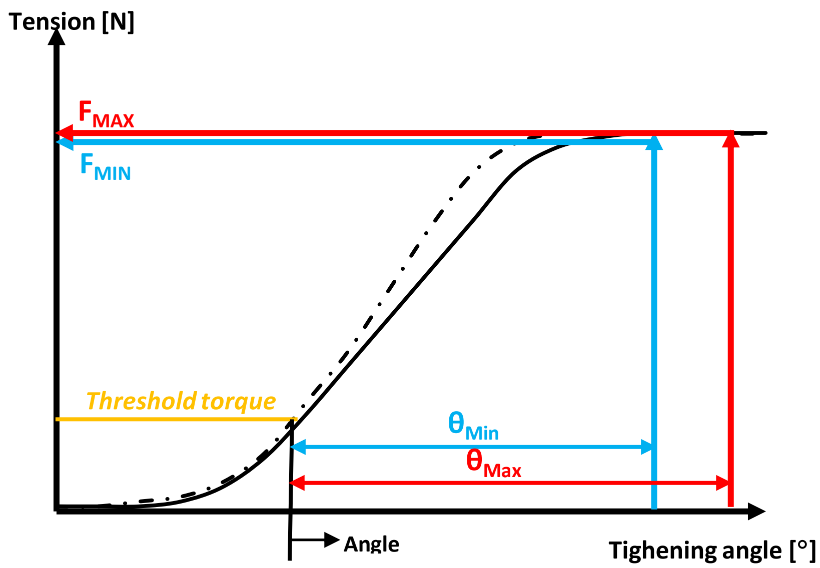



*Figure 1.9 Angle-controlled tightening (in plastic domain) with torque monitoring.*

## 1.4 Objectives

The main objective of this study is to make a complete analysis including the design and optimization of the new bolt tightening procedure to reduce the clamping load lost due to embeddings in the bolted joint systems. In this scope a detailed work will be sequentially performed as follows:

- Study of the embedding phenomenon: as the main reason of clamping load lost, some measurements are performed on the tightened bolt and clamped components. We will try to understand which is the key factor of self-relaxation;

- Design new tightening procedures: after consider all these factors, some new tightening procedures will be designed to against clamping load lost;

- Calibration of bolt elastic deformation property: to measure the clamping load in the real assembling situation, a indirectly clamping load measuring method will be carried out, in order to connect the elongation measured by the ultrasonic device to the corresponding clamping load, a calibration of the bolt is performed;

- Testing on the dummy: first all the tightening procedures will be performed on the bolts tightened on the dummy parts to prevent the unnecessary waste, In these tests, as the reference parameter, the clamping load will be measured to get a complete understand of the working performance of each tightening procedure;

- Testing on real calipers: after the tests on the dummy and according to the results, some good-performing tightening procedures will be chosen and applied on the real calipers.

# CHAPTER 2: EMBEDDING PHENOMENON

The embedding phenomenon is the loss of applied preload because of the plastic deformation of bolt and clamped components or the flattening of the clamped surfaces' irregularities after tightening.

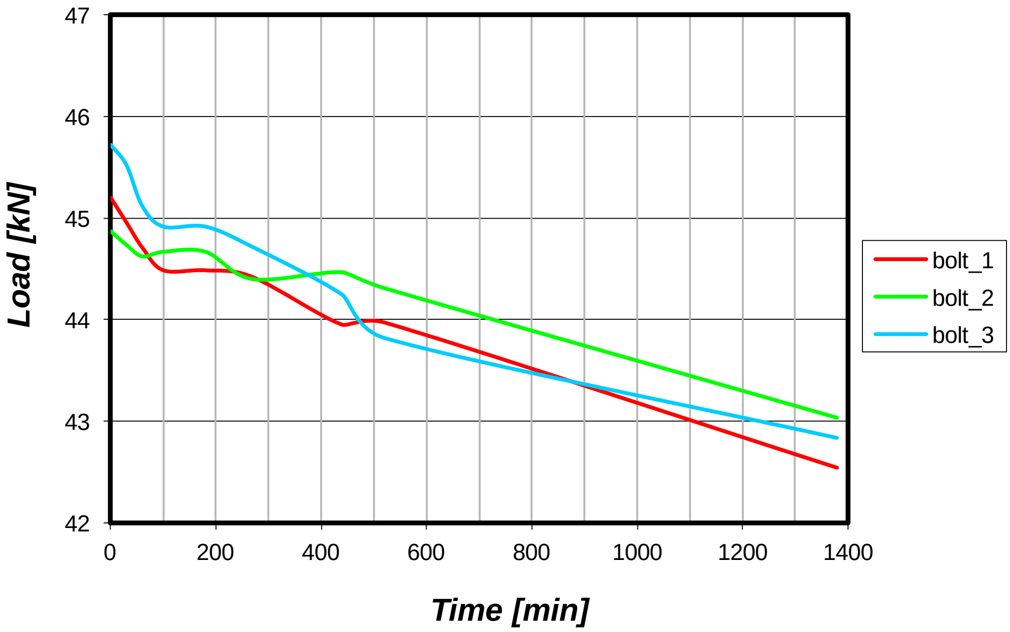



*Figure 2.1 the curve of clamping load of M10X60 changes with time*

As shown in the Fig. 2.1 in a tightened joint system, after the tightening the clamping load decreases with time, we find that in the normal environment temperature and no loading situation, the preload losses about 5% after 1300 mins. This kind of preload lost is an inevitable drawback of the bolt fastener industry.

In this thesis, new tightening procedures are designed to decrease this kind of phenomenon, so a comprehensive understanding of embedding is necessary.

## 2.1 Embedding phenomenon

### *2.1.1 Plastic deformation under the bolt head*

*Figure 2.2 The bolt under head surface of before(left)/after(right) tightening*

The left bolt is the under bolt-head surface before tightening and on the right is the same but after tightening; we can see that the coating has been scraped away.

*Figure 2.3 the area on the clamped component contact with under bolt head*

The shiny surface is caused by the compression of the axial clamping force and also the friction between two contact surfaces. On the clamped part, plastic deformation happens on the mating surface accompanied by the change of roughness.

### 2.1.2 Plastic deformation on the threads

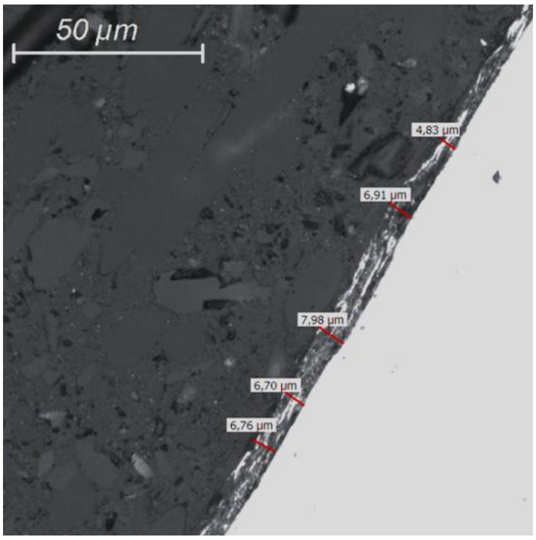



*Figure 2.4a) the coating thickness on the thread measured by microscope before tightening*

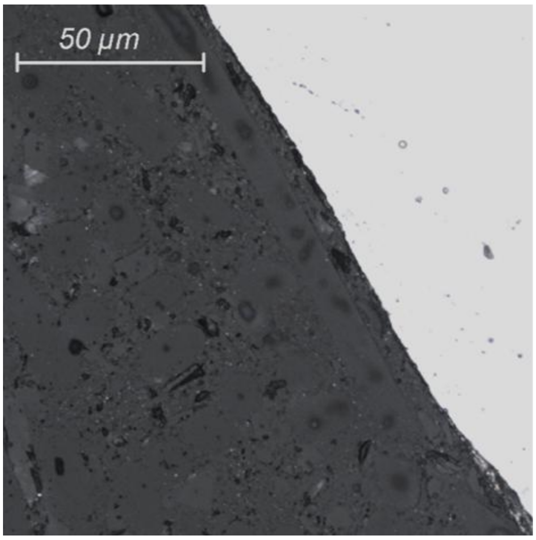



*Figure 2.4b) the coating thickness on the thread measured by microscope after tightening*

As shown in Fig. 2.4 a) which is the microscope image of thread before tightening and in Fig. 2.4 b) which refers to the bolt after tightening, we can see that due to the friction the coating has been scraped away

Pay attention, all the plastic deformation shown above is the total plastic deformation happens during and after tightening; we know that the plastic deformation after tightening is the main reason which lead to embedding, but it is technically hard to distinguish it from the total, so here the total deformation was discussed trying to explain the reason why embedding happens.

### 2.1.3 Summarize

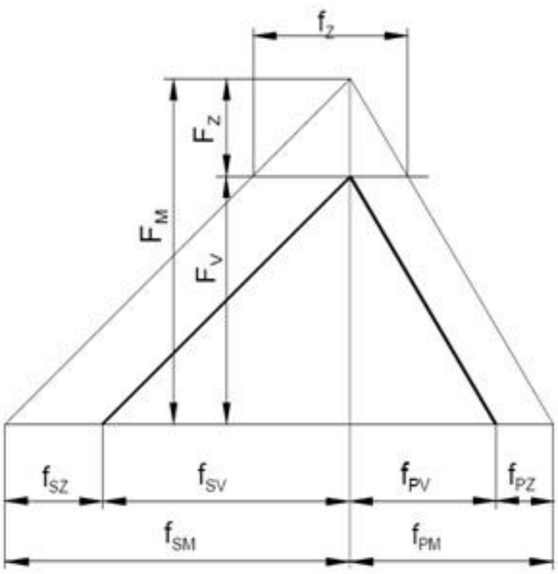



*Figure2.5 The force/deformation curve of an ideal fastener system*

The Fig. 2.5 is the Force/Deformation curve of an ideal fastener system, which is affected by the embedding, the clamping force decrease from Fm to Fv due to the embedding $f_z$. As explained in chapter 1.2 the preload is the determiner of:

- The accuracy of tightening method
- The working condition of the joint
- The maximum working load (to avoid lift-off)
- The risk of self-loosening

Therefore a stable preload is the premise of a reliable and safety assembling. As one of the biggest influencing factor, embedding should be taken into consideration.

### *2.1.4 Methods to decrease the embedding phenomenon*

According to the test results, the plastic deformation during and after tightening is mainly located on the contact surfaces between bolt and clamped part or between two clamped parts. So according to Dr. Grote[1] the plastic deformation which causes embedding, can be influenced by some variables as listed below:

- Number of separating gaps
- Surface roughness of the adjoining parts(hardness, roughness, evenness/waviness, cleanliness coatings)
- Production-caused failures
- Direction of the operating forces(in the separating gaps)
- Co-clamped parts and elements
- Amount of surface pressure at bolt head and nut contact area

Based on these, some methods can be applied to reduce the embedding influence on the functionality of the joint.

First method: when assembling, the bolt is tightened to a force a little higher than what is demanded so that after embedding, the reduced clamping force will equal to the target value.

[1] prof. Carl Grote- Otto von Guericke University Magdeburg - College of Mechanical Engineering

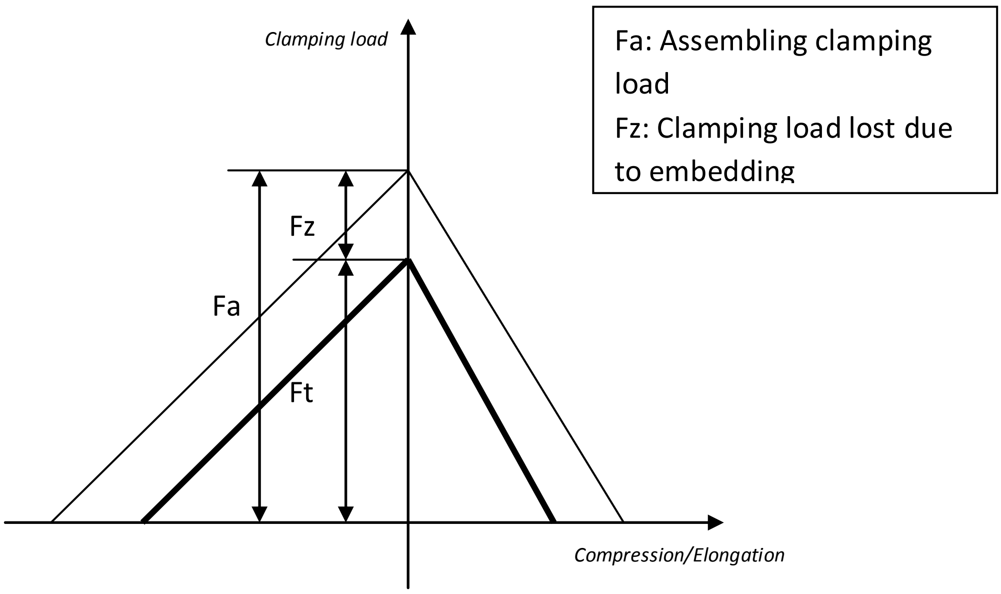



***Figure 2.6 The force/deformation curve change due to embedding phenomenon***

In the Fig. 2.6 Fa is the assembling load which equals to the sum of Ft and Fz, Ft is the target load which is required in the working condition and Fz is the clamping load lost due to embedding. To apply this method we need to measure the amount of preload lost due to embedding as precisely as possible.

Second method: to use a more resilient blot, which means, for example, adopt a thinner pitch diameter or a longer shank. We know that actually the lost of preload is the lost of elongation of bolt; by using a less stiff bolt, the clamping force will be less sensitivity to the variation of elongation

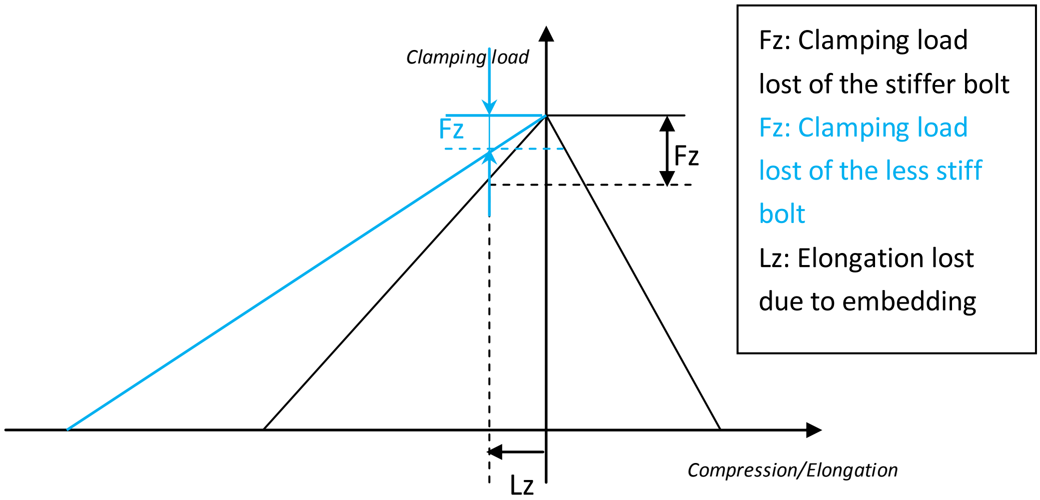



***Figure 2.7: The force/deformation curve of two kinds of bolts with different stiffness***

For the bolted joint system tested in this thesis, the assembled preload and the tightened bolt geometry already fixed. To improve the joint condition, instead of modify the components in the joint system, more attention is paid on the tightening procedure.

First of all, the stress situation on the mating surface where the plastic deformations happen is studied.

## 2.2 Stress situation

When tightening, the contact surface under bolt head is loaded by a nominal compression stress (s) applied by bolt and a shear stress (τ) applied by the friction; these kind of wearing and cutting phenomenon cause a plastic deformation of the surface

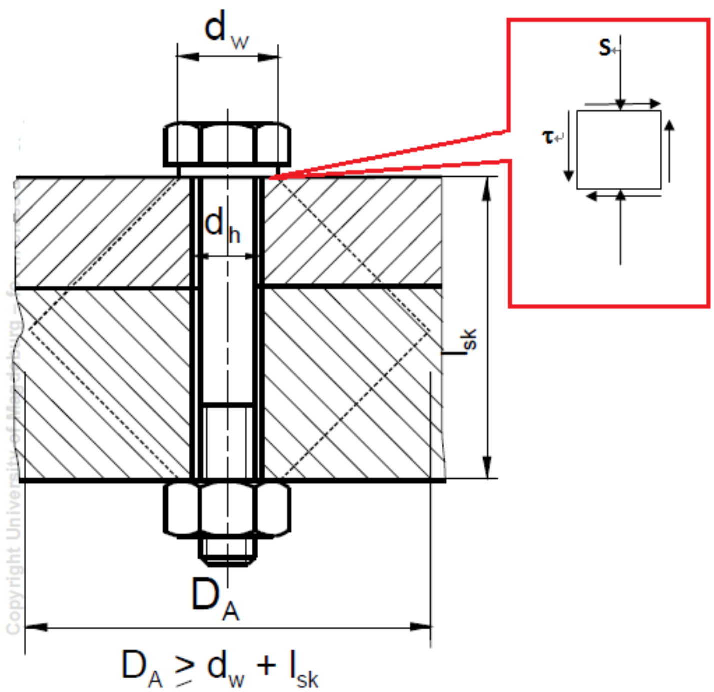



***Figure 2.8:*** ***Stressed situation on the surface of component contact with under bolt head.***

As we know in the ideal situation the clamping force is proportional to the tightening torque when the bolt is elastically deformed.

$$M = K_{tot} F$$

The stress under the bolt-head can be computed as:

$$S = \frac{4F}{\pi d_w^2}$$

$$\tau = \mu_{head} S$$

In which, $d_w$ is the under bolt-head contact diameter, $\mu_{head}$ is the friction coefficient between bolt-head and the mounted part.

As shown in the calculation we can get the equivalent stress (according to octahedral shear stress theory) applied on the component's surface.

$$S_{equivalent} = \sqrt{S^2 + 3\tau^2}$$

During tightening the stress is high enough to plastically deform the contact surface both on bolt and clamped parts.
And also on the thread, the stress situation is similar to the under bolt head surface: the higher is the tightening torque, the higher is the stress applied on the contact surfaces. After knowing the relationship between the tightening torque, the key parameter of the tightening procedure and the stress distribution on the contact surfaces, some new tightening procedures can be designed.
As mentioned above the self-relaxation of clamping force is because of the plastic deformation on the contact surface between the bolt and assembled components after tightened; therefore the new tightening procedures will mainly focus on minimizing this "delayed" plastic deformation. But because the bolt's tightening mechanism is a complex and specific issue, there are only few theories that could be use to explain what really happens on the contact surface between bolt and clamped parts. So here, in order to find the correct direction of design, the relaxation theory and the wearing theory are studied.

## 2.3 Stress relaxation theory

Relaxation in metals has long been recognized but still not be completely understood and described by models. It's based on the condition that, the plastic strain increase with time at the expense of elastic strain but the total strain keeps constant. And it's more evident at high temperature but takes place also at room temperature. A typical relaxation curve exhibit two clearly-defined sections shown in Fig. 2.9:

I) Rapid fall in stress

II) Slower fall of stress

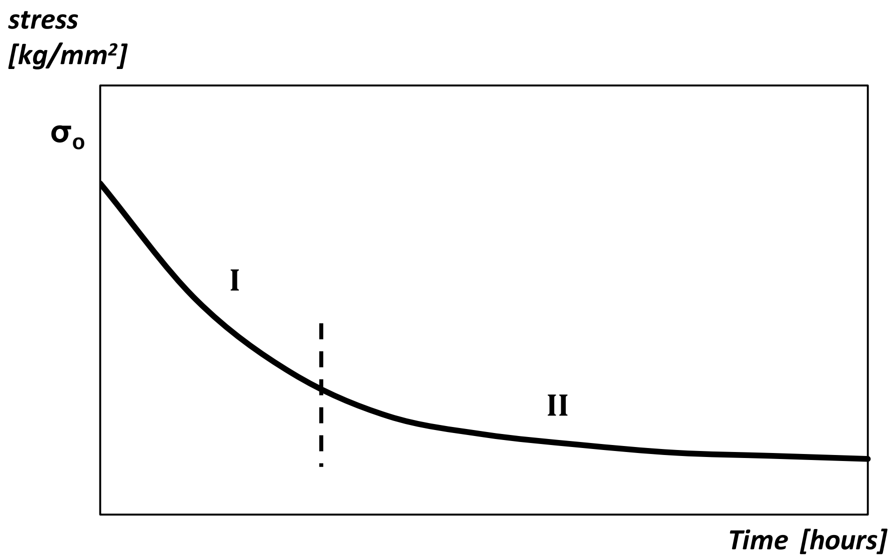



*Figure 2.9 A typical relaxation curve*

Relaxation process in metals and alloys depends on the physical properties of the material and its viscoelastic behavior but also is affected by pre-stressing and the loading history.

Outstanding contribution to the understanding of metal's relaxation phenomenon has made by the engineers from Soviet Union.

In the relaxation tests done by Vsesoi͡uznyĭ institut nauchnoĭ, some test-pieces were prepared from austenitic heat-resisting stainless steels. The test-pieces were loaded at 630°C, at an initial stress $\sigma_o$=18 kg/mm$^2$ (curve 1 shown in Fig. 2.9). After 150 hours, the test-piece was again loaded up to the original stress level of 18 kg/mm$^2$ and the relaxation test repeated in the same way for a further 150 hours (curve 2 shown in Fig. 2.8). By comparing the curve 1 and 2 we can find that the relaxation phenomenon in the repeated loading process is less pronounced.

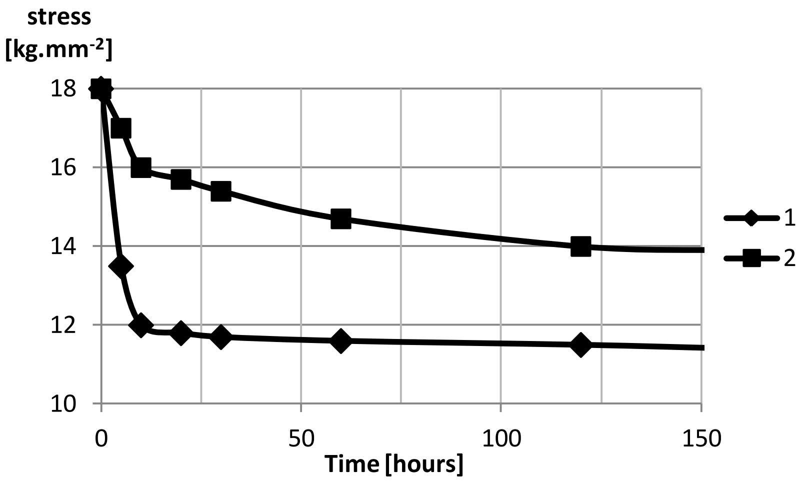



*Figure 2.9: repeated loading relaxation test*

Here, need to note that, in the tests $\sigma_o$ means the stress level which the test-piece is loaded in the second loading process (curve 2 in Fig. 2.8.), and $\sigma_{pre}$ is the stress level when the test-piece is loaded in the first loading process (curve 1 in Fig. 2.8) (pre-stress level).

Some more experimental data can complement this topic. As demonstrate by Vsesoi͡uznyĭ institut nauchnoĭ, with different combination of $\sigma_o$ and $\sigma_{pre}$, the relationship between the drop in stress $\Delta\sigma$ and the initial stress $\sigma_o$ after different pre-stress $\sigma_{pre}$ processes can be shown as following:

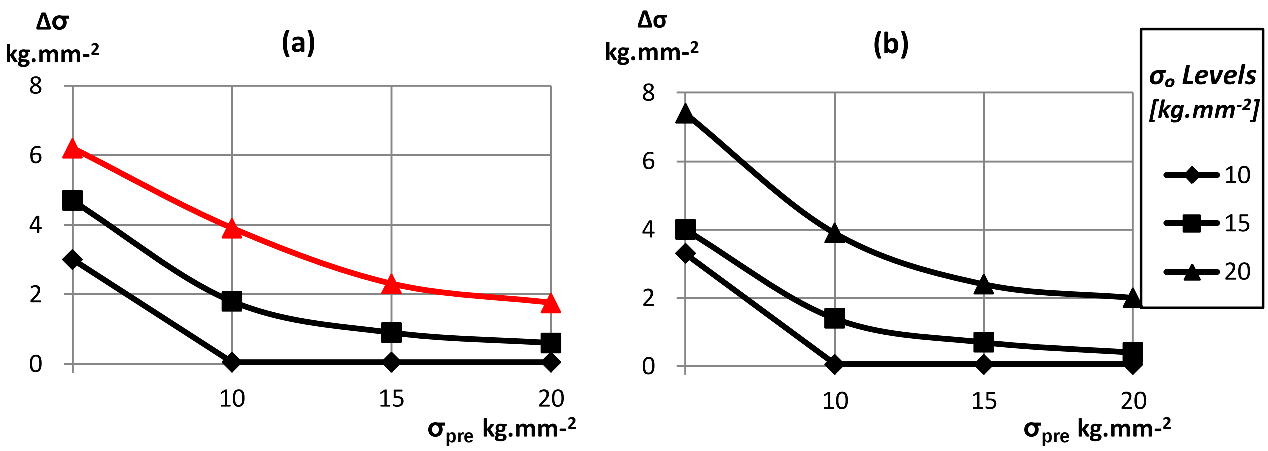



*Figure 2.10: Drop in stress Δσ as a function of prior stressing (a) testing time 20 hours;(b) testing time 200 hours.*

In these graphs, for example the curve of $\sigma_o$=20 kg.mm$^{-2}$ shown in Fig. 2.10a.
At an initial stress $\sigma_o$= 20 kg.mm$^{-2}$, the fall in stress after 20 hours without pre-stressing ( on x-axis $\sigma_{pre}$= 0 kg.mm$^{-2}$) is $\Delta\sigma$= 6.4 kg.mm$^{-2}$, whereas when pre-stressing to $\sigma_{pre}$= 10 kg.mm$^{-2}$ and $\sigma_o$= 20 kg.mm$^{-2}$ as before we observed a decrease of $\Delta\sigma$= 4.9 kg.mm$^{-2}$. moreover after applying a pre-stress $\sigma_{pre}$= 20 kg.mm$^{-2}$, the fall in stress shown on relaxation curve is only $\Delta\sigma$= 1.7 kg.mm$^{-2}$, that means three times smaller than the $\Delta\sigma$ in the no pre-stress treatment situation. Similar variations occur in other $\sigma_o$ level situation.

The results show that the fall in stress $\Delta\sigma$ under the subsequent loading depends not only on the initial stress $\sigma_o$ actually applied but also on the pre-stress $\sigma_{pre}$, and the pre-stressing is more effective if it is equal to or greater than the initial stress level $\sigma_o$ of the subsequent relaxation.
Based on this theory, some ideas come out: if a pre-stressing loading step can also decrease the fall in stress in a bolted joint system? And if yes, how to achieve a repeated loading process in the joint system?

## 2.4 The wearing theory

The tested bolt in this thesis is made of heat-treated steel whose tensile strength is about 1000 MPa and coated with Zinc flake the material of clamped parts is Al alloy. When tightening, a complex three-body wearing happens on the contact surface between bolt and clamped parts. According to the adhesive wear and abrasive wear theory, the amount of wearing is generally proportional to the nominal load **F** and the sliding distance **x**.
Based on this theory and according to what mentioned in chapter 1, the clamped load F is proportional to the tightening angle in an angle control tightening method, and the sliding distance x is the relative motion between bolt head and upper clamped part, by this way, with the increase of the tightening angle, the amount of wear increases too. What need to be noted is that the wearing phenomenon could increase the irregularity on the sliding surface, which could increase the embedding phenomenon in the bolted joint system significantly. So a complex tightening procedure with a large tightening angle needs to be avoided.

# CHAPTER 3: DESIGN OF NEW TIGHTENING PROCEDURES

The following chapter is aimed to describe the new tightening procedures in comparison with the nominal one which is actually in use for the real application of the bolt under investigation.

## 3.1 Nominal tightening procedure

In the assembling line, the tested bolt is tightened by an angle-controlled tightening procedure, shown as following graph. The first step is a torque controlled quick step, the bolt is tightened to a required torque quickly to eliminate the gaps between clamped components, then an angle controlled step proceeds, from the torque threshold, the bolt is tightened to rotate a designed angle.

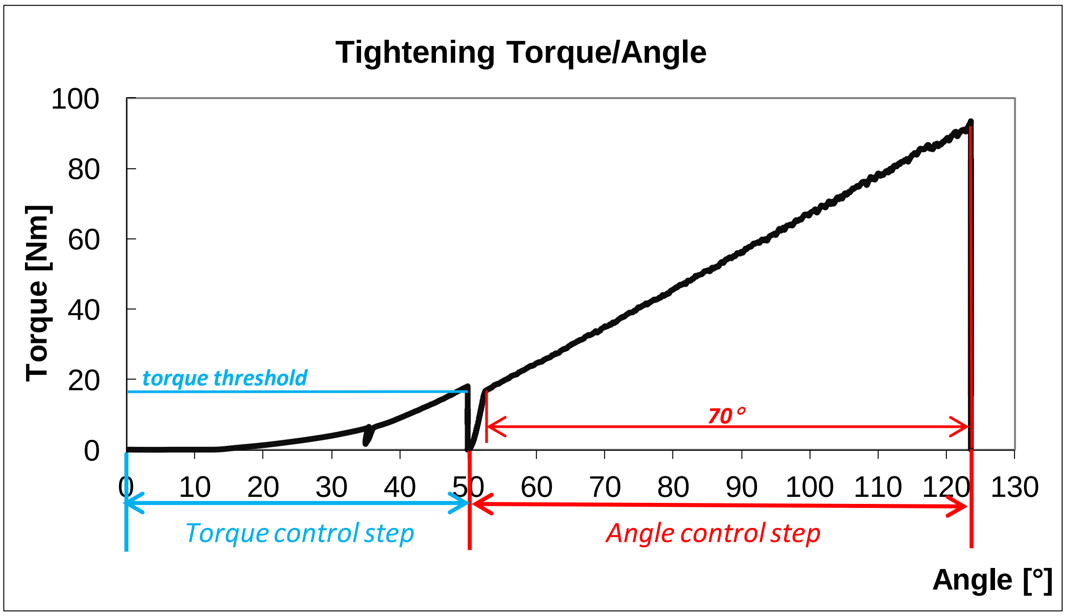



***Figure 3.1: a torque and angle controlled tightening curve***

the detail of the tightening procedure can be introduced as follows:

### *3.1.1 a):Nominal tightening procedure*

The actual tightening procedure used in assembling line of the bolt M10X60 is

Step 1: Quick-tight up to 5Nm @200RPM

Step 2: Tight up to 18Nm @20RPM and then rotate the bolt 70 ± 2° @ 10RPM

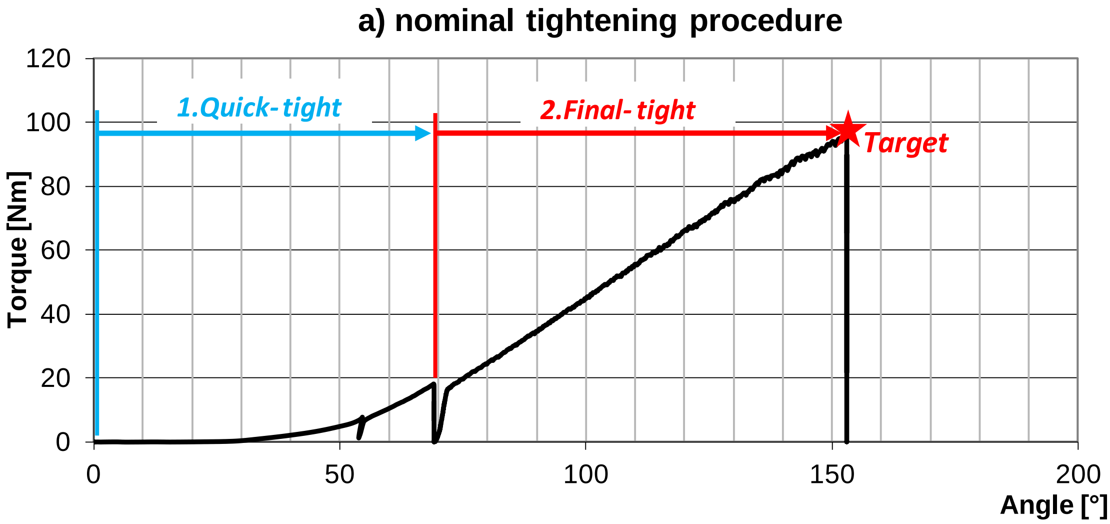



*Figure 3.2: Torque/Angle curve of nominal tightening procedure a)*

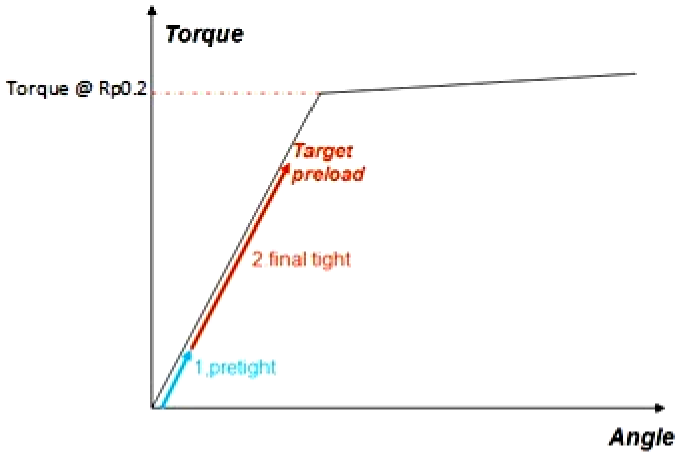



*Figure 3.2: description of nominal tightening procedure a)*

According to the theories and on the base of the nominal tightening procedure, some new tightening procedures have been designed to meet the following targets:

- Decrease the embedding phenomenon
- Increase the tightening accuracy
- Limit the difference from nominal tightening procedure

## 3.2 Tightening procedures based on the stress relaxation and wearing theory

Based on the relaxation and wearing theory some new tightening procedures (here named as b), c), d), e) and f) shown as follows) are designed. These new tightening procedures are the combination of a pre-tightening step and the nominal tightening procedure.

### 3.2.1 b): Two times of the nominal tightening procedure

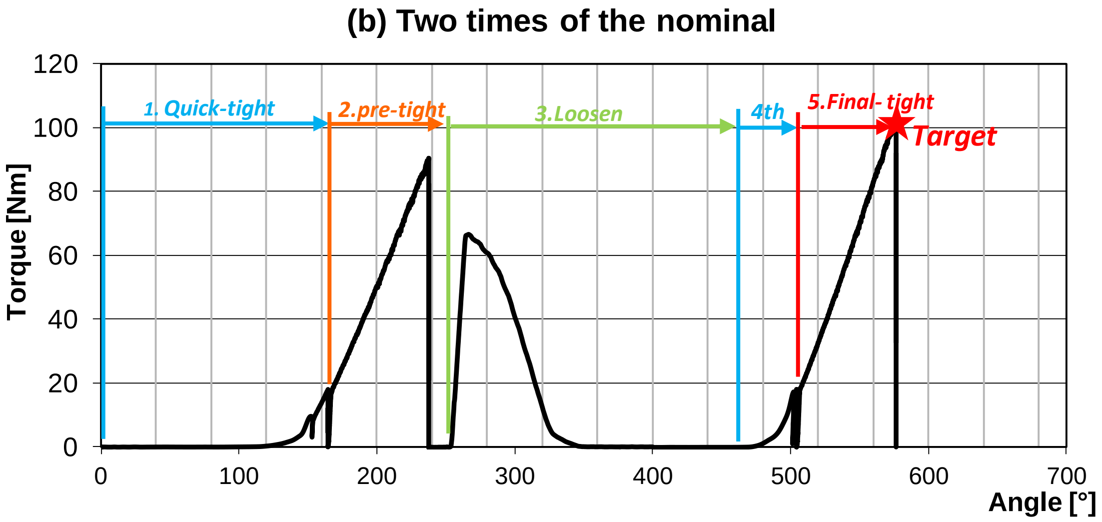
Step 1: Quick-tight up to 5Nm @200RPM

Step 2: Tight up to 18Nm @20RPM and then rotate the bolt 70±2° @ 10RPM

Step 3: Complete un-tightening

Step 4: Quick-tight up to 5Nm @200RPM

Step 5: Tight up to 18Nm @20RPM and then rotate the bolt 70±2° @ 10RPM



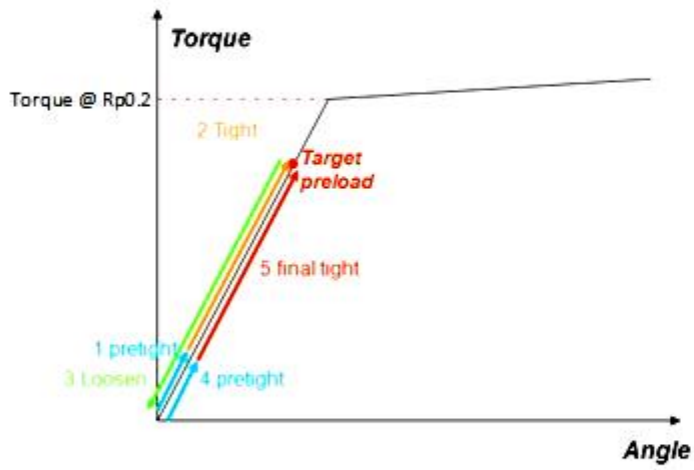




*Figure3.3: description of two times the nominal tightening procedure b)*

For the tightening procedure b) shown in Fig. 3.3, in the first two steps, the bolt is tightened by a angle-controlled tightening procedure whose cut-off angle is 70 degrees as the nominal tightening procedure. This pre-tight step applies a pre-stress $\sigma_{pre}$ to the joint system. Then in step 3, the pre-stress is unloaded. And in step 4 and step 5, the joint system is again loaded up by a nominal tightening procedure to the stress level $\sigma_o$, so that $\sigma_o \approx \sigma_{pre}$.

According to the relaxation theory, the fall in stress decreases significantly when a proper pre-load is applied to the test-piece. But on the opposite side, a large amount of tightening angle is needed here, so the vantage brought by pre-stressing could not be effective to win the relaxation increased by wearing phenomenon.

### 3.2.2 c): Tightening in 2 steps[2]

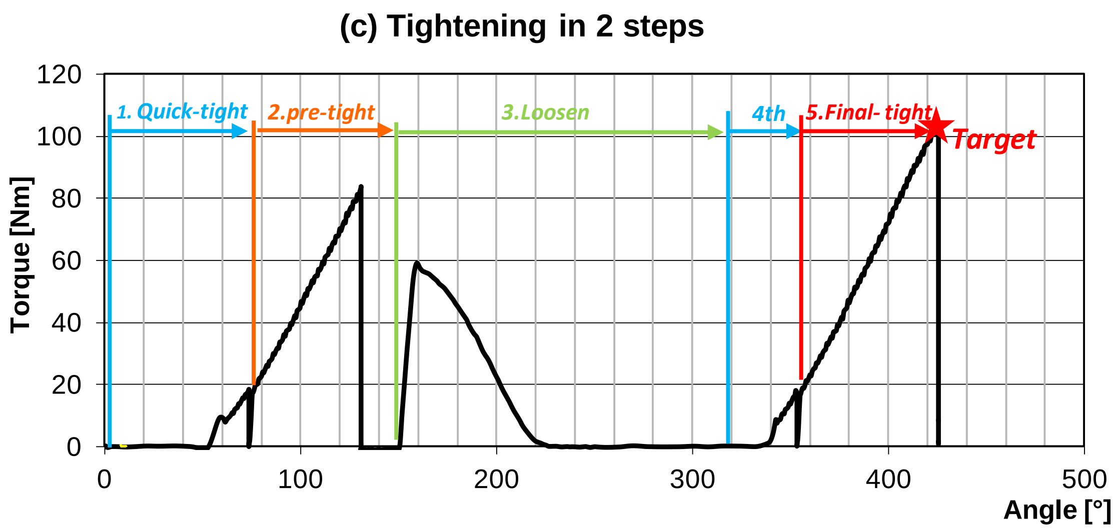
Step 1: Quick-tight up to 5Nm @200RPM

Step 2: Tight up to 18Nm @20RPM and then rotate the bolt 50±2° @ 10RPM

Step 3: Complete un-tightening

Step 4: Quick-tight up to 5Nm @200RPM

Step 5: Tight up to 18Nm @20RPM and then rotate the bolt 70±2° @ 10RPM



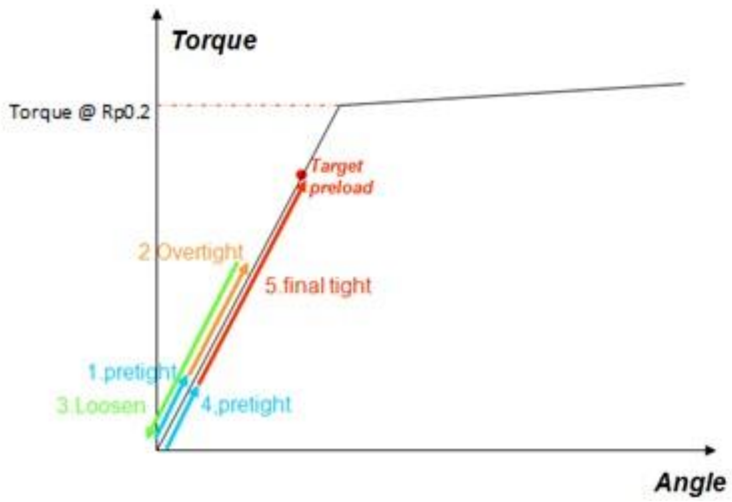




*Figure 3.4: Description of 2 steps tightening procedure c)*

This procedure is a modification of tightening procedure b); the pre-tightening angle is decreased to 50 degrees. As mentioned above, actually the pre-tightening angle decides the trade-off between pre-stressing and wearing phenomenon. A large pre-tightening angle can provide a high pre-stress level but long sliding distance lead to a heavy wearing between contact surfaces; on the other hand, a small pre-tightening angle can prevent the contact surface from wearing but the pre-stress applied may be too low to weaken the relaxation would happen in subsequent tightening steps.

2 Here we call a full tightening cycle: quick-tight, final-tight and un-tight as a STEP

### 3.2.3 d): Tightening in 3 steps

Step 1: Quick-tight up to 5Nm @200RPM

Step 2: Tight up to 18Nm @20RPM and then rotate the bolt 30±2° @ 10RPM

Step 3: Complete un-tightening

Step 4: Quick-tight up to 5Nm @200RPM

Step 5: Tight up to 18Nm @20RPM and then rotate the bolt 50±2° @ 10RPM

Step 6: Complete un-tightening

Step 7: Quick-tight up to 5Nm @200RPM

Step 8: Tight up to 18Nm @20RPM and then rotate the bolt 70±2° @ 10RPM

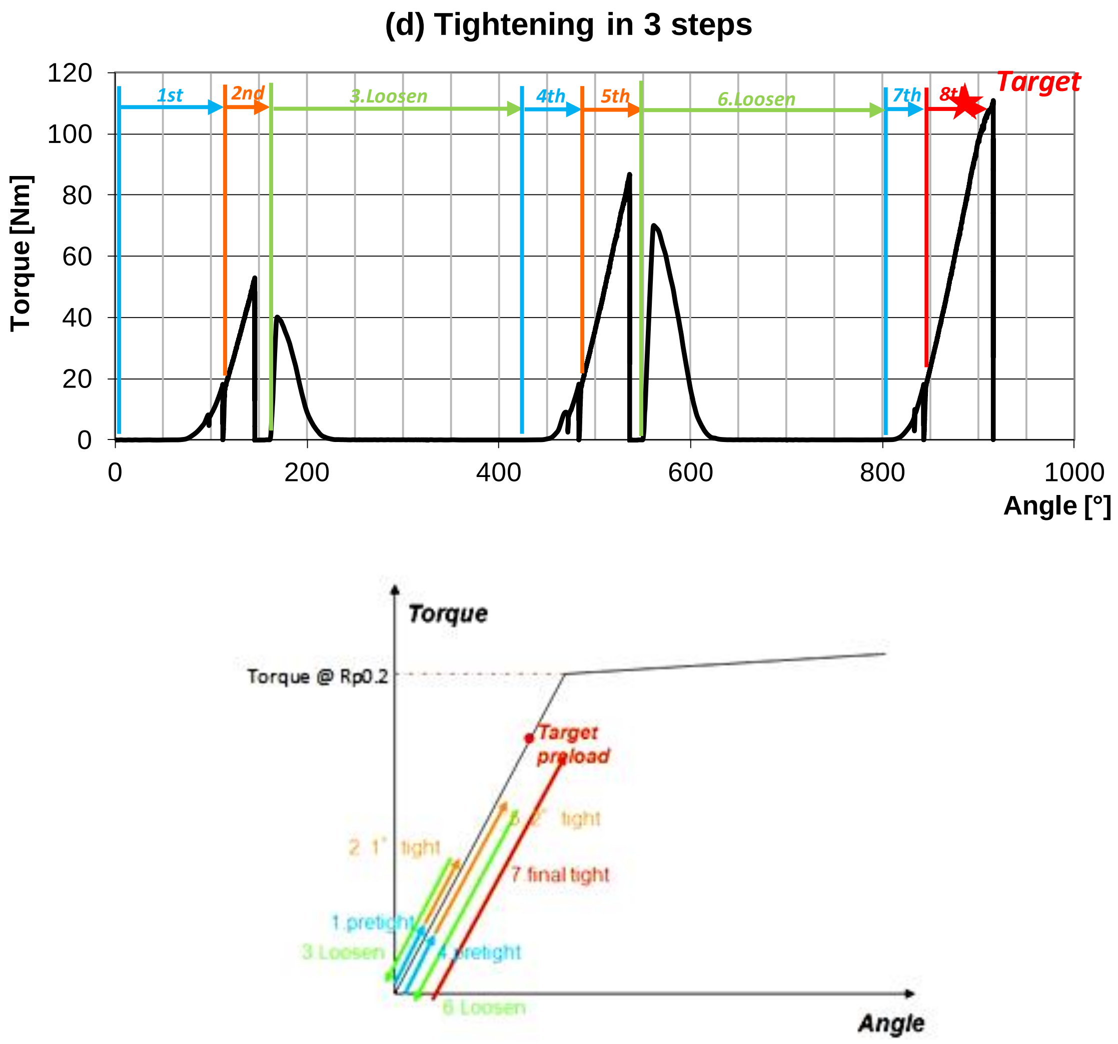



*Figure 3.5: Description of 3 steps tightening procedure d)*

This procedure is a further complication of procedure c), here the possible benefit of progressive and repeated pre-stressing is evaluated.

### 3.2.4 e): Over-tightening the bolt in the elastic domain and then loosen the bolt to the target tightening situation

Instead of a traditional "tight to target" method, e) is a "loose to target" tightening procedure shown as follows:

Step 1: Quick-tight up to 5Nm @200RPM

Step 2: Tight up to 18Nm @20RPM and then rotate the bolt 80±2° @ 10RPM

Step 3: Pre-loose up to 10Nm @10RPM

Step 4: un-tight angle 30±2° @10RPM

Step 5: Quick-tight up to 10Nm@10RPM

Step 6: Tight angle22±2° @10RPM to the target

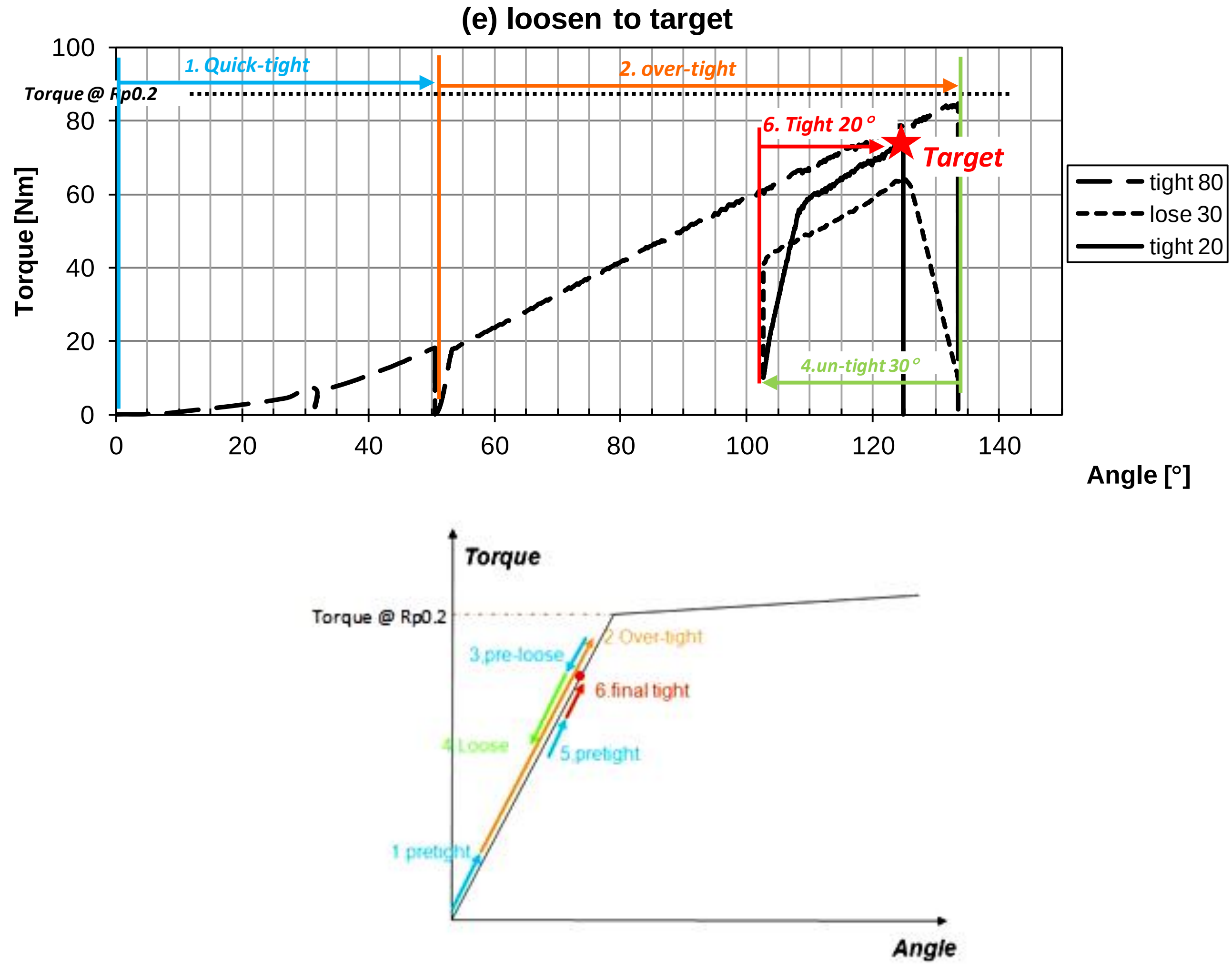



*Figure 3.7: description of over tightening and then loosen to target tightening procedure e)*

According to the wearing theory, with the increasing of the tightening steps, because of wearing phenomenon, the irregularity on the contact surfaces increases too.

In the multi-tightening procedure, like procedures b), c), d) and f), a large amount of wearing may happen under bolt head and on the threads, because of the doubled sliding distance x and the extra pre-tightening load. So here, according to the wearing theory, tightening procedure e) was designed to aim not only to gain the benefit of a high pre-tightening stress but also to shorten the sliding distances on the contact surfaces to avoid heavy wearing.

### 3.2.5 f): Over-tightening the bolt into elastic- plastic domain and then l nominal tightening procedure

Step 1: Quick-tight up to 5Nm @200RPM

Step 2: Tight up to 18Nm @20RPM and then rotate the bolt 100±2° @ 10RPM

Step 3: Complete un-tightening

Step 4: Quick-tight up to 5Nm @200RPM

Step 5: Tight up to 18Nm @20RPM and then rotate the bolt 70±2° @ 10RPM

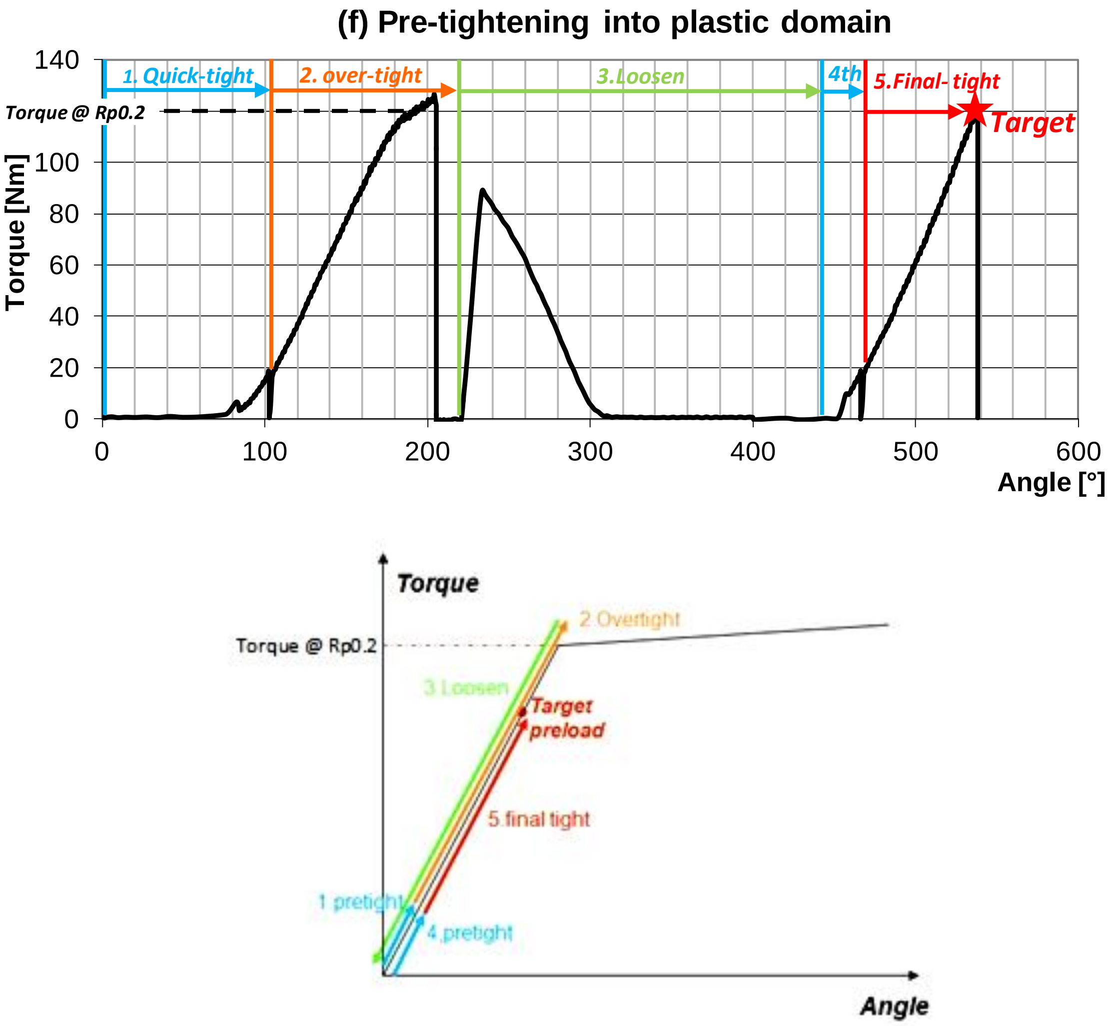



*Figure 3.6: description of over-tightening procedure f)*

This procedure is designed to measure the potential benefit of a high pre-tightening angle, which can tight the bolt into elastic-plastic domain.

Need to note that, the relaxation theory mentioned above is based on the tests done in high testing temperature and the pre-stress was loaded for a significant long time. In the bolt tightening situation, the pre-tightening is carried out in the room temperature and last only for few minutes, so further tests need to be done to examine if the designed pre-tightening step can decrease the relaxation in the following steps.
In the following chapters tests will be done on the bolts tightened at room temperature by each new tightening procedure. Clamping force will be measured by the ultrasonic method over time. Considered as a reference value the clamping load lost has been measured for each tightening procedure to evaluate the best performance based on the criteria mentioned in section 3.1.

# CHAPTER 4: PREPARATION FOR THE TESTS

## 4.1 Test pieces

### *4.1.1 Tested bolt*

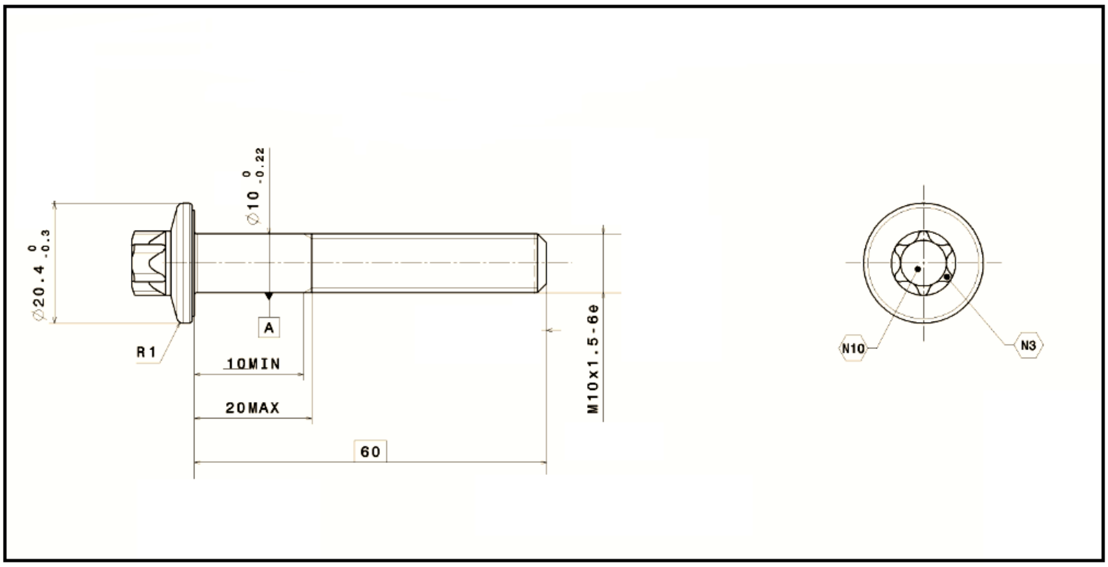



***Figure 4.1: Agrati M10X60 bolt for fixation caliper***

The basic characteristic of the tested M10X60 bolt:

- Shank length: 60 mm, nominal diameter: 10 mm, Metric screw thread, pitch=1.5 mm
- Bolt head shape: Hexalobular flanged screws.
- Material: 30MnB4 steel grade, Property class: 10.9.
- Coating: Delta protect KL100 + Topcoat VH301 GZ
- Usage: Fixation of caliper for automotive brake system.

To reflect the ultrasonic wave two flattened surface are required; so the tested bolt need to be machined both on the bolt head and on the point. To ensure the test accuracy these two machined surfaces need to fulfill the demanded" parallelism =0.04mm max, roughness Ra=3µm max"

*Figure 4.2: A comparison between original bolt (left) and flattened bolt (right)*

### *4.1.2 Tested calipers*

The caliper is the key component of the disc brake system, and it's the assembly that houses the brake pads and pistons. Caliper operates like a hydraulic clamp designed to grip the brake disc and stop the car. When the driver tread on the brakes, a high-pressure fluid is channeled into the caliper where it pushes the piston inward; in this way the brake caliper action moves the pads against the brake disc, and the friction stops the vehicle. In the braking process, brakes convert motion to heat energy, so for the components of the brake system, the proper functioning in high temperature is necessary.

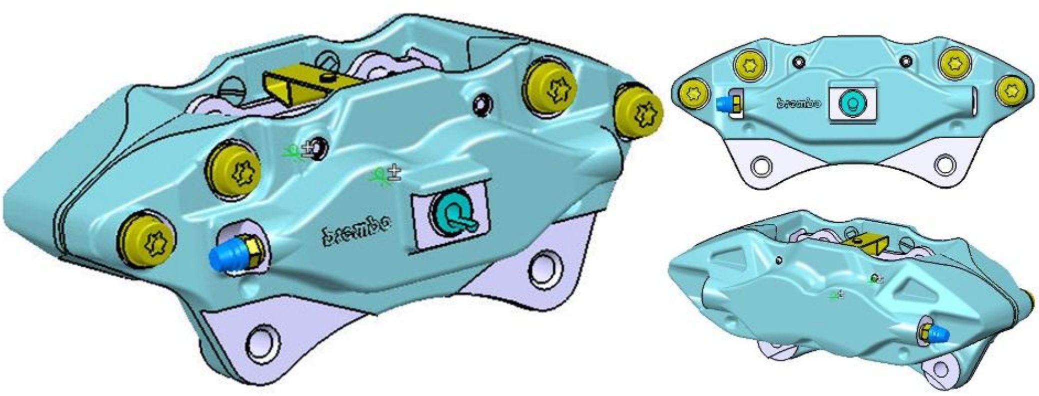



*Figure 4.3: Tested Caliper*

The tested caliper is the 4 pistons bolted caliper

### *4.1.3 Dummy of the tested caliper*

#### 4.1.3.1 Introduction

For preliminary assessment, a dummy component is designed to replace the real component used in the tests. After tightening, the surface of assembled components contact with bolt head and also threads will be plastically deformed, which means the components can not be reused. Take in to account the economic reason the dummy component is designed and is required to have the following features:

- Can provide a loading condition similar to the real caliper gives to the bolt.
- Similar plastic deformation when tightening compare with real caliper (same hardeness)
- Proper geometry for clamping, machining and measuring (same stiffness)
- Low cost of production

#### 4.1.3.2 Material of dummy components

The material we choose to build dummy parts is Al – Anticorodal 100 – AW6082 according to UNI 3571; here are some basic mechanical properties of Anticorodal 100

- Constituent elements: Al – 97%, Si – 1%, Mn – 0.8%,.
- Hardness :105 HR Ø 2.5mm
- Rp 0.2: 230 MPa
- Young's modulus 70 GPa
- Shear modulus 26 GPa
- Melting temperature: 600℃

#### *4.1.3.3* Geometry of dummy components

The dummy component is built on the base of the dummy model used in the FEM simulation done by AGRATI group. All the dimensions are shown below:

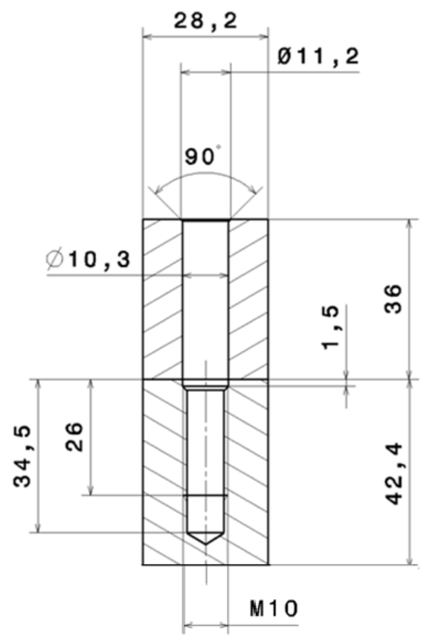



***Figure 4.4: Dummy parts***

## 4.2 Experimental equipments

### *4.2.1 Ultrasonic Device*

The device used in this thesis,

- SOFRANEL-NDT System: model TG410
- Contact transducer(axial connection)
- Portable system(display 240X320 LCD)
- Pressure wave frequency of transducer = 10MHz, Ø=3mm magnetic sensor
- Resolution is 0.0001 mm
- Test range is 0.005~20 mm
- RS-232 I/O:Download data via logger USB connection


***Figure 4.5 The US device***

### *4.2.2 Micrometer*

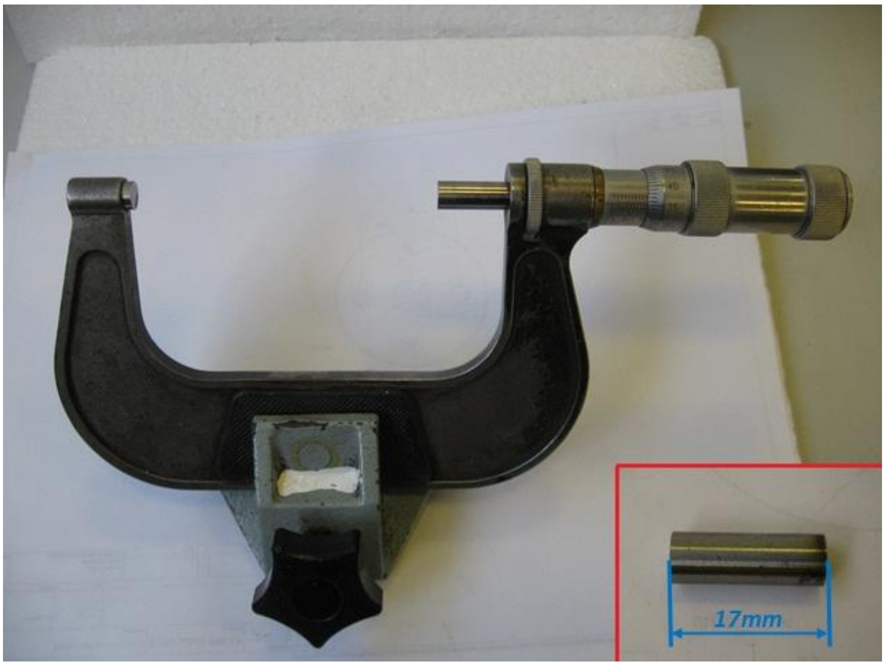



***Figure 4.6 Micrometer and block for measuring***

In order to assist the measurement, a block with constant length (17mm) is cut from Ø 5.9 hole-gauge. This block is inserted in the bottom of the clamped part with thread to contact with the point of bolt, thus the length information can be transferred to the micrometer whose spindle is not long enough to touch the end of bolt.

### *4.2.3 Torque driver unit*

***Figure 4.7: Driver unit***

The driver unit in the test is ETD DS9-100-13ST of Atlascopco, the technical parameters are list below:

| DS9-100-13ST | |
|---|---|
| **Weight** | 3.2 kg |
| **Max velocity** | 0.208 |

***Table 4.1 Data of driver unit***

### *4.2.4 Reference bolt*

***Figure 4.8: The reference bolt protected by PE bubble paper***

Because the U.S. signal can be affected by the changes of the room temperature, a reference bolt similar to the tested bolt is chosen as a standard to examining the sensor's working condition. This reference bolt is protected by PE bubble paper from the touching of the hands, and it is always put beside the testing samples.

### 4.2.5 Electrical oven

An electrical oven is used to simulate the high temperature working condition.


***Figure 4.9 Electrical oven in Agrati faciaties***

### 4.2.6 Profilemeter and microscope

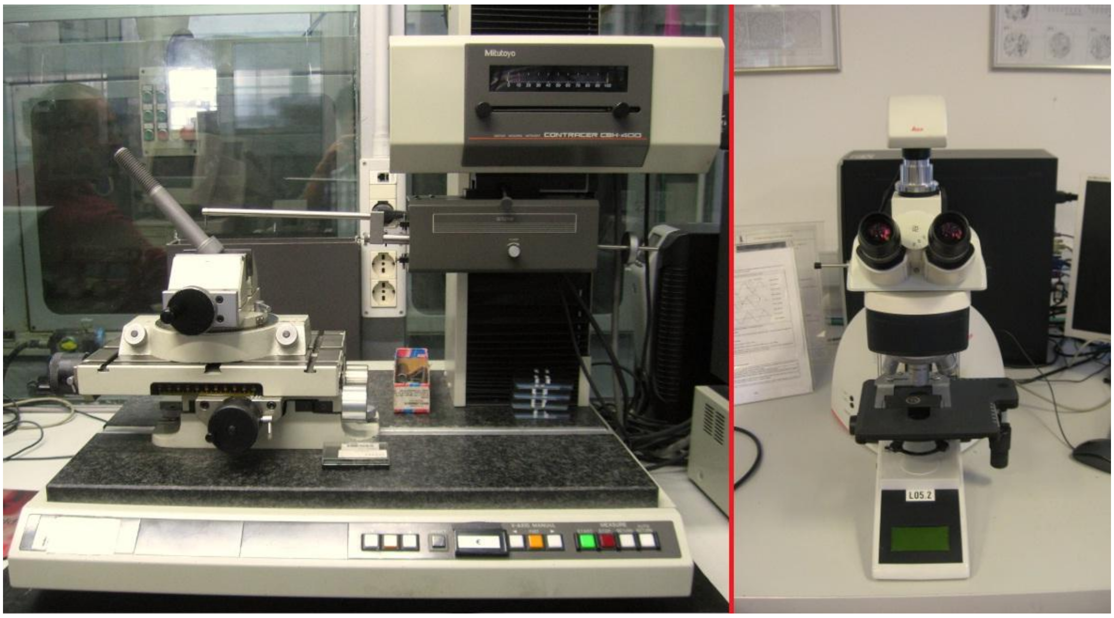



***Figure 4.10 Profilemeter (left) and microscope (right)***

## 4.3 The calibration of the bolt's elastic resilience

### *4.3.1 Introduction*

In the bolt fastener industry the clamping force can be measured by some ways:

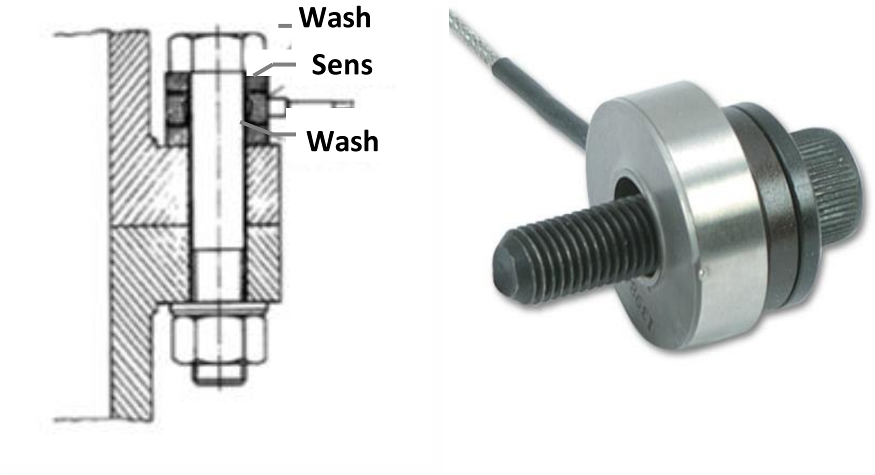



***Figure 4.11: directly measurement of clamping force***

Directly clamping force measurements are possible by using a load ring and a corresponding analyze.


***Figure 4.12: indirectly measurement of clamping force***

Indirect measurement, is based on the concept that a bolt is stressed in the elastic region Hook's law says that elongation is directly proportional to the force. So to measure the clamping force we just need to measure the elongation of the stressed bolt

In the situation of this thesis, the bolt and clamped components are all decided, there is no space for a load ring. So an indirectly measuring method will be used. And to insure the accuracy an ultrasonic device will be used for the measurement of elongation.

To link the elongation with the clamping force, the resilience of the screw needs to be calculated. The screw is considered like an assembly of separate cylindrical elements.

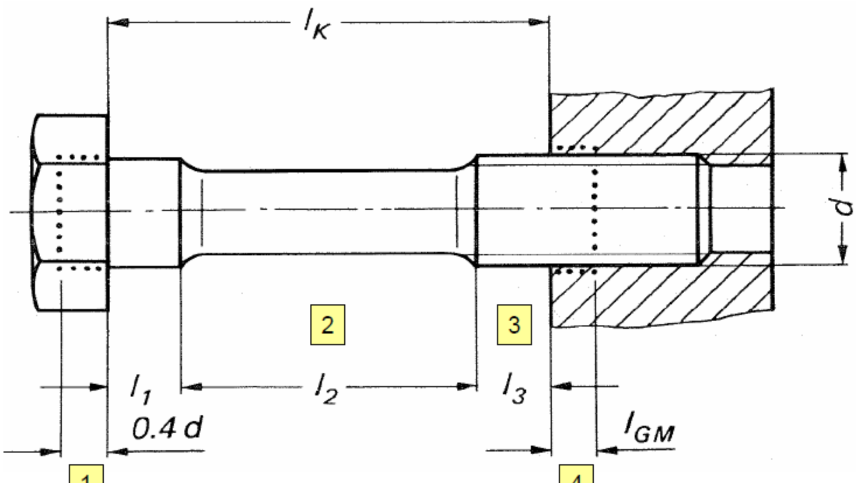





***Figure 4.13: 4 characteristic of elastic elements of the screw.***

For a tightened bolt the elastic deformation can be divided into 4 parts:

1. Elastic part of the bolt head
2. The unthreaded part of the shank.
3. The loaded part of the thread shank
4. The

But because of the geometry of screw and irregularity of elastic deformed part of the bolt head, a precise resilience modulo is hard to calculate. So an experimental method is taken into consideration for this thesis.

### *4.3.2 Test method*

#### 4.3.2.1 Basis theory

***Figure 4.14 Basic theory of ultrasonic measurement method***

To measure the elongation of the bolt with an ultrasonic sensor, a pulse (the red wave in the graph) is generated from a transducer on top of the bolt, the instrument measure the delay between the pulse and its echo (the orange wave in the graph) returned from the bottom of the bolt. As the bolt is tightened the bolt elongates and the delay increases. The delta time is proportional to the delta length which is proportional to the clamping force generated on the

#### 4.3.2.2 Test steps

*Step 1： The set up of ultrasonic device*


***Figure 4.15: Zero calibration of ultrasonic device and the reference sample.***

First, zero calibration:

- Switch on the device, and maintain the US sensor in the testing environment for at least 15 mins
- Set the sensor on the reference sample (thickness = 5mm)
- Set the velocity = 5920m/s, positive polarity (+) and the threshold value as preferred (65%-75%)
- Push the ‘zero – low cal’ button and change the value to read 5.000mm on the display


*Figure 4.16: Velocity calibration of ultrasonic device.*

Then, velocity calibration:

- Measure the real bolt length by micrometer
- Then measure the same bolt with US device
- Push the button 'Vel-High cal' and modify the velocity value to see on the display the real bolt length
-

Note: in some situation in order to read the best echo signal, you can change the polarity from upward (+) to downward (-): in case of the change of polarity, a re-calibration of the zero is necessary before the bolt calibration

After the set up of ultrasonic device, the setup parameters can be decided shown as following:

| SET UP TG410 | |
|---|---|
| mode | 1 |
| zero - offset | 0.208 |
| polarity | + |
| threshold | 60% |
| velocity | 5.8907 |
| Pick of analysis | 1 |
| Range RNG | 99.140 |
| IP BLK | 4.262 |
| US sensor | d3 magnetic |

*Table 4.2 set up of ultrasonic device*

*<u>Step 2： Calibration of the relationship between force and elongation</u>*

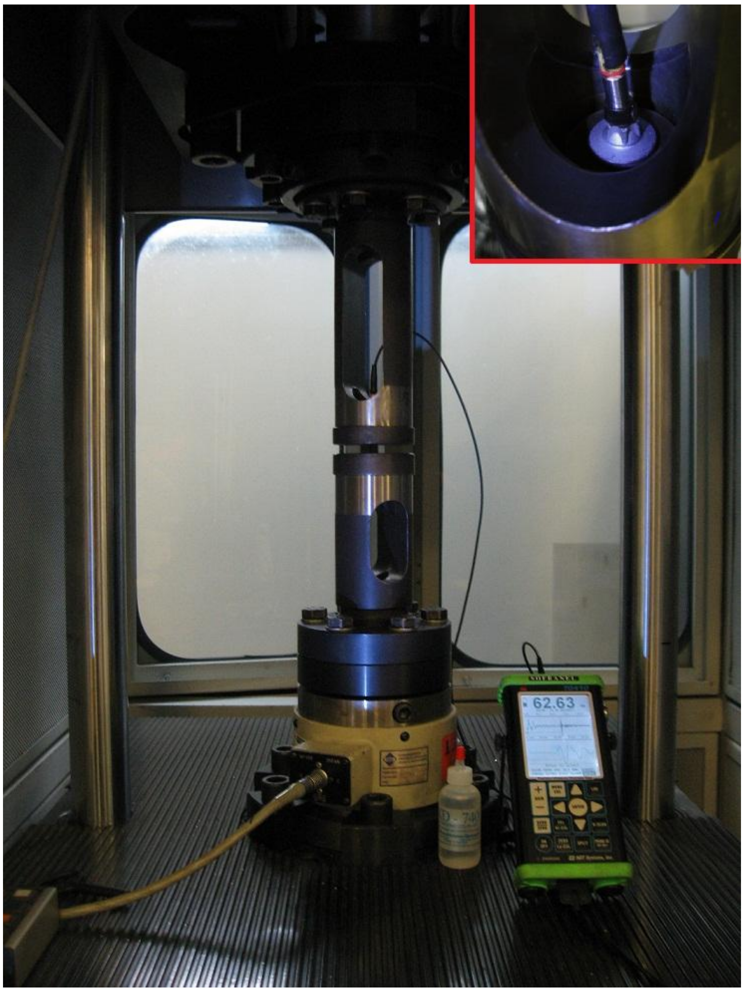



***Figure 4.17: tensile testing machine and US device***

This test is achieved on tensile testing machine, the tested bolt is mounted on the machine by the suitable adaptor: The concept is to tensile the bolt with a known axial force and to measure the bolt elongation by U.S. device. By this way the law which correlates the axial force and U.S. bolt elongation is defined. To be noted that it's important to reproduce the same bolt clamping length as in the real working condition.

Before testing, a 20 kN preload is applied to the bolt for 5mins to correct the geometry error and contact surface irregularity.

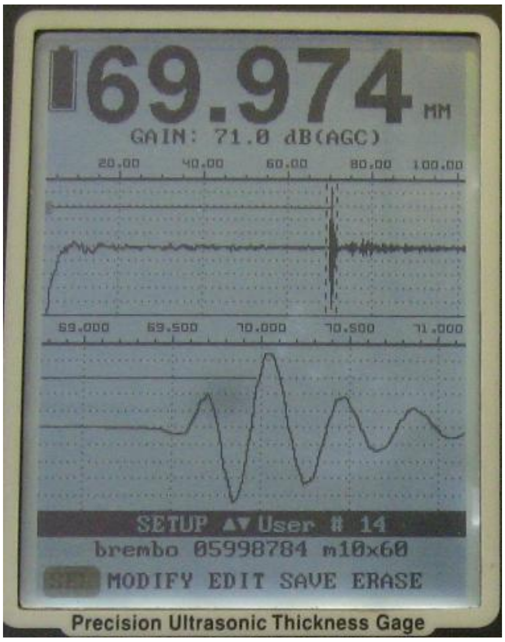



***Figure 4.17: display of the US device after***

Then, mount the US sensor to the centre of the flattened bolt head, adjust the position of the sensor in order to achieve a stable, clear and low noise signal. As shown in Fig 4.17 Then, the bolt is loaded step by step from zero to 80% of the real elastic limit (Rp 0.2), and after each loading step, a corresponding length of the bolt can be measured by the U.S. device. To increase the reliability of the measurements, at least 3 loading (from 0 to 80% of $R_p$ 0.2) process should be done on one tested bolt, and other 4 bolts of the same test batch need to be tested.

In the test, the data of force and corresponding bolt's elongation will be collected in EXCEL file. Because the bolt is loaded in the elastic domain, a linear law between force and elongation can be defined.

### *4.3.3 Test result and discussion*

At the end of the test, 32 loading procedures have been applied on 6 bolts from the same tested batch. By comparing the different testing results, the most reliable testing results are chosen to format the data base for the calibration of linear relationship between clamping load and bolt's elongation.

And during the test, the correct positioning o the US sensor, parallelism of the bolt flattened surfaces and accuracy in the measurement method are the key factors for a reliable calibration, needed to pay attention.

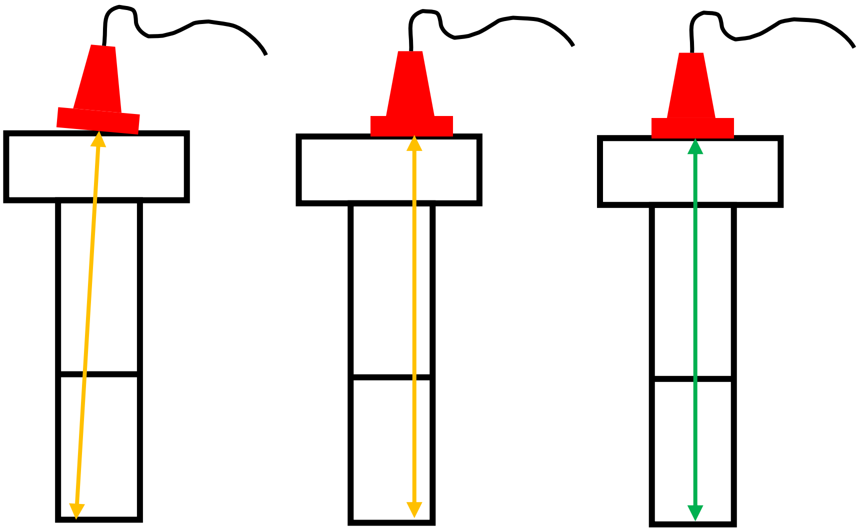


*Figure 4.18: Different install situation of U.S. sensor*

After statistic analysis the relationship between clamping force and bolt's elongation is shown in the following linear equation:

$$y=67.1x$$

where x is the elongation and y is the corresponding clamping load.
Here as shown in the graph, the $R^2$ is the coefficient of determination, which compares estimated and actual values of y, and ranges in value 0 to 1. If it is 1, means that the estimated y-values and the actual y-value are correlated perfectly.

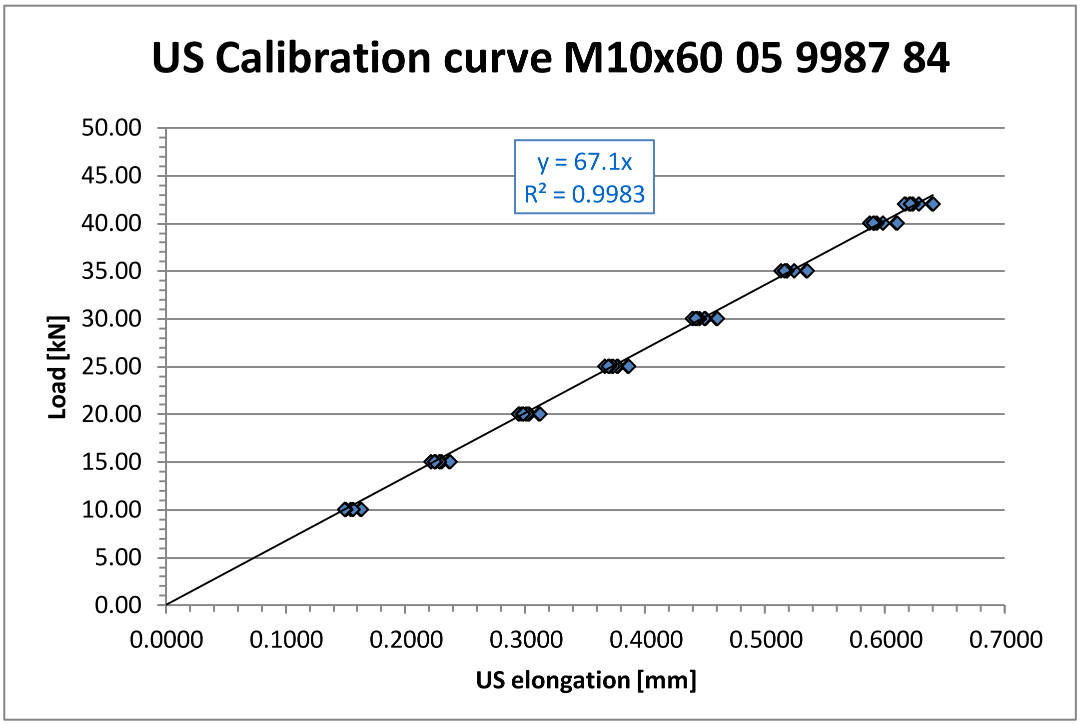



*Figure 4.19: Linearization of test results*

After knowing this linear equation, to measuring the clamping force of this kind of bolt, we just need to measure the elongation with U.S. device and calculate the force with the equation. This is the basic logic of the indirectly clamping force measuring method, compare with the directly method, U.S. measurement has following advantages:

1. Lower influence on the bolt joint system, no need to insert a force ring.
2. Can measure the clamping force in the real assembled condition
3. After calibrated the force/elongation relationship, the test is easy and quick
4. Lower cost, no need to build special force sensor for bolts with different diameter

But on the other hand, U.S. testing method also has some drawbacks:

1. Before test, a calibration is necessary
2. Sensitive to the testing environment
3. Because of indirectly measuring, during calculation the error may happen

### *4.3.4 Re-calibration of the plastically deformed bolts.*

In the tightening procedure f) the bolt will be over-tightened into the plastic domain, although the second tightening step is still deformed elastically, but because of the changing of initial bolt length the relationship between clamping load and elongation shown in chapter 3 will be no longer suitable.

In order to measure the clamping load of this plastic deformed bolt, a new calibration needs to be done. So the whole calibration procedure is carried out again on the bolts plastically deformed by the first tightening step of f).

After the calibration, the relationship between clamping load and elongation changes to:

$$\mathbf{y = 69.498x - 0.6626}$$

where x is the elongation and y is the corresponding clamping load.

The chosen sets of results are shown in the following graph:

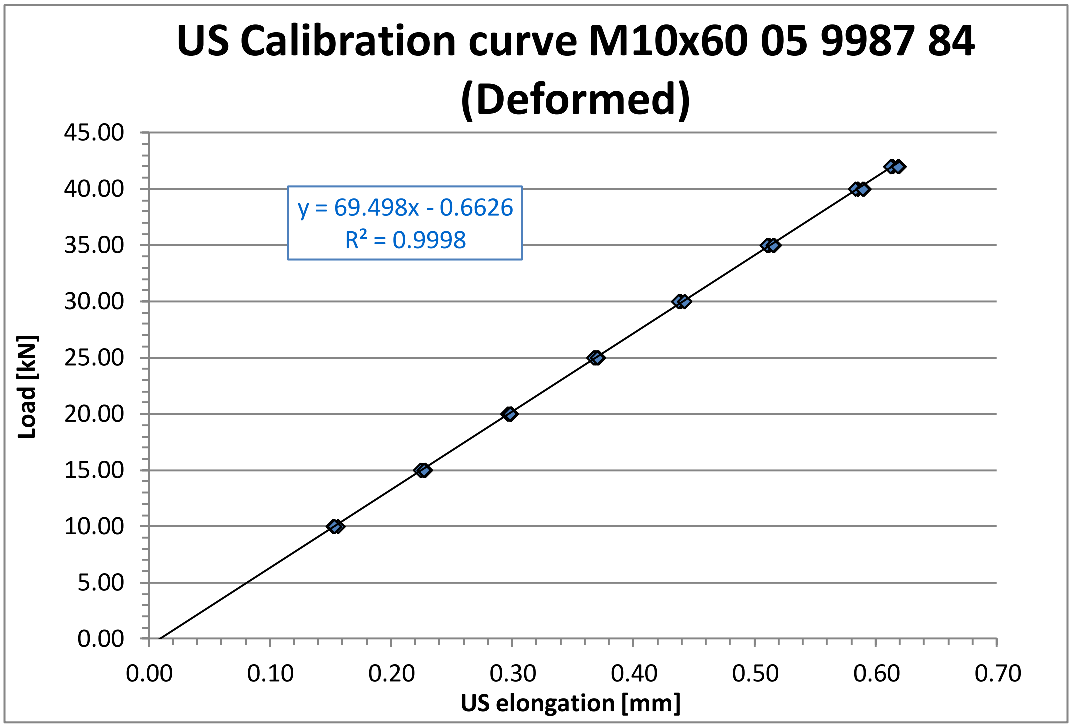



***Figure 4.20:*** *The result of re-calibration of the plastically deformed.*

Pay attention that when measuring the clamping load of a plastically deformed bolt, the initial clamping length should be measured after the first over-tight step, which means that firstly the bolt is over-tightened to plastic deformation, then the bolt is loosen and at this time the initial length is measured by U.S. device.

# CHAPTER 5: TESTING PROCESS AND TEST RESULTS


***Figure 5.1 Dummy joint assemblies***

In this chapter, the dummy joint system (Fig. 5.1) and the real joint on caliper (Fig. 4.3) will be tightened with M10X60 bolts by the new tightening procedures, and the clamping load will be measured by the ultrasonic device during the designed test procedures.

Experience tells that usually the clamping load loss 2%-10% in 24 hours after tightening at room temperature and no loading situation. So in test A) the fall in clamping load over time will be measured. Because the tested bolt is used on the caliper fixation of car’s brake system, a good performance in the dynamic temperature working condition is very important. Base on the thermal cycles used by the bolt user to test the working property of the caliper in high temperature and dynamic loading situation, test B) is designed to understand in each step of the thermal cycles, how much clamping load is lost.

A) Tracing the trend of clamping load in the joint system over 1400mins after tightening at room temperature and no loading situation.

B) Measuring the lost of clamping load during designed thermal cycles; one step of thermal cycle is shown in Fig. 5.2; for the full thermal cycles the same heating and cooling procedure is repeated for 5 times.

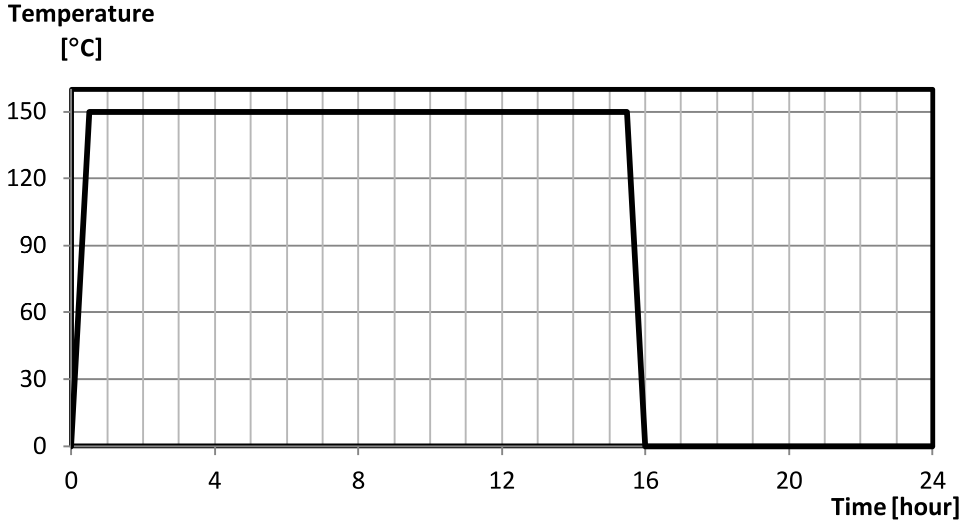



*Figure 5.2: one step of the Thermal cycles in test B)*

After the series of tests a complete understanding of joint's performance linked to the tightening procedures under investigation is expected.

## 5.1 Tests on dummy joint system

### *5.1.1 Test procedure*

#### 5.1.1.1 Procedure of test A)

1. For each of the new tightening procedures 3 dummy joints, which are the assembly of M10X60 bolts (Section 4.1.1) and the dummy of caliper (section 4.1.3), are prepared. And the ultrasonic device TG410 (Section 4.3.1) with the ultrasonic transducer Ø=3mm (magnetic) which used for the calibration of the bolt is ready to start up.

   On the transducer a mark is made as shown in the Fig 5.3, in the test this mark will match with another mark sighed on the head of tested bolt. By this way the measuring position of the U.S. sensor is fixed.

*Figure 5.3: the mark signed on ultrasonic sensor and bolt head*

2. Ultrasonic device needs to be switched-on at least 15 minutes before testing and the set up information is exactly the same as in the calibration test (section 4.3.2).
3. Before the tests, the reference bolt (section 4.2.4) needs to be measured first at least 10 times, until the signal is stable and a constant reading is available.
4. All the tested bolts are numbered and the initial length of these bolts is measured by U.S. device.
5. The bolts are tightened by new tightening procedures. Each of the new tightening procedure is carried out on 3 dummy joints. The tested bolts are tightened by driver unit mentioned in section 4.2.3, and the tightening torque is recorded over angle.
6. According to the schedule, at each Point-in-time, the length of tested bolts are measured; the measuring method mentioned here can be divided into 4 steps[3]:
   **First**, the length of the reference bolt is measured to verify the working condition of the U.S. sensor.
   **Second**, the length of tested bolt is measured by U.S. device, a stable and minimum result is always required.
   **Third**, the same length of the tested bolt is measured again by micrometer (section 4.2.2) as a reference to assess the reliability of the U.S. measurement.
   **Forth**, repeat the second and third steps other 2 more times.
7. After 1500 mins, loose the bolts and record the loosening torque.
8. Data record and analysis.

#### 5.1.1.2 Procedure of test B)

1. The test procedures from step 1 to step 5 as mentioned above are carried out again, U.S. device is set up and for each tightening procedures 2 dummy joints[4] are prepared.
2. The bolts will be measured[5] immediately after tightening, then, after 6 hours before put the joints in the oven (section 4.2.5) the clamping load will be measured again.
3. The joints are heated up to 150°C for 15 hours, then cooling at room temperature for 8 hours, the clamping lengths are measured 3 hours after the parts are taken out of the oven.
4. Repeat step 3 for other 4 times.
5. Data record and analysis.

### *5.1.2 Test results and discussion*

The performance of new tightening procedure is judged from three aspects:

1. As the main issue in this paper the self-relaxation resistance property is taken into consideration first, the percentage of clamping load lost during the test procedure is calculated and considered as a reference parameter.
2. Then, the tightening accuracy is evaluated by the computation of the clamping load's standard deviation of the bolts tightened by the same tightening procedure. The clamping load achieved by the nominal tightening procedure is set as a standard clamping load. The difference of the

---

[3] All these four steps need to be carried out continuously, because the working condition of U.S. sensor may change with the ambient temperature
[4] In test B), 2 dummy joints, instead of 3, are tested. Because the fall in clamping load of dummy joint during thermal cycles is significantly higher than the no load and room temperature situation, two test-pieces are enough to guarantee the required reliability.
[5] 4 steps measuring process as mentioned in section 5.1.1.1

clamping load achieved by the new tightening procedures to the standard one is also taken into consideration as another parameter to evaluate the accuracy of tightening procedure.

3. The joint security is described by the maximum torque (named as Breaking Torque) when the bolt is un-tightening. But due to the uncertainty of tightening procedures and friction properties of the joints, the clamping condition of the joints can be different from one to the other, even if the same tightening procedure is used. So instead of taking the breaking torque as the reference parameter the "Break Ratio" is calculated and considered.
   The break ratio is the ratio between the maximum un-tightening torque and the maximum tightening torque. In a multi tightening procedure the maximum tightening torque means the maximum torque in the last tightening step. For example, the trend of tightenig torque over the angle when a bolt is tightened (a) or untightenied (b) is recorded and shown in the following graphs.

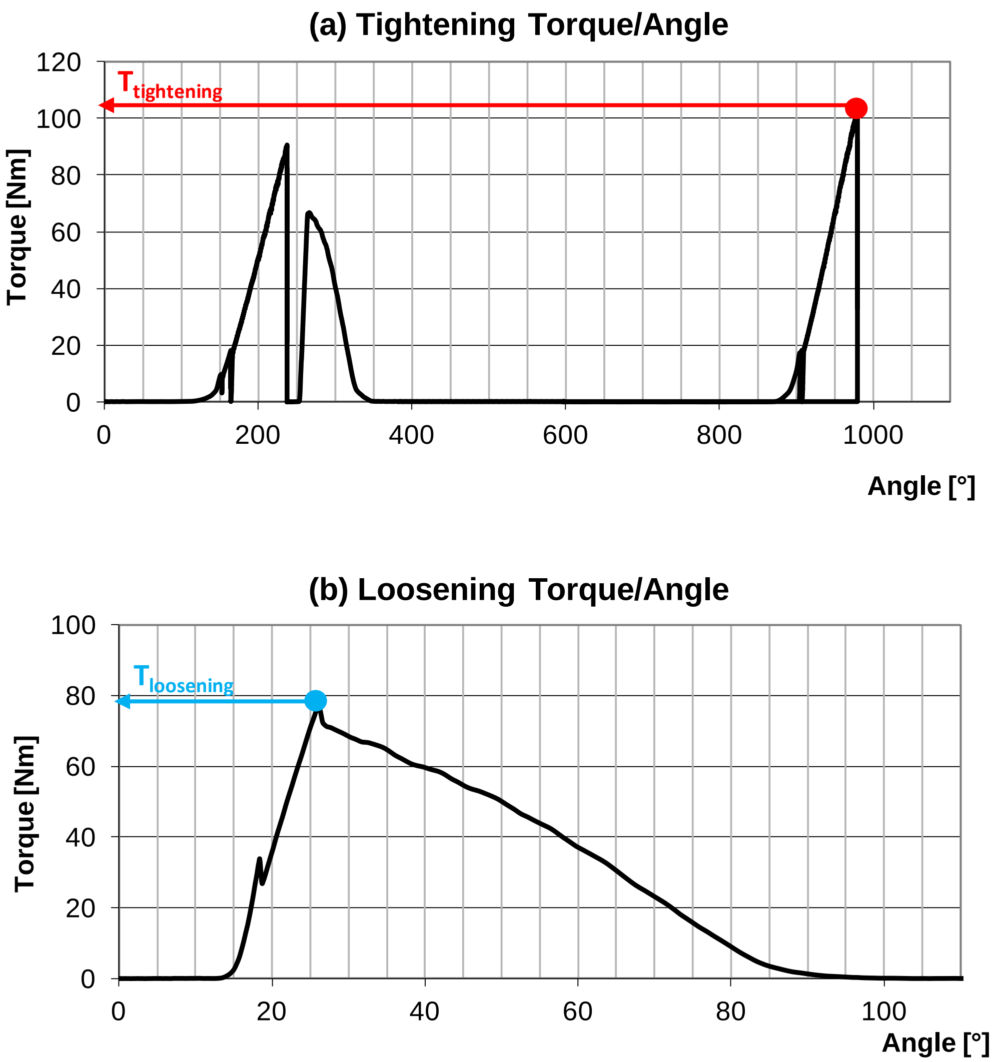



*Figure 5.4 The Torque/Angle curves when a bolt is tightened (a) and then loosened (b)*

The maximum tightening torque is noted as the red point in Fig. 5.4a and the maximum un-tightening torque is noted as the blue point in Fig. 5.4b.
Therefore:

$$B.R. = \frac{T_{loosening}}{T_{tightening}} \%$$

B.R. is the break ratio and it is calculated by the formulae above.

#### 5.1.2.1 Test results of test A)

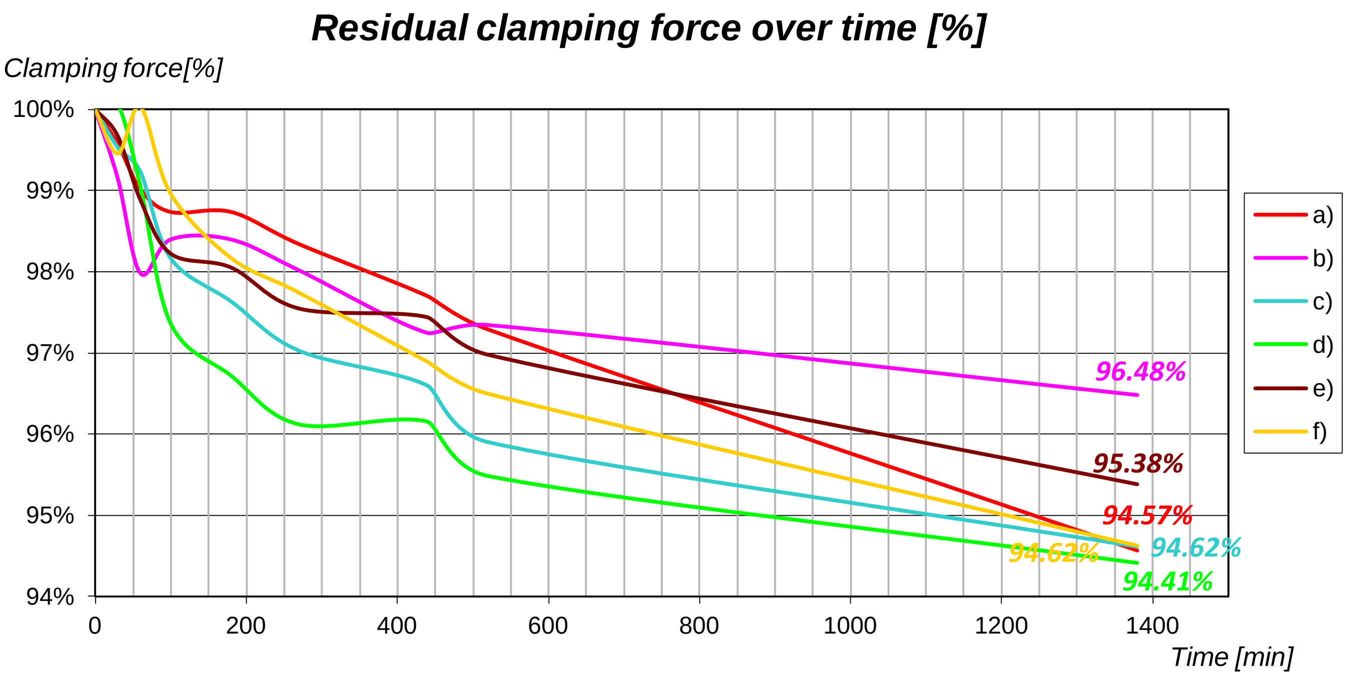



***Figure 5.5: Remaining clamping load over time***

The letters in the legend represent the tightening procedures:

a) Original tightening procedure
b) Two times of nominal tightening procedures
c) Tightening in 2 steps
d) Tightening in 3 steps
e) Over-tightening the bolt in the elastic domain and then loosen the bolt to the target tightening situation
f) Over-tightening the bolt into plastic domain and then loosen completely the bolt to apply the nominal tightening procedure

**Self relaxation resistance**

| | a) | b) | c) | d) | e) | f) |
|---|---|---|---|---|---|---|
| Average Force after tightening [kN] | 45.3 | 47.22 | 50.4 | 46.0 | 41.8 | 49.3 |
| Average Force after 1380mins [kN] | 42.8 | 45.5 | 47.7 | 43.5 | 39.8 | 46.6 |
| Clamping load lost [%] | **5.4%** | **3.6%** | **5.4%** | **5.6%** | **4.6%** | **5.5%** |

***Table 5.1: The clamping load lost of the dummy joints over time***

**Tightening accuracy**

| | a) | b) | c) | d) | e) | f) |
|---|---|---|---|---|---|---|
| Average Force after tightening [kN] | 45.3 | 47.2 | 50.4 | 46.0 | 41.8 | 49.3 |
| Standard deviation[6] [kN] | 0.43 | 1.26 | 0.22 | 0.64 | 0.94 | 1.45 |
| Offset from nominal[7](after tightening) | 0.00% | 4.30% | 11.40% | 1.70% | -7.80% | 9.00% |
| Average Force after 1380 mins [kN] | 42.8 | 45.5 | 47.7 | 43.5 | 39.8 | 46.6 |
| Standard deviation [kN] | 0.25 | 0.39 | 0.16 | 0.82 | 0.54 | 1.14 |
| Offset from nominal (after1380 hours) | 0.00% | 6.40% | 11.40% | 1.50% | -7.00% | 8.90% |

***Table 5.2: Tightening accuracy of each kind of tightening procedure performed on dummy joints***

**Joint security**

| | a) | b) | c) | d) | e) | f) |
|---|---|---|---|---|---|---|
| Ave. Max. tightening torque [Nm] | 93.7 | 99.4 | 102.0 | 75.8 | 111.7 | 93.7 |
| Ave. Max. loosening torque [Nm] | 64.5 | 74.2 | 74.0 | 61.8 | 78.7 | 64.5 |
| Ave. Break ratio [%] | 69% | 75% | 73% | 82% | 70% | 69% |

***Table 5.3: the breaking ratio of the dummy joints tightened by new tightening procedures***

a): _nominal tightening procedure_

By considering the test results of nominal tightening procedure, the changing law of clamping load over time in the no extra loading and room temperature working condition is measured. And can be shown as below.

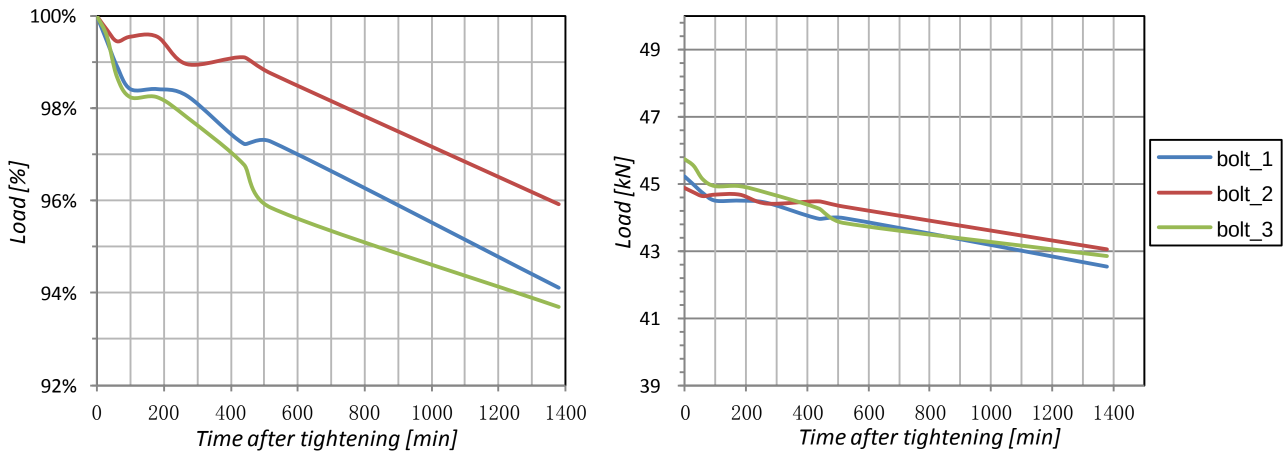



***Figure 5.6: the clamping load lost of the dummies tightened by nominal tightening procedure over time.***

6 The standard deviation of the bolts tightened by the same tightening procedure

7 The different of clamping load between new tightening procedure and nominal tightening procedure

The average clamping load of nominal tightening procedure is 45.3 kN, and after the tightening the clamping load decreases immediately, after about 1400 mins the clamping load becomes stable and the average lost of clamping load is about 5.4%.
During the decreasing of the clamping load, the accuracy of clamping load can be improved, the standard deviation of the clamping load changes from 0.43 kN after the tightening to 0.25 kN after 1400 mins.
Compared with the nominal tightening procedure, the new tightening procedures will be judged from 3 aspects: self-relaxation resistance, tightening accuracy and joint security.

*b): 70°Pre-tight + Nominal tightening procedure*

The lost of clamping load of each bolt tightened by b) can be shown:

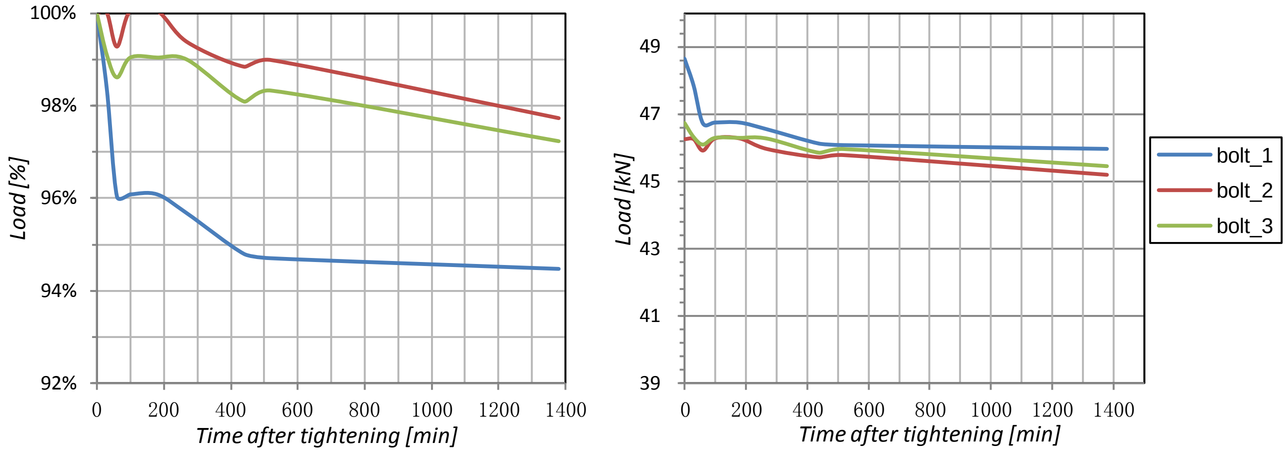



***Figure 5.7: the clamping load lost of the dummies tightened by tightening procedure b) over time.***

Tightening procedure b) shows a good performance of self-relaxation resistance, it decreases the clamping load lost to 3.6%. b) achieved a high level of tightening accuracy, the average clamping load is 47.2 kN and standard deviation is 0.39 kN after 1400 mins. And the breaking ratio increases from 69% to 75% compare with the nominal tightening situation.

*c): 50°Pre-tight + Nominal tightening procedure*

The lost of clamping load of each bolt tightened by c) can be shown:

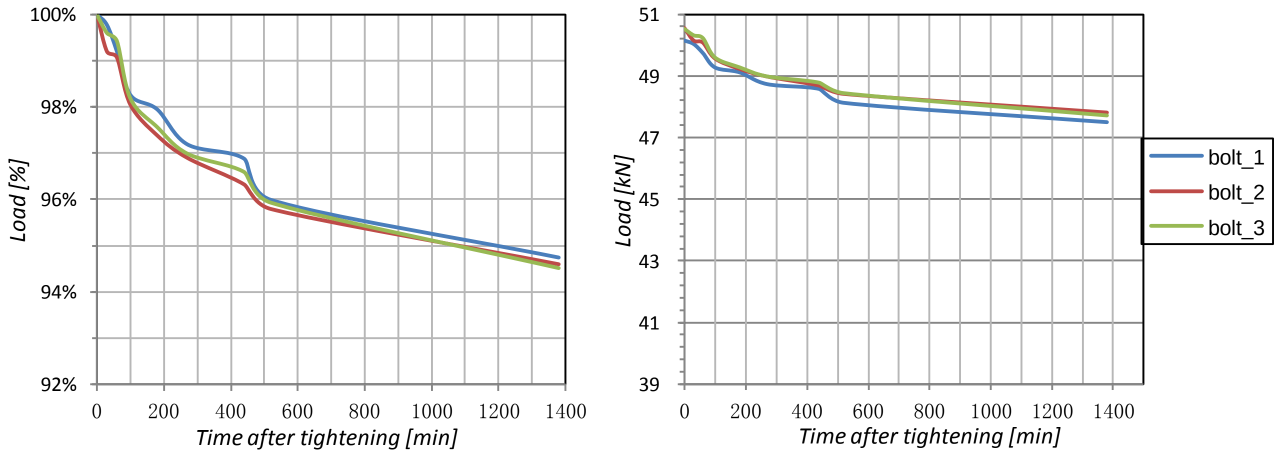



***Figure 5.8: the clamping load lost of the dummies tightened by tightening procedure c) over time.***

During the test A) the average clamping load of the bolts tightened by tightening procedure c) decreases from 50.4 kN to 47.7 kN, lost about 5.4%. Compare with the nominal tightening procedure, c) doesn't improve the self-relaxation resistance property. But, on the other hand, c) increased the tightening accuracy. The standard deviation[8] decreases from 0.43 kN to 0.22 kN after tightening compare with nominal tightening situation, and from 0.25 kN to 0.16 kN after 1400 mins.

*d): 30°First pre-tight + 50°Second pre-tight + Nominal tightening procedure*

The lost of clamping load of each bolt tightened by d) can be shown:

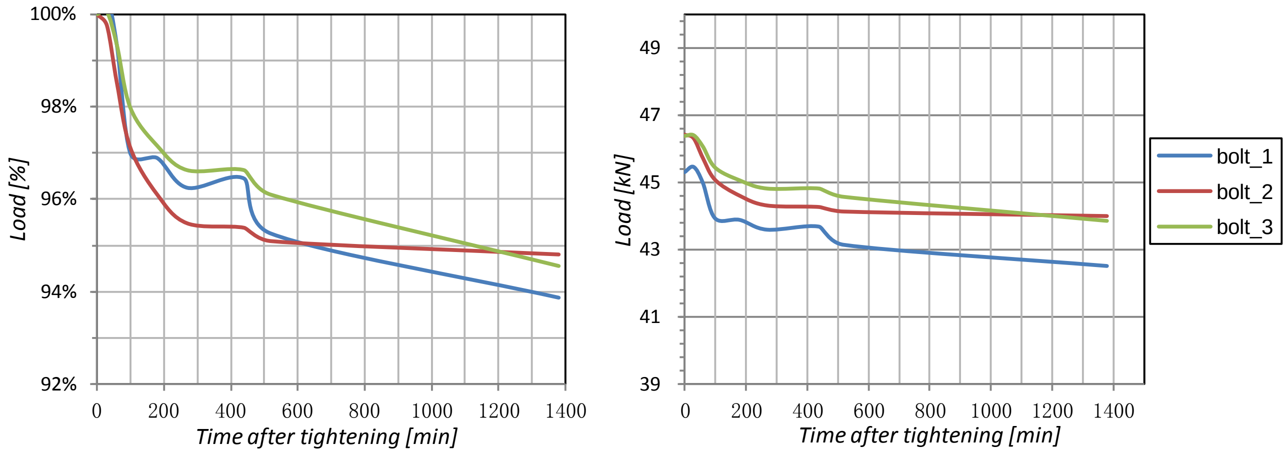



***Figure 5.9: the clamping load lost of the dummies tightened by tightening procedure d) over time.***

The average clamping load of the bolts tightened by tightening procedure d) decreases from 46.0 kN to 43.5 kN, lost about 5.6%, which is even higher than the nominal tightening situation. And because of its 3 steps tightening procedure, a large numbers of relative movement happens on the contact surfaces[9], which increases the wearing phenomenon as discussed in section 2.4. As a result, the standard deviation increases from 0.25 kN to 0.82 kN at the end of the test compare with nominal tightening procedure.

Need to be noted that, tightening procedure d) improved the joint security. The average breaking ratio of the bolts tightened by d) increases from 69% to 82% compare with nominal tightening situation.

*e):80°Pre-tight + 30°Un-tight +20°tight*

The lost of clamping load of each bolt tightened by f) can be shown:

[8] Mentioned in section 5.1.2
[9] The surface where the bolt contacts with the clamped parts.

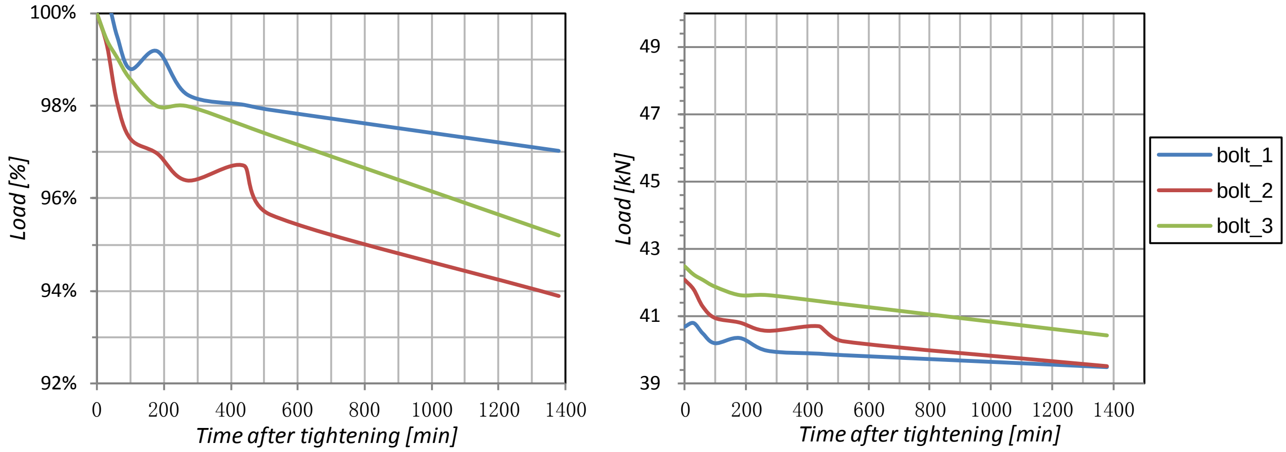



***Figure 5.10: the clamping load lost of the dummies tightened by tightening procedure e) over time.***

Different from those “tight to target” tightening procedure, tightening procedure e) is a “loose to target” tightening procedure. It decreases the relative movement on the contact surfaces to decrease the effects of wearing phenomenon, and also applies a significant high pre-stress to the joint system.

The test results show that, e) improved the self-relaxation resistance property, the clamping load lost decreases to 4.6%. But because of the special tightening method, the tightening accuracy is hard to ensure: the average clamping load achieved by tightening procedure e) is lower than the nominal tightening situation.

*f): 100 ° Pre-tight + Nominal tightening procedure*

The lost of clamping load of each bolt tightened by f) can be shown:

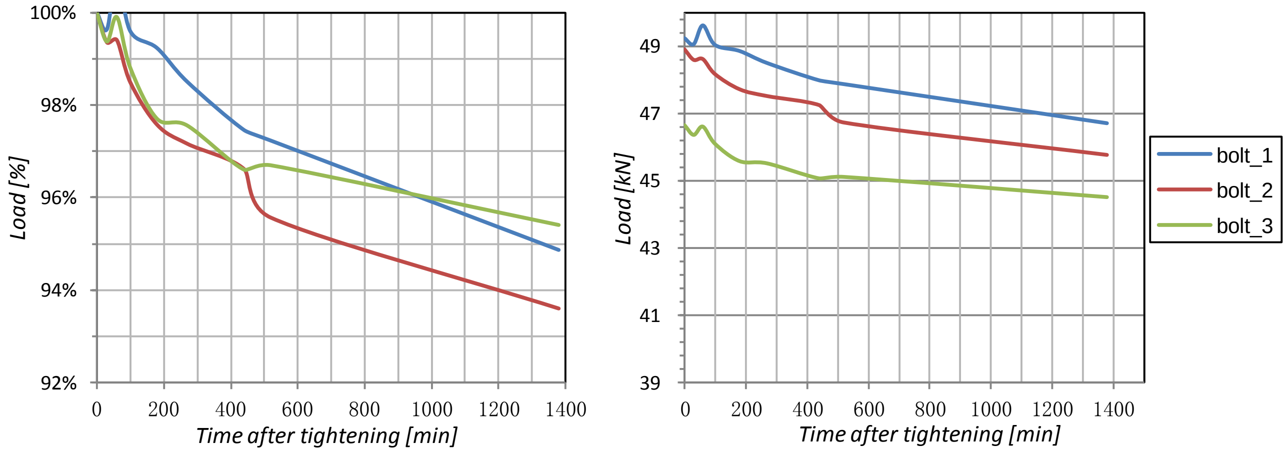



***Figure 5.11: the clamping load lost of the dummies tightened by tightening procedure f) over time.***

At the end of the test, the bolts tightened by tightening procedure f) lost 5.5% of clamping load. This result is out of expectation, according to the relaxation theory mentioned in section 2.3, a higher pre-load is more effective to resist the the fall in stress in the following step. Apparently the pre-stress achieved by 100° pre-tightening step is the highest among the new tightening procedures, but instead of decreases the fall in clamping load, the tightening procedure f) lost even more. In chapter 6 more tests will be done to explain this phenomenon.

The standard deviation of the clamping load of the bolts tightened by f) reaches to 1.14 at the end of the test.

#### 5.1.2.2 Test results of test B)

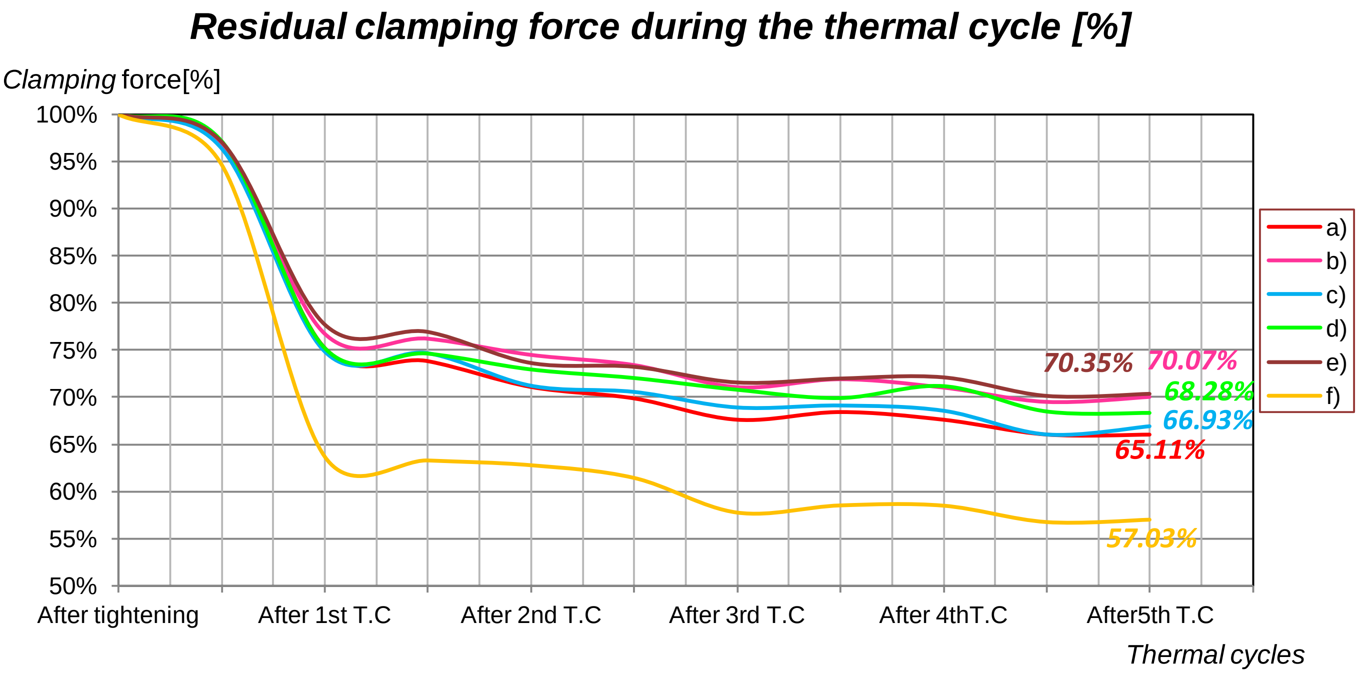



***Figure 5.12: Clamping load change with thermal cycle***

The letters in the legend represent the tightening procedures:

g) Original tightening procedure
h) Two times of nominal tightening procedures
i) Tightening in 2 steps
j) Tightening in 3 steps
k) Over-tightening the bolt in the elastic domain and then loosen the bolt to the target tightening situation
l) Over-tightening the bolt into plastic domain and then loosen the bolt to apply the nominal tightening procedure

**Self relaxation resistance**

| | a) | b) | c) | d) | e) | f) |
|---|---|---|---|---|---|---|
| Initial load [kN] | 41.2 | 45.0 | 40.8 | 41.6 | 39.3 | 41.3 |
| lost in 1 [%] | 21.9% | 20.1% | 21.5% | 22.0% | 19.3% | 31.0% |
| lost in 2 [%] | 2.7% | 2.8% | 3.4% | 1.7% | 3.3% | 1.9% |
| lost in 3 [%] | 2.3% | 2.3% | 1.7% | 1.2% | 1.7% | 2.9% |
| lost in 4 [%] | 0.8% | 0.9% | 1.7% | 1.1% | -0.1% | 0.0% |
| lost in 5 [%] | 0.0% | -0.5% | -0.9% | 0.2% | -0.2% | -0.3% |
| final lost [%] | ***34.0%*** | ***29.9%*** | ***33.1%*** | ***31.7%*** | ***29.7%*** | ***43.0%*** |
| final load [kN] | 27.2 | 31.5 | 27.3 | 28.4 | 27.7 | 23.6 |

***Table 5.4: The clamping load of the dummy joints lost during thermal cycles***

**Tightening accuracy**

| | a) | b) | c) | d) | e) | f) |
|---|---|---|---|---|---|---|
| Average Force Immediately [kN] | 41.2 | 45.0 | 40.8 | 41.6 | 39.3 | 40.5 |
| Standard deviation [kN] | 2.0 | 2.1 | 2.2 | 1.2 | 1.2 | 0.3 |
| Offset from nominal(after tightening) | 0.00% | 9.20% | -1.10% | 1.00% | -4.60% | -1.70% |
| after 5th T.C. [kN] | 27.2 | 31.5 | 27.3 | 28.4 | 27.7 | 23.4 |
| Standard deviation [kN] | 3.0 | 0.7 | 1.7 | 0.3 | 2.1 | 0.5 |
| Offset from nominal (after 5th T.C.) | 0.00% | 10.40% | 0.10% | 2.80% | 1.10% | -9.30% |

***Table 5.5: Tightening accuracy of each kind of tightening procedures performed on dummy joints in test B)***

**Joint security**

| | a) | b) | c) | d) | e) | f) |
|---|---|---|---|---|---|---|
| Ave. Max. tightening torque [Nm] | 105.5 | 104.3 | 110.3 | 86.8 | 100.7 | 105.5 |
| Ave. Max. loosening torque [Nm] | 88.1 | 96.7 | 98.3 | 82.9 | 97.7 | 88.1 |
| Ave. Break ratio | 84% | 93% | 89% | 95% | 97% | 84% |

***Table 5.6: The breaking ratio of the dummy joints tightened by new tightening procedures in test B)***

a): *nominal tightening procedure*

The test results of the bolts tightened by the nominal tightening procedure are taken as reference to explain the decreasing law of clamping load during the thermal cycles.

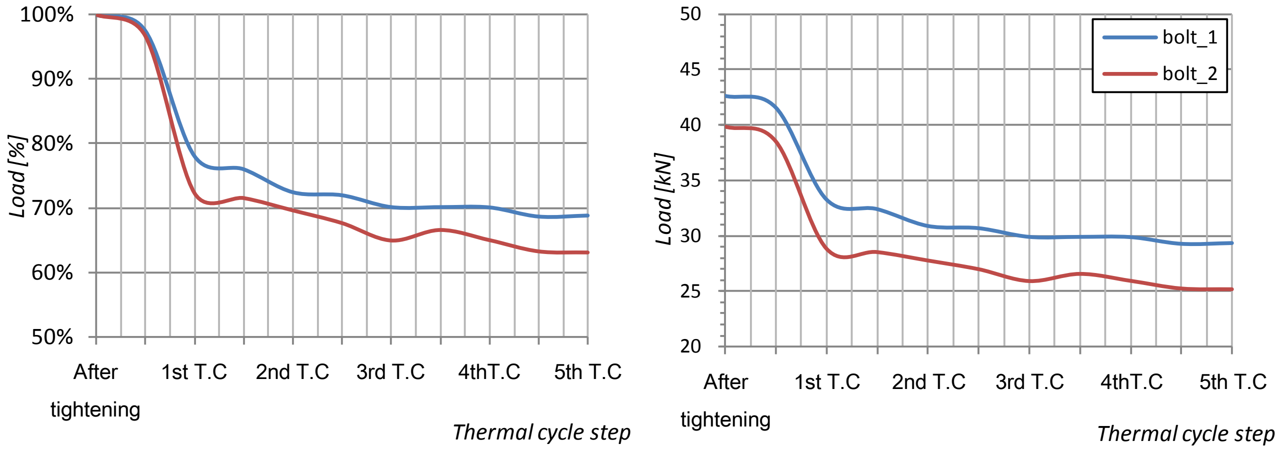



***Figure 5.13: The clamping load lost of the dummy tightened by nominal tightening procedure during thermal cycles***

As shown in the graph, two bolts tightened by the nominal tightening procedure lose their clamping load after the heating/cooling process, especially in the first thermal cycle; compare with the clamping load measured immediately after the tightening, about 22% of clamping load is lost. With the processing of thermal cycle, the decreasing rate of the clamping load reduces. At last the clamping load tends to be stable in the $4^{th}$ and $5^{th}$ heating steps. At the end of the test, 34.0% of clamping load is lost.

In test B), because of the high amount of clamping load lost, two test-pieces are enough to define the self-relaxation resistance property of each tightening procedure. But the standard deviation which is used to judge the tightening accuracy, based on only two test data, is no more reliable. So, here, the composition of the "discussion" part will be modified to mainly focus on the self-relaxation resistance property and joint security.

*b): 70$^{\circ}$ Pre-tight + Nominal tightening procedure*

The lost of clamping load of each bolt tightened by b) can be shown:

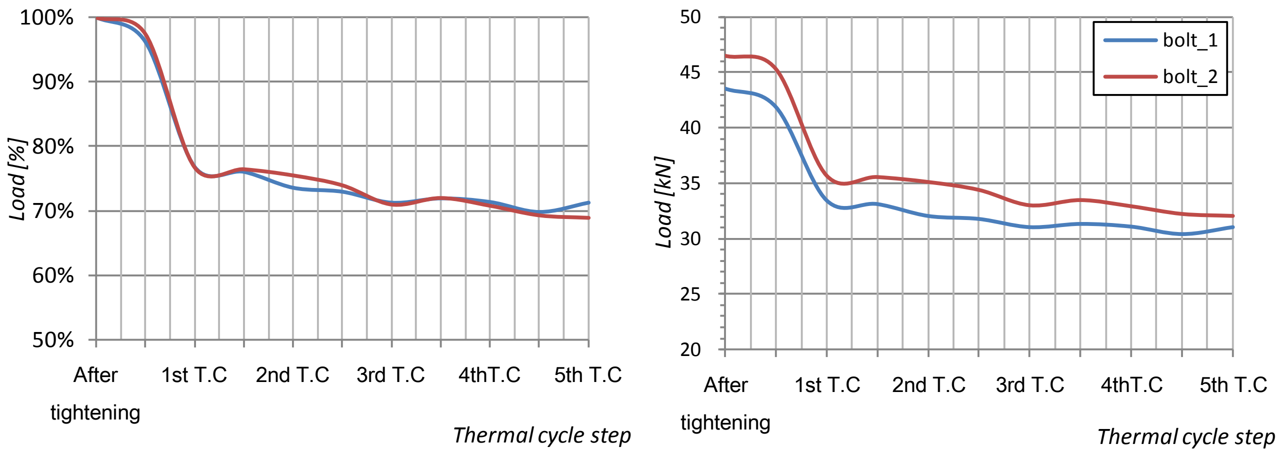



***Figure 5.14: The clamping load lost of the dummy tightened by tightening procedure b) during thermal cycles***

Test B) confirmed the conclusion which is made by the test results of test A). The new tightening procedure b) still provides a good self-relaxation resistance performance in the variable working temperature. After the 5 thermal cycles, the joints tightened by b) lost about 30% of clamping load on average. About 31.5 kN clamping load remains in the dummy joints, which is 4.5 kN higher compared with the nominal tightening situation.

Need to note that the average breaking ratio of the joints tightened by b) in test A) is 75%, but in test B) after the repeated heating and cooling processes, the breaking ratio increases to 93%. And the similar "Increasing of braking ratio" phenomenon happens on all the joints tested in test B).

*c): 50° Pre-tight + Nominal tightening procedure*

The lost of clamping load of each bolt tightened by c) can be shown:

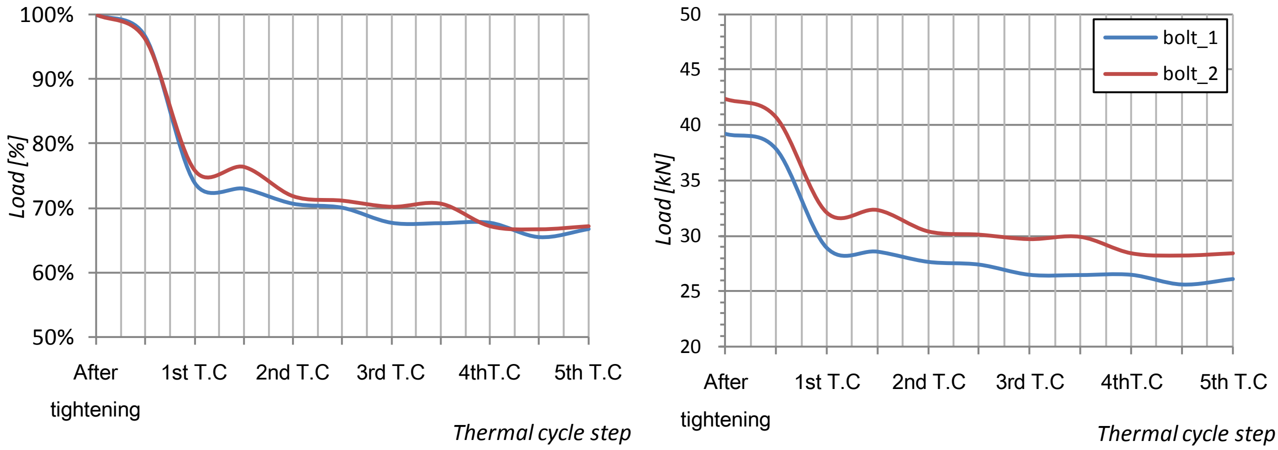



***Figure 5.15: The clamping load lost of the dummy tightened by tightening procedure c) during thermal cycles***

After all the 5 thermal cycles, the clamping load achieved by tightening procedure c) lost 33%, and the breaking ratio increases to 89%. Both results show that the 50° pre-tightening step seem makes no different on the joint system. The clamping condition achieved by c) is quite similar to the nominal tightening situation.

*d): 30° First pre-tight + 50° Second pre-tight + Nominal tightening procedure*

The lost of clamping load of each bolt tightened by d) can be shown:

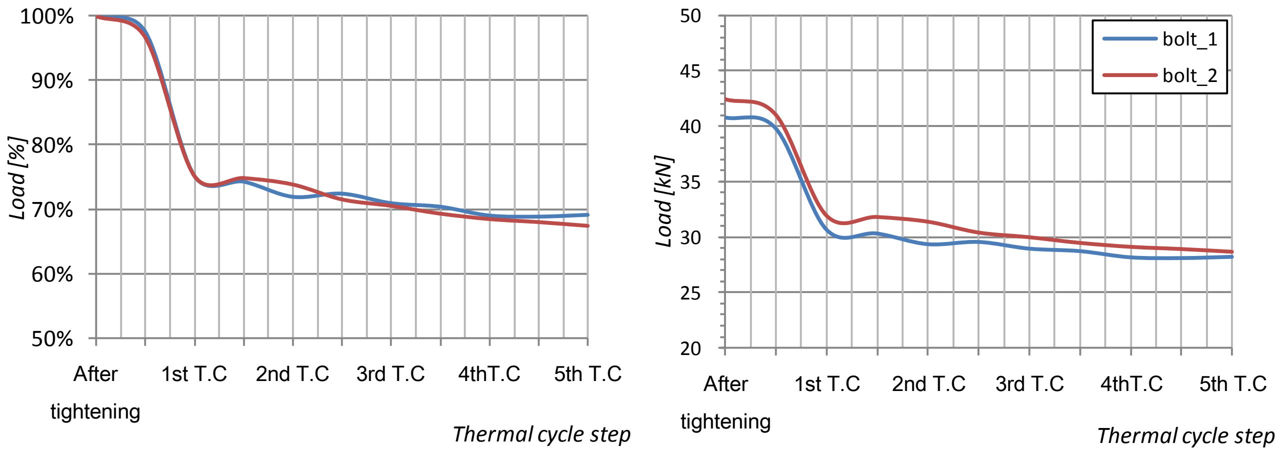



***Figure 5.16: The clamping load lost of the dummy tightened by tightening procedure d) during thermal cycles***

The 32% lost of clamping load makes the tightening procedure d) in the same self-relaxation resistance level as the nominal tightening procedure.
But the special benefit brought by d), which was discovered in test A), happens again. The breaking ratio increases from 84% to 95% compare with the nominal tightening situation.

*e):80°Pre-tight + 30°Un-tight +20°tight*

The lost of clamping load of each bolt tightened by f) can be shown:

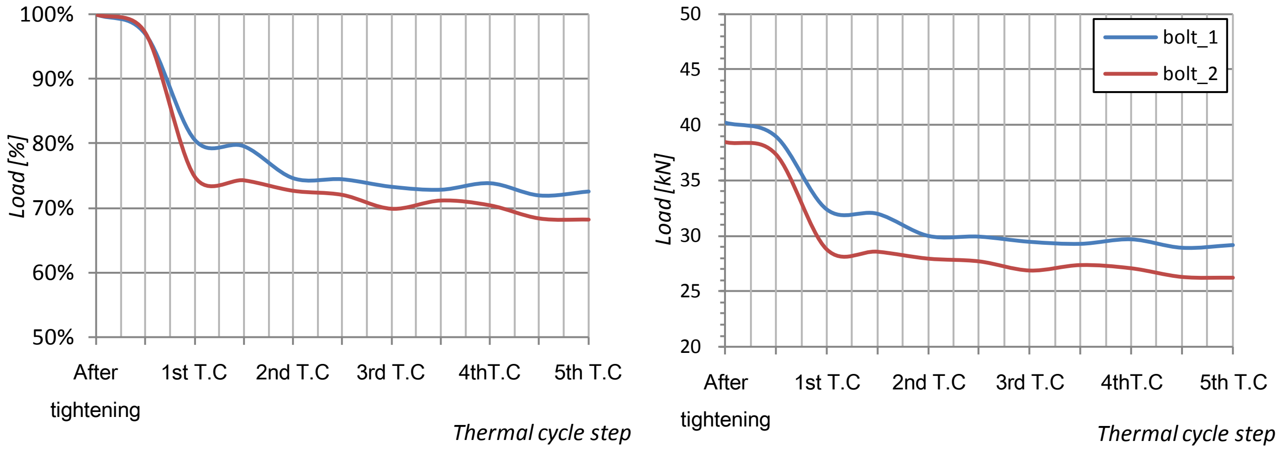



***Figure 5.17: The clamping load lost of the dummy tightened by tightening procedure e) during thermal cycles***

No doubt that, the tightening procedure e) has the best performances not only on the self-relaxation resistance but also on the joint security. e) decreases the lost of clamping load to 29.7% and increases the breaking ratio to 97%. The only defect is that, the average clamping load is little lower than the standard clamping load[10].

*f): 100°Pre-tight + Nominal tightening procedure*

The lost of clamping load of each bolt tightened by f) can be shown:

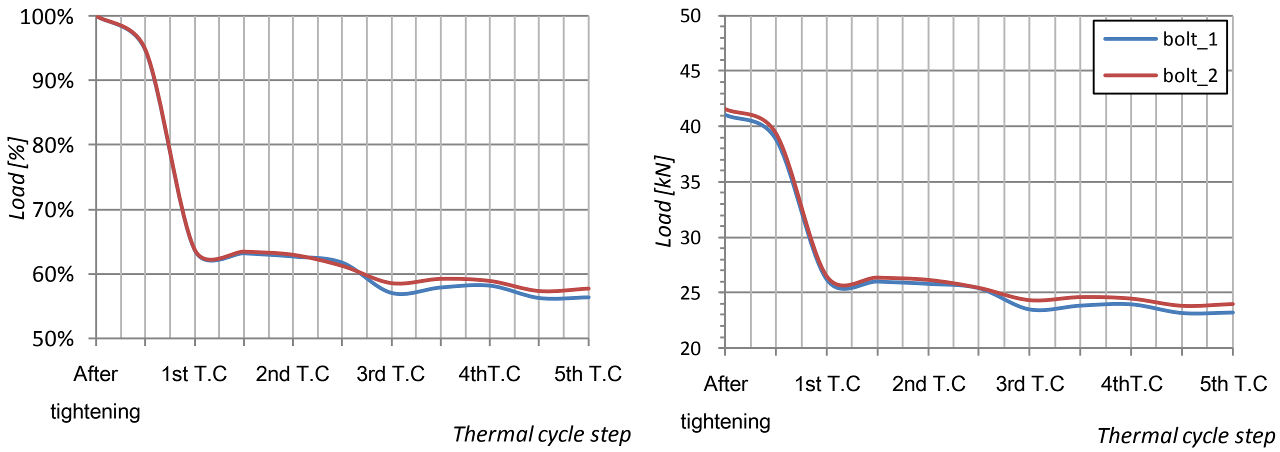



***Figure 5.18: The clamping load lost of the dummy tightened by tightening procedure f) during thermal cycles***

The worst performed tightening procedure to against clamping load lost during thermal cycle is f), which is over-tight the bolt into elastic-plastic domain first and then un-tight the bolt to process the nominal tightening step.

[10] The average value of the clamping load achieved by nominal tightening procedure.

At the end of the test the bolts tightened by f) lost 42.1% of clamping load, even more than the nominal tightening procedure. This shows that the self relaxation resistance can not be improved easily just by increasing the pre-tight torque, because the damages on the contact surface made by the pre-tight step should also be considered.

### *5.1.3 Conclusion*

According to the tests on the dummy joints, a comprehensive understanding of the new tightening procedures is done. The actual result does not fully comply with the expectation made according to the theory, but some tightening procedures do prevent the joint from the lost of clamping load more efficiently.

The bolts tightened by tightening procedure c) and d), whose pre-tightening angle is lower than the nominal tightening angle, lost almost the same percentage of clamping load as the nominal tightening situation during the test process, which means that, a low level pre-stress doesn't improve significantly the self-relaxation resistance property of a bolted joint system. But as shown in the test results, the scatter of the clamping load of the bolts tightened by c) is decreased, and d) increases the breaking ratio of a bolted joint system. So a conclusion can be made that, a proper pre-tight step can adjust the irregularities both of bolt and clamped parts by seizing effect, and this improves the tightening accuracy; and a proper multi pre-tight step can modify the mechanism on the contact surface to increase the breaking torque needed to un-tight the bolt: the contact surfaces are flattened progressively and pre-stressed gradually; this makes more effective the initial seizing effect so that the final tightening is done in more "stable-state' joint.

The tightening procedure f) has the highest pre-tightening angle, but the highest clamping load lost and large clamping load scatter remind that, a high pre-stress should be prevented in this tightening situation.

Both the tightening procedure b) and e) show a good self-relaxation resistance property, high tightening accuracy and high breaking ratio. The working property of a bolted joint system can be improved by these new tightening procedures, so in the following chapter, b) and e) will be performed on the real calipers to verify the reliability of the improvements they provide to the joints.

## 5.2 Tests on real calipers

For the tests done on the real calipers, the test A) is carried out first immediately after the tightening; then after 24 hours, the same component is heated up in the electrical oven and test B) is performed continuously.

### *5.2.1 Test procedure*

1. As the test step 1 to step 4 in section 5.1.1.1, the ultrasonic device is switch-on and the tested bolts are prepared.
2. 3 pairs of caliper are prepared: for each pair, four bolts are tightened by the same tightening procedure following the sequence shown in Fig. 5.19.

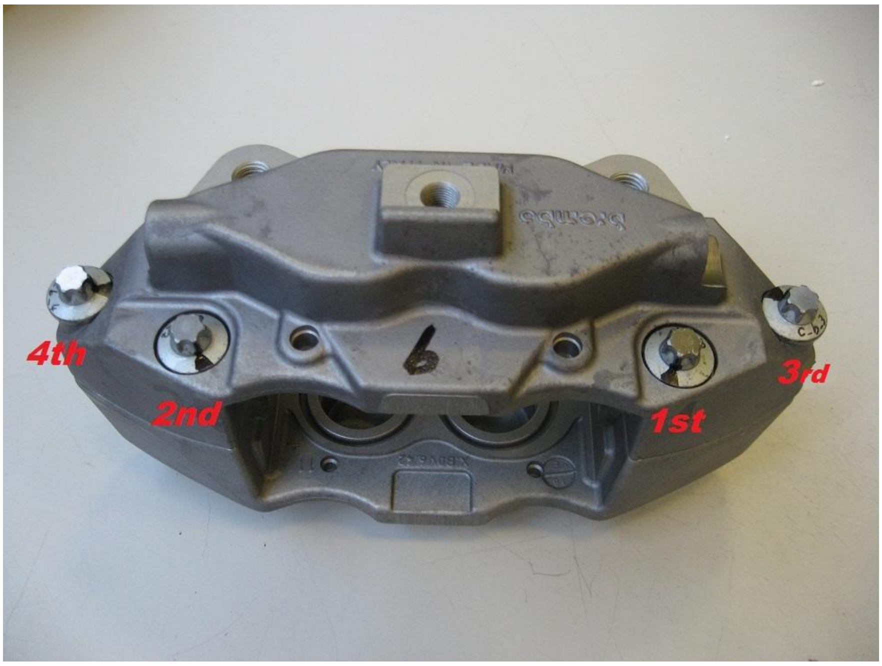



***Figure 5.19: tightening sequence of the caliper's bolts***

3. After tightening, according to the schedule, at each point-in-time, the length of tested bolts will be measured[11] by U.S. device.
4. After 24 hours at room temperature, the joints are heated up to 150°C for 15 hours, and then cooled at the room temperature for 8 hours[12]; the clamping lengths are measured 3 hours after the parts are taken out of the oven.
5. Repeat step 4 for other 4 times.
6. Data record and analysis.

---

[11] 4 steps measuring process as mentioned in section 5.1.1.1
[12] The thermal cycle mentioned in section Fig. 5.2.

### 5.2.2 Test results and discussion

#### 5.2.2.1 Test results of test A)

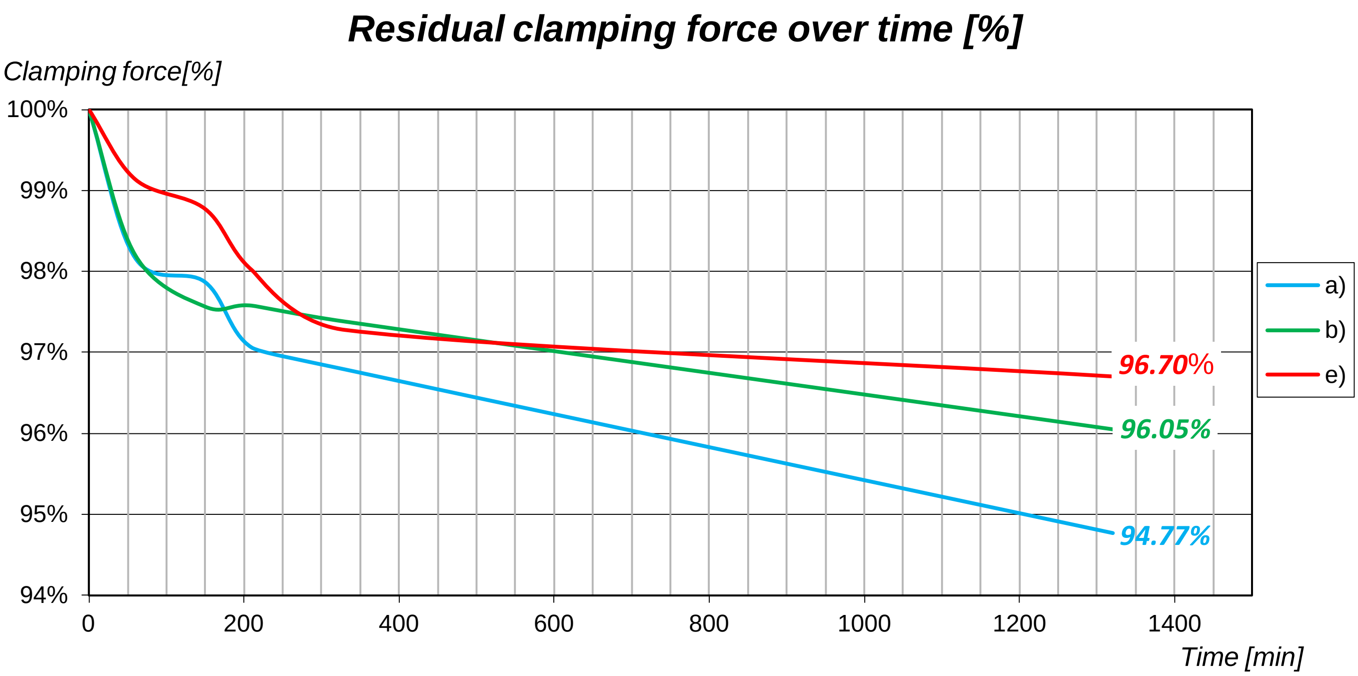



*Figure 5.20: Clamping force changes with time on caliper*

The letter in the legend corresponding to the tightening procedures:

a) Original tightening procedure

b) Two times of nominal tightening procedures

e) Over-tightening the bolt in the elastic domain and then loosen the bolt to the target tightening situation

**Clamping load lost over time**

| | a) | b) | e) |
|---|---|---|---|
| Average Force after tightening [kN] | 46.3 | 46.7 | 43.6 |
| Average Force after 1380 mins [kN] | 44.0 | 44.8 | 42.1 |
| Force lost [%] | **4.9%** | **4.0%** | **3.3%** |

*Table 5.7: The clamping load of the joints on caliper lost over time*

**Tightening accuracy**

| | a) | b) | e) |
|---|---|---|---|
| After tighening [kN] | 46.3 | 46.7 | 43.6 |
| Standard deviation [kN] | 1.1 | 2.2 | 1.5 |
| Offset[13] (after tightening) | 0.00% | 0.80% | -6.00% |
| After 1380h [kN] | 44.0 | 44.8 | 42.1 |
| Standard deviation [kN] | 0.9 | 1.7 | 1.5 |
| Offset(after1380 hours) | 0.00% | 1.70% | -4.40% |

***Table 5.8: Tightening accuracy of each kind of tightening procedures performed on calipers in test A)***

The clamping load of the bolts tightened on the real calipers during the test procedure A) can be shown as following:

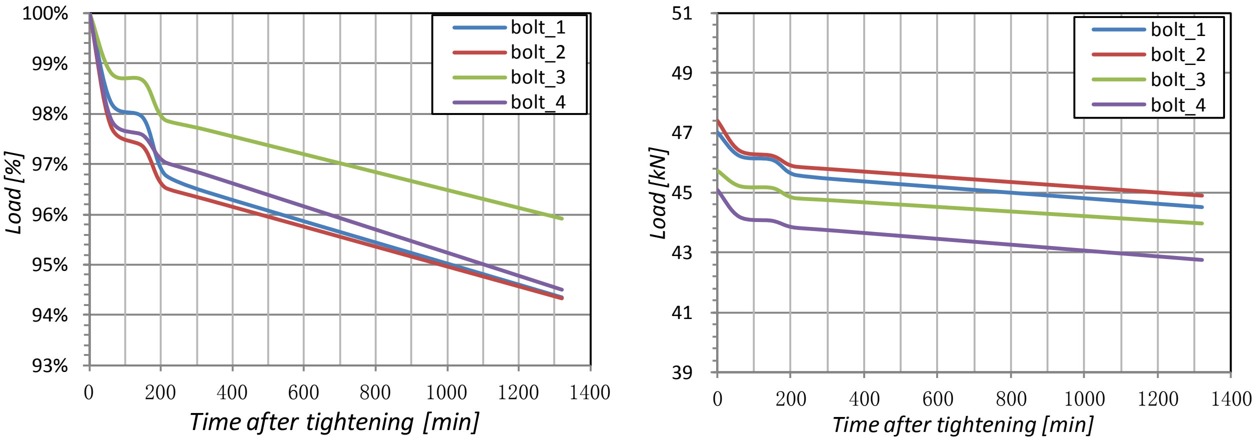



***Figure 5.21: the clamping load lost of the joints on caliper tightened by nominal tightening procedure over time.***

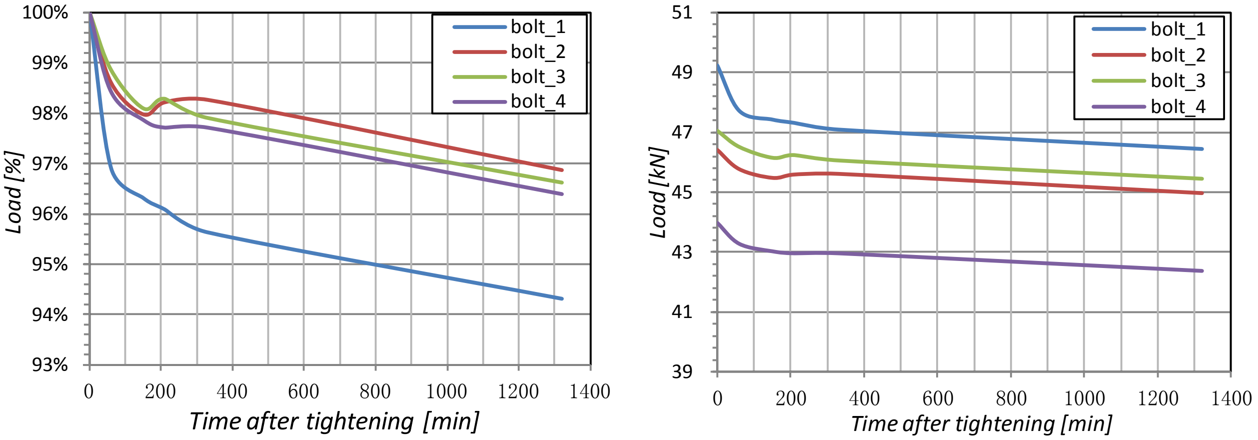



***Figure 5.22: the clamping load lost of the joints on caliper tightened by tightening procedure b) over time.***

[13] The different of clamping load between new tightening procedure and nominal tightening procedure

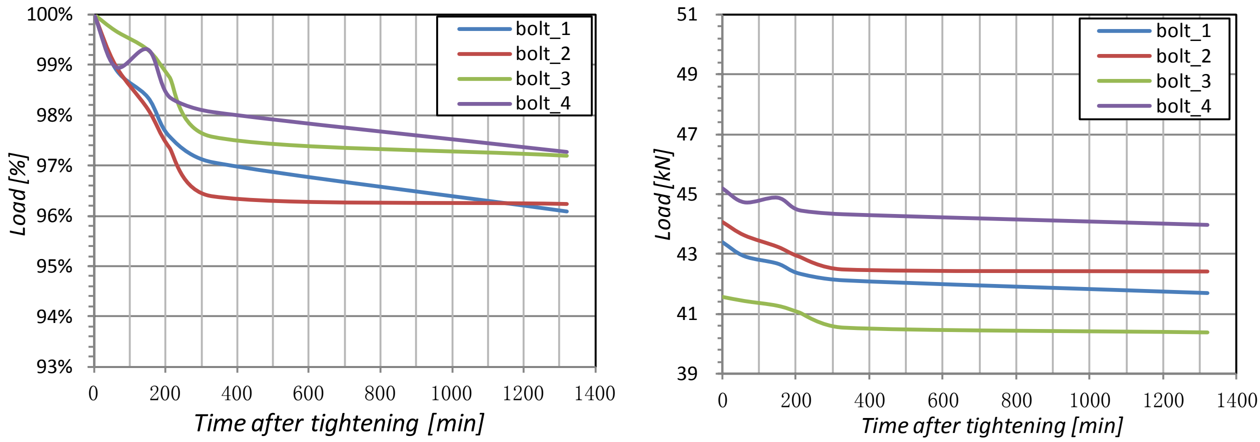



***Figure 5.23: the clamping load lost of the joints on caliper tightened by tightening procedure e) over time.***

The graphs show that, in the no extra loading and room temperature condition, the clamping load decreases rapidly in the first 200 mins after tightening, the major part of embedding phenomenon happens in this period. For example, for the joints tightened by nominal tightening procedure, about 3% of clamping load lost happens in the first 200 mins and at the end of the test the lost of clamping load reach to 5%.

By the laboratory facilities used in these tests, only one bolt can be tightened in 1 time. So even if the bolts are tightened by the designed sequence, the same tightening condition is hard to guarantee for each bolt. That's why the standard deviation of the 4 bolts tightened on same caliper is higher than the standard deviation of the bolts tightened on the dummy blocks with the same tightening procedure.

According to the graph, also the lost of clamping load is affected by the tightening sequence. The first bolt tightened on the caliper tends to lost more clamping load than the others, marked as the blue lines in the above graphs.

As on dummy blocks' tests the tightening procedure b) and e) carried out on the calipers still prevent the lost of clamping load more efficiently than the nominal tightening procedure.

The tightening procedure b) provide an average clamping load almost the same as the nominal tightening procedure, but the high value of standard deviation presents a large scatter of the clamping load. For tightening procedure e), the same problem happens again, the average clamping load is lower than the standard[14].

[14] The average clamping load of the bolt tightened by nominal tightening procedures

#### 5.2.2.2 Test results of test B)

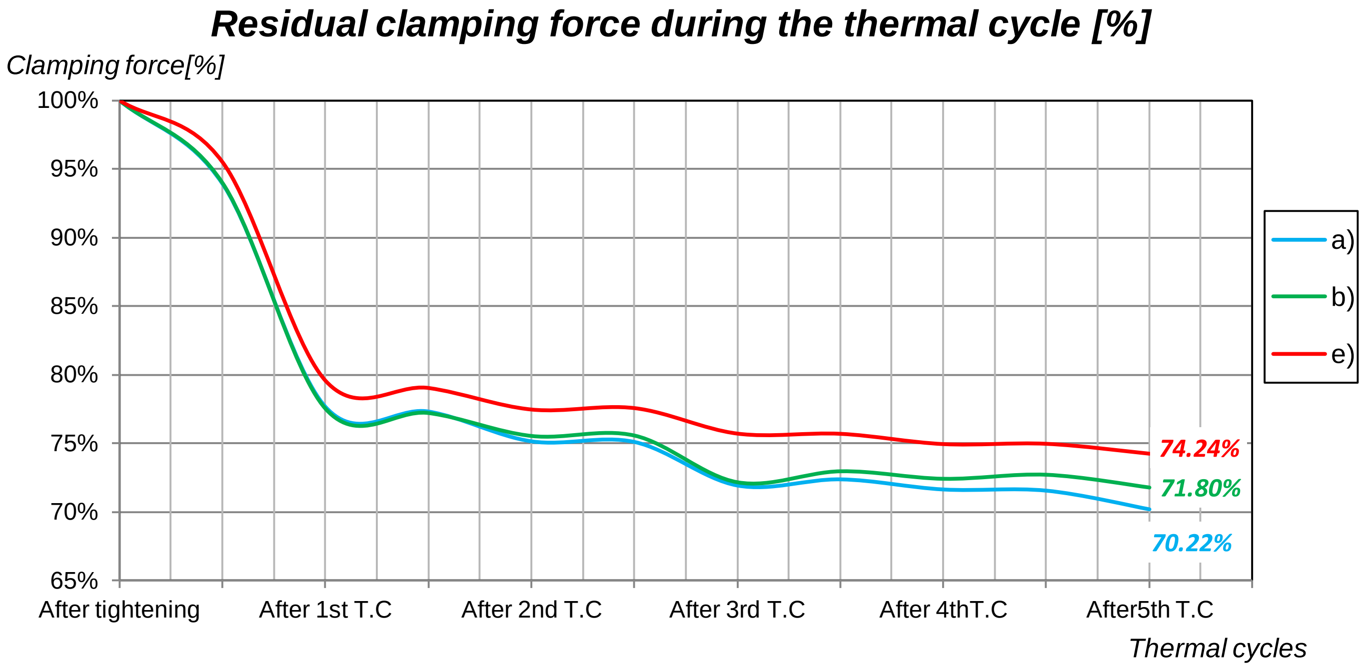



*Figure 5.24 Clamping force changes with thermal cycles.*

The letter in the legend corresponding to the tightening procedures:

a) Original tightening procedure
b) Two times of nominal tightening procedures
e) Over-tightening the bolt in the elastic domain and then loosen the bolt to the target tightening situation

**The lost of clamping load**

| | a) | b) | e) |
|---|---|---|---|
| Initial load [kN] | 46.3 | 46.7 | 43.6 |
| Lost in $1^{st}$ thermal cycle | 16.3% | 16.5% | 16.0% |
| Lost in $2^{nd}$ thermal cycle | 2.2% | 1.7% | 1.6% |
| Lost in $3^{rd}$ thermal cycle | 3.2% | 3.4% | 1.9% |
| Lost in $4^{th}$ thermal cycle | 0.7% | 0.6% | 0.8% |
| Lost in $5^{th}$ thermal cycle | 1.4% | 0.9% | 0.7% |
| Final lost [%] | ***29.8%*** | ***28.2%*** | ***25.8%*** |
| Final load [kN] | 32.5 | 33.5 | 32.3 |

*Table 5.9: The clamping load lost of the caliper joints during thermal cycles*

**Tightening accuracy**

| | a) | b) | e) |
|---|---|---|---|
| After tightening [kN] | 46.3 | 46.7 | 43.6 |
| Standard deviation [kN] | 1.1 | 2.2 | 1.5 |
| Offset(after tightening) | 0.00% | 0.80% | -6.00% |
| after 5th T.C. [%] | 32.5 | 33.5 | 32.3 |
| Standard deviation [kN] | 0.9 | 2.0 | 1.3 |
| Offset(after 5th T.C.) [%] | 0.00% | 3.00% | -0.60% |

***Table 5.10: Tightening accuracy of each kind of tightening procedures performed on calipers in test B)***

The clamping load of the bolts tightened on the real calipers during the test procedure B) can be shown as following:

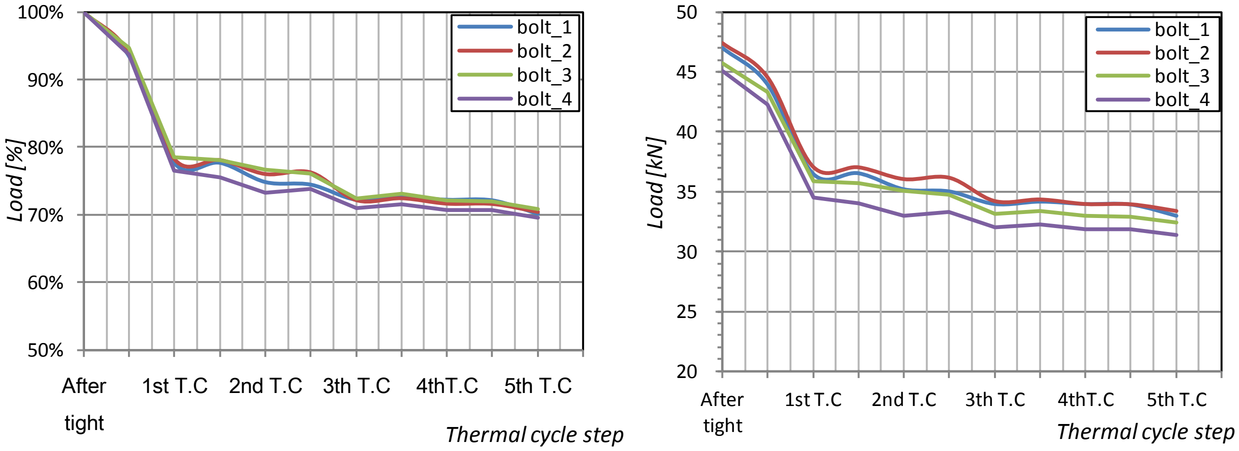



***Figure 5.25: The clamping load lost of the joints on caliper tightened by nominal tightening procedure during thermal cycles***

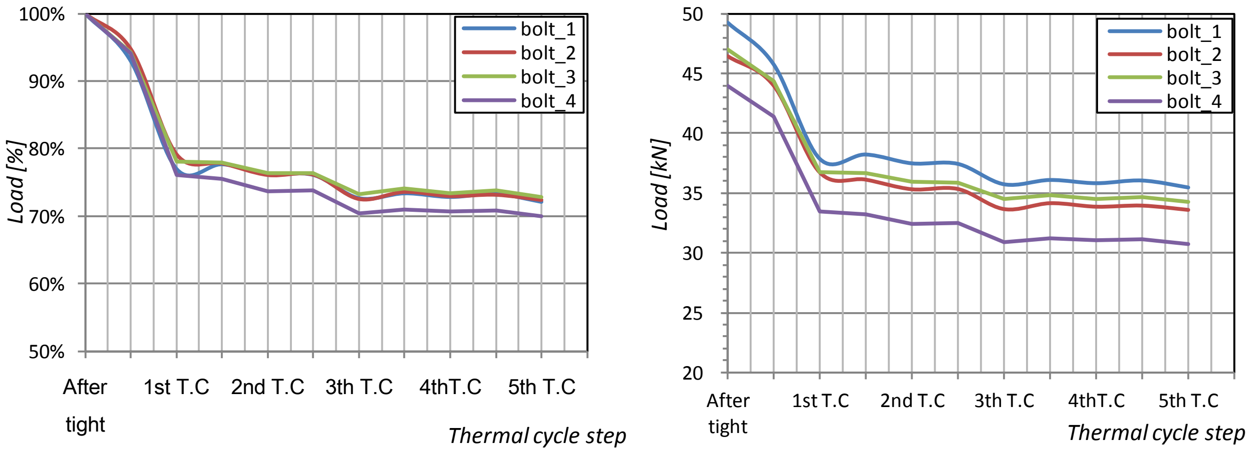



***Figure 5.26: The clamping load lost of the joints on caliper tightened by tightening procedure b) during thermal cycles***

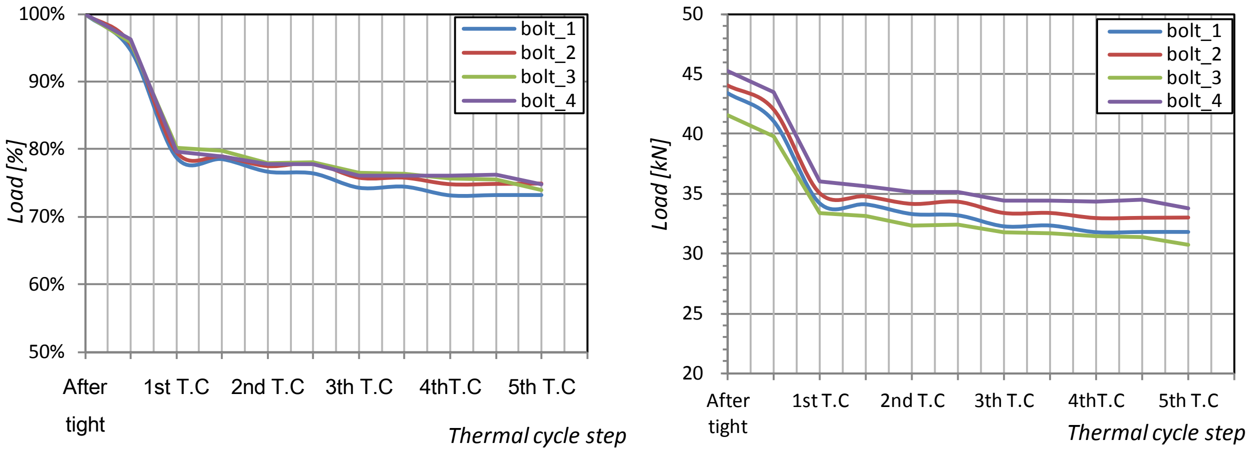



***Figure 5.27: The clamping load lost of the joints on caliper tightened by tightening procedure e) during thermal cycles***

The test results confirmed the observation done on dummy joints. About 60% of clamping load lost happens in the first thermal cycle, and the decreasing ratio of clamping load reduce with the proceeding of the thermal cycle, until the 4$^{th}$ and 5$^{th}$ thermal step the clamping load become stable. And the effectiveness of tightening procedures b) and e) to minimize relaxation is verified again on the caliper joints during thermal cycles.

## 5.3 Conclusion

Until now, the self-relaxation resistance properties of all the tightening procedures have been studied. For preventing the lost of clamping force, the best performed tightening procedure is b) and e) , compare with the nominal tightening procedure a), a summary is shown as follows:

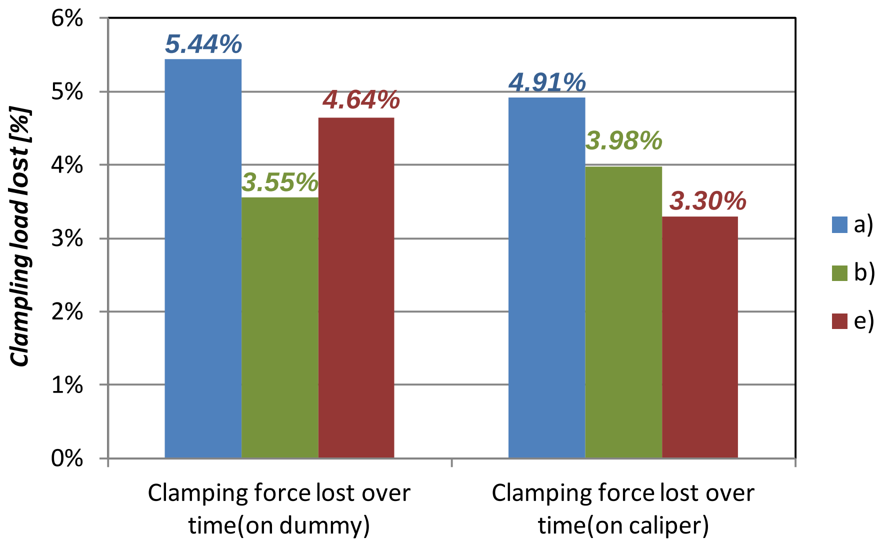



***Figure 5.28 the clamping load lost of the bolts tightened by tightening procedure a), b) and e) after 1400 mins at room temperature***

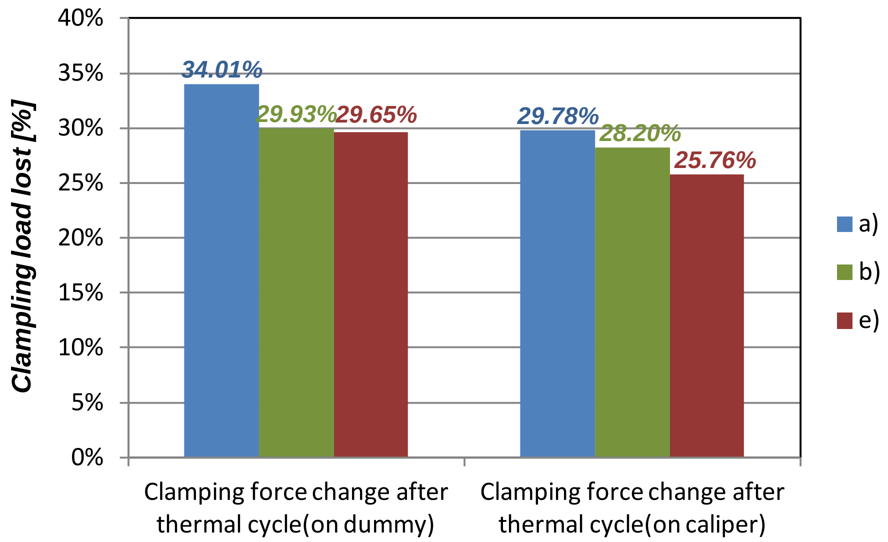



***Figure 5.29 the clamping load lost of the bolts tightened by tightening procedure a), b) and e) after 5 thermal cycles***

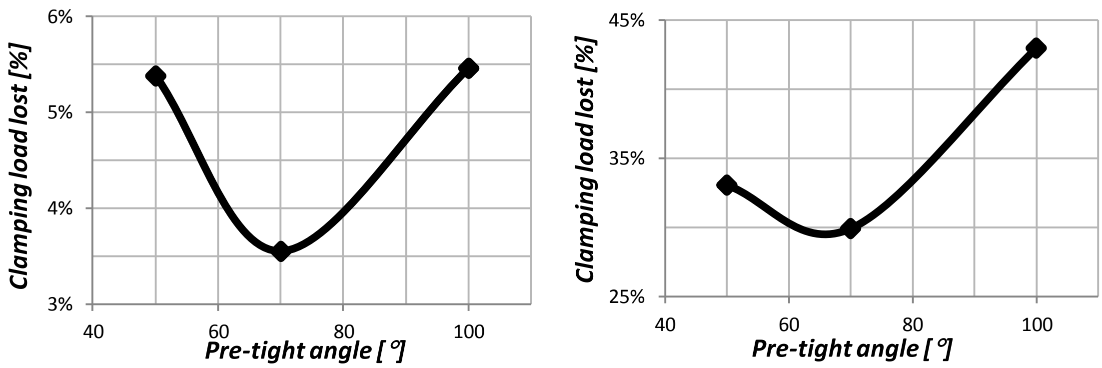
This illustrates that, no matter on the dummy part or on the caliper and no matter in the no extra loading and room temperature working condition or in the various temperature working condition, the bolts tightened by the new tightening procedures have a better performance to minimize self-relaxation. A lower lost of the clamping load means a more reliable final preload condition, and an accuracy good designed preload can dramatically promote the working performance of the joint system.

But the multi tightening procedure also leads to some problems, from the sight of final clamping load, the new tightening procedures are not as stable as nominal procedure. This is because of the coating system, which is used to control the friction coefficient, is scraped away during the first tightening step. When the tightening procedure moves to the second step, the unstable friction coefficient results a large scatter of clamping load,
For tightening procedure e), the effect of uncertain friction coefficient problem can be weakened thanks to the short tightening angle of the second tightening step. But because of the influence of the gaps between bolt head and tightening tool, the accuracy is hard to fulfill when a small angle turning or a precise reverse turning is performed. Therefore, suitable angle should be designed.

After the tests, the improvements brought by the new tightening procedures are confirmed. In the following chapter the tests will focus on the new tightening procedures that can’t improve the joint’s working property. By comparing the “good” and “bad” tightening procedures, a further understanding of what the new tightening procedure bring to the joint system is expected.

# CHAPTER 6: FURTHER INVESTOGATOPMS

In this chapter, tightening procedures b), c), f) are investigated furthermore, because they all have one pre-tight step which is different from d) and they are all the “tight to target” procedures while e) is the “loose to target” tightening procedure. The only difference among them is the pre-tightening angle; after the tests on dummy joints and on calipers a summary can be made. The relationship between clamping load lost and the pre-tightening angle can be shown as below:




a) Test result from test A)

b) Test results from test B)

*Figure 6.1 Pre-tight Angle/Clamping load lost*

Need to note that, in the following tests, the bolt’s under head surface is chosen as a reference position to reflect the overall tightening situation and the following influence on the joint system due to the new tightening procedures.

## 6.1 Reconsideration of the factors which affect the resistance to self-relaxation

Tightening procedure f) has the highest pre-tightening load, but instead of improving the self-relaxation resistance property, the bolts pre-tightened into elastic-plastic domain lose even more clamping load compare with the bolts tightened by nominal tightening procedure. As mentioned in chapter 2, a multi-tightening procedure could decrease the fall in stress in followed loading step, but it can also increases the irregularity on the contact surface which could promote the embedding phenomenon.
So here, some further tests have been done to understand better which one of these two factors play a key role in the relaxation phenomenon.

In the following statement, “contact surface” means the mating surface between under head bolt surface of bolt head and aluminum clamped part as showed in Fig 6.2

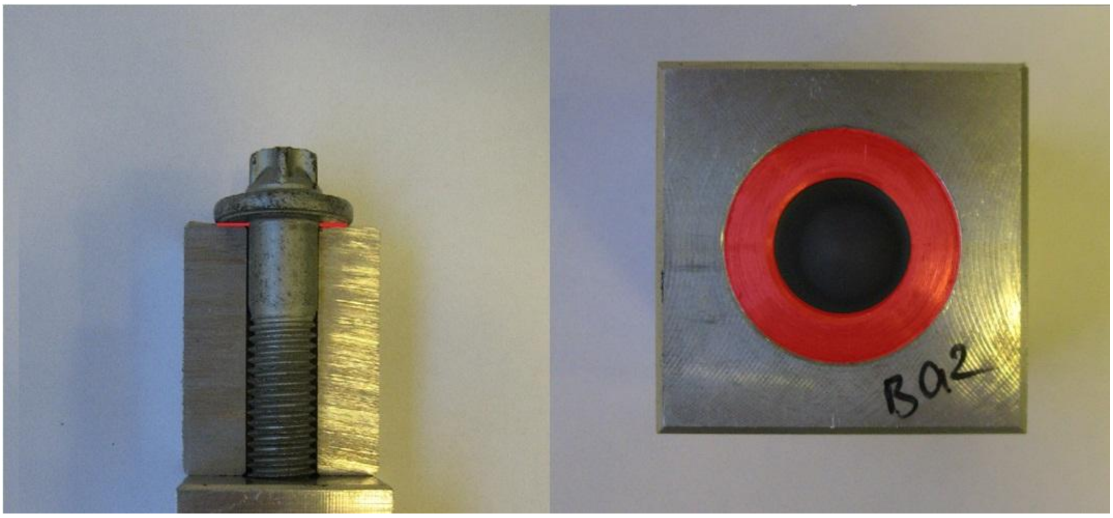



*Figure 6.2 Contact surface of under head bolt and clamped part (the red area in the picture)*

### *6.1.1 Embedment depth*

In this test we will focus on the embedment depth after tightening on the aluminum counterparts. This depth connected directly with the amount of plastic deformation in the bolted joint system, and it is easy to measure because it's located on the outer surface of aluminum parts. To quantify the embedding phenomenon some measurements will be done both by profilemeter and microscope (section 4.3.6).

For the profilemeter, the measurement can be carried out directly on the tightened surface without special treatment. Based on this, a test procedure is designed as follows:

1 A bolt is pre-tightened by procedure b).on an assembly of an aluminum plate and dummy parts
2 After the pre-tightening step and bolt un-tightening, four paths of profile measurements are performed on the contact surface between aluminum plate and bolt head, as shown in (Fig. 6.3)
3 Then, the pre-tightened aluminum plate is reassembled with the same bolt and same clamped part as in step 1, and the second step of the tightening procedure is carried on continually.
4 After full tightening procedure, the bolt is un-tightened immediately, and the same profile measurements like step 2 are performed again on the aluminum plate.
5 Repeat step 1 to step 4 on each of the bolts tightened by procedures c), e), and f).

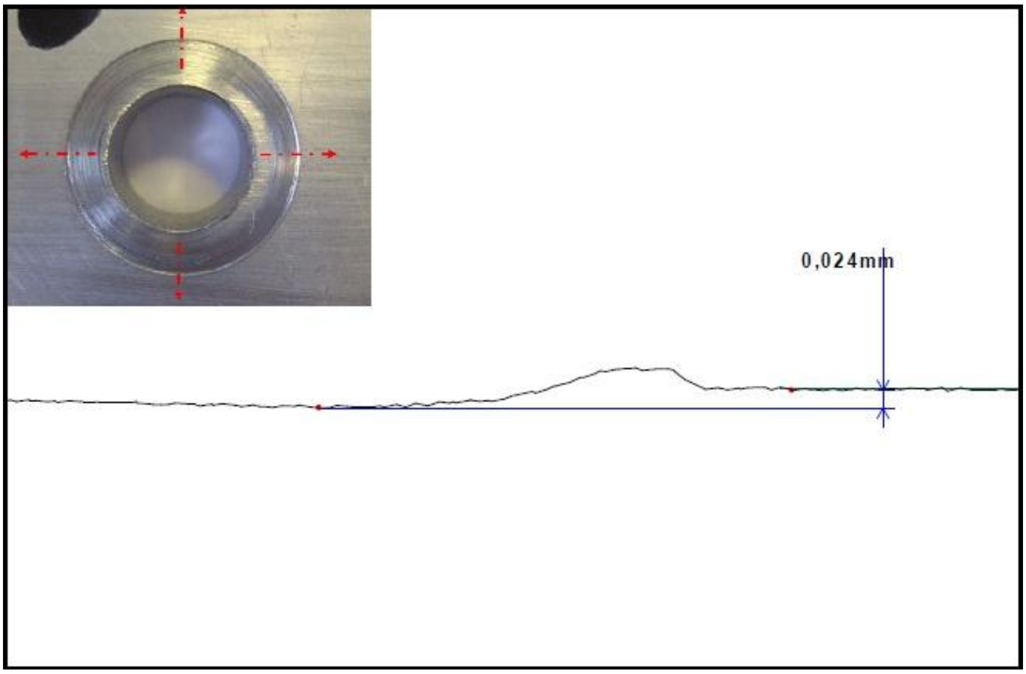



*Figure 6.3 Profilemeter tests*

To measure the embedment depth by microscope, the cross section of the contact surface need to be made into polished samples, which means that the tightening procedure can't be preformed continually on the same clamped part, so that the test procedure changes into:

1. Two bolts are pre-tightened by procedure b) on an assembly which is the aluminum plate and dummy parts.
2. Then the tightening procedure proceeds only on one of the bolts tightened in step 1.
3. Un-tight the bolts immediately, and make the samples of the contact surfaces for both the pre-tightened and fully tightened bolt (as shown in Fig 6.4).
4. Step 1 to 3 are repeated on each of the bolts tightened by procedures c), e) and f).

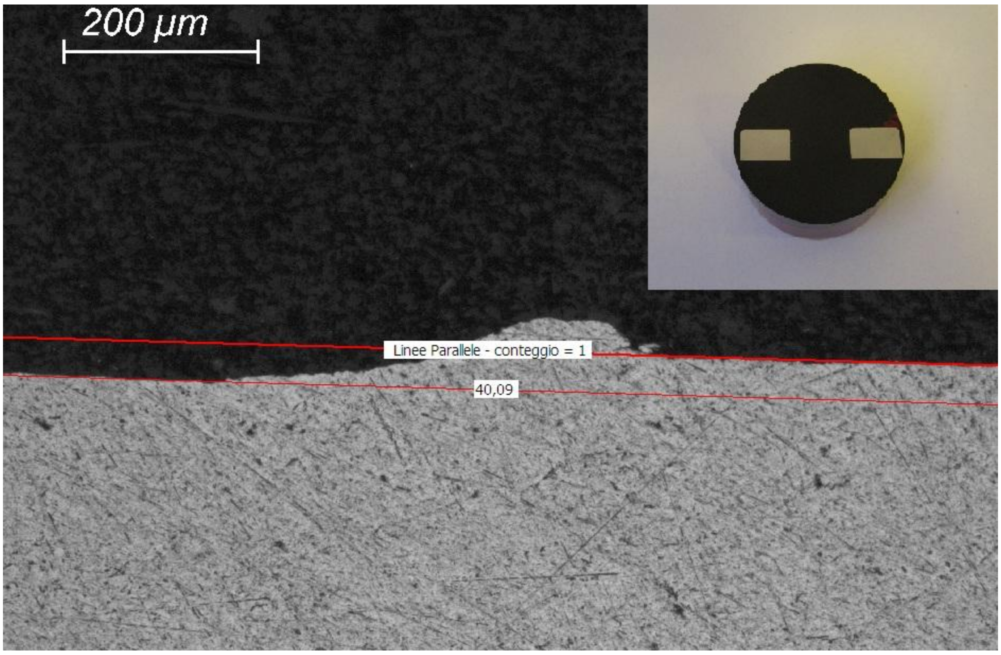



*Figure 6.4 Microscope inspection*

Then as the reference, the embedment depth on the dummy blocks tightened by b), c), e) and f) after the thermal cycles mentioned in chapter 4.3 are measured both by profilemeter and microscope.
After the consideration of all the test results from profilemeter and microscope a summary can be made (Fig. 6.5):

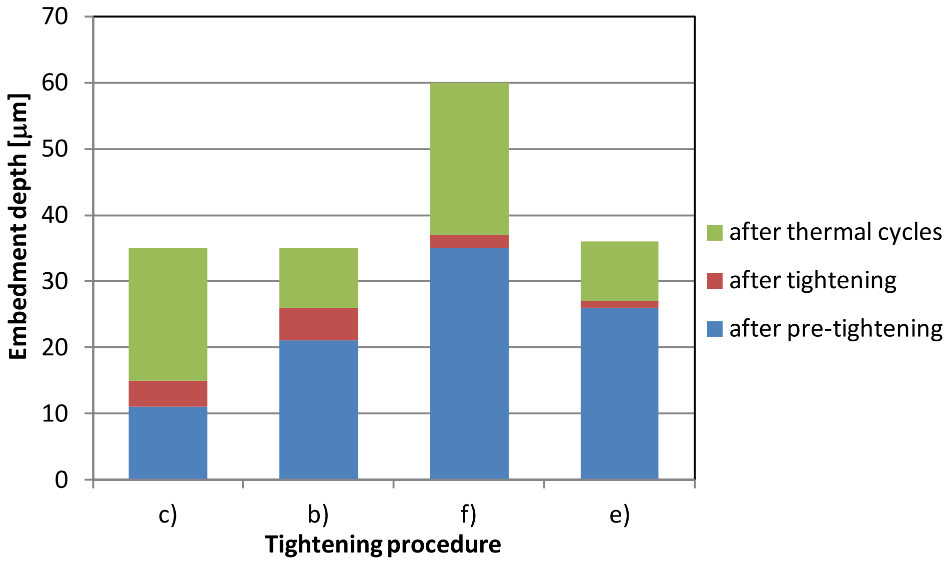



***Figure 6.5 Embedment depth after each tightening step***

In the first tightening step the plastic deformation of the counterpart which reflects in the embedment depth, increases with the degree that bolt is tightened in the angle control stage. This trend meets what is expected in chapter 2. In the second tightening steps of tightening procedure b), c) and f), on the contrary, the embedment depth reduces dramatically, when the pre-tightening angle exceeds the nominal tightening[15] angle. For example, for the tightening procedure f), whose pre-tightening angle is 100 degrees and second step tightening angle is 70 degrees like the nominal one, the embedment depth in second tightening step is even lower than the roughness of the contact surface.

### *6.1.2 Roughness on the tightened surface*

According to the theory mentioned in the chapter 2, the irregularities on the contact surface of the clamped part increases with clamping load and the distance of the relative movement, but this conclusion is made under the precondition that the initial situation on the contact surfaces is the same. But as the tightening procedure progresses, the second tightening step is performed on initial conditions which are different from one to the other caused by the different pre-tightening steps, so after the full tightening procedure the condition on the contact surface is hard to predict. So in this test the roughness are measured after each tightening step and taken as a reference value to reflect the irregularity.

[15] Because the second tightening step of the multi tightening procedure b), c) and f) is the same of the nominal tightening procedure, so the nominal tightening angle mentioned here means 70 degrees.

Because the dimension of the contact surface is not enough for a standard roughness test whose measuring length is 4mm, the roughness is measured by a 2 mm measuring length nonstandard roughness test.
Because of the complexity of the mechanism of wearing phenomenon, the roughness on the contact surface is affected by many factors like: irregularity of the bolt's geometry, variation of compress load, relative movement speed…
But after multiple experiments and some statistic al analysis, some measuring errors can be neglected, and conclusion can be made based on the test results.

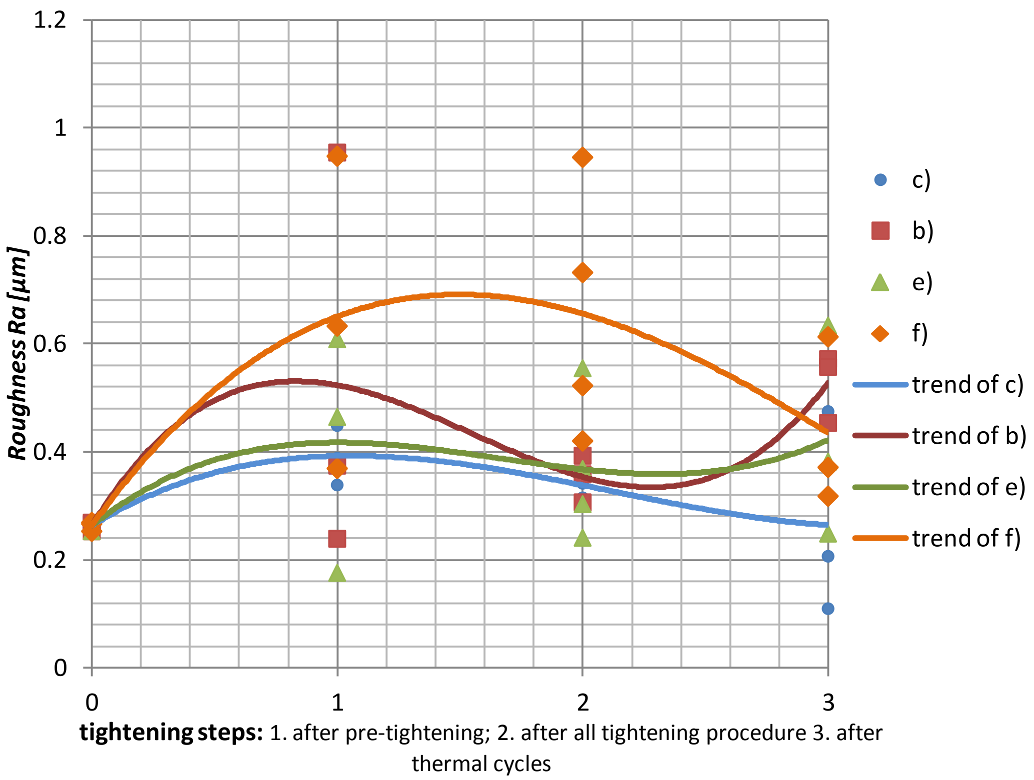



*Figure 6.6: roughness value on the contact surface at each tightening steps*

From the graph we can see that, the roughness on the contact surface increase with the tightening angle in pre-tightening step. And for the tightening procedure whose pre-tightening angle does not exceed the nominal one[16], after the second tightening step, which is same as the nominal tightening procedure, the roughness on the contact surface does not change much from nominal situation. But for tightening procedure f) the roughness keeps high even after the second tightening step.

## 6.2 Conclusion and Discussion

With the increase of pre-tightening angle, the embedment depth increases. But in a high pre-tightening angle condition the embedment depth in the second tightening step is lower even

[16] 70 degrees

than the surface roughness, which means that the gaps and clearances between bolt and clamped parts can not be eliminated efficiently during tightening. And what’s more important, a high pre-tightening angle also brings to a high amount of wearing, this lead to a high level of irregularity on the contact surface. So for a high pre-tight angle tightening procedure, instead of improves the self-relaxation resistance property, there are more space for compressing when a load is applied. According to these tests, a pre-tightening step similar with the nominal tightening procedure is the best choice for the multi-tightening procedure. It not only provides a proper plastic deformation on the contact surface but also keeps the roughness in the same level as nominal tightening procedure.

# CHAPTER 7: Conclusion and final remarks

After series of research and test based on the M10X60 bolts, 3 conclusions can be made:

1) The working property of a bolted joint can be improved by a proper designed tightening procedure.
2) The working properties of the M10X60 bolt used in the fixation of the brake's caliper can be improved by the new tightening procedures shown as follows:

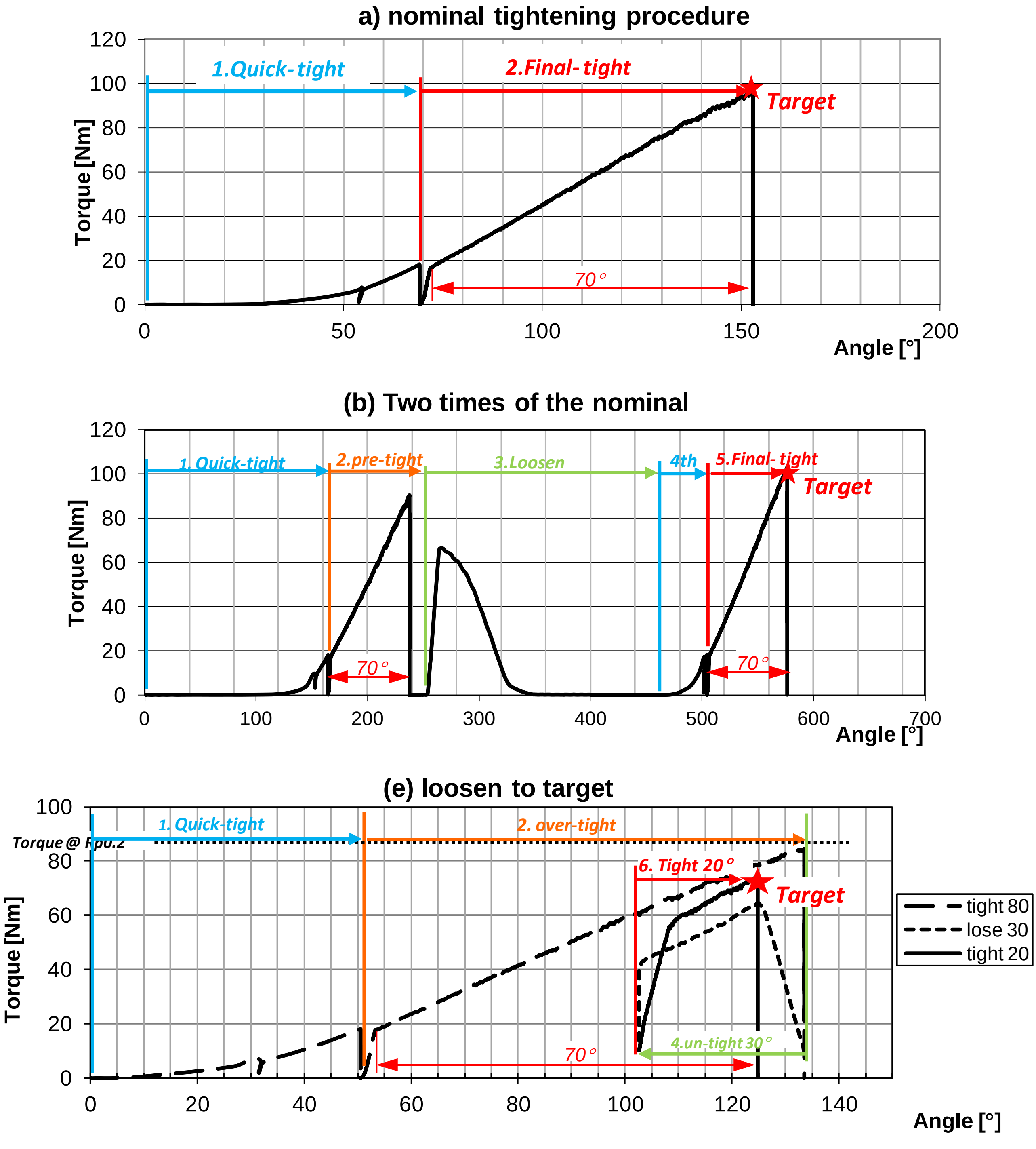



*Figure 7.1 Description of new tightening procedures*

named as:

b) Two times of the nominal tightening procedure
e) Over tightening the bolt into the elastic domain and then loosen the bolt to the target tightening angle

These two new tightening procedures can decrease the clamping load lost over time and during the 5 steps' thermal cycle; can control the scatter of clamping load in an acceptable range; can increase the breaking torque against self-loosening.

In the Fig. 7.1(a) the nominal tightening procedure used in the assembling line is shown as contrast; Fig. 7.1(b) is the procedure of two times of the nominal tightening procedure and Fig. 7.1(e) is the "loosen to target" procedure.

3) The pre-stress which a pre-tightening step can applied to the bolted joint need to fulfill two requests in order to improve the self-relaxation resistance:

- Need to high enough to eliminate the gaps and irregularities between bolt and components
- Can't be too high to scrape away the coating and increase the wearing phenomenon

In order to back these conclusions up, the whole design and test procedure is divided into 3 parts and explained as follows:

The first part of the study is to design the new tightening procedures which may improve the working properties of the joint. To achieve this goal, the basic working principle of a bolted joint system is studied and the main factors which may affect the embedding phenomenon are considered and assessed by laboratory tests. As the result, we found that the embedding phenomenon is mainly affected by the mechanism on the contact surface between bolt and clamped parts, which include for example the roughness, the hardness, the friction coefficient, etc, and these factors can be partly influenced by the compressive stress and the sliding distance when bolt and clamped part are relatively moved. And it is known that the stress which a tightened bolt can apply to the contact surface is linked to the tightening angle. So, on these basics a new tightening procedure is researched for the promotion of tribologic mechanism on the contact surfaces which resists the embedding phenomenon more effectively.

According to the relaxation theory commonly used in high temperature applications, in a repeated loading process, the fall in stress through the second loading step is affected by the first loading process. This concept is transferred to the bolted joint and the repeated loading process is simulated by a multi tightening procedure, which means to pre-tight the bolt to a target value and then lose it for the second and last tightening procedure.

On the other side, based on the wearing theory, high compressive stress and long relative sliding distance can produce irregular contact surface; so some multi tightening procedures are modified to achieve a high pre-stress and at the same time decrease the relative sliding.

After the design of new tightening procedures which have the possibility to improve the working condition of a bolted joint. In the second part the research of the optimum solution is done by experimental tests. Two testing methods are designed and named as A) and B), both tests are used to collect data on dummy joints and on real calipers.

In test A), the clamping load of the bolt tightened by new tightening procedure is traced over time ( up to 1400 minutes) after tightening in the no extra loading and room temperature conditions.

In test B), the joints tightened by new tightening procedures is repeatedly heated and cooled down during a 5 steps thermal cycle, and the residual clamping force after each thermal step is recorded.

Thanks to the ultrasonic method, the clamping load of the tested joints can be measured anytime. The fall of clamping load during each step of both the test A) and B) is measured and recorded.

After the analysis of the test data, the embedding resistance property, the tightening accuracy and the joint security against self loosening are evaluated, and all the new designed tightening procedures are judged from these three criteria.

As final result, the best performing tightening procedures are:

- Two times of the nominal tightening procedure
- Over tightening the bolt into the elastic domain and then loosen the bolt the target tightening angle.

In a bolted joints system, thanks to these tightening procedures, the clamping load lost over time and during 5 steps' thermal cycles are decreased, the scatter of clamping load is controlled in an acceptable range and thanks to the higher residual clamping load, the breaking torque against self-loosening is increased. So the overall working property of the joint is optimized.

After lab tests and experiments, more researches are done to the third part. The objective of this part is to find the differences on the contact surface generated by the different tightening procedures. The contact surface between under bolt-head and upper clamped part is taken as a reference, on this surface the embedment depth and roughness are measured after each tightening steps.

Based on these tests, a conclusion can be made that, to improve the embedding resistance of a bolted joint by multi-tightening procedure the pre-stress applied by the pre-tightening step need to be high enough to eliminate the gaps between assembled parts and to active the plastic deformation on the contact surface between bolt and components. But at the same time the pre-stress can't be too high to stress the bolt in to elastic –plastic domain which will destroy the coating of the bolt to increase the irregularity of the contact surface caused by wearing, which, on the other hand, can increase the embedding phenomenon.

These conclusions match with the results of tests A) and B): the embedding phenomenon can only be weaken by a proper pre-tightening step, which can provide a stress on the contact surface similar to the stress achieved by the subsequent tightening step. For example in an angle controlled tightening procedure, the pre-tightening angle should be similar to the nominal tightening angle or a little bit higher.

The optimum tightening procedure in this study is just a brief guide to show, which is the right direction to improve the self-relaxation resistance property by tightening procedure. For the real optimization of tightening procedure further tests need to be done for each specific joint working condition.

Here, some suggestions are made to simplify the further testing procedures. According to the tests, the test results of test A) and B) are matched with each other, so in the selection stage, only test A) is enough to choice the tightening procedure which can provide a good self-relaxation resistance. And a well designed dummy part can realistically simulate the real loading condition on the components so that the tests done on the dummy parts are reliable and cost saving.

# References

*[1]. Prof. Dr. Carl Grote:* Bolted joints - Introduction *- Otto von Guericke University Magdeburg - College of Mechanical Engineering*

*[2]. John H. Bickford:* An introduction to the design and behavior of bolted joints - *3rd edition*

*[3]. Ernest Rabinowicz:* Friction and wear of materials - *2. ed. - New York [etc.] : Wiley, ©1995. - XV, 315 p. : ill. ; 24 cm*

*[4]. Akademii͡a nauk SSSR., Vsesoi͡uznyĭ institut nauchnoĭ i tekhnicheskoĭ informat͡sii (Soviet Union). Ivan Avgustovich Oding, Alfred James Kennedy edit:* Creep and stress relaxation in metals - *University of Michigan, Oliver & Boyd, 1965.*

*[5]. The list of Thermal expansion coefficients*
*http://www.engineeringtoolbox.com/linear-expansion-coefficients-d_95.html*
*Last visit: Nov. 2012*

*[6]. Mechanical properties of ANTICORODAL 6082*
*http://www.migliarialluminio.it/Migliari/eng/6082.htm*
*last visit:Nov. 2012*

*[7]. Basic Theory of Bolts/Agrati Group Training cours. 2012*

*[8]. K. L. Johnson:* Contact mechanics - *1. paperback ed. with corrections. - Cambridge : Cambridge University Press, 1987.*

*[9]. FEM – Simulation results of M10X60 Hexalobular flanged screws. Agrati Group 2012*

*[10]. VDI 2230 standard: calculation method of bolts. All rights reserved*

[11]. *Tutorial US technique for clamping force measurements. Matteo Villa. Agrati Group*

# Appendix

## Data of test A) on calipers

| Tightening procedure | a) | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | Elongation[mm] | | | Load[kN] | | | | Load[%] | | | |
| Time [min] | bolt_1 | bolt_2 | bolt_3 | bolt_1 | bolt_2 | bolt_3 | Ave. | bolt_1 | bolt_2 | bolt_3 | Ave. |
| 0 | 0.67 | 0.67 | 0.68 | 45.20 | 44.87 | 45.72 | 45.26 | 100.0% | 100.0% | 100.0% | 100.0% |
| 30 | 0.67 | 0.67 | 0.68 | 44.96 | 44.73 | 45.52 | 45.07 | 99.5% | 99.7% | 99.6% | 99.6% |
| 60 | 0.67 | 0.66 | 0.67 | 44.71 | 44.62 | 45.11 | 44.82 | 98.9% | 99.5% | 98.7% | 99.0% |
| 100 | 0.66 | 0.67 | 0.67 | 44.49 | 44.67 | 44.91 | 44.69 | 98.4% | 99.6% | 98.2% | 98.7% |
| 180 | 0.66 | 0.67 | 0.67 | 44.49 | 44.67 | 44.91 | 44.69 | 98.4% | 99.6% | 98.2% | 98.7% |
| 270 | 0.66 | 0.66 | 0.67 | 44.42 | 44.40 | 44.71 | 44.51 | 98.3% | 99.0% | 97.8% | 98.3% |
| 440 | 0.65 | 0.66 | 0.66 | 43.95 | 44.46 | 44.24 | 44.22 | 97.2% | 99.1% | 96.8% | 97.7% |
| 520 | 0.66 | 0.66 | 0.65 | 43.97 | 44.31 | 43.82 | 44.03 | 97.3% | 98.8% | 95.8% | 97.3% |
| 1380 | 0.63 | 0.64 | 0.64 | 42.54 | 43.03 | 42.83 | 42.80 | 94.1% | 95.9% | 93.7% | 94.6% |
| | | | | | | | | *5.9%* | *4.1%* | *6.3%* | *5.4%* |

| Tightening procedure | b) | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | Elongation[mm] | | | Load[kN] | | | | Load[%] | | | |
| Time [min] | bolt_1 | bolt_2 | bolt_3 | bolt_1 | bolt_2 | bolt_3 | Ave. | bolt_1 | bolt_2 | bolt_3 | Ave. |
| 0 | 0.73 | 0.69 | 0.70 | 48.65 | 46.25 | 46.75 | 47.22 | 100.0% | 100.0% | 100.0% | 100.0% |
| 30 | 0.71 | 0.69 | 0.69 | 47.84 | 46.25 | 46.32 | 46.81 | 98.3% | 100.0% | 99.1% | 99.1% |
| 60 | 0.70 | 0.68 | 0.69 | 46.72 | 45.92 | 46.10 | 46.25 | 96.0% | 99.3% | 98.6% | 98.0% |
| 100 | 0.70 | 0.69 | 0.69 | 46.75 | 46.28 | 46.30 | 46.44 | 96.1% | 100.0% | 99.0% | 98.4% |
| 180 | 0.70 | 0.69 | 0.69 | 46.75 | 46.28 | 46.30 | 46.44 | 96.1% | 100.0% | 99.0% | 98.4% |
| 270 | 0.69 | 0.69 | 0.69 | 46.55 | 45.96 | 46.28 | 46.26 | 95.7% | 99.4% | 99.0% | 98.0% |
| 440 | 0.69 | 0.68 | 0.68 | 46.12 | 45.72 | 45.85 | 45.90 | 94.8% | 98.8% | 98.1% | 97.2% |
| 520 | 0.69 | 0.68 | 0.68 | 46.08 | 45.78 | 45.96 | 45.94 | 94.7% | 99.0% | 98.3% | 97.3% |
| 1380 | 0.69 | 0.67 | 0.68 | 45.96 | 45.20 | 45.45 | 45.54 | 94.5% | 97.7% | 97.2% | 96.5% |
| | | | | | | | | *5.5%* | *2.3%* | *2.8%* | *3.5%* |

| Tightening procedure | c) | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | Elongation[mm] | | | Load[kN] | | | | Load[%] | | | |
| Time [min] | bolt_1 | bolt_2 | bolt_3 | bolt_1 | bolt_2 | bolt_3 | Ave. | bolt_1 | bolt_2 | bolt_3 | Ave. |
| 0 | 0.75 | 0.75 | 0.75 | 50.15 | 50.55 | 50.50 | 50.40 | 100.0% | 100.0% | 100.0% | 100.0% |
| 30 | 0.75 | 0.75 | 0.75 | 50.03 | 50.15 | 50.30 | 50.16 | 99.8% | 99.2% | 99.6% | 99.5% |
| 60 | 0.74 | 0.75 | 0.75 | 49.74 | 50.08 | 50.21 | 50.01 | 99.2% | 99.1% | 99.4% | 99.2% |
| 100 | 0.73 | 0.74 | 0.74 | 49.27 | 49.56 | 49.59 | 49.48 | 98.3% | 98.1% | 98.2% | 98.2% |
| 180 | 0.73 | 0.73 | 0.73 | 49.12 | 49.23 | 49.27 | 49.21 | 97.9% | 97.4% | 97.6% | 97.6% |
| 270 | 0.73 | 0.73 | 0.73 | 48.74 | 48.98 | 48.98 | 48.90 | 97.2% | 96.9% | 97.0% | 97.0% |
| 440 | 0.72 | 0.73 | 0.73 | 48.58 | 48.69 | 48.78 | 48.68 | 96.9% | 96.3% | 96.6% | 96.6% |
| 520 | 0.72 | 0.72 | 0.72 | 48.13 | 48.42 | 48.45 | 48.33 | 96.0% | 95.8% | 95.9% | 95.9% |
| 1380 | 0.71 | 0.71 | 0.71 | 47.51 | 47.82 | 47.73 | 47.69 | 94.7% | 94.6% | 94.5% | 94.6% |
| | | | | | | | | *5.3%* | *5.4%* | *5.5%* | *5.4%* |

| *Tightening procedure* | *d)* | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | ***Elongation[mm]*** | | | ***Load[kN]*** | | | | ***Load[%]*** | | | |
| **Time [min]** | ***bolt_1*** | ***bolt_2*** | ***bolt_3*** | ***bolt_1*** | ***bolt_2*** | ***bolt_3*** | ***Ave.*** | ***bolt_1*** | ***bolt_2*** | ***bolt_3*** | ***Ave.*** |
| 0 | 0.67 | 0.69 | 0.69 | 45.29 | 46.41 | 46.39 | 46.03 | 100.0% | 100.0% | 100.0% | 100.0% |
| 30 | 0.68 | 0.69 | 0.69 | 45.45 | 46.30 | 46.41 | 46.05 | 100.3% | 99.8% | 100.0% | 100.1% |
| 60 | 0.67 | 0.68 | 0.69 | 44.98 | 45.72 | 46.08 | 45.59 | 99.3% | 98.5% | 99.3% | 99.0% |
| 100 | 0.65 | 0.67 | 0.68 | 43.93 | 45.07 | 45.45 | 44.82 | 97.0% | 97.1% | 98.0% | 97.4% |
| 180 | 0.65 | 0.66 | 0.67 | 43.88 | 44.60 | 45.07 | 44.52 | 96.9% | 96.1% | 97.2% | 96.7% |
| 270 | 0.65 | 0.66 | 0.67 | 43.59 | 44.31 | 44.82 | 44.24 | 96.2% | 95.5% | 96.6% | 96.1% |
| 440 | 0.65 | 0.66 | 0.67 | 43.68 | 44.26 | 44.82 | 44.26 | 96.4% | 95.4% | 96.6% | 96.1% |
| 520 | 0.64 | 0.66 | 0.66 | 43.15 | 44.13 | 44.58 | 43.95 | 95.3% | 95.1% | 96.1% | 95.5% |
| 1380 | 0.63 | 0.66 | 0.65 | 42.52 | 44.00 | 43.86 | 43.46 | 93.9% | 94.8% | 94.6% | 94.4% |
| | | | | | | | | *6.1%* | *5.2%* | *5.4%* | *5.6%* |

| *Tightening procedure* | *e)* | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | ***Elongation[mm]*** | | | ***Load[kN]*** | | | | ***Load[%]*** | | | |
| **Time [min]** | ***bolt_1*** | ***bolt_2*** | ***bolt_3*** | ***bolt_1*** | ***bolt_2*** | ***bolt_3*** | ***Ave.*** | ***bolt_1*** | ***bolt_2*** | ***bolt_3*** | ***Ave.*** |
| 0 | 0.61 | 0.63 | 0.63 | 40.68 | 42.09 | 42.47 | 41.75 | 100.0% | 100.0% | 100.0% | 100.0% |
| 30 | 0.61 | 0.62 | 0.63 | 40.80 | 41.80 | 42.23 | 41.61 | 100.3% | 99.3% | 99.4% | 99.7% |
| 60 | 0.60 | 0.62 | 0.63 | 40.48 | 41.29 | 42.07 | 41.28 | 99.5% | 98.1% | 99.1% | 98.9% |
| 100 | 0.60 | 0.61 | 0.62 | 40.19 | 40.95 | 41.87 | 41.01 | 98.8% | 97.3% | 98.6% | 98.2% |
| 180 | 0.60 | 0.61 | 0.62 | 40.35 | 40.82 | 41.62 | 40.93 | 99.2% | 97.0% | 98.0% | 98.0% |
| 270 | 0.60 | 0.60 | 0.62 | 39.97 | 40.57 | 41.62 | 40.72 | 98.2% | 96.4% | 98.0% | 97.5% |
| 440 | 0.59 | 0.61 | 0.62 | 39.88 | 40.71 | 41.45 | 40.68 | 98.0% | 96.7% | 97.6% | 97.4% |
| 520 | 0.59 | 0.60 | 0.62 | 39.84 | 40.26 | 41.36 | 40.48 | 97.9% | 95.6% | 97.4% | 97.0% |
| 1380 | 0.59 | 0.59 | 0.60 | 39.48 | 39.52 | 40.44 | 39.81 | 97.0% | 93.9% | 95.2% | 95.4% |
| | | | | | | | | *3.0%* | *6.1%* | *4.8%* | *4.6%* |

| *Tightening procedure* | *f)* | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | ***Elongation[mm]*** | | | ***Load[kN]*** | | | | ***Load[%]*** | | | |
| **Time [min]** | ***bolt_1*** | ***bolt_2*** | ***bolt_3*** | ***bolt_1*** | ***bolt_2*** | ***bolt_3*** | ***Ave.*** | ***bolt_1*** | ***bolt_2*** | ***bolt_3*** | ***Ave.*** |
| 0 | 0.73 | 0.73 | 0.70 | 49.23 | 48.89 | 46.66 | 48.26 | 100.0% | 100.0% | 100.0% | 100.0% |
| 30 | 0.73 | 0.72 | 0.69 | 49.05 | 48.58 | 46.37 | 48.00 | 99.6% | 99.4% | 99.4% | 99.5% |
| 60 | 0.74 | 0.72 | 0.69 | 49.61 | 48.60 | 46.61 | 48.27 | 100.8% | 99.4% | 99.9% | 100.0% |
| 100 | 0.73 | 0.72 | 0.69 | 49.03 | 48.16 | 46.10 | 47.76 | 99.6% | 98.5% | 98.8% | 99.0% |
| 180 | 0.73 | 0.71 | 0.68 | 48.85 | 47.71 | 45.58 | 47.38 | 99.2% | 97.6% | 97.7% | 98.2% |
| 270 | 0.72 | 0.71 | 0.68 | 48.49 | 47.51 | 45.52 | 47.17 | 98.5% | 97.2% | 97.6% | 97.7% |
| 440 | 0.71 | 0.70 | 0.67 | 47.98 | 47.24 | 45.07 | 46.76 | 97.5% | 96.6% | 96.6% | 96.9% |
| 520 | 0.71 | 0.70 | 0.67 | 47.86 | 46.72 | 45.11 | 46.57 | 97.2% | 95.6% | 96.7% | 96.5% |
| 1380 | 0.70 | 0.68 | 0.66 | 46.70 | 45.76 | 44.51 | 45.66 | 94.9% | 93.6% | 95.4% | 94.6% |
| | | | | | | | | *5.1%* | *6.4%* | *4.6%* | *5.4%* |

## ***Data of test B) on calipers***

| *Tightening procedure* | a) | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | **Elongation [mm]** | | **Load [kN]** | | | **Load [%]** | | | Lost in each step [%] | Total lost |
| After tightening | **bolt_1** | **bolt_2** | **bolt_1** | **bolt_2** | **Ave.[kN]** | **bolt_1** | **bolt_2** | **ave.[%]** | | |
| | 0.64 | 0.59 | 42.63 | 39.81 | 41.22 | 100.0% | 100.0% | 100.0% | | |
| 1st T.C. | 0.62 | 0.57 | 41.58 | 38.49 | 40.04 | 97.5% | 96.7% | 97.1% | | |
| 1st T.C | 0.50 | 0.43 | 33.28 | 28.81 | 31.04 | 78.1% | 72.4% | 75.2% | 21.9% | |
| 2nd T.C. | 0.48 | 0.42 | 32.41 | 28.50 | 30.45 | 76.0% | 71.6% | 73.8% | | |
| 2nd T.C | 0.46 | 0.41 | 30.89 | 27.73 | 29.31 | 72.5% | 69.7% | 71.1% | 2.7% | |
| 3rd T.C. | 0.46 | 0.40 | 30.69 | 26.95 | 28.82 | 72.0% | 67.7% | 69.8% | | |
| 3rd T.C | 0.45 | 0.39 | 29.90 | 25.88 | 27.89 | 70.1% | 65.0% | 67.6% | 2.3% | |
| 4th T.C. | 0.45 | 0.40 | 29.90 | 26.53 | 28.22 | 70.1% | 66.6% | 68.4% | | |
| 4thT.C | 0.45 | 0.39 | 29.88 | 25.90 | 27.89 | 70.1% | 65.1% | 67.6% | 0.8% | |
| 5th T.C. | 0.44 | 0.38 | 29.28 | 25.21 | 27.24 | 68.7% | 63.3% | 66.0% | | |
| 5th T.C | 0.44 | 0.37 | 29.35 | 25.14 | 27.24 | 68.8% | 63.1% | 66.0% | 0.0% | ***34.0%*** |

| *Tightening procedure* | b) | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | **Elongation [mm]** | | **Load [kN]** | | | **Load [%]** | | | Lost in each step [%] | Total lost |
| After tightening | **bolt_1** | **bolt_2** | **bolt_1** | **bolt_2** | **Ave.[kN]** | **bolt_1** | **bolt_2** | **ave.[%]** | | |
| | 0.65 | 0.69 | 43.50 | 46.50 | 45.00 | 100.0% | 100.0% | 100.0% | | |
| 1st T.C. | 0.62 | 0.68 | 41.85 | 45.31 | 43.58 | 96.2% | 97.5% | 96.8% | | |
| 1st T.C | 0.50 | 0.53 | 33.42 | 35.67 | 34.55 | 76.8% | 76.7% | 76.8% | 20.1% | |
| 2nd T.C. | 0.49 | 0.53 | 33.08 | 35.54 | 34.31 | 76.0% | 76.4% | 76.2% | | |
| 2nd T.C | 0.48 | 0.52 | 32.01 | 35.09 | 33.55 | 73.6% | 75.5% | 74.5% | 2.8% | |
| 3rd T.C. | 0.47 | 0.51 | 31.74 | 34.38 | 33.06 | 73.0% | 73.9% | 73.4% | | |
| 3rd T.C | 0.46 | 0.49 | 31.00 | 32.99 | 32.00 | 71.3% | 70.9% | 71.1% | 2.3% | |
| 4th T.C. | 0.47 | 0.50 | 31.29 | 33.46 | 32.38 | 71.9% | 72.0% | 71.9% | | |
| 4thT.C | 0.46 | 0.49 | 31.04 | 32.90 | 31.97 | 71.4% | 70.8% | 71.1% | 0.9% | |
| 5th T.C. | 0.45 | 0.48 | 30.37 | 32.21 | 31.29 | 69.8% | 69.3% | 69.5% | | |
| 5th T.C | 0.46 | 0.48 | 31.00 | 32.03 | 31.51 | 71.3% | 68.9% | 70.1% | -0.5% | ***29.9%*** |

| *Tightening procedure* | c) | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | **Elongation [mm]** | | **Load [kN]** | | | **Load [%]** | | | Lost in each step [%] | Total lost |
| After tightening | **bolt_1** | **bolt_2** | **bolt_1** | **bolt_2** | **Ave.[kN]** | **bolt_1** | **bolt_2** | **ave.[%]** | | |
| | 0.58 | 0.63 | 39.19 | 42.34 | 40.76 | 100.0% | 100.0% | 100.0% | | |
| 1st T.C. | 0.56 | 0.61 | 37.84 | 40.71 | 39.28 | 96.6% | 96.1% | 96.4% | | |
| 1st T.C | 0.43 | 0.48 | 28.94 | 32.12 | 30.53 | 73.9% | 75.9% | 74.9% | 21.5% | |
| 2nd T.C. | 0.43 | 0.48 | 28.58 | 32.34 | 30.46 | 72.9% | 76.4% | 74.7% | | |
| 2nd T.C | 0.41 | 0.45 | 27.67 | 30.42 | 29.04 | 70.6% | 71.8% | 71.2% | 3.4% | |
| 3rd T.C. | 0.41 | 0.45 | 27.42 | 30.13 | 28.77 | 70.0% | 71.2% | 70.6% | | |
| 3rd T.C | 0.39 | 0.44 | 26.50 | 29.73 | 28.11 | 67.6% | 70.2% | 68.9% | 1.6% | |
| 4th T.C. | 0.39 | 0.45 | 26.48 | 29.93 | 28.20 | 67.6% | 70.7% | 69.1% | | |
| 4thT.C | 0.39 | 0.42 | 26.50 | 28.45 | 27.48 | 67.6% | 67.2% | 67.4% | 1.7% | |
| 5th T.C. | 0.38 | 0.42 | 25.63 | 28.25 | 26.94 | 65.4% | 66.7% | 66.1% | | |
| 5th T.C | 0.39 | 0.42 | 26.12 | 28.45 | 27.29 | 66.7% | 67.2% | 66.9% | -0.9% | *33.1%* |

| *Tightening procedure* | d) | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | **Elongation [mm]** | | **Load [kN]** | | | **Load [%]** | | | Lost in each step [%] | Total lost |
| After tightening | **bolt_1** | **bolt_2** | **bolt_1** | **bolt_2** | **Ave.[kN]** | **bolt_1** | **bolt_2** | **ave.[%]** | | |
| | 0.61 | 0.63 | 40.75 | 42.47 | 41.61 | 100.0% | 100.0% | 100.0% | | |
| 1st T.C. | 0.59 | 0.61 | 39.77 | 41.07 | 40.42 | 97.6% | 96.7% | 97.1% | | |
| 1st T.C | 0.46 | 0.48 | 30.64 | 31.92 | 31.28 | 75.2% | 75.1% | 75.2% | 22.0% | |
| 2nd T.C. | 0.45 | 0.47 | 30.28 | 31.78 | 31.03 | 74.3% | 74.8% | 74.6% | | |
| 2nd T.C | 0.44 | 0.47 | 29.32 | 31.36 | 30.34 | 72.0% | 73.8% | 72.9% | 1.7% | |
| 3rd T.C. | 0.44 | 0.45 | 29.52 | 30.37 | 29.95 | 72.4% | 71.5% | 72.0% | | |
| 3rd T.C | 0.43 | 0.45 | 28.92 | 29.95 | 29.43 | 71.0% | 70.5% | 70.7% | 1.2% | |
| 4th T.C. | 0.43 | 0.44 | 28.70 | 29.43 | 29.07 | 70.4% | 69.3% | 69.9% | | |
| 4thT.C | 0.42 | 0.43 | 28.14 | 29.08 | 28.61 | 69.0% | 68.5% | 68.8% | 1.1% | |
| 5th T.C. | 0.42 | 0.43 | 28.07 | 28.88 | 28.47 | 68.9% | 68.0% | 68.4% | | |
| 5th T.C | 0.42 | 0.43 | 28.18 | 28.63 | 28.41 | 69.2% | 67.4% | 68.3% | 0.2% | *31.7%* |

| *Tightening procedure* | e) | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | **Elongation [mm]** | | **Load [kN]** | | | **Load [%]** | | | Lost in each step [%] | Total lost |
| After tightening | **bolt_1** | **bolt_2** | **bolt_1** | **bolt_2** | **Ave.[kN]** | **bolt_1** | **bolt_2** | **ave.[%]** | | |
| | 0.60 | 0.57 | 40.17 | 38.49 | 39.33 | 100.0% | 100.0% | 100.0% | | |
| 1st T.C. | 0.58 | 0.56 | 38.94 | 37.40 | 38.17 | 96.9% | 97.2% | 97.0% | | |
| 1st T.C | 0.48 | 0.43 | 32.36 | 28.81 | 30.59 | 80.6% | 74.8% | 77.7% | 19.3% | |
| 2nd T.C. | 0.48 | 0.43 | 31.96 | 28.58 | 30.27 | 79.6% | 74.3% | 76.9% | | |
| 2nd T.C | 0.45 | 0.42 | 29.97 | 27.96 | 28.96 | 74.6% | 72.6% | 73.6% | 3.3% | |
| 3rd T.C. | 0.45 | 0.41 | 29.90 | 27.71 | 28.81 | 74.4% | 72.0% | 73.2% | | |
| 3rd T.C | 0.44 | 0.40 | 29.43 | 26.88 | 28.16 | 73.3% | 69.8% | 71.6% | 1.7% | |
| 4th T.C. | 0.44 | 0.41 | 29.26 | 27.38 | 28.32 | 72.8% | 71.1% | 72.0% | | |
| 4thT.C | 0.44 | 0.40 | 29.66 | 27.09 | 28.37 | 73.8% | 70.4% | 72.1% | -0.1% | |
| 5th T.C. | 0.43 | 0.39 | 28.90 | 26.30 | 27.60 | 71.9% | 68.3% | 70.1% | | |
| 5th T.C | 0.43 | 0.39 | 29.14 | 26.24 | 27.69 | 72.6% | 68.2% | 70.4% | -0.2% | ***29.6%*** |

| *Tightening procedure* | f) | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | **Elongation [mm]** | | **Load [kN]** | | | **Load [%]** | | | Lost in each step [%] | Total lost |
| After tightening | **bolt_1** | **bolt_2** | **bolt_1** | **bolt_2** | **Ave.[kN]** | **bolt_1** | **bolt_2** | **ave.[%]** | | |
| | 0.60 | 0.61 | 41.08 | 41.57 | 41.33 | 100.0% | 100.0% | 100.0% | | |
| 1st T.C. | 0.57 | 0.58 | 38.88 | 39.39 | 39.14 | 94.6% | 94.8% | 94.7% | | |
| 1st T.C | 0.39 | 0.39 | 26.19 | 26.49 | 26.34 | 63.7% | 63.7% | 63.7% | 31.0% | |
| 2nd T.C. | 0.38 | 0.39 | 25.98 | 26.35 | 26.16 | 63.2% | 63.4% | 63.3% | | |
| 2nd T.C | 0.38 | 0.39 | 25.77 | 26.14 | 25.96 | 62.7% | 62.9% | 62.8% | 1.8% | |
| 3rd T.C. | 0.37 | 0.38 | 25.38 | 25.42 | 25.40 | 61.8% | 61.2% | 61.5% | | |
| 3rd T.C | 0.35 | 0.36 | 23.45 | 24.31 | 23.88 | 57.1% | 58.5% | 57.8% | 2.9% | |
| 4th T.C. | 0.35 | 0.36 | 23.80 | 24.59 | 24.19 | 57.9% | 59.2% | 58.5% | | |
| 4thT.C | 0.35 | 0.36 | 23.92 | 24.45 | 24.18 | 58.2% | 58.8% | 58.5% | 0.0% | |
| 5th T.C. | 0.34 | 0.35 | 23.13 | 23.80 | 23.46 | 56.3% | 57.3% | 56.8% | | |
| 5th T.C | 0.34 | 0.35 | 23.18 | 23.96 | 23.57 | 56.4% | 57.6% | 57.0% | -0.3% | ***43.0%*** |

## *Data of test A) on real calipers*

| | a) | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Elongation[mm] | | | | Load[kN] | | | | | Load[%] | | | | |
| Time [min] | bolt_1 | bolt_2 | bolt_3 | bolt_4 | bolt_1 | bolt_2 | bolt_3 | bolt_4 | Ave. | bolt_1 | bolt_2 | bolt_3 | bolt_4 | Ave. |
| 0 | 0.70 | 0.71 | 0.68 | 0.67 | 47.01 | 47.42 | 45.74 | 45.09 | 46.32 | 100.0% | 100.0% | 100.0% | 100.0% | 100.0% |
| 60 | 0.69 | 0.69 | 0.67 | 0.66 | 46.23 | 46.41 | 45.23 | 44.20 | 45.52 | 98.2% | 97.7% | 98.8% | 97.9% | 98.2% |
| 150 | 0.69 | 0.69 | 0.67 | 0.66 | 46.10 | 46.23 | 45.16 | 44.06 | 45.39 | 97.9% | 97.3% | 98.7% | 97.6% | 97.9% |
| 210 | 0.68 | 0.68 | 0.67 | 0.65 | 45.61 | 45.87 | 44.82 | 43.84 | 45.04 | 96.8% | 96.5% | 97.9% | 97.0% | 97.1% |
| 330 | 0.68 | 0.68 | 0.67 | 0.65 | 45.45 | 45.76 | 44.73 | 43.73 | 44.92 | 96.4% | 96.3% | 97.7% | 96.8% | 96.8% |
| 1320 | 0.66 | 0.67 | 0.66 | 0.64 | 44.53 | 44.89 | 43.97 | 42.77 | 44.04 | 94.3% | 94.3% | 95.9% | 94.5% | 94.8% |
| | | | | | | | | | | 5.7% | 5.7% | 4.1% | 5.5% | 5.2% |

| | b) | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Elongation[mm] | | | | Load[kN] | | | | | Load[%] | | | | |
| Time [min] | bolt_1 | bolt_2 | bolt_3 | bolt_4 | bolt_1 | bolt_2 | bolt_3 | bolt_4 | Ave. | bolt_1 | bolt_2 | bolt_3 | bolt_4 | Ave. |
| 0 | 0.73 | 0.69 | 0.70 | 0.66 | 49.23 | 46.41 | 47.04 | 43.97 | 46.66 | 100.0% | 100.0% | 100.0% | 100.0% | 100.0% |
| 60 | 0.71 | 0.68 | 0.69 | 0.65 | 47.71 | 45.76 | 46.50 | 43.28 | 45.81 | 96.9% | 98.6% | 98.9% | 98.4% | 98.2% |
| 150 | 0.71 | 0.68 | 0.69 | 0.64 | 47.42 | 45.47 | 46.14 | 43.03 | 45.52 | 96.3% | 98.0% | 98.1% | 97.9% | 97.6% |
| 210 | 0.70 | 0.68 | 0.69 | 0.64 | 47.31 | 45.58 | 46.23 | 42.97 | 45.52 | 96.1% | 98.2% | 98.3% | 97.7% | 97.6% |
| 330 | 0.70 | 0.68 | 0.69 | 0.64 | 47.08 | 45.61 | 46.05 | 42.97 | 45.43 | 95.6% | 98.3% | 97.9% | 97.7% | 97.4% |
| 1320 | 0.69 | 0.67 | 0.68 | 0.63 | 46.43 | 44.96 | 45.45 | 42.38 | 44.81 | 94.3% | 96.9% | 96.6% | 96.4% | 96.1% |
| | | | | | | | | | | 5.7% | 3.1% | 3.4% | 3.6% | 3.9% |

| | e) | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Elongation[mm] | | | | Load[kN] | | | | | Load[%] | | | | |
| Time [min] | bolt_1 | bolt_2 | bolt_3 | bolt_4 | bolt_1 | bolt_2 | bolt_3 | bolt_4 | Ave. | bolt_1 | bolt_2 | bolt_3 | bolt_4 | Ave. |
| 0 | 0.65 | 0.66 | 0.62 | 0.67 | 43.39 | 44.06 | 41.56 | 45.20 | 43.55 | 100.0% | 100.0% | 100.0% | 100.0% | 100.0% |
| 60 | 0.64 | 0.65 | 0.62 | 0.67 | 42.92 | 43.61 | 41.42 | 44.73 | 43.17 | 98.9% | 99.0% | 99.7% | 99.0% | 99.1% |
| 150 | 0.64 | 0.64 | 0.62 | 0.67 | 42.68 | 43.23 | 41.27 | 44.89 | 43.02 | 98.4% | 98.1% | 99.3% | 99.3% | 98.8% |
| 210 | 0.63 | 0.64 | 0.61 | 0.66 | 42.34 | 42.90 | 41.04 | 44.46 | 42.69 | 97.6% | 97.4% | 98.8% | 98.4% | 98.0% |
| 330 | 0.63 | 0.63 | 0.60 | 0.66 | 42.12 | 42.47 | 40.55 | 44.33 | 42.37 | 97.1% | 96.4% | 97.6% | 98.1% | 97.3% |
| 1320 | 0.62 | 0.63 | 0.60 | 0.66 | 41.69 | 42.41 | 40.39 | 43.97 | 42.12 | 96.1% | 96.2% | 97.2% | 97.3% | 96.7% |
| | | | | | | | | | | 3.9% | 3.8% | 2.8% | 2.7% | 3.3% |

## *Data of test B) on real calipers*

a)

| cycle | Elongation[mm] | | | | Load[kN] | | | | | Load[%] | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | bolt_1 | bolt_2 | bolt_3 | bolt_4 | bolt_1 | bolt_2 | bolt_3 | bolt_4 | Ave. | bolt_1 | bolt_2 | bolt_3 | bolt_4 | Ave. |
| After tight | 0.70 | 0.71 | 0.68 | 0.67 | 47.01 | 47.42 | 45.74 | 45.09 | 46.32 | 100.0% | 100.0% | 100.0% | 100.0% | 100.0% |
| 1st T.C. | 0.65 | 0.66 | 0.65 | 0.63 | 43.93 | 44.53 | 43.30 | 42.25 | 43.50 | 93.4% | 93.9% | 94.7% | 93.7% | 93.9% |
| 1st T.C | 0.54 | 0.55 | 0.53 | 0.51 | 36.48 | 37.08 | 35.90 | 34.47 | 35.98 | 77.6% | 78.2% | 78.5% | 76.4% | 77.7% |
| 2nd T.C. | 0.54 | 0.55 | 0.53 | 0.51 | 36.52 | 37.04 | 35.72 | 34.04 | 35.83 | 77.7% | 78.1% | 78.1% | 75.5% | 77.3% |
| 2nd T.C | 0.52 | 0.54 | 0.52 | 0.49 | 35.18 | 36.06 | 35.05 | 33.01 | 34.82 | 74.8% | 76.0% | 76.6% | 73.2% | 75.2% |
| 3th T.C. | 0.52 | 0.54 | 0.52 | 0.50 | 35.00 | 36.17 | 34.78 | 33.26 | 34.80 | 74.5% | 76.3% | 76.0% | 73.8% | 75.1% |
| 3th T.C | 0.51 | 0.51 | 0.49 | 0.48 | 33.95 | 34.22 | 33.13 | 32.03 | 33.33 | 72.2% | 72.2% | 72.4% | 71.0% | 72.0% |
| 4th T.C. | 0.51 | 0.51 | 0.50 | 0.48 | 34.15 | 34.36 | 33.42 | 32.23 | 33.54 | 72.6% | 72.5% | 73.1% | 71.5% | 72.4% |
| 4thT.C | 0.51 | 0.51 | 0.49 | 0.48 | 33.95 | 33.97 | 32.97 | 31.89 | 33.20 | 72.2% | 71.7% | 72.1% | 70.7% | 71.7% |
| 5th T.C. | 0.51 | 0.51 | 0.49 | 0.47 | 33.91 | 33.95 | 32.92 | 31.85 | 33.16 | 72.1% | 71.6% | 72.0% | 70.6% | 71.6% |
| 5th T.C | 0.49 | 0.50 | 0.48 | 0.47 | 32.97 | 33.39 | 32.41 | 31.34 | 32.53 | 70.1% | 70.4% | 70.9% | 69.5% | 70.2% |
| | | | | | | | | | | ***29.9%*** | ***29.6%*** | ***29.1%*** | ***30.5%*** | ***29.8%*** |

b)

| cycle | Elongation[mm] | | | | Load[kN] | | | | | Load[%] | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | bolt_1 | bolt_2 | bolt_3 | bolt_4 | bolt_1 | bolt_2 | bolt_3 | bolt_4 | Ave. | bolt_1 | bolt_2 | bolt_3 | bolt_4 | Ave. |
| After tight | 0.73 | 0.69 | 0.70 | 0.66 | 49.23 | 46.41 | 47.04 | 43.97 | 46.66 | 100.0% | 100.0% | 100.0% | 100.0% | 100.0% |
| 1st T.C. | 0.68 | 0.66 | 0.66 | 0.62 | 45.74 | 43.95 | 44.33 | 41.38 | 43.85 | 92.9% | 94.7% | 94.2% | 94.1% | 94.0% |
| 1st T.C | 0.56 | 0.55 | 0.55 | 0.50 | 37.87 | 36.70 | 36.73 | 33.44 | 36.18 | 76.9% | 79.1% | 78.1% | 76.0% | 77.5% |
| 2nd T.C. | 0.57 | 0.54 | 0.55 | 0.49 | 38.22 | 36.10 | 36.66 | 33.21 | 36.05 | 77.6% | 77.8% | 77.9% | 75.5% | 77.2% |
| 2nd T.C | 0.56 | 0.53 | 0.54 | 0.48 | 37.49 | 35.29 | 35.92 | 32.39 | 35.27 | 76.1% | 76.0% | 76.4% | 73.7% | 75.6% |
| 3th T.C. | 0.56 | 0.53 | 0.53 | 0.48 | 37.44 | 35.32 | 35.90 | 32.48 | 35.28 | 76.1% | 76.1% | 76.3% | 73.9% | 75.6% |
| 3th T.C | 0.53 | 0.50 | 0.51 | 0.46 | 35.74 | 33.64 | 34.47 | 30.93 | 33.70 | 72.6% | 72.5% | 73.3% | 70.3% | 72.2% |
| 4th T.C. | 0.54 | 0.51 | 0.52 | 0.47 | 36.10 | 34.13 | 34.82 | 31.22 | 34.07 | 73.3% | 73.5% | 74.0% | 71.0% | 73.0% |
| 4thT.C | 0.53 | 0.50 | 0.51 | 0.46 | 35.83 | 33.84 | 34.51 | 31.07 | 33.81 | 72.8% | 72.9% | 73.4% | 70.7% | 72.4% |
| 5th T.C. | 0.54 | 0.51 | 0.52 | 0.46 | 36.06 | 33.93 | 34.69 | 31.13 | 33.95 | 73.2% | 73.1% | 73.8% | 70.8% | 72.7% |
| 5th T.C | 0.53 | 0.50 | 0.51 | 0.46 | 35.47 | 33.57 | 34.27 | 30.75 | 33.52 | 72.1% | 72.3% | 72.8% | 69.9% | 71.8% |
| | | | | | | | | | | ***27.9%*** | ***27.7%*** | ***27.2%*** | ***30.1%*** | ***28.2%*** |

e)

| | ***Elongation[mm]*** | | | | ***Load[kN]*** | | | | | ***Load[%]*** | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| ***cycle*** | ***bolt_1*** | ***bolt_2*** | ***bolt_3*** | ***bolt_4*** | ***bolt_1*** | ***bolt_2*** | ***bolt_3*** | ***bolt_4*** | ***Ave.*** | ***bolt_1*** | ***bolt_2*** | ***bolt_3*** | ***bolt_4*** | ***Ave.*** |
| After tight | 0.65 | 0.66 | 0.62 | 0.67 | 43.39 | 44.06 | 41.56 | 45.20 | 43.55 | 100.0% | 100.0% | 100.0% | 100.0% | 100.0% |
| 1st T.C. | 0.61 | 0.63 | 0.59 | 0.65 | 41.04 | 42.05 | 39.81 | 43.48 | 41.60 | 94.6% | 95.4% | 95.8% | 96.2% | 95.5% |
| 1st T.C | 0.51 | 0.52 | 0.50 | 0.54 | 34.18 | 35.05 | 33.35 | 36.01 | 34.65 | 78.8% | 79.5% | 80.2% | 79.7% | 79.6% |
| 2nd T.C. | 0.51 | 0.52 | 0.49 | 0.53 | 34.09 | 34.78 | 33.15 | 35.65 | 34.42 | 78.6% | 78.9% | 79.8% | 78.9% | 79.0% |
| 2nd T.C | 0.50 | 0.51 | 0.48 | 0.52 | 33.28 | 34.15 | 32.36 | 35.14 | 33.73 | 76.7% | 77.5% | 77.9% | 77.7% | 77.5% |
| 3th T.C. | 0.49 | 0.51 | 0.48 | 0.52 | 33.17 | 34.33 | 32.45 | 35.16 | 33.78 | 76.4% | 77.9% | 78.1% | 77.8% | 77.6% |
| 3th T.C | 0.48 | 0.50 | 0.47 | 0.51 | 32.25 | 33.39 | 31.81 | 34.42 | 32.97 | 74.3% | 75.8% | 76.5% | 76.2% | 75.7% |
| 4th T.C. | 0.48 | 0.50 | 0.47 | 0.51 | 32.32 | 33.39 | 31.72 | 34.42 | 32.96 | 74.5% | 75.8% | 76.3% | 76.2% | 75.7% |
| 4thT.C | 0.47 | 0.49 | 0.47 | 0.51 | 31.76 | 32.97 | 31.45 | 34.38 | 32.64 | 73.2% | 74.8% | 75.7% | 76.1% | 74.9% |
| 5th T.C. | 0.47 | 0.49 | 0.47 | 0.51 | 31.78 | 32.99 | 31.36 | 34.47 | 32.65 | 73.2% | 74.9% | 75.5% | 76.2% | 75.0% |
| 5th T.C | 0.47 | 0.49 | 0.46 | 0.50 | 31.78 | 33.01 | 30.75 | 33.80 | 32.34 | 73.2% | 74.9% | 74.0% | 74.8% | 74.2% |
| | | | | | | | | | | ***26.8%*** | ***25.1%*** | ***26.0%*** | ***25.2%*** | ***25.8%*** |

## *Test results of the calibration of bolt*

| *F applied load* | *elongation US of 1st test* | *elongation US of 2nd test* | *elongation US of 3rd test* | *elongation US of 4th test* | *elongation US of 5th test* | *elongation US of 6th test* | *elongation US of 7th test* | *elongation US of 8th test* | *elongation US of 9th test* | *elongation US of 10th test* | *elongation US of 11th test* | *elongation US of 12th test* | *elongation US of 13th test* | *elongation US of 14th test* | *elongation US of 15th test* | *elongation US of 16th test* |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| [kN] | [mm] | [mm] | [mm] | [mm] | [mm] | [mm] | [mm] | [mm] | [mm] | [mm] | [mm] | [mm] | [mm] | [mm] | [mm] | [mm] |
| 0.00 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 |
| 10.00 | 0.158 | 0.161 | 0.154 | 0.150 | 0.162 | 0.168 | 0.157 | 0.156 | 0.154 | 0.149 | 0.150 | 0.145 | 0.149 | 0.149 | 0.151 | 0.150 |
| 15.00 | 0.231 | 0.235 | 0.230 | 0.222 | 0.236 | 0.242 | 0.229 | 0.228 | 0.230 | 0.222 | 0.224 | 0.216 | 0.221 | 0.221 | 0.223 | 0.225 |
| 20.00 | 0.304 | 0.309 | 0.303 | 0.297 | 0.311 | 0.316 | 0.299 | 0.300 | 0.305 | 0.295 | 0.298 | 0.289 | 0.291 | 0.295 | 0.295 | 0.297 |
| 25.00 | 0.378 | 0.383 | 0.377 | 0.371 | 0.385 | 0.390 | 0.372 | 0.372 | 0.380 | 0.367 | 0.370 | 0.361 | 0.362 | 0.366 | 0.366 | 0.369 |
| 30.00 | 0.453 | 0.457 | 0.450 | 0.444 | 0.459 | 0.465 | 0.443 | 0.445 | 0.454 | 0.439 | 0.443 | 0.433 | 0.435 | 0.440 | 0.441 | 0.442 |
| 35.00 | 0.528 | 0.532 | 0.524 | 0.520 | 0.534 | 0.538 | 0.517 | 0.518 | 0.529 | 0.513 | 0.518 | 0.506 | 0.509 | 0.513 | 0.515 | 0.516 |
| 40.00 | 0.605 | 0.607 | 0.598 | 0.595 | 0.609 | 0.615 | 0.594 | 0.593 | 0.603 | 0.589 | 0.591 | 0.581 | 0.584 | 0.587 | 0.583 | 0.590 |
| 42.00 | 0.637 | 0.638 | 0.628 | 0.625 | 0.639 | 0.644 | 0.625 | 0.623 | 0.633 | 0.621 | 0.621 | 0.610 | 0.616 | 0.617 | 0.621 | 0.621 |
| 0.00 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 |
| 10.00 | 0.160 | 0.160 | 0.154 | 0.155 | 0.163 | 0.168 | 0.157 | 0.156 | 0.155 | 0.149 | 0.150 | 0.147 | 0.148 | 0.149 | 0.151 | 0.149 |
| 15.00 | 0.234 | 0.234 | 0.229 | 0.229 | 0.237 | 0.242 | 0.229 | 0.228 | 0.230 | 0.223 | 0.224 | 0.218 | 0.221 | 0.221 | 0.225 | 0.224 |
| 20.00 | 0.309 | 0.309 | 0.302 | 0.303 | 0.312 | 0.317 | 0.301 | 0.301 | 0.306 | 0.297 | 0.298 | 0.291 | 0.291 | 0.294 | 0.297 | 0.298 |
| 25.00 | 0.382 | 0.382 | 0.376 | 0.376 | 0.386 | 0.390 | 0.373 | 0.373 | 0.382 | 0.369 | 0.370 | 0.363 | 0.364 | 0.366 | 0.368 | 0.369 |
| 30.00 | 0.457 | 0.457 | 0.449 | 0.450 | 0.460 | 0.465 | 0.445 | 0.445 | 0.455 | 0.443 | 0.443 | 0.435 | 0.437 | 0.439 | 0.442 | 0.442 |
| 35.00 | 0.531 | 0.531 | 0.524 | 0.524 | 0.535 | 0.539 | 0.518 | 0.518 | 0.529 | 0.517 | 0.517 | 0.508 | 0.511 | 0.513 | 0.515 | 0.516 |
| 40.00 | 0.606 | 0.606 | 0.598 | 0.599 | 0.610 | 0.615 | 0.593 | 0.593 | 0.603 | 0.590 | 0.591 | 0.582 | 0.584 | 0.587 | 0.588 | 0.590 |
| 42.00 | 0.637 | 0.637 | 0.628 | 0.629 | 0.640 | 0.644 | 0.624 | 0.623 | 0.633 | 0.620 | 0.620 | 0.612 | 0.615 | 0.616 | 0.620 | 0.621 |

***Test results of the calibration of bolt (plastically deformed)***

| *F applied load* | *elongation US of 1st test* | *elongation US of 2nd test* | *elongation US of 3rd test* | *elongation US of 4th test* | *elongation US of 5th test* |
|---|---|---|---|---|---|
| [kN] | [mm] | [mm] | [mm] | [mm] | [mm] |
| 0 | 0 | 0 | 0 | 0 | 0 |
| 10 | 0.16 | 0.156 | 0.153 | 0.152 | 0.153 |
| 15 | 0.235 | 0.228 | 0.226 | 0.225 | 0.227 |
| 20 | 0.306 | 0.299 | 0.299 | 0.297 | 0.298 |
| 25 | 0.379 | 0.369 | 0.371 | 0.368 | 0.371 |
| 30 | 0.451 | 0.439 | 0.444 | 0.438 | 0.442 |
| 35 | 0.523 | 0.512 | 0.518 | 0.511 | 0.516 |
| 40 | 0.598 | 0.585 | 0.592 | 0.585 | 0.59 |
| 42 | 0.628 | 0.613 | 0.622 | 0.614 | 0.619 |
| 0 | 0 | 0 | 0 | 0 | 0 |
| 10 | 0.161 | 0.156 | 0.152 | 0.152 | 0.153 |
| 15 | 0.234 | 0.228 | 0.225 | 0.224 | 0.227 |
| 20 | 0.305 | 0.299 | 0.297 | 0.296 | 0.298 |
| 25 | 0.38 | 0.368 | 0.368 | 0.367 | 0.37 |
| 30 | 0.453 | 0.439 | 0.441 | 0.437 | 0.442 |
| 35 | 0.528 | 0.511 | 0.513 | 0.51 | 0.515 |
| 40 | 0.602 | 0.585 | 0.586 | 0.583 | 0.589 |
| 42 | 0.631 | 0.613 | 0.617 | 0.612 | 0.618 |