EXPERIMENTAL DETERMINATION OF THE FRICTION COEFFICIENT IN BOLTED JOINTS WITH DIFFERENT SURFACE CONDITIONS

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Abstract. *Knowledge of effective slip strength is essential when a bolted joint is designed to work by friction. Axial load and friction coefficient are uncertain due to surface and bolt conditions. European standards indicate necessary tightening torque, but experimental torque-tension relationship is needed for many cases. Torque and axial load relaxation during time is also a common problem not so investigated. In this work, the friction coefficient and the effective slip strength are experimentally determined on a set of bolted joints operating on different surface conditions: prescriptions by standards demonstrate to be conservative not in all cases.*

Keywords: *friction coefficient; steel bolted joint; COR-TEN steel.*

1 INTRODUCTION AND LITERATURE REVIEW

In a pioneeristic work dated 1931 Whittermore *et al.* (Whittermore, 1931) analysed the relation between applied torque and axial load in a wide series of bolted joints and, as the authors wrote, "thread locking devices". From that exhaustive work, nothing really new has been produced, because nothing new for this mechanical system exists from then.

In the following years, many other studies were conducted and published about particular conditions or situations in which thread-locking devices can operate, especially regarding the friction phenomenon. Improvement in technology and in metal working processes and refined methods of measurement made it possible, in about 80 years, a better understanding of the mechanical quantities (forces) involved in the process of tighten of a bolt; for example, Jiang *et al.* (Jiang, 2001) precisely measured the thread friction and the bearing friction between the nut surface and the clamped surface, and conducted a statistical analysis to allow for a reliability assessment of the bolted joints in terms of the clamping force control; Nassar *et al.* (Nassar, 2005-2007) investigated the effect of surface roughness on the torque-tension relationship in threaded fasteners: different levels of surface roughness are considered for the fastener underhead and the joint surface, and the torque-tension data are expressed in terms of the value of the nut factor. Again, an experimental procedure is proposed for studying the underhead and thread friction in fasteners (Brickford, 1997), based on the effective bearing friction radius, the underhead friction coefficient, and the thread friction coefficient which are experimentally determined for standard fasteners.

In conclusion, from the study dated 1931, all these works brought us a greater accuracy in determining the value of the torque components that are consumed in overcoming friction in threaded fasteners, and then to a more reliable torque-tension correlation enhancing the safety and quality of bolted assemblies.

1.1 Design methods and recommendations

After a threaded fastener has been tightened, both the level and the stability of the achieved fastener tension will have a significant impact on the reliability of bolted assemblies used in various mechanical and structural applications. Most often, the fastener tension is achieved by turning the fastener head or nut using a torque. Tribological aspects of the fastener tightening are critical to the torque-tension relationship and to the integrity, quality, and to the safety of many mechanical and structural components.

The tightening torque is mostly consumed in overcoming the combined effect of two frictional torque components. The first friction torque component is consumed in overcoming the underhead bearing friction during the turning of the fastener head during the tightening process. The other friction torque component overcomes the thread friction. After overcoming friction, the remaining torque component is what produces the fastener tension and creates the joint clamping force. The scheme in Figure 1 summarizes the torque distribution in a tightened bolt. The torque-tension relationship in threaded fasteners is highly sensitive to the friction torque variations. Moderate friction torque variations, which are particularly common in most industrial applications, have significant impact on both the level and the stability of the clamp load in bolted assemblies (Bickford, 1997 and Sakai, 2008). Recent studies put in light that friction stresses appear only near the bolt holes, and contact stress on the contact surface is like a ring around the hole, (Huang, 2010). At the edge of the bolt hole, the stress is the largest, but at a certain distance from the edge of the bolt hole, the stress is decreased to nearly zero. Distribution of the friction stress on the contact surface is similar to the contact stress in a restricted region, which is called the pressure effect region that is nearly a circular area.

The problems pertaining to structural dynamics with bolted joints have been also addressed, see (Ibrahima, 2005). These problems are complex in nature because every joint involves different sources of uncertainty and non-smooth non-linear characteristics. For example, the contact forces are not ideally plane due to manufacturing tolerances of contact surfaces. Furthermore, the initial forces will be redistributed non-uniformly in the presence of lateral loads. This is in addition to the prying loading, which is non-linear tension in the bolt and non-linear compression in the joint. Under environmental dynamic loading, the joint preload experiences some relaxation that results in time variation of the structure's dynamic properties. Most of the reported studies focused on the energy dissipation of bolted joints, linear and non-linear identification of the dynamic properties of the joints, parameter uncertainties and relaxation, and active control of the joint preload.

Regarding design specifications and standards, recent European (2003), American (1980 and 1989) and British Codes (1982) have been developed in order to regulate the choice, the design and safety calculation to be followed in designing connections and joints with bolts. Different approaches are followed in calculating the slip strength of bolted connections, depending from friction coefficients and model of calculus of the system. In the following, our experimental results will be compared with these models. Due to safety requirements and material performance optimisation, the question of the effective friction conditions and friction coefficients to use in the calculation is then of primary importance. Despite the numerous studies aimed at determining the slip resistance of bolted joints, new materials and evolving surface treatments makes it necessary a continuous testing of systems to guarantee the high safety standard.

For example, the usage of COR-TEN steel (Corrosion-Tension) for important construction as the bridge of Figure 2 is relatively new; coefficients in this case are uncertain or unknown at all.

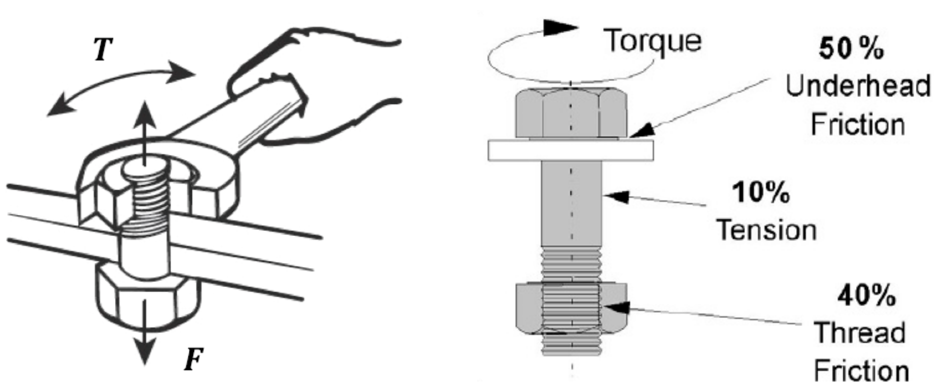


Figure 1. Torque distribution in a tightened bolt.

Figure 2. A brand-new COR-TEN bridge structure (Ululone bridge, north of Italy).

Other situations, as environmental effects of dust, lubricants, stain or vibrations, or as repeated tightening, are difficult to predict and are taken into consideration only by increasing safety factors and, consequently, by decreasing the performance of bolted joints.

In this work, a precise determination of the friction coefficients and the analysis of the friction phenomenon is obtained for joints with different surface conditions. The strength of joints against slipping is obtained from test in laboratory, and considerations about dispersion of data are taken. The most relevant conclusion is that in particular cases the prescription from design codes are not conservative.

2 EXPERIMENTAL ACTIVITY

2.1 Specimens

The experimental campaign has been conducted on double butt-strap joints with four 8.8 strength class bolts. Two different thicknesses of the joint have been tested, with bolts M16 and M20, with 3 different surface conditions. Geometry of the test specimens and different surfaces are illustrated in Figure 3. Table 1 summarizes the three conditions we examined.

The geometry of the specimen is chosen as indicated by standards and is designed in order to obtain two values of axial load at which a slip of the joints correspond, for each test.

Table 1. Summary of tested specimens and conditions.

Specimen	Joint thickness (mm)	Bolts	Surface condition
S16-1	8+16+8		*As is* S235J steel
S16-2	8+16+8	4xM16 class 8.8	COR-TEN steel
S16-3	8+16+8		Zinc-coated
S20-1	10+20+10	4xM20 class 8.8	*As is* S235J steel

Figure 3. Specimens used for the experimental campaign.

Test consisted in mounting the specimen on a MTS universal machine and loading it in tension. The tension-displacement curve is then recorded and analysed.

2.2 Torque and axial load

The relation between applied torque T and bolt axial load F depends on the friction coefficient μ_t between threads of screw and nut, and on the friction coefficient μ_c of the bearing portion. It can be expressed as:

$$T = F\left(\frac{p}{2\pi} + \frac{\mu_t r_t}{\cos\alpha} + \mu_c r_c\right). \quad (1)$$

The three terms of Eq. (1) are related to the torque necessary to elongate the bolt $\left(F\frac{p}{2\pi}\right)$, the torque spent for the threads (average radius r_t and angle α) friction $\left(F\frac{\mu_t r_t}{\cos\alpha}\right)$, the torque portion due to friction between bolt underhead and bearing ring of average radius r_c $\left(F\mu_c r_c\right)$. A simplified relation is often found also in the form:

$$T = 0.2Fd \quad (2)$$

with d the nominal bolt diameter.

In the first part of our experimental study, verification of Eqs. (1) and (2) has been made by measuring the torque, which has been applied using a dynamometric key, and the relative axial load quantified by an annular load cell. Results are shown in Figure 8.

2.3 Slip strength

The friction coefficient of the joints is evaluated by the measure of the axial force at which a measurable slip of the joint plates occurs. The relation between the slip resistance of the joint P_{slip} and the total compressive load between the plates can be expressed as:

$$P_{slip} = \mu_t m \sum_{i=1}^{n} F_i \quad (3)$$

where μ_t is the global friction coefficient, m is the number of possible slip planes (we have $m = 4$), $\sum_{i=1}^{n} F_i$ is the sum of the axial loads in bolts. From Eq. (3) it is possible to obtain the friction coefficient the joint is working with:

$$\mu_t = P_{slip} \big/ mnF_i \, . \quad (4)$$

Since we have 2 slips per test, we call μ_{t1} the friction coefficient occurring at the first slip, μ_{t2} the friction coefficient occurring at the second slip, and $\mu_t = (\mu_{t1} + \mu_{t2})/2$ the average total friction coefficient.

Tensioning of the joints has been made by a MTS universal testing machine, by a load-rate controlled ramp. Correspondingly, the monitoring of the axial load in bolts is conducted in real time by the annular cell and a NI acquisition system. An image of the experimental set-up is reported in Figure 4.

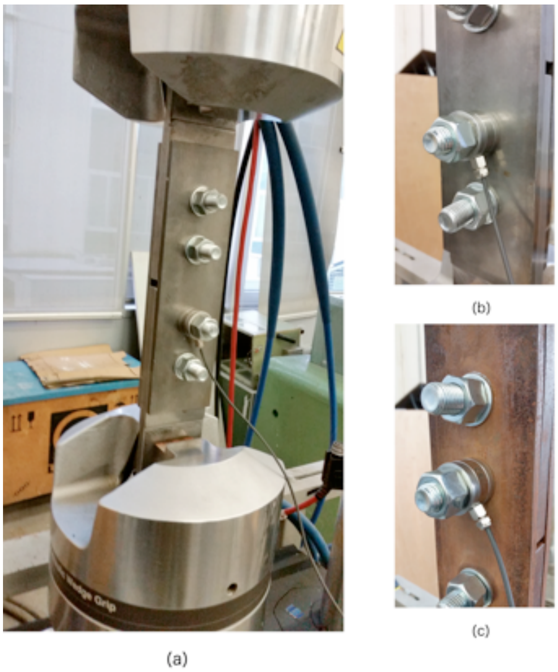


Figure 4. (a) Experimental set-up for the test; (b) S235J steel joint; (c) COR-TEN steel joint.

3 RESULTS AND DISCUSSION

Since no significative differences have been found for the M16 and M20 joints, in the following the results are presented with no more distinction. For the elaboration of results, data relative to M16 and M20 are merged.

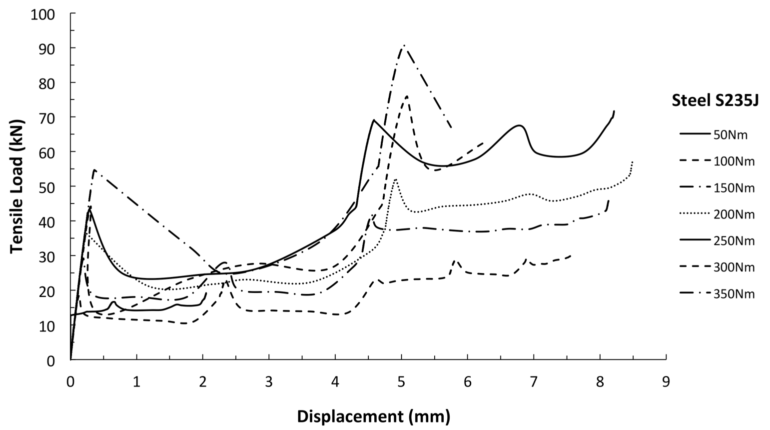
3.1 Load – displacement response

Figure 5 shows the tensile load-displacement response of the tested joints, for increasing values of the applied torque from 50 to 350 Nm. It is possible to notice that:

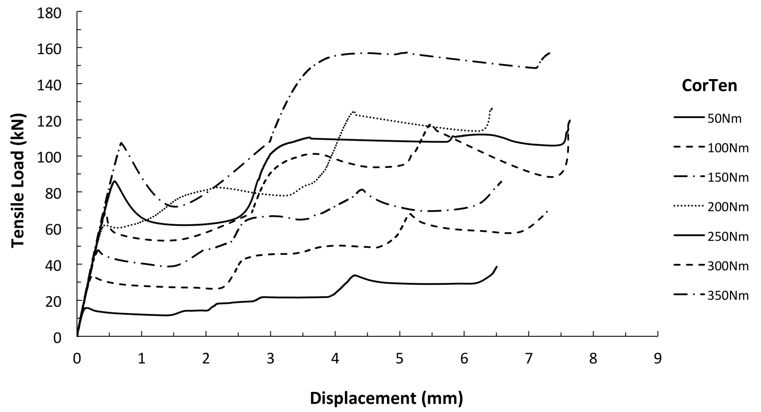
1. as expected, tensile load increases when bolt torque increases;
2. a very different behaviour results depending from the surface condition;

3. tensile load at which slips occur is clearly defined for *as is* and COR-TEN condition while it is not for the zinc-coated plates.

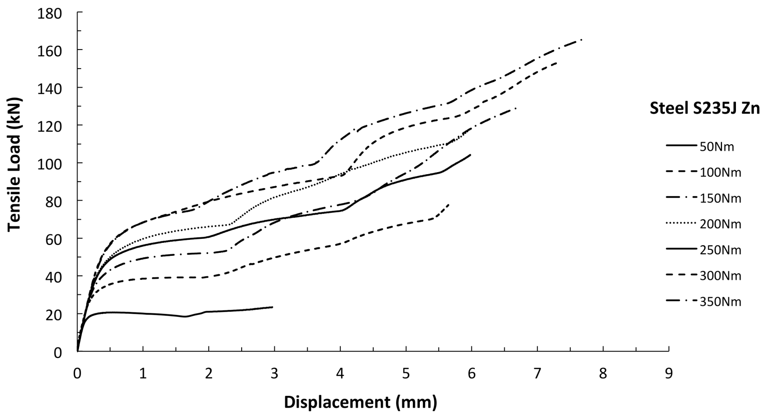
This last evidence is due to a different friction mechanism occurring between the zinc-coated surfaces. Other similar evidences are reported in the technical literature, see for example (Eccles, 2010).



(a)



(b)



(c)

Figure 5. Load – displacement relationships for tested joints.

However, in the curves, despite the applied torque, it can be noticed a double peak followed by a plateau indicating a slide occurred; in correspondence of these load peaks the friction coefficient is calculated applying relation of Eq. (4), and averaged values are calculated. Elaboration of results is shown in Figure 6, where average friction coefficients are ordered following the applied torque. From these points it follows that *as is* steel exhibits lower friction than COR-TEN and zinc-coated plates, respectively, and that different mechanisms occur in the sliding, being different the dependence fro the applied torque. In particular, while Zn-coated and show a strong dependence from the bolt load, COR-TEN does not. In other words, the slip strength of COR-TEN joints is not sensitive to the bolt load, while Zn-coated and *as is* decrease and increase, respectively.

When the friction values are averaged between all tests and plotted with data from literature, we obtain the graph of Figure 7. Friction coefficients found in literature goes from 0.15 to 0.6 with big scatter within the same surface finishing too. Summarizing, averaged results with standard deviation are: 0.31 ± 0.11 for *as is* steel, 0.38 ± 0.11 COR-TEN, 0.47 ± 0.18 zinc-coated. These values are within the range from literature.

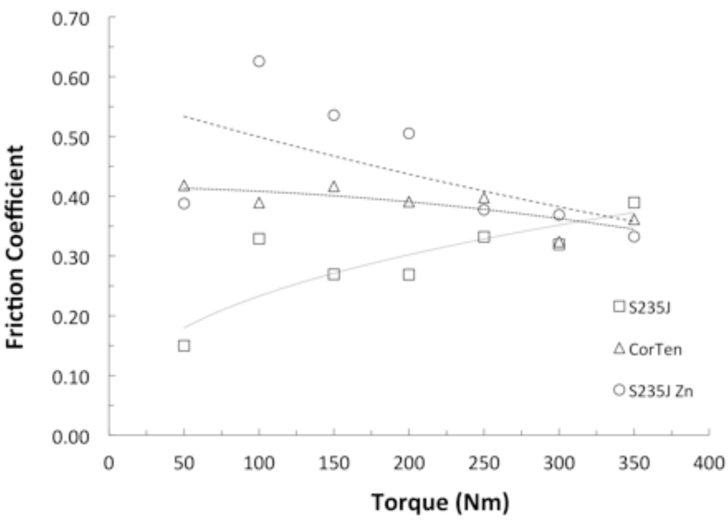


Figure 6. Effect of torque on friction coefficient.

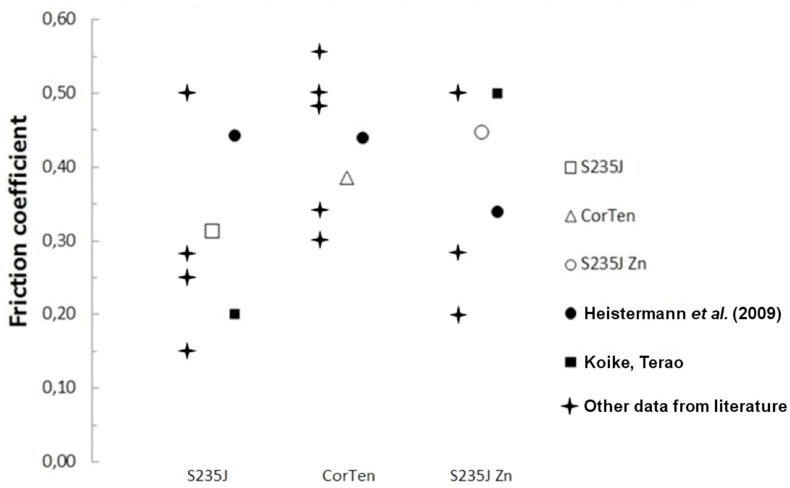


Figure 7. Averaged values of friction coefficient.

Heistermann (Heistermann et al., 2009) founds the same friction coefficient (0.45) for *as is* and COR-TEN steel, and lower value for Zn-coated; in an internal report, Koike and Terao found coefficients very similar to ours for *as is* and Zn-coated.

3.2 Torque – axial load relationship

Figure 8 shows the relationship between the applied bolt torque and the axial load, determined by the annular load cell that is visible in Figure 4(b) and 4(c). Data points are obtained for different values of applied torque, even if the torque prescribed by codes for in-exercise bolts working by friction is the torque that causes an axial stress of 70% of the yield stress (for our 8.8 class M16 bolts is $T = 256$ Nm). Dispersion of data is very low, and a linear relationship between torque and load is always evidenced for any surface finishing. Results reflect what evidenced in the plot of Figure 6: bolts tightening Zn-coated joints are loaded in tension more than COR-TEN's and *as is*' steel respectively, which is reflected by the friction coefficients found. Since the bolts are the same on all tested joints, looking at Eq. (1) this means that torque term spent for friction between plate and bolt underhead – term $\mu_c r_c F$ in Eq. (1) – diminishes from *as is* to Zn-coated condition.

Equations (1) and (2) are plotted together with experimental data in Figure 8; Eq. (2), which is more simple, does not take into account different contribution of the applied torque, gives a good estimation for Zn-coated plates, but overestimates the other finishing; more detailed Eq. (1), in which experimentally found coefficients are used for the underhead term, gives more precise estimation.

3.3 Effect of repeated tightening

As already put in evidence elsewhere, see for example (Jiang *et al.*, 2001), we found that repeated tightening of bolts is dramatically detrimental for the efficiency of the connection, especially when working at higher load.

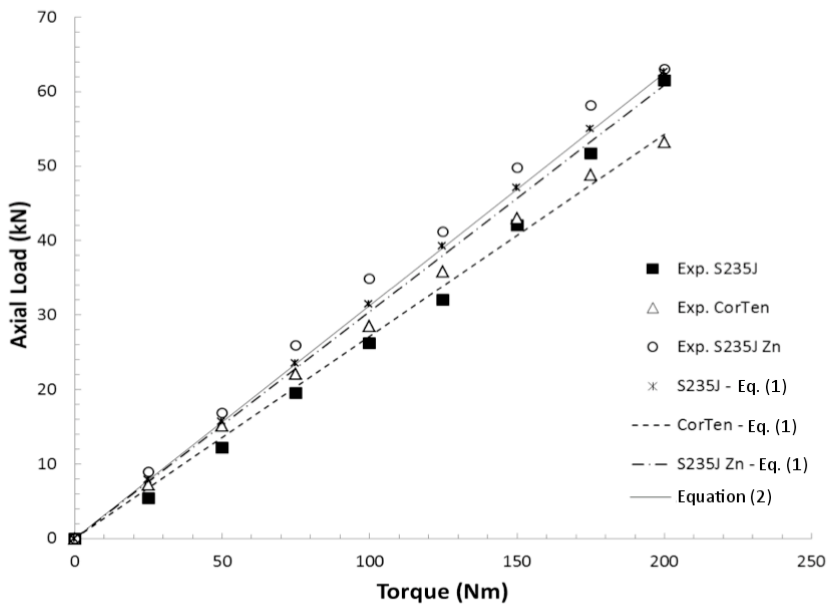


Figure 8. Torque – axial load relationship.

Even after 3 or 4 tightening operations, the load cell reported a huge loss (30 – 40%) in the axial load, and consequently very low slip resistance of the joint is found. This is certainly due to the damage and plasticization of the first threads of the nut, which do not permit any further loading in tension of the bolt.

3.4 Comparison with standards

Finally, a comparison with prescription from current design codes has been carried out with our experimental data. The result is somehow surprising, since the relationships indicated in the current Eurocode 3, see the plot in Figure 8, revealed to be not conservative, especially at higher torques, for which the experimental slip strength vary from linearity.

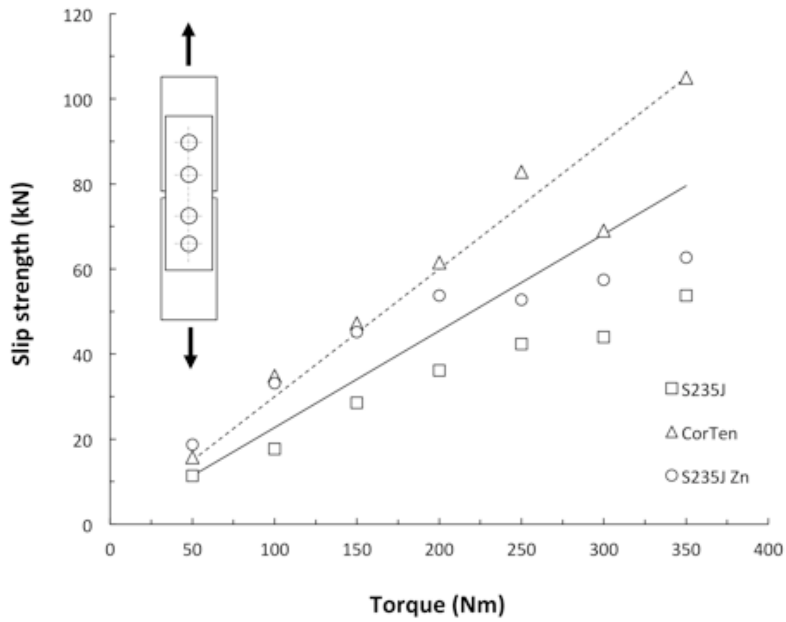


Figure 9. Slip strength as experimentally determined and as predicted from normative (dashed line: dismissed Italian CNR-UNI 10011; solid line: Eurocode 3).

4 CONCLUSIONS

A set of steel bolted joints with different surface conditions has been tested in laboratory in order to determine the slip strength of bolts; we can draw the following conclusions:

1. Regarding the tightening torque – axial load relationship, a good correlation has been found between experiments and theoretical models;
2. Friction coefficient depends from the tightening torque: for treated surfaces (COR-TEN and zinc-coated) it slightly decreases when applied torque increases;
3. Friction coefficients averaged on all test, 0.31 ± 0.11 (*as is* steel), 0.38 ± 0.11 (COR-TEN), 0.47 ± 0.18 (zinc-coated), indicate a dependence from the surface condition: zinc-coated plates exhibit higher friction and higher dispersion of data;

4. the current Eurocode 3 for steel design overestimates the joint slip resistance by about 10-15% for *as is* and zinc-coated conditions; this surprising finding should be more deeply investigated.

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