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THE FUNCTION OF WASHERS IN A BOLTED JOINT

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Introduction:

It is common practice to use a washer as an integral part of a bolted joint. Improper use of a washer may compromise the integrity of a bolted joint. Therefore, it is very important to understand the reasons and limitations behind their use.

There are various shapes and types of washers used in industry for various purposes. Hardened washers, unhardened washers, spring washers, and load indicating washers are some of the most commonly used.

In some specific situations cup/spherical washers, High-tolerance washers, Belleville washers, wave washers, Direct Tension Indicating (DTI) washers and Locking washers are used. Although these washers have their own specific characteristics, they should satisfy most of the essential characteristics of a washer.

This paper discusses the function of a standard washer using first order approximations and also presents a few guide lines in selecting the appropriate washer.

Investigation:

Standard Washers

In general, standard washers are used for two perceived reasons, namely:

- a) to minimise damage to the mating material due to nut rotation
- b) to increase the effective bearing surface of the bolt.

If used for reason (a) alone a washer is only needed under the rotated component and whether the washer is a hardened or unhardened does not really matter. However, using a unhardened washer in a high tensile bolted joint may compromise the integrity of the joint due to bearing failure at the nut/washer

interface. Furthermore, delayed bearing failure (resembles “creep”) of the unhardened washer may reduce the tension on the bolt with time.

When joining materials with strengths lower than that of the bolt strength, a washer must be used to avoid bearing failure at the bolt/nut-material interface. In this case a washer should be used under both the nut and head of the bolt.

When using high tensile bolts, the above would be the norm. Furthermore, if the joint is a tensile joint, the bolt tension becomes important, and using a hardened washer under both the nut and the head of the bolt becomes paramount. The following analysis is focussed on this configuration.

First Order Analysis:
Bearing Failure

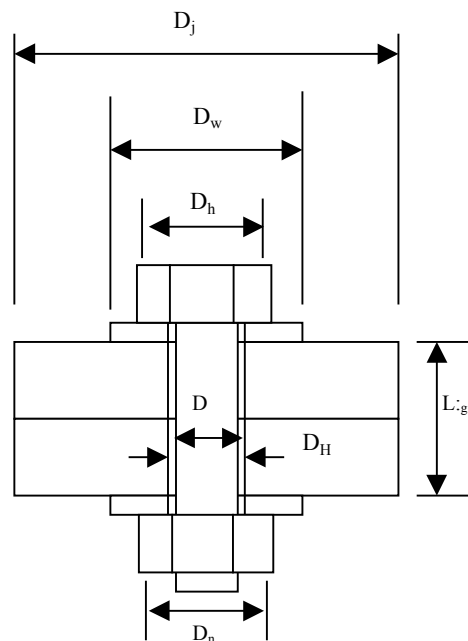


Figure 1: Joint Configuration

A typical bolted joint configuration is shown in Figure 1. It shows a joint with grip length L_g clamped with a bolt of nominal diameter D . For simplicity, assume that the hole diameter of the joint and the washer are the same D_H and aligned on the central axis of the bolt. For analytical purposes, let the bolt head bearing diameter is D_b , the nut bearing diameter D_n , the washer diameter D_w and the effective joint diameter D_j .

The yield stresses of the bolt material σ_{yb} , nut material σ_{yn} , washer material σ_{yw} and the joint material σ_{yj} are also important in the analysis.

Let's assume the Proof load of the bolt is F_y . Then the under-head and under-nut bearing stress can be given as;

$$\sigma_b = \frac{F_y}{\pi(D_b^2 - D_H^2)} \quad (1)$$

$$\sigma_n = \frac{F_y}{\pi(D_n^2 - D_H^2)} \quad (2)$$

In order to avoid bearing failure at the interface;

$$\sigma_b < \sigma_{yw}; \sigma_n < \sigma_{yw}; \quad (3)$$

if a washer is used or;

$$\sigma_b < \sigma_{yj}; \sigma_n < \sigma_{yj} \quad (4)$$

if a washer is not used.

With softer joint materials, since σ_{yj} could be significantly smaller, this may be the critical criteria on the maximum tensile load applicable on the bolt. With the use of a washer having a yield stress of σ_{yw} , criteria in (1) can be better satisfied. The resulting interface between the washer and the joint material will have stresses:

$$\sigma_{bw} = \frac{F_y}{\pi(D_w^2 - D_H^2)} \quad (5)$$

$$\sigma_{nw} = \frac{F_y}{\pi(D_w^2 - D_H^2)} \quad (6)$$

As D_w is significantly larger than D_b or D_n , σ_{bw} and σ_{nw} will be significantly smaller than σ_b and σ_n , hence making it possible to tighten the bolt to a higher tensile load.

The above analyses establish one use of a washer under both the bolt head and the nut in a bolted joint, ie: to avoid bearing failure at the weaker interface. A properly used hardened washer will contribute more to the behaviour of a bolted joint than just preventing bearing failure.

The above analyses did not prescribe the thickness of the washer. The main effect of the thickness of the washer is to increase the effective stiffness of the joint. The effect of joint stiffness on the performance of the joint is analysed in the following section.

Function of a Hardened Washer in a Tensile Bolted Joint:

In a typical bolted joint, one of the main functions of the bolt is to maintain an adequate positive clamping force during the service life of the joint in order to prevent problems such as leaks, relative movement, wear and fretting. To achieve a particular service life requirement for a bolted joint, it is very important to understand the effect of bolt pre-tension (F_i) and the applied load (F_a) on the Clamping force (F_c) and the bolt tension (F_b). The following equations (7) and (8) shows the relationship between the above parameters. k_b and k_c are the stiffness of the bolt and the joint respectively.

$$F_b = F_i + \frac{k_b \cdot F_a}{(k_b + k_c)} \quad (7)$$

$$F_c = F_i - \frac{k_c \cdot F_a}{(k_b + k_c)} \quad (8)$$

The variation of bolt load (F_b) and the clamp load (F_c) with the applied load (F_a) is shown in Figure 2. Equation (7) confirms that only a component of the applied load is contributing to the increase of tension in the bolt. Typically, k_c is larger than k_b , and hence the increase in the bolt tension will be less than the decrease in the clamping force. Therefore, the parameter k_c/k_b has a significant impact on the performance of the joint.

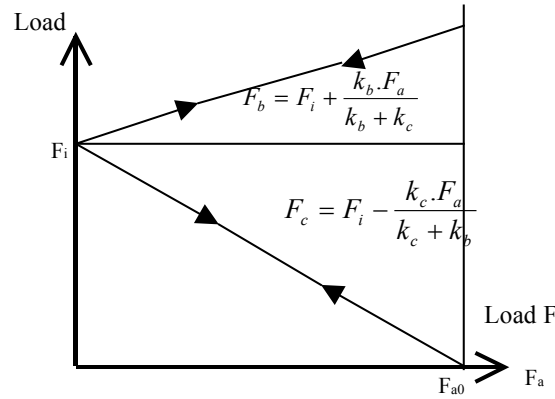


Figure 2: Behaviour of a pre-tensioned joint

Now, it is apparent that by increasing the ratio k_c/k_b the contribution of the applied load on the bolt can be minimised. As such, in a dynamic joint, the bolt will experience only a fraction of the applied fluctuating load. This fraction f is:

$$f = \frac{1}{1 + \frac{k_c}{k_b}} \quad (9)$$

By increasing k_c , the contribution factor f can be reduced. As the fluctuating force on the bolt is reduced its fatigue life will increase.

The stiffness of the bolt can be calculated using the equation:

$$k_b = \frac{A_b \cdot E_b}{L_b} \quad (10)$$

$$A_b \cong \frac{\pi}{4} (D^2) \quad (11)$$

where A_b is the effective stress area of the bolt, E_b is Young's modulus of bolt material, L_b is the effective length of the bolt and D is the nominal diameter of the bolt.

Similarly, the stiffness of the joint can be represented as:

$$k_c = \frac{A_c \cdot E_c}{L_c} \quad (12)$$

where A_c is the effective stress area of the joint members, E_c is Young's modulus of joint material and L_c is the effective length of the joint.

If $D_j < D_b$

$$A_c = \frac{\pi}{4} (D_j^2 - D_H^2) \quad (13)$$

where D_j is the joint diameter, D_b is the bolt under-head/washer bearing diameter and D_H is the hole diameter.

If joint thickness $t < 8D$ and $D_b < D_j < 3D_b$, The effective joint stress area A_c can be approximated by:

$$A_c = \frac{\pi}{4} (D_b^2 - D_H^2) + \frac{\pi}{8} \left(\frac{D_j}{D_b} - 1 \right) \left(\frac{D_b L_g}{5} + \frac{L_g^2}{100} \right) \quad (14)$$

If $D_j > 3D_b$ then

$$A_c = \frac{\pi}{4} \left[\left(D_b + \frac{L_g}{10} \right)^2 - D_H^2 \right] \quad (15)$$

where L_g is the grip length of the joint.

In general, due to the larger stress area ($A_c > A_b$), the joint stiffness is larger than the bolt stiffness ($k_c > k_b$) (Eqn (10), (12)). As shown in equations (14) and (15), by increasing the bolt head/nut bearing diameter (D_b) the effective area of the joint (A_c) and hence the effective stiffness of the joint k_c can be increased.

By using a stiff washer with a larger diameter D_w , it is possible to effectively make $D_b \approx D_w$, thereby increasing the joint stiffness. However, it should be noted that to make $D_b = D_w$ the washer must have adequate out of plane stiffness. This implies that the larger the washer diameter the thicker and stiffer the washer should be. It is also apparent that the strength of the washer must be at least equal to the strength of the bolt. The author has conducted a non-linear finite element analysis on the effect of the washer stiffness on a bolted joint; however, the results of this study is beyond the scope of this paper.

Specialized Washers:

Coronet Load Indicating Washers (LIW)

Load Indicating Washers (LIW) are typically used to assure that the designed pre-tension load is achieved on the joint. These are hardened washers carrying four to seven pre-forged protrusions depending on bolt diameter. LIWs are generally assembled with the protrusions bearing against the underside of the bolt head. This will initially leave a gap between the main washer surface and the bolt head.. The nut is then tightened until the protrusions are reduced to a prescribed value. In applications where it is necessary to rotate the head of the bolt, the LIW can be fitted under the nut using an extra hardened washer under the nut provided the LIW protrusions bear against this washer.



In a single bolt bolted joint, tightening can be carried out in a single stage. In a multiple bolt bolted joint, multiple stages of tightening will increase the effectiveness and accuracy of the LIW. In the first round, all the bolts must be brought to snug tight condition. This will make sure that the mating materials are properly aligned and make proper contact. The second round of tightening should be done in an appropriate sequence making sure that approximately twice the desired gap width is achieved. In a third and final round, all the gaps should be brought to the prescribed value in an appropriate sequence.

Coronet LIWs are **not re-useable**. During the above tightening process, due to some or other reason if the **joint** had to be **loosened**, it is necessary to **replace all the LIWs** in order to achieve correct tightening of the joint.

LIWs are not suitable for tightening very large joints such as those found in slew-rings. In this case, the first bolts tightened will still be loose when the subsequent bolts are tightened.

LIWs are extremely sensitive to the joint mis-alignments. If the load on the LIW is not axisymmetric, the deformation of protrusions will be uneven and will not be representative of the tensile load in the joint.

Direct Tension Indicating Washer (DTI)

Instead of having a feeler gauge measuring the deformation of protrusions as with coronet load indicating washers, DTIs use a plastic stage die to indicate the correct tension. As the protrusions flatten, the die will creep out the side of the washer, indicating that the desired load is achieved. This washer also suffers from all the other disadvantages of load indicating washers.

Spring Washers:

a) Split Washers

Split washers are commonly available in small sizes. These hardened washers have pre-made splits and undergo out of plane deformation. They should be used under the head of the bolt which should then be tightened by the nut. If they need to be used on the nut side, another hardened round washer should be used between the nut and the split washer. A particular prescribed tension can be achieved by flattening these washers. However, split washers do not indicate any over-tightening of the joint. They may be suitable to assure that at least a minimum tension load is achieved on a joint. These washers could also act as locking washers under some circumstances.



b) Belleville Washer/Cone Washer:

This type of spring washer is commonly used in some mechanical engineering applications. The washer initially has the form of a cone which progressively flattens as the bolt is tightened. In the initial tightening this will generate a similar effect compared with split washers. However, as tightening continues the load deflection curve will have a negative gradient due to large geometric changes in the shape of the washer. A typical Load-Displacement curve for a Belleville washer is shown in Figure 3.



As shown, the washer should operate in the region where the gradient is negative. This way, if the joint is loosened, it will increase the load on the bolt; counteracting the loosening of the joint. These washers can be used in multiples in order to achieve the desired load characteristics.

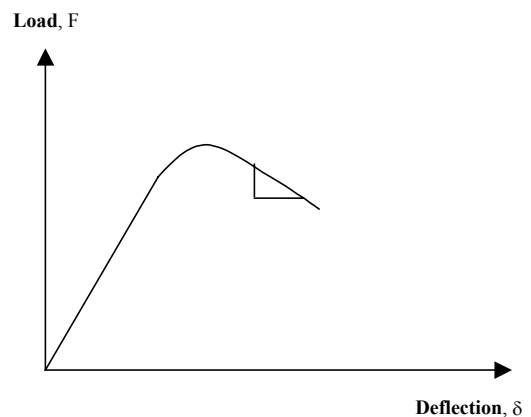


Figure 3: Behaviour of Belleville Washer

Spherical Washers

Spherical Washers accommodate up to 10 – 15° variation in the joint parallelism. A cup washer and a cone washer slide relative to each other preventing bending stresses on the bolt.



Wedge Washers

A square or circular wedge washer (approximately 12:1 slope) accounts for non-parallel joint surfaces. It is possible to overcome adverse effects due to non-parallel joints by rotating the washer, by using a combination of several washers, or both.



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Ajax Fastener Innovations (AFI) offers a consulting service to assist in the design of bolted joints in specific applications. AFI has the experience; test equipment, analysis methods, and analysis tools developed over many years, to provide our customers with a greater level of confidence in the design of critical joints. Furthermore, AFI is dedicated to developing fastening solutions that cater for the specific needs of industry.

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