Strojnícky časopis – *Journal of* MECHANICAL ENGINEERING,
VOL 70 (2020), NO 1, 143 - 146

PRELOADED BOLTED JOINT MADE WITH A SINGLE ROW OF FASTENERS

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Abstract: The purpose of this technical note is to present a method of analysis of a joint made using a single row of bolts, typical of a bolts around the edge of a closure plat or a simple bracket. Classical analysis methods are applied to the joint subjected to combinations of both in-plane and out-of-plane loads and moments. An analysis of loads and stresses in a single bolt is developed. The note brings together a number of concepts and links them into a practical design analysis process that is applicable for many cases of joints made with a single bolt or a single line of bolts and are adequate to demonstrate the structural integrity of the joint. In some cases finite element methods may be more appropriate, and the methods discussed can be used in the validation process.

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

1 Introduction

The classical analysis of load distributions within preloaded bolted joints has been presented in references [1] and [2]. In the conclusions of references [1] and [2] it was noted that the design analysis approach could not be applied to all bolted joint configurations. In particular, joints with single bolts, or a single line of bolts have to be considered using first principles.

This technical note considers joints made with a single line of bolts; typical of a closure plate or simple bracket attachments. The analyses presented here use the understanding of how preloaded joints work, provided by reference (1), and the interaction of the joint's components, shown in reference (2).

2 Nomenclature

A_b Tensile area of thread
A_f Area of the faying surface
A_j Total area of the joint (Faying surface plus thread tensile area)
F_b Axial load in a bolt
F_{dp} Design preload for the cam follower thread
F_p Preload in cam follower thread
F_y External In-plane force acting in the *y*-direction
F_z External axial load in the direction of the 'z' axis
$I_{xx.j}$ Second Moment of Area of the joint about the 'x' axis
M_x External moment acting about the 'x' axis
M_{xx} Resultant moment about the neutral axis in the direction of the 'x' axis
P_f Contact pressure at faying surface, external loads applied
P_p Preload contact pressure at faying surface
w_f Width of faying surface
y Coordinate in plane of joint face

DOI: 10.2478/scjme-2020-0014, Print ISSN 0039-2472, On-line ISSN 2450-5471 ©2020 SjF STU Bratislava

μ_f Friction coefficient at the faying surface

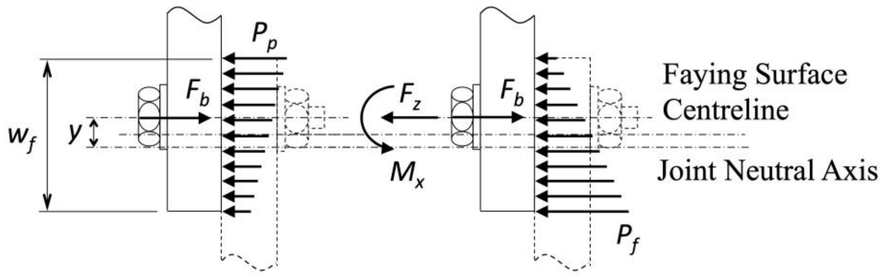
σ_c Maximum compressive stress at faying surface

3 Bolted Joint with a Single Row of Fasteners

Closure plates, with a single line of bolts around the edge of the plate, fall into this category of joint. The load per unit length and moment per unit length on the joint at the edge of the plate can be calculated using plate theory. This allows the joint to be analysed by considering individual bolts as supporting a proportion of the external loads.

3.1 Analysis Methods

Figure (1) illustrates the free body loads around one bolt in a typical joint of this type.



(a) Preloaded joint (b) Preload plus external loads

Fig. 1 Free Body Loads Around one Bolt

Ideally, preloading a joint made with multiple bolts of induces a uniform contact pressure at the faying surface. However, a single line of bolts, or a single bolt, could produce a linearly distributed contact pressure in an asymmetrical joint, as illustrated in Figure (1a). When external loads are applied to the joint any resulting tensile stress components act to reduce this contact pressure. It is only when a resulting tensile stress component attempts to exceed the pre-compression at the faying surface that joint failure occurs by separation of the joint. Similarly, when external loads act to increase the contact pressure, the tensile load on an individual bolt could reduce. It is only when the reduction in bolt tension relaxes the bolt preload to a level where the bolt could loosen, particularly under vibration, the joint can also be considered to have failed.

The least compressive value of contact pressure or compressive stress at the faying surface produced by the preload is given by the following equation.

$$P_p = \frac{-F_p}{A_f} + \frac{1}{2} \cdot \frac{F_p \cdot |y|}{I_{xx.j}} \cdot w_f \qquad (1)$$

Where 'y' is the offset of the bolt from the centroid, or neutral axis, of the joint. If the bolt is at the centre of the joint and faying surface then the bolt offset is zero and equation (1), and subsequent equations can be simplified. The negative sign in equation (1) indicates that the faying surface is subject to a compressive stress. Using the modulus of the bolt offset from the joint centroid, $|y|$, in equation (1) ensures that the "right hand rule" is applied and the least compressive contact pressure is calculated; irrespective of the direction of the bolt offset 'y'. The second moment of area of the joint, $I_{xx.j}$, is based on the effective length of joint surrounding one bolt. Typically the pitch of the bolt centres.

When external loads and moments are applied the contact pressure at the faying surface changes to the linearly distributed pressure illustrated in Figure (1b). The contact pressures at the outer edges of the faying surface are given by the following equation:

$$P_f = \frac{-F_p}{A_f} + \frac{F_z}{A_j} \pm \frac{1}{2} \cdot \frac{|M_{xx} - F_p \cdot y|}{I_{xx.j}} \cdot w_f \tag{2}$$

Where M_{xx} is the moment about the neutral axis of the joint and is given by;

$$M_{xx} = M_x + F_z \cdot y \tag{3}$$

Again, the modulus of the resultant moment about the joint centroid is used. This ensures that the least compressive contact pressure is calculated when using the positive sign for the last term of equation (2), irrespective of the direction of the resultant moment. Similarly, the maximum contact pressure is found when using the negative sign.

The requirement for any joint is that a contact pressure at the faying surface is always maintained, which is expressed by $P_f < 0$. The minimum bolt preload, or design load, to produce this requirement is found from equation (2), using the positive end term, with $P_f = 0$ and is expressed by the condition;

$$F_{dp} > \frac{\frac{F_z}{A_j} + \frac{1}{2} \cdot \left(\frac{|M_{xx}|}{I_{xx.j}} \cdot w_f\right)}{\frac{1}{A_f} + \frac{1}{2} \cdot \left(\frac{y}{I_{xx.j}} \cdot w_f\right) \cdot \frac{M_{xx}}{|M_{xx}|}} \tag{4}$$

Using the modulus of the out-of-plane moment, $|M_{xx}|$, and the term $M_{xx}/|M_{xx}|$ in equation (4) ensures that the "right hand rule" is applied, irrespective of the sign of the moment M_{xx}.

The maximum contact pressure is calculated from equation (2), using the negative end term, and the maximum bolt preload produced by the make up torque.

If the external axial force F_z is negative, i.e. it acts to compress the joint and reduce the bolt tensile load, then the limit on the design preload has to be based on retaining some tensile load on the bolt. When the joint is supporting the external loads the axial bolt load is given by:

$$F_b = F_p + \frac{F_z \cdot A_b}{A_j} + \frac{M_{xx}}{I_{xx.j}} \cdot A_b \cdot y \tag{5}$$

External out-of-plane moments produce a stress gradient across the faying surface. This results in a bending stress component on the single threaded fastener. Because of he narrow footprint, the stress gradient and resulting bending stress can be significant. The stresses in the bolt are given by the following equation;

$$\sigma_b = \frac{F_p}{A_b} + \frac{F_z}{A_j} + \frac{M_{xx}}{I_{xx.j}} \cdot y \pm \frac{M_{xx}}{I_{xx.j}} \cdot \sqrt{\frac{A_b}{\pi}} \tag{6}$$

This bolt stress comprises two components, the axial stress produced by the bolt load F_b and the bending stress component produced by the moment M_{xx} acting about the joint centroid.

If the external loads are acting to keep the joint closed the bolt load will be reduced to less than the preload. The design requirement is that the external loads should not totally relax any bolts, which is expressed by $\sigma_b > 0$. The minimum design load to produce this condition is found from equation (6), using the negative end term, with $\sigma_b = 0$ and is expressed by:

$$F_{dp} > -A_b \cdot \left(\frac{F_z}{A_j} + \frac{M_{xx}}{I_{xx.j}} \cdot y\right) + A_b \cdot \frac{M_{xx}}{I_{xx.j}} \cdot \sqrt{\frac{A_b}{\pi}} \tag{7}$$

3.2 *Design Analysis Considerations*

The static analysis that has been described here is carried out for the design bolt preload, which can be taken to be 2/3 of the applied bolt preload:

$$F_{dp} = \frac{2}{3} \cdot F_p \tag{8}$$

This design bolt preload takes account of a number of factors, including tolerances on the bolt preload applied during assembly.

If the joint bolts have a long grip length, say 4 times the nominal bolt diameter, the loss of bolt preload resulting from secondary tensile loads and stresses due to thread bending may need to be considered. A method of calculating the additional tensile load and bending stress is presented in reference [3].

The external in-plane load should be supported by friction at the faying surface. To guard against joint slip and fretting at the faying surface the minimum contact pressure should be able to support the shear force. This is achieved by applying the condition described by the following equation.

$$F_y < \left(F_p - \frac{F_z \cdot A_f}{A_j} - \frac{A_f \cdot w_f}{2} \cdot \left| \frac{-F_p \cdot y}{I_{xx.j}} + \frac{M_{xx}}{I_{xx.j}} \right| \right) \cdot \mu_f \tag{9}$$

where μ_f is the friction coefficient at the faying surface.

CONCLUSION

Joints made with a single line of bolts are commonly found attaching closure plates or simple brackets. This type of joint can be analysed by considering individual bolts.

Preloading a single line of bolts, or a single bolt, could produce a linearly distributed contact pressure in an asymmetrical joint. When external loads are applied to the joint any resulting tensile stress components act to reduce the compressive stress produced by the preload. As long as the faying surface retains some compressive stress the joint will continue to perform as if it were a continuous member.

When external loads act to increase the contact pressure, the preload on an individual bolt could reduce. If the reduction in bolt tension is sufficient to relax the bolt preload to a level where the bolt could loosen the joint can be considered to have failed.

External out-of-plane moments produce a stress gradient, which can result in a significant bending stress component.

External in-plane loads are supported by friction at the faying surface.

The method presented here can also be applied to square and rectangular joints made with a single fastener by using the appropriate section properties.

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