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# FACTORS INFLUENCING THE PRELOAD LEVEL OF HIGH STRENGTH BOLTS FOR STRUCTURAL STEEL CONNECTIONS

BY

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**Abstract.** For steel structures subjected to reversible or shock loads all current design codes impose the use of high strength pre-tensioned bolts. The behaviour of pre-tensioned connections, in addition to proper dimensioning, is strongly influenced by the assembly process as well by the need to ensure the pretension level taken into consideration when designing the connection. The pre-tension stress of a bolt varies in time and is characterized by three specific values: the initial pre-tension, represented by the value of tensile stress after the first tightening, the residual pretension value, represented by the value of tensile stress once all of the bolts have been tightened, the final pre-tension represented by the value of tensile stress at the time of operation. The value of the final pre-tension force is closely related to the value of the original pre-tension force. The value of the initial pre-tension force can be controlled directly and with great precision hence the correct initial pre-tension force is essential to ensure the desired behaviour of the connection.

The detailed methods of pre-tensioning the bolts used in structural steel connections are presented. The advantages and disadvantages of the methods presented in the specifications are highlighted. At the end of the paper are chronologically listed different patents of direct tension indicator devices.

**Key words**: steel structures; bolted connections; bolt preload; bolt tightening methods.

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## 1. Introduction

Rivets were the principal fasteners in the early days of iron and steel, but occasionally bolts of mild steel were used in structures. It had long been known that hot-driven rivets generally produced clamping forces. However, the axial force was not controlled and varied substantially. Therefore it could not be evaluated for design.

Batho and Bateman were the first to suggest that high-strength bolts could be used to assemble steel structures. In 1934 they reported to the Steel Structures Committee of Scientific and Industrial Research of Great Britain that bolts could be tightened enough to prevent slip in structural joints.

## 2. Bolted Connections Categories

According to the European norm Eurocode 3 (EN 1993-1-8) bolted connections are divided into two main categories: connections loaded in shear and connections loaded in tension.

Bolted connections loaded in shear should be designed as one of the following:

*Category A* (Bearing type). In this category bolts from class 4.6 up to and including class 10.9 should be used. No pre-loading and special provisions for contact surfaces are required. The design ultimate shear load should not exceed the design shear resistance, nor the design bearing resistance.

*Category B* (slip – resistant at serviceability limit state). In this category pre-loaded bolts of classes 8.8 and 10.9 should be used. Slip should not occur at the serviceability limit state. The design serviceability shear load should not exceed the design slip resistance. The design ultimate shear load should not exceed the design shear resistance, nor the design bearing resistance.

*Category C* (slip – resistant at ultimate limit state). In this category pre-loaded bolts of classes 8.8 and 10.9 should be used. Slip should not occur at the ultimate limit state. The design ultimate shear load should not exceed the design slip resistance, nor the design bearing resistance. In addition for a connection in tension, the design plastic resistance of the net cross-section at bolt holes should be checked at the ultimate limit state.

Bolted connection loaded in tension should be designed as one of the following:

*Category D* (non-preloaded). In this category bolts from class 4.6 up to and including class 10.9 should be used. No pre-loading is required. This category should not be used when the connections are frequently subjected to variations of tensile loading. However, they may be used in connections designed to resist normal wind loads.

*Category E* (pre-loaded). To this category belong pre-loaded classes 8.8 and 10.9 bolts with controlled tightening.

According to Eurocode 8 (EN 1998-1) in bolted connections of primary seismic members of a building, high strength bolts of bolt class 8.8 or 10.9 should be used. Categories B and C of bolted joints in shear and category E of bolted joints in tension are allowed. Shear joints with fitted bolts are also allowed. The tightening of pre-loaded bolts shall be in accordance with European Standard EN 1090, “Execution of steel structures – Part 1: Requirements for the execution of steel structures”. The bolts shall be tightened to at least the specified minimum pre-load. Unless otherwise specified in the project specification the minimum preload shall be taken as

$$F_p = 0.7 f_{ub} A_s \,, \tag{1}$$

where: $f_{ub}$ is the specified ultimate tensile strength of the bolt, $A_s$ – the tensile stress area of the bolt.

When the pre-load is not explicitly used in the design calculations for shear resistances but is required for execution purposes or as a quality measure then the level of pre-load can be specified in the National Annex (EN 1993-1-8).

According to “Seismic Provisions for Structural Steel Buildings” – AISC 360-2005 pre-tensioned joints, slip-critical joints or welds shall be used for the following connections: column splices in all multi-story structures over 38 m in height; connections of all beams and girders to columns and any other beams and girders on which the bracing of columns depends on structures over 38 m in height; in all structures carrying cranes of over 50 kN capacity – roof truss splices and connections of trusses to columns, column splices, column bracing, knee braces, and crane supports; connections for the support of machinery and other live loads that produce impact or reversal of load. The erection of connections with high strength bolts shall be in accordance with “Specification for Structural Joints Using ASTM A325 or A490 Bolts” – 2004, prepared by Research Council on Structural Connections. Minimum bolt pretension must be equal to 70% of the specified minimum tensile strength of bolts.

According to “Seismic Provisions for Structural Steel Buildings” – AISC 341-05, all bolts shall be pre-tensioned high strength bolts. The potential for full reversal of design load and the likelihood of inelastic deformations of members and/or connected parts make necessary that pre-tensioned bolts be used in bolted joints in the SLRS.

The Romanian seismic design code P100-1-2006, in addition to the European norm Eurocode 8 provisions, requires that the beam–column connection with end plate to be assembled using high strength bolts and to provide a pretension force of 50% of that required for shear connections with restrained slip.

The clamping force that a bolt exerted on the joint is usually called or equally to the so-called *preload* in the bolt. This term is generally used in most of the literature regarding the bolting to describe the tension in the bolt at any time, but this, in our opinion, is a mistake. We like to think of the pre-load created in an individual fastener when it is first tightened as ''initial'' pre-load, even though that term may be redundant. As you'll see, the effects we're about to discuss will frequently modify this pre-load as the fastener relaxes or as we tighten other fasteners in the joint. We call the final pre-load in the bolts the *residual* pre-load. When the joint is put into service, a variety of things can act to further modify the pre-load in individual fasteners. This could be called *in-service tension in the bolts*.

According to European Standard EN 1090, "Execution of Steel Structures – Part 1: Requirements for the Execution of Steel Structures", tightening shall be carried out using one of the following methods: torque control method, turn-of-the-nut method, direct tension indicator method or combined method which combines the torque and turn-of-the-nut methods.

The American norm "Specification for Structural Joints Using ASTM A325 or A490 Bolts", 2004, specifies that for erection of pre-tensioned joints one of following methods shall be used: turn-of-nut pre-tensioning, calibrated wrench pre-tensioning, twist-off-type tension-control bolt pre-tensioning or direct-tension-indicator pre-tensioning.

## 3. Bolt Tightening Methods

### 3.1. Torque Control Method

The bolts shall be tightened using a torque wrench. The wrench shall be set to a torque value of nut less than the minimum torque required to achieve the minimum pre-load. Before the beginning of pre-loading, the bolts in a group shall be snug-tightened.

The snug-tightened condition is attained when the connected components are drawn together such that they achieve firm contact. The term *snug-tight* can generally be identified as that achievable by the effort of one man using a normal sized spanner without any extension arm; it can be set as the point at which a percussion wrench starts hammering. Residual gaps up to 2 mm may be left between contact faces except where full contact bearing is required by project specification (EN 1090-1).

Research Council on Structural Connections (RCSC) (Chicago, 2004), defines snug-sight condition as the tightness that exists when all plies in a joint are in firm contact. This level is approximately 50% of the fully pre-tensioned case. The snug-tight condition is considered sufficient for most shear/bearing joints (Fleischman *et al.*, 1973).

Experience and theoretical analysis say that there is usually a linear relationship between the torque applied to a fastener and the preload developed in a given fastener (Bickford, 2008)

$$T = F_p C \,. \tag{2}$$

A number of equations have been derived that attempt to define the constant *C*. The following eq. has been proposed by Motosh (1976),

$$T = F_p \left( \frac{P}{2\pi} + \frac{\mu_t r_t}{\cos\beta} + \mu_n r_n \right), \tag{3}$$

where: $T$ it is torque applied to the fastener; $F_p$ – pre-load created in the fastener; $P$ – the pitch of the threads; $\mu_t$ – the coefficient of friction between nut and bolt threads; $r_t$ – the effective contact radius of the threads; $\beta$ – the half-angle of the threads; $\mu_n$ – the coefficient of friction between the face of the nut and the upper surface of the joint; $r_n$ – the effective radius of contact between the nut and joint surface.

This eq. shows that the input torque is resisted by three reaction torques. These are as follows: reaction produced by the inclined plane action of nut threads on bolt threads, reaction torque created by frictional restraint between nut and bolt threads, reaction torque created by frictional restraint between the face of the nut and the washer or joint. This force reaction affect the amount of initial preload we get when we tighten a fastener. The coefficient of friction is very difficult to control and virtually impossible to predict. There are some 30 or 40 variables that affect the friction seen in a threaded fastener. These include such things as: hardness of all parts, surface finishes, type of materials, speed with which the nut is tightened, fit between threads, presence or absence of washers (Bickford, 2008).

The things which affect the torque *vs.* pre-load dependence can be summarized as follows: friction, operator, geometry, tool accuracy, relaxation. Friction includes not only lubricant but also surface finish, speed of tightening, type of materials involved, and many, many more variables. Geometry includes not only the manufacturing tolerances on parts but that important perpendicularity between nut face, axis hole, and joint surface. Relaxation includes embedment and elastic interactions, both of which occur as we tighten a group of bolts. Operator and tool accuracy are self-explained (Bickford, 2008).

Usage of the twist-off bolts F 1852 (Fig. 1), provided as tightening method in the American design code “Specification for Structural Joints Using ASTM A325 or A490 Bolts”, 2004, is a very precise method in terms of torque control.

The twist-off bolt (Fig. 1), cannot be held or turned from the head. Instead, the bolt is held by the assembly tool from the nut end. An inner spindle on the tool grips a spline section connected to the main portion of the bolt by a turned-down neck. An outer spindle on the tool turns the nut and tightens the fastener, with the tool reacting against the spline section. When the design torque level has been reached, the reaction forces on the spline snap it off, as shown in Fig. 1. The building inspector can determine whether or not a minimum amount of torque was applied to the fastener by looking to see whether or not the spline sections have indeed been snapped loose from the bolts.

If, between calibration and use, the bolts are allowed to become rusty or in any other way suffer a change of lubricity, then the amount of tension actually achieved in field assembly can be quite different from that achieved in the calibration stand.

The fact that this fastener can be calibrated in the as-used condition, however, and, even more important, the fact that the inspector has a way to determine whether or not a minimum torque was applied to the fastener make this a popular item.

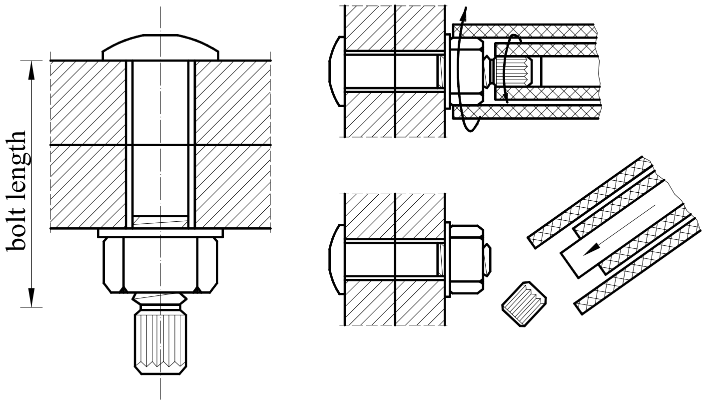

Fig. 1 – The twist-off bolt.

Using torque control method the pre-load of bolts can vary by ±25%…30% (Bickford, 2008).

### 3.2 Turn-of-the-Nut Method

When we apply torque, the nut turns too. We can use the angle through which the nut turns, instead of torque, to control pre-load. At first glance this looks very promising. After all, when we turn the nut on a machine-tool lead screw by 360º, the screw advances or retracts with a linear displacement equal to exactly one pitch of the threads. Won't a bolt stretch by this amount when we rotate the nut one turn? If so, we could use the lead screw eq. to relate bolt stretch to turn of the nut. We could then get bolt pre-load very easily, assuming that we knew the spring constant or stiffness of the bolt (Bickford, 2008)

$$F_p = K_B \Delta L = K_B P \frac{\theta_R}{360^0}, \tag{4}$$

where: $F_p$ is the bolt pre-load; $P$ – the pitch of the threads; $\Delta L$ – bolt stretch; $\theta_r$ – the angle of nut rotation; $K_B$ – bolt stiffness.

The first few turns of the nut produce no preload at all, because the nut has not yet been run down against joint members and they are therefore not yet involved. This situation is shown in Fig. 2 *a*. Finally the nut starts to pull joint members together. There may be frictional restraint between joint members and surrounding structures. Joint members may not be perfectly flat. There may be a bent washer. As a result, although we start to produce some tension in the bolt, most of the input turn is absorbed by the joint and the bolt sees only a small increase in pre-load, as suggested by Fig. 2 *b*. This process is called *snugging the joint*, and the amount of turn required varies unpredictably, even between apparently identical bolts or joints.

After the joint has been snugged, all bolts and joint members start to deform simultaneously, with individual deformations in inverse proportion to individual spring constants. Pre-load now starts to build more rapidly in the bolt, following a straight line whose slope is equal to (Bickford, 2008)

$$\alpha = \frac{\Delta F_P}{\Delta \theta_R} = \frac{K_B K_J}{K_B + K_J} \cdot \frac{P}{360^0}, \tag{5}$$

where: $K_B$ is the spring constants of bolt; $K_J$ – spring constants of joint members; $P$ – the pitch; $F_P$ – pre-load; $\theta_R$ – the input angle of turn, [degrees].

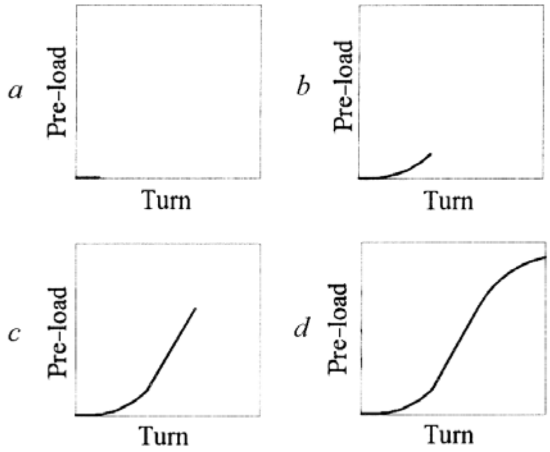

Fig. 2 – Step-by-step build-up of pre-load in a joint when the turn of the nut relative to the bolt equals turn with respect to ground.

During this straight-line portion of the process, there is usually a linear relationship between additional input turn and additional pre-load, as shown in Fig. 2 *c*. If we could predict the spring constants involved–and if we could determine where this straight-line portion of the curve starts–measuring turn would give us good control of preload. Unfortunately, however, we will find it very difficult to determine where the straight-line portion of this curve starts. It will vary from bolt to bolt, from assembly to assembly, and from application to application, adding to the uncertainties in spring constant.

If we continue to turn the nut, something in the joint will eventually start to yield. This ends the linear buildup of preload in the joint, as suggested in Fig. 2 *d*.

### 3.3 Direct Tension Indicator Method

The interest in a guaranteed minimum preload has led the structural steel industry to adopt several new types of fasteners which improve the chances that the fasteners will be pre-loaded properly and make it easier to inspect previously tightened fasteners for minimum tension. These fasteners are formally classified as either “alternate design bolts”, to be discussed soon, or fasteners which allow “direct tension indicator tightening”.

The most common type of direct tension indicator (DTI) at the present time is a washer with “bumps” on its upper surface (Fig. 3) (Bickford, 2008). In one of several assembly procedures, a DTI washer is interposed between the head of the bolt and the surface of the joint. As the nut is tightened, the bumps on the DTI washer yield plastically, reducing the gap between the head of the bolt and the washer. A feeler gage is used to measure this gap. When the gap has been reduced below a preselected maximum value, the tightening process is stopped.

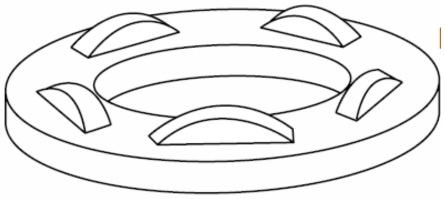

Fig. 3 – Direct tension indicator (DTI).

Several studies have been made to evaluate the accuracy with which the DTI washer controls initial preload in a fastener. In one series of experiments, the accuracy of the device, when used between parallel joint surfaces, ranged from +4%…–6% to +12%…–10%. When used on nonparallel surfaces (structural steel members are often tapered), the best-case accuracy was +15%…–11% and the worst-case, +23%…–15%. In every case, however, the minimum tension required in structural steel work was achieved (Struik & Fisher, 1973).

A major advantage of direct tension-indicating fasteners usage is the ease and speed of executing pre-tensioned bolted connections as well as ease of assembly.

The direct tension-indicating fasteners would eliminate most of the problems, such things as bolt twist, heat loss in the threads, and reaction to prevailing torque. They wouldn't be able to compensate for severe bending of the bolt, but this is rarely a real problem.

Due to the necessity of using pre-tensioned connections in the case of steel structures, there has been a constant concern regarding bolts tightening. Thus, many researchers have studied and patented various direct tension-indicating fasteners applicable to steel structures.

G.M. Curtis and D.P. Wagner have patented in 1978 a tension indicating washer unit (Fig. 4). A multipiece, preassembled washer unit incorporating an upper washer and a lower conical washer with a ring gauged interposed between the outer marginal surfaces of the washers so that the gauge is clamped between the superimposed washers upon compression of the unit to a predetermined amount. The clamping of the gauge in an indicative of a predetermined accurate tension level in the joint. The ring gauge includes means to accurately size itself and thereby accommodate and/or minimize errors due to tolerances in cold headed clamping members (Curtis & Wagner, 1978).

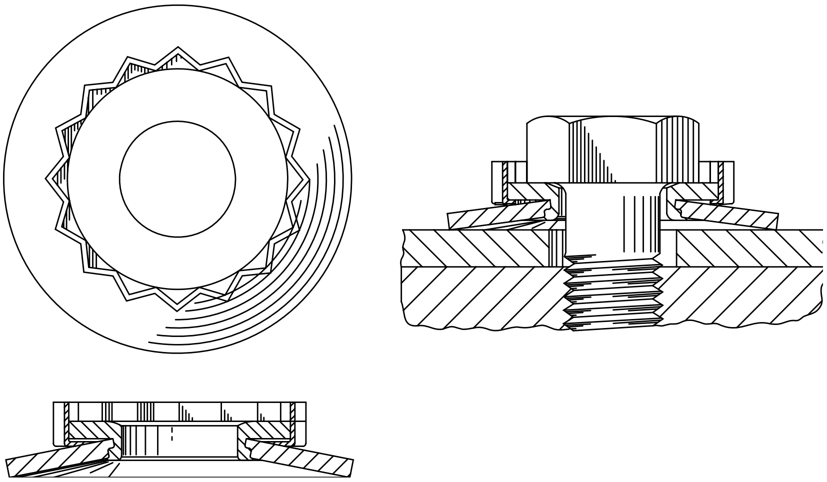

Fig. 4 – Tension indicating washer unit (Curtis & Wagner, 1978).

F.C. Peterson has patented in 1981 three types of tension indicating washers (Fig. 5). A washer indicates the amount of load placed on a fastener joint. A disc-like body has a pair of arms extending outwardly and then upwardly from two below portions. These two arms will deflect toward another and, when a predetermined load is reached, they will touch. Any loosening within the joint will result in the arms disengaging contact presenting an immediate visual indication (Peterson, 1981).

E.G. Swick and J.M. Forsberg have patented in 1986 a tension indicating washer improvements (Fig. 6). A tension indicating device is provided which includes at least one indicating arm and reference means carried by a stamped generally conical spring washer. A relieved area in the bearing surface of the washer prevents work surface irregularities from producing erroneous tension indications. The arm and reference means may mechanically engage one another and the arm may be made separately and attached to the washer. Indications made by the arm are designed to be visually discernable from a distance (Swick &Forsberg, 1986).

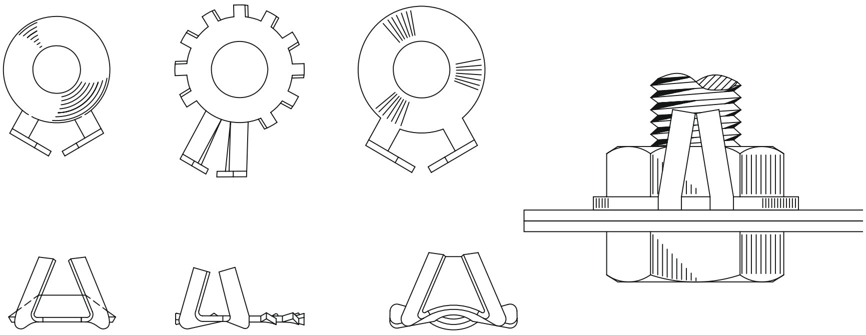

Fig. 5 – Tension indicating washers (Peterson, 1981).

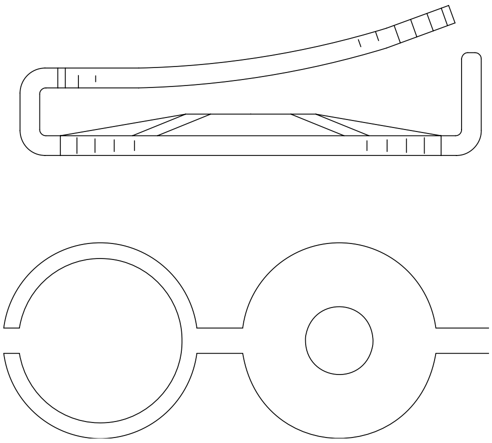

Fig. 6 – Tension indicating washer improvements (Swick & Forsberg, 1986).

A.M Turner has patented, in 1993, a bolt tension indicator having an annular washer part of concave cross section for fitment beneath the head of a bolt or beneath a nut, the indicator being made of spring steel and having at least one projecting tab element continuous with the annular washer part so that the lying flat of the tab element against a clamping face indicates a tension in a bolt (Fig. 7) (Turner, 1993).

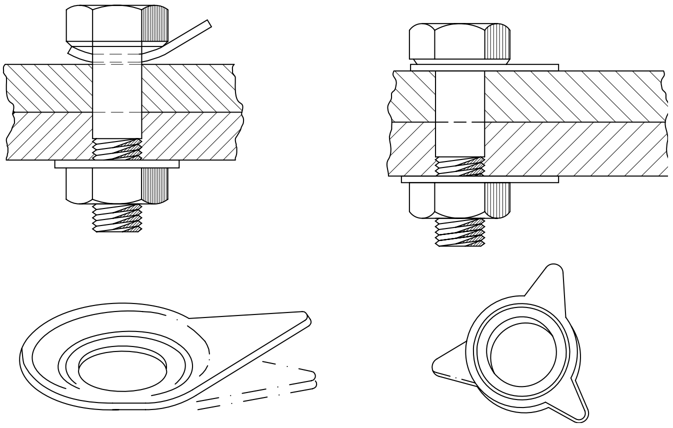

Fig. 7 – Bolt tension indicator (Turner, 1993).

I.W. Wallace and J.A. Herr have patented in 2000 two direct tension indicating washers (Fig. 8 *a*).

A direct tension indicating washer includes a body having an internal opening formed therein and at least one arched tab connected to the body. The arched tab has a fixed end integral with the body and a distal end movable with respect to the body. Indicia are formed on the arched tab and when the arched tab direct tension indicating washer is tensioned, the arched tab moves away from the body. Alignment indicia with a reference indicate proper tension. Another embodiment of the invention is a direct tension indicating washer having a body having an internal opening formed therein and at least one arch connected to the body (Fig. 8 *b*). The arch has a first end integral with the body, a second end integral with the body and an intermediate portion between the first end and the second end. The intermediate portion is positioned above a top surface body. The arch is configured to deform upon application of a predetermined amount of force to form a deformed arch indicating that a predetermined amount of bolt tension has been achieved (Wallace & Herr, 2000).

Wallace I.W. has patented in 2008 an innovative direct tension indicating washer (Fig. 9). This direct tension indicating washer includes: a first surface having a discrete protuberance formed thereon, a second surface having a discrete indentation formed opposite to the protuberances; and an indicating material has a cured skin on the outside of the indicating material and a compressible, liquid core in the inner of the indicating material. When the bolt tension reaches a predetermined level, the liquid cores erupts through the cured akin causing a climatic and dramatic appearance of the indicating material about an edge of the washer (Wallace, 2008).

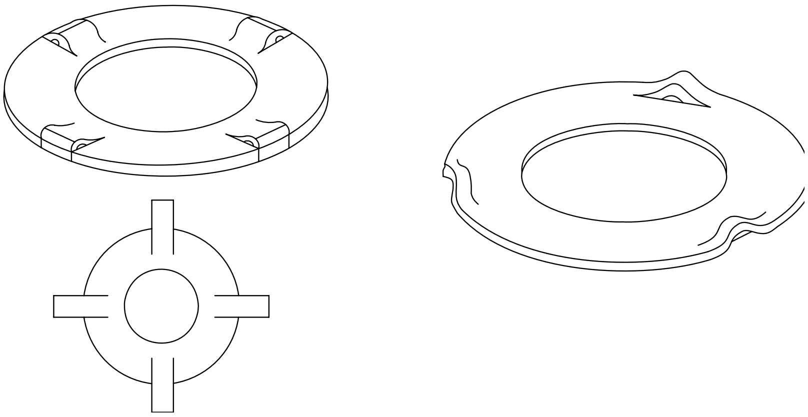

Fig. 8 – Direct bolt tension indicating washers (Wallace & Herr, 2000).

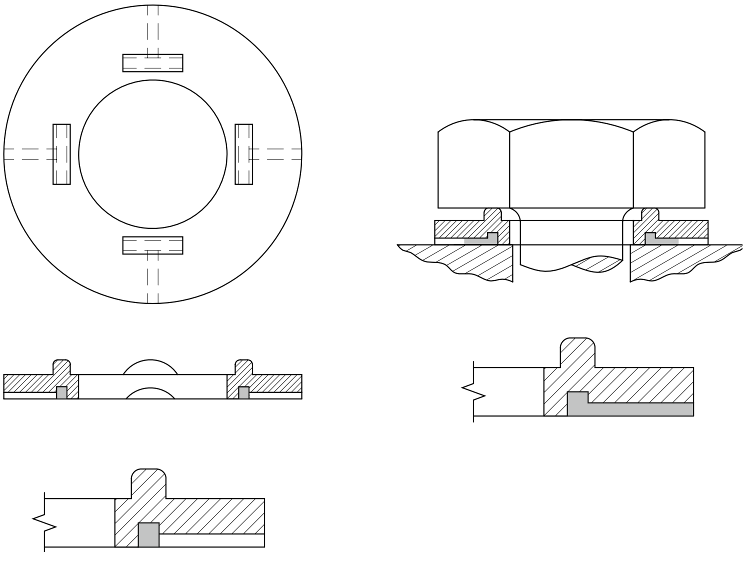

Fig. 9 – Bolt tension indicating washer (Wallace, 2008).

## 4. Conclusions

As presented in this paper, the use of pre-tensioned high strength bolts is imposed by current regulations in many situations. Due to the widespread use of high strength bolts in structural steel connection there has been a constant towards bolts tightening.

There is a large variety of factors that can influence the pre-tension level. To achieve the desired level of pre-tension, and thus the expected behaviour of the connection, extra attention must be paid during the execution and control stage.

Bolt tightening by means of devices, such as those presented in this paper, remove the disadvantages of torque control method or nut spin angle method.

Bolt tightening by means of direct tension indicators is the most accurate pre-tension method for the case of steel structures. Using this bolt tightening method does not eliminate the geometric tolerances of the connection. For this reason, the bolt pre-tension level may have significant variations.

Besides increased accuracy, the use direct tension indicators significantly reduce time and cost of building's erection. Their use allows a more accurate and easy control, in many cases requiring only a visual inspection.

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## ANALIZA CRITICĂ A PROCEDEELOR DE PRETENSIONARE A ŞURUBURILOR DE ÎNALTĂ REZISTENŢĂ PENTRU ÎMBINĂRI LA STRUCTURI METALICE

(Rezumat)

Pentru structurile metalice supuse acţiunilor reversibile sau cu caracter de şoc toate normele de proiectare impun utilizarea şuruburilor de înaltă rezistenţă pretensionate. Comportarea îmbinărilor cu şuruburi pretensionate, pe lângă alcătuirea şi dimensionarea corectă, este puternic influenţată de montajul acestora şi asigurarea nivelului de pretensionare luat în calcul la dimensionare. Efortul de preîntindere dintr-un şurub diferă în timp şi este caracterizat prin trei valori specifice: pretensionarea iniţială, reprezentată de valoarea efortului de întindere după prima strângere; pretensionarea reziduală, reprezentată de valoarea efortului de întindere rămas după strângerea tuturor şuruburilor din îmbinare; pretensionarea finală, reprezentată de valoarea efortului de întindere în momentul exploatării. Pretensionarea finală este strâns legată de cea iniţială, care de altfel poate fi controlată direct şi cu o precizie sporită, astfel că pretensionarea iniţială corectă este esenţială în vederea asigurării comportamentului dorit al îmbinărilor.

Se prezintă detaliat metodele de pretensionare a şuruburilor folosite la îmbinările structurilor metalice. Se evidenţiază avantajele şi dezavantajele metodelor de pretensionare prevăzute în normele de execuţie a structurilor metalice. În final sunt prezentate cronologic diferite brevete de invenţie a unor dispozitive pentru indicarea directă a pretensionării şuruburilor.