BOLTED JOINT PRELOAD DISTRIBUTION FROM TORQUE TIGHTENING

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Abstract: The purpose of this paper is to develop an understanding of how bolt preloads are distributed within a joint as each bolt is tightened in turn by the use of a calibrated torque wrench. It discusses how the order that the joints nuts/bolts are tightened can affect the final bolt preload. It also investigates the effect on incrementally increasing the bolt preload through a series of applications of the controlled torque tightening sequence.

Classical analysis methods are used to develop a method of analysis that can be applied to most preloaded bolted joints. It is assumed that the static friction coefficient is approximately 15% less than the dynamic friction.

It is found that the bolt preload distribution across the joint can range from slightly above the target preload to significantly less than the target preload. The bolts with a preload greater than the target preload are found to be those tightened towards the end of the tightening sequence, usually located close to the outer edges of the joint's bolt array. The bolts with a preload less than the target preload are those tightened early in the tightening sequence, located centrally within the joints bolt array.

The methods presented can be used to optimise bolted joint design and assembly procedures. Optimising the design of preloaded bolted joints leads to more efficient use of the joints.

Keywords: bolted joint, preloaded bolt, bolt preload, bolt tension, multiple bolt, multi bolt

1 Introduction

Preloaded bolted joints are a common feature in mechanical engineering. Preloading the bolts produces a stiff joint with good resistance to fatigue. However, accurate and consistent bolt preloading is required to provide optimum joint performance. A common method of producing a preload in bolted joints during assembly is by the use of a calibrated torque wrench. The use of a torque wrench is also the most popular way of remaking joints during maintenance and repair. When bolt torque is used as an indicator to bolt preload the variations in friction between the nut/bolt head and washer and between the nut and bolt threads result in potential errors in the bolt preload. In addition to this, variations in bolt preload can arise from the elastic redistribution of load as each bolt is tightened in turn.

This article considers the elastic distribution of bolt loads and contact pressure within a joint as the individual bolts are preloaded using a calibrated torque wrench. The analysis shows how variations of bolt preload within a joint can occur. The paper also considers procedures to minimise variations in bolt preload and contact pressure at the faying surface under the preload condition and optimizing the joint's performance.

The method of analysis presented assumes that as each bolt is tightened in turn the bolt preload is introduced as a load on the joint. This preload remains on the bolt being tightened and also influences the preloads on other bolts within the joint by elastic redistribution. The detail method of analysis used in this paper is an adaption of the method presented in reference [1]. The method presented here considers the preload induced in each bolt as similar to an external load on the joint.

2 Nomenclature

A_b	Tensile area of each bolt
A_f	Area of faying surface
A_j	Total area of joint (Faying surface plus bolts)
F_{dp}	Design preload
F_p	Preload in each bolt
$F_{p(n,i)}$	Preload in bolt 'n' at step 'i'
$F_{p.nom}$	Nominal bolt preload resulting from make up torque
F_{zp}	Bolt load induced by torque tightening
F'_{zp}	Change in bolt preload induced by torque tightening
$I_{xx.j}$	Second Moment of Area of joint about 'x' axis
$I'_{xx.j}$	Second Moment of Area transposed about x'-axis
$I_{xy.j}$	Product Moment of Area of joint
$I_{yy.j}$	Second Moment of Area of joint about 'y' axis
$I'_{yy.j}$	Second Moment of Area transposed about y'-axis
$K_{b(n,i)}$	Bolt 'resistance'
$K_{j(n,i)}$	Joint 'resistance'
M_x	External moment acting about 'x' axis
M'_x	Transposed moment
M_y	External moment acting about 'y' axis
M'_y	Transposed moment
P_p	Pressure at faying surface, preload pressure
$P_{p(n,i)}$	Pressure at faying surface local to bolt 'n' at step 'i'
x	Coordinate in plane of joint face
$x_{(n)}$	Coordinate of bolt 'n'
$x'_{(n)}$	Transposed coordinate of bolt 'n'
y	Coordinate in plane of joint face
$y_{(n)}$	Coordinate of bolt 'n'
$y'_{(n)}$	Transposed coordinate of bolt 'n'
$\delta P_{f(n)}$	Change in contact pressure local to bolt 'n'
θ	Angle of principal axis

2.1 Suffices

i	Step in bolt tightening sequence. Incrementally increases when a bolt is tightened.
n	Bolt number. Identifies each bolt within the joint or bolt group.
s	Bolt number in the bolt tightening sequence.

3 Tightening Sequence

Bolt-tightening procedures are used to try to achieve optimum preload conditions of the joint. Procedures often prescribe a sequence, or order, in which the bolts are tightened. The bolt tightening sequence usually starts with the bolt nearest the centre of the joint. The tightening sequence for the bolts then spreads outwards, with the intention of avoiding any locked in bending stresses in the flanges. Circular flanges, with circular bolt arrays, typical of piping joins, are usually tightened in a cross-pattern sequence. The bolts are also tightened in increments to help minimise the variations in contact pressure across the joint throughout the tightening procedure. The objective is to produce an as near uniform distribution of bolt preload and spread of contact pressure across the joint as possible. Locked in bending stresses can be considered as analogues to bubbles trapped under a bonded laminate sheet. They can result in deformation of the flanges resulting in an uneven contact pressure and partial lack of contact at the faying surface.

The tightening procedure usually aims to tighten the bolts by incremental steps, the final increment being the target or nominal bolt preload required for the joint. The target preload would be based on a percentage of the bolt's proof load but the tightening procedure would specify a bolt/nut 'make up' torque, which has been calculated or experimentally shown to achieve the required preload.

A typical bolt tightening procedure can be described as follows:

1. Establish joint alignment and "nip up" the bolts to prevent reintroduction of misalignment.
2. Snug tighten the bolts, following the prescribed tightening sequence for the bolts, closing up the joint.
3. Torque tightens the bolts to 25% of final make up torque, following the tightening sequence for the bolts.
4. Torque tightens the bolts to 75% of final make up torque, following the tightening sequence for the bolts.
5. Torque tightens the bolts to 100% of make up torque, following the tightening sequence.
6. Repeat step 5 until no further nut/bolt rotation occurs during the tightening operation.

When tightening a bolt that already has some preload the breakaway torque, the torque at which the nut/bolt starts to turn, is influenced by both the current level of preload and the static friction between the nut or bolt and its washer and the static friction between the threads of the nut and bolt. When the nut/bolt starts to turn the friction influence changes to that of dynamic friction. Since dynamic friction is always less than static friction the torque required for maintaining movement of the nut/bolt is less than the breakaway torque. The significance of this is that, during step 6 of the tightening procedure, it is possible for a bolt to have a preload that is less than the target preload and yet the target preload cannot be achieved because the breakaway torque is greater than the makeup torque, which is based on dynamic friction.

3.1 Snug Tightening

It can be assumed that during the tightening procedure each of the bolts is snug tightened to the same load. This will leave the bolts with minimal preload. Under this condition the contact pressure at the faying surface would also be near zero. The initial bolt load after snug tightening can be described by the following condition:

$$F_{p(n,i)} = \text{snug load} \quad (1)$$

The suffix (n, i) indicates the preload applies to bolt number n when the tightening sequence is at step i . At this point i represents the first step in the tightening sequence.

The snug load could be taken as zero or a small percentage of the final make up load, typically 1% or 2% say.

The faying surface contact pressure local to each bolt is given by:

$$P_{p(n,i)} = \frac{-1}{A_f} \cdot \sum_n F_{p(n,i)} - F_{p(n,i)} \cdot \sum_n \left(\frac{x_{(n)}^2}{I_{yy,j}} - \frac{y_{(n)}^2}{I_{xx,j}} \right) \quad (2)$$

The negative signs in equation (2) indicate the contact pressure is a compressive stress at the faying surface. The second term represents the internal moment on the joint produced by the bolt preloads and follows the ‘right-hand rule’. Hence, a positive moment about the joints y-axis will produce an increase in magnitude of contact pressure local to bolts with positive x-axis coordinates. Similarly, a negative moment about the joints x-axis will also produce an increase in magnitude of contact pressure local to bolts with positive y-axis coordinates.

3.2 First Pass of Torque Tightening

During the first pass of the torque tightening sequence each bolt is tightened in turn to the prescribed percentage of the make up torque, typically 25% of the full make up torque for the first pass. The load induced can be defined as:

$$F_{zp} = 25\% \cdot F_{p,nom} \quad (3)$$

Where $F_{p,nom}$ is the target, or required, final bot preload.

The force F_{zp} is positive when closing the joint. Hence, following the ‘right-hand rule’, a positive F_{zp} combined with a positive bolt coordinate $y_{(n)}$ will lead to a negative moment about the x-axis of the joint. Similarly, a positive F_{zp} combined with a positive bolt coordinate $x_{(n)}$ will lead to a positive moment about the y-axis of the joint. In effect, a positive F_{zp} is considered as representing what would normally be regarded as a negative axial load F_z on the joint.

The loads and moments applied to the joint during torque tightening the first bolt of the tightening sequence are based on the change in bolt load required to reach the required intermediate torque tightened load F_{zp} (in this case, 25% of the target torque).

The change in load, or additional load, applied to the first bolt in the tightening sequence by the intermediate torque tightening is given by the equation:

$$F'_{zp} = F_{zp} - F_{p(s,i)} \quad (4)$$

The subscript (s, i) indicates the bolt being tightened and the step in the tightening sequence respectively. Hence, $F_{p(s,i)}$ is the preload in bolt s at step i in the tightening sequence. The preload at the current step in the tightening sequence is the snug tightened load on the bolt.

Hence, the moments applied to the joint by torque tightening the first bolt are given by the equations presented below.

$$M_x = -F'_{zp} \cdot y_{(s)} \quad (5a)$$

$$M_y = F'_{zp} \cdot x_{(s)} \quad (5b)$$

The moments M_x and M_y are defined with respect to the joints coordinate system, usually the principal axes of the joint. If the joint is asymmetrical the moments M_x and M_y are resolved to act about the principal axes that are aligned at an angle to the joint coordinate system, as illustrated in Figure (1). The angle of principal axis from the joints x-axis (positive anticlockwise) is given by:

$$\theta = \frac{1}{2} \cdot \arctan\left(\frac{2 \cdot I_{xy.j}}{I_{yy.j} - I_{xx.j}}\right) \quad (6)$$

Fig. 1 Moments defined in the joint coordinate system

Hence, the resultant moments, the transposed coordinates and the transposed second moment of area of the joint are given by the following equations:

$$M'_x = M_x \cdot \cos(\theta) + M_y \cdot \sin(\theta) \quad (7)$$

$$M'_y = M_y \cdot \cos(\theta) - M_x \cdot \sin(\theta) \quad (8)$$

$$x'_{(n)} = x_{(n)} \cdot \cos(\theta) + y_{(n)} \cdot \sin(\theta) \quad (9)$$

$$y'_{(n)} = y_{(n)} \cdot \cos(\theta) - x_{(n)} \cdot \sin(\theta) \quad (10)$$

$$I'_{xx.j} = I_{xx.j} \cdot \cos^2(\theta) + I_{yy.j} \cdot \sin^2(\theta) - I_{xy.j} \cdot \sin(2 \cdot \theta) \quad (11)$$

$$I'_{yy.j} = I_{yy.j} \cdot \cos^2(\theta) + I_{xx.j} \cdot \sin^2(\theta) - I_{xy.j} \cdot \sin(2 \cdot \theta) \quad (12)$$

The bolt axial load component of F'_{zp} on the first bolt to be tightened (bolt s) will act to produce a compressive contact pressure at the faying surface local to the bolt. The torque tightening of bolt s will also influence the contact pressure local to the other bolts in the joint.

The change in faying surface contact pressure local to each of the bolts is given by:

$$\delta P_{f(n)} = \frac{-F'_{zp}}{A_j} + \frac{M'_x}{I'_{xx.j}} \cdot y'_{(n)} - \frac{M'_y}{I'_{yy.j}} \cdot x'_{(n)} \quad (13)$$

Equation (13) shows that a positive moment M'_x will act to reduce the contact pressure local to bolts with a positive y' coordinate. That is, the contact pressure will become less compressive. Therefore, the faying surface contact pressure local to bolt n after bolt s has been tightened is given by:

$$P_{p(n,i+1)} = P_{p(n,i)} - \frac{F'_{zp}}{A_j} + \frac{M'_x}{I'_{xx,j}} \cdot y'_{(n)} - \frac{M'_y}{I'_{yy,j}} \cdot x'_{(n)} \quad (14)$$

In equation (14) the term $P_{p(n,i)}$ represents the contact pressure local to bolt n at step i , prior to tightening bolt s and the term $P_{p(n,i+1)}$ represent the contact pressure after tightening bolt s . Hence, $P_{p(n,i+1)}$ is the contact pressure at the end of step i and the start of step $i + 1$.

A positive contact pressure cannot exist at the faying surface. A load that attempted to produce a positive contact pressure would result in an additional axial load on the bolt.

The corresponding change in load on each of the bolts is given by:

$$F_{p(n,i+1)} = F_{p(n,i)} - \frac{F'_{zp}}{A_j} \cdot A_b + \left(\frac{M'_x}{I'_{xx,j}} \cdot y'_{(n)} - \frac{M'_y}{I'_{yy,j}} \cdot x'_{(n)} \right) \cdot A_b \quad (15)$$

Equation (15) applies to all bolts other than bolt s , the bolt being tightened. Bolt s is loaded to the intermediate torque-tightening load, as defined by the condition presented in equation (16).

$$F_{p(s,i+1)} = F_{zp} \quad (16)$$

Only positive bolt loads can exist. A loading situation that attempted to produce a negative bolt load would result in a compressive contact pressure on the faying surface.

3.3 Second and subsequent bolt tightening

The torque tightening of the second, and subsequent, bolts can be analysed by applying equations (3) to (16) with the appropriate values for subscripts (s, i) and (n, i) .

The second bolt to be tightened in the tightening sequence could already have a preload $F_{p(s,i)}$, induced from the snug tightening process and from tightening the first bolt in the tightening sequence. This preload is that which has already been calculated by equation (12). The suffix s now denotes the bolt number of the second bolt in the tightening sequence. In this instance, the tightening sequence, step i , has been incrementally increased by 1 from the previous, snug tightened, state and indicates the second bolt in the sequence is about to be tightened.

The effective load being applied to each bolt in the joint during the first pass of torque tightening continues to be F_{zp} . The moments applied to the joint by torque tightening the second bolt in the sequence are again based on the change in bolt load required to reach the required intermediate preload F_{zp} .

If, after the first bolt of the sequence has been tightened, the load at any other bolt is found to be negative then there is no tensile load on that bolt and the load is being reacted as a contact load at the faying surface local to the bolt.

The effects of torque tightening the second bolt in the tightening sequence can be analysed by applying equations (3) to (16). These equations can be resolved as simultaneous equations and combined/reduced into two equations, one for the contact pressure $P_{p(n,i)}$ and one for the intermediate bolt preloads $F_{p(n,i)}$.

When applying these equations the subscript (s, i) would relate to the bolt being tightened, in this instance the second bolt in the bolt tightening sequence, and the step in the tightening

sequence respectively. Hence, $F_{p(s,i)}$ is the preload in bolt s at step i in the tightening sequence. The preload at the incremented step i is the load calculated from equation (15) when considering the first, or previous, bolt in the tightening sequence.

Equations (5a) and (5b) can be substituted into equation (15) to give an equation for the bolt preload after tightening the bolt:

$$F_{p(n,i+1)} = F_{p(n,i)} - \frac{F'_{zp}}{A_j} \cdot A_b - F'_{zp} \cdot \left(\frac{y'_{(n)} \cdot y'_{(s)}}{I'_{xx,j}} + \frac{x'_{(n)} \cdot x'_{(s)}}{I'_{yy,j}} \right) \cdot A_b$$

Equation (4) can then be used to eliminate the terms of F'_{zp}

$$F_{p(n,i+1)} = F_{p(n,i)} - (F_{zp} - F_{p(s,i)}) \cdot \left(\frac{1}{A_j} + \frac{y'_{(n)} \cdot y'_{(s)}}{I'_{xx,j}} + \frac{x'_{(n)} \cdot x'_{(s)}}{I'_{yy,j}} \right) \cdot A_b \quad (17)$$

If a dimensionless 'stiffness' array is written for the bolts where:

$$K_{b(n,i)} = \left(\frac{1}{A_j} + \frac{y'_{(n)} \cdot y'_{(s)}}{I'_{xx,j}} + \frac{x'_{(n)} \cdot x'_{(s)}}{I'_{yy,j}} \right) \cdot A_b \quad (18)$$

Then equation (17) can be written as:

$$F_{p(n,i+1)} = F_{p(n,i)} - (F_{zp} - F_{p(s,i)}) \cdot K_{b(n,s)} \quad (19)$$

As before, when considering equation (15), the bolt being tightened, bolt s , is loaded to the intermediate torque tightening load, as defined by the condition presented in equation (16). Hence;

$$F_{p(s,i+1)} = F_{zp}$$

Applying this load condition for the bolt being tightened to equation (19) allows equation (19) to be written as:

$$F_{zp} = F_{p(n,i)} - (F_{zp} - F_{p(s,i)}) \cdot K_{b(n,s)}$$

The resulting equation can then be rearranged to give:

$$K_{b(n,s)} = \left(\frac{F_{p(n,i)} - F_{zp}}{F_{zp} - F_{p(s,i)}} \right)$$

This term can then finally be simplified to give:

$$K_{b(n,n)} = -1 \quad (20)$$

The equations for the contact pressure, $P_{p(n,i)}$, can be treated in a similar manner to those for the bolt load, $F_{p(n,i)}$. Equations (5a) and (5b) can be substituted into equation (14) and equation (4) used to eliminate terms of M_x , M_y and F'_{zp} in a similar manner as previous, which would lead to the equation:

$$P_{p(n,i+1)} = P_{p(n,i)} - (F_{zp} - F_{p(s,i)}) \cdot \left(\frac{1}{A_j} + \frac{y'_{(n)} \cdot y'_{(s)}}{I'_{xx,j}} + \frac{x'_{(n)} \cdot x'_{(s)}}{I'_{yy,j}} \right) \quad (21)$$

Equation (21) can be written as:

$$P_{p(n,i+1)} = P_{p(n,i)} - \frac{(F_{zp} - F_{p(s,i)})}{A_j} \cdot K_{j(n,s)} \quad (22)$$

Where $K_{j(n,s)}$ is a dimensionless 'stiffness' array for the joint.

$$K_{j(n,i)} = \left(1 + \left(\frac{y'_{(n)} \cdot y'_{(s)}}{I'_{xx,j}} + \frac{x'_{(n)} \cdot x'_{(s)}}{I'_{yy,j}} \right) \cdot A_j \right) \quad (23)$$

For analysis purposes, equations (18), (20) and (23) can be used to calculate stiffness's for the bolts and joint using the joint geometry. Equation (19) can then be used for each bolt in turn, following the bolt tightening sequence, to calculate the intermediate bolt preloads. Finally, equation (22) can be used to calculate the faying surface contact pressures local to each bolt, again following the bolt tightening sequence. This procedure needs to be followed for each pass of the torque tightening sequence. That is, it needs to be applied for each step in the torque tightening procedure.

4 Analysis Results

Figures 2 to 9 illustrate the bolt preload distribution on a range of typical bolted joints.

Figures 2 to 7 illustrate joints that have bolt patterns symmetrical about both primary axes of the joint. Figures 8 and 9 illustrate joints that are asymmetrical about one primary axis of the joint.

Each of the joints considered in the analyses are based on M16 grade 8.8 bolts with a target preload of 60% of the bolt proof load. The bolt numbering used in each of the figures follows the bolt tightening sequence considered in the analyses. The calculated final bolt preloads are given as percentages of the target preload following a 2%, 25%, 75%, 100% makeup torque tightening procedure. It was also assumed that the breakaway torque for a bolt with a preload of 85% or more of the target would be greater than the makeup torque.

4.1 Resultant Bolt Preloads from an Iterative Bolting Procedure

Fig. 2 Compact symmetrical 8 bolt joint

Figures 2 and 3 illustrate joints with an edge distance of 24mm (1.5 times the bolt diameter) from the hole centre and the hole centres are on a pitch of 32mm (2 time the bolt diameter) in the directions of both axes.

Figure 4 illustrates a joint with an edge distance of 24mm (1.5 times the bolt diameter) from the hole centre and the hole centres are on a pitch of 32mm (2 times the bolt diameter) in the direction of the x-axis and 48mm (3 times the bolt diameter) in the direction of the y-axis.

Fig. 3 Compact symmetrical 6 bolt joint

Fig. 4 Symmetrical 6 bolt joint

Fig. 5 Symmetrical 8 bolt joint

Fig. 6 Symmetrical 6 bolt joint

Figures 5 and 6 illustrate joints with an edge distance of 35mm (approximately 2 times the bolt diameter) from the hole centre and the hole centres are on a pitch of 100mm (approximately 6 times the bolt diameter) in the direction of the x-axis and 50mm (approximately 3 times the bolt diameter) in the direction of the y-axis.

Fig. 7 Symmetrical 6 bolt joint

Figure 7 illustrates a joint with an edge distance of 35mm (approximately 2 times the bolt diameter) from the hole centre and the hole centres are on a pitch of 100mm (approximately 6 times the bolt diameter) in the x-direction and 75mm (approximately 4 times the bolt diameter) in the y-direction.

Fig. 8 Compact asymmetrical 6 bolt joint

Figure 8 illustrates a joint with an edge distance of 24mm (1.5 times the bolt diameter) from the hole centre and the hole centres are on a pitch of 32mm (2 times the bolt diameter) in the direction of the x-axis and hole centres of 32mm and 64mm (3 and 6 times the bolt diameter respectively) in the direction of the y-axis.

Fig. 9 Asymmetrical 6 bolt joint

Figure 9 illustrates a joint with an edge distance of 35mm (approximately 2 times the bolt diameter) from the hole centre and the hole centres are on a pitch of 100mm (approximately 6 times the bolt diameter) in the direction of the x-axis and hole centres of 50mm and 100mm (approximately 3 and 6 times the bolt diameter respectively) in the direction of the y-axis.

Fig. 10 Compact symmetrical 8 bolt joint

Fig. 11 Symmetrical 6 bolt joint

Fig. 12 Compact asymmetrical 6 bolt joint

4.2 Resultant Bolt Preloads from a Single Pass Tightening Sequence

Figures 10 to 12 illustrate the same joints as illustrated in figures 2 to 4 respectively. In these cases the calculated final bolt preloads are given as percentages of the target preload following a single pass tightening procedure of 100% of the makeup torque.

4.3 Resultant Faying Surface Pressure from a Single Pass Tightening Sequence

Figures 13 to 15 illustrate the faying surface contact pressures for the same joints as illustrated in figures 2 to 4 respectively. The contact pressures are calculated for a single pass tightening procedure of 100% of the makeup torque. The pressure results are given as percentages of the nominal pressure, calculated by using the target preload in equation (2).

Fig. 13 Compact symmetrical 8 bolt joint

Fig. 14 Symmetrical 6 bolt joint

Fig. 15 Compact asymmetrical 6 bolt joint

5 Discussion

Figures 2 to 9 show that, following the incremental torque tightening procedure as outlined, the preload in bolts located around the central area of the joint (i.e. those at the beginning of the tightening sequence) tended to have a preload slightly less than the target, or nominal, preload. Typically up to 5% less than the target preload. Whereas, some bolts at the

outer edges of the joint area were slightly more than the target, typically 1%. Overall, the sum, or total, preload on the joint was slightly less than the total target load.

These variations in preload are as a result of elastic redistribution of loads during torque tightening. They do not include the effect of variations in friction at the sliding interfaces of the bolt, nut and washers.

The analyses presented in Figures 10 to 12 also showed that if incremental torque tightening was not used and the bolts were tightened to 100% of the makeup torque during a single pass tightening sequence, the preload in bolts located around the central area of the joint could have a preload up to 17% less than the target preload.

This characteristic of the distribution for the bolt preload acts to the benefit of the bolted joint. A study of bolt bending under the influence of shear loads [2] shows that the higher shear loads caused by in-plane loads, particularly torsional moments, will be acting at the outer edges of the joint and in the region occupied by the bolts with the slightly higher preload. This higher preload should give these bolts a marginal advantage in supporting the shear loads through friction at the faying surface.

Overall, the sum, or total, preload on the joint could be up to 5% less than the total target load.

The significant shortfall in achieving the target preload illustrated in Figures (10) and (12) shows why a design bolt preload, which is significantly less than the target preload, should be used when analysing joint designs. Section 3.8 of BS 7608:1990 "*Code of practice for Fatigue design and assessment of steel structures*" [3] recommends that the design preload should be taken as two thirds the target preload, i.e. $F_{dp} = \frac{2}{3} \cdot F_p$.

The design preload accounts for a number of factors that includes both elastic redistribution of loads during tightening and variation in friction at the bolt and nut. In addition the design preload also includes an allowance for bolt preload relaxation during service. An estimation of in-service bolt preload relaxation could be made using the methods presented in reference [2].

Figures (13) to (15) show that the contact pressure at the faying surface can be represented as an inclined plane. However, figures (10) to (12), which are for the same load cases, clearly show that the bolt preloads do not lie on a similar, or corresponding, plane. These differences reflect the effects of the elastic redistribution on the bolt preloads during torque tightening.

The method of used in this paper analysis assumes there is no out-of-plane deflection at the faying surface. This is, in effect, an assumption that there is symmetry of the joint at the faying surface. The variation in bolt preloads would result in a similar variation in through flange stresses local to each bolt and some variation in contact pressure that is not reflected in the analysis. The variation in through flange stresses would also result in some local bending in the flanges.

The contact pressure at the faying surface extends to the edge of the flange. Figure (15) shows that in joints with asymmetrical bolt patterns the maximum contact pressure local to a bolt could be up to 34% greater than the nominal pressure calculated by using only the target preload, and slightly larger at the edge of the flange. This maximum contact pressure occurs at an edge of the flange and would produce bending stresses in the flange. Reference [4] discusses flange bending in more detail and presents a method of calculating these bending stresses.

CONCLUSION

The analysis methods presented will not be required for the majority of bolted joints. However, they may be of benefit when analysing compact, highly loaded joints.

The design preload accounts for a number of factors that includes both elastic redistribution of loads due to elastic redistribution of loads during torque tightening and variation in friction at the bolt and nut. An understanding of the bolt preload variation due to the elastic redistribution of loads would allow the effects of sequential torque tightening to be removed from the factors considered when determining the design preload. This could lead to higher design preloads for used in the analyses. It could also lead to the specification of design preloads for each bolt in the joint. This would allow for a more efficient use of the joint.

Alternatively, an analysis showing that the likely bolt preloads would be below the target could allow a higher target preload, and hence higher makeup torque to be used. This would also lead to a safe and more efficient use of the joint.

The analysis methods may also be applicable to checking that a joint, originally assembled using multi-spindle nut tightening equipment, can be remade using a calibrated torque wrench, following a sequential torque tightening procedure, to produce a joint with suitable structural integrity following a repair.

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