Technology

Fastener technology involves itself with all aspects of the joint. While much is written about the bolts, threads and torque, there are a few parts that rarely get a mention although their function is often as important as the major attachment parts. Among these is the seldom-noticed group called washers. Used since prehistoric times, they serve silently. While thought of as a primitive fastener, if considered a fastener at all, incorrectly used or mis-engineered they can cause destruction of equipment and serious joint failures.

# Behold! The Lowly Washer

by Thomas Doppke

## Washer Types

Washers are manufactured in several ways with most of the types being stamped from sheet or strip metal. Non-metallic washers are cut from sheets of material by "cookie cutter" dies or cut by high-pressure water jet. Washers can be classified into several basic families, based upon their function or shape. These are:

**Flat washers:** are parts with flat faces. Internal and external shapes are open to design requirements. While generally round, any shape is possible.

**Lock washers:** are parts that incorporate a feature that retains some level of tension in an installed joint. Common types are split helical, internal and/or external tooth, and ramp faced.

**Countersunk washers:** are parts that are designed to accept a countersunk fastener. They are used to spread the loading when attaching to plastics and soft materials and to prevent pull-through in textiles and fibers. Flaring or finishing washers are two common types.

**Spring washers:** are parts which are specifically designed to maintain tension in the attachment through some distance of loading and unloading. The usual method is through flexure of a crowned or wave form manufactured in the washer. The most commonly encountered types are "bowed" (cylindrically curved), "wave" (one or more curves in the periphery), and the "Belleville" or conical spring washer with numerous variations such as offset crowns and variations to the external shape (i.e., square, multi-sided).

**Shoulder washers:** are parts with a raised portion, usually around the center hole, used to space the attached material from being pinched, to center an attachment, to insulate a pin or fasteners (i.e., from electrical current), or to locate the attachment more accurately. They have been used as axle locators in inexpensive components. Grommets are a type of shoulder washer.

**Alignment washers:** are special parts used to level joints and take up irregularities in the attachment. While not in great use in the transportation industry, examples are found in heavy machinery, construction and military areas.

**Special washers:** are those parts that are designed for a special and usually unique function. Among the various types are washer made of mastics, plastic, rubber, copper and other soft materials used in sealing liquids or gasses. Washers with a bend down tab for locational security, and the usual types that defy classification elsewhere.

## Flat Washers

Flat washers are among the oldest bearing surface fasteners known to man. Prehistoric in origin, they have been used, and still are, to spread loads over wide areas, to provide a smoother bearing surface to reduce rubbing (from an axle on a cart to a turbine shaft on a modern generator), and to help maintain the joint torque-tension relationship.

While the flat washer appears to be a simple part, several of its functions do involve some engineering. Their common feature is that they are flat and should remain so during their functional life. The most common failures seen with flat washers are pull-through into the inter-joint hole clearance due to wrong size holes and/or too soft/ too thin basic material with embedment of the mating fasteners. Use of too thin or too soft a material causes yielding of the washer. The supporting material (i.e., washer) should be stronger, per unit stress, than the load being applied. To calculate the required parameters for a flat washer to sustain the loading some facts

Figure 1. Bolt Cutaway

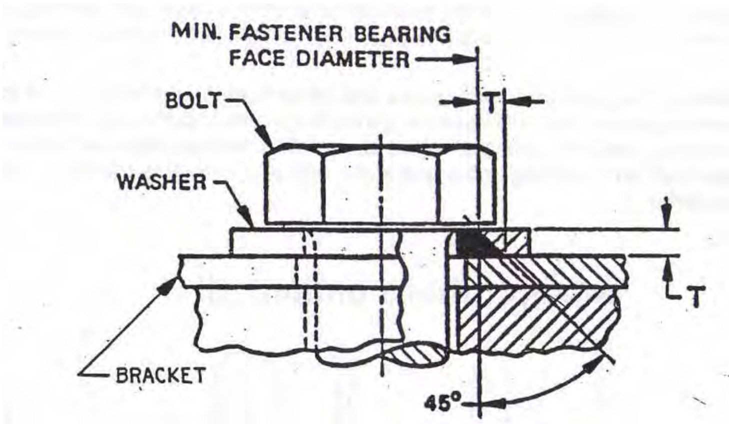
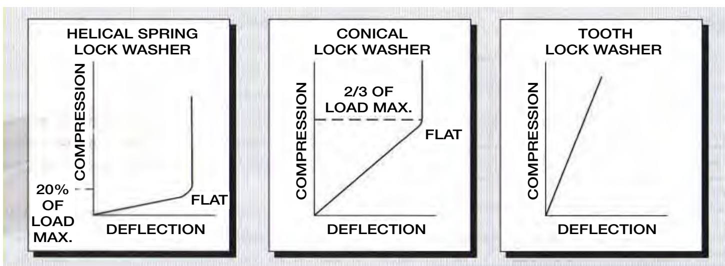



Figure 2. Typical Loading Characteristics of Washers




need be noted. One, the load must be spread over a large enough area to reduce the unit stress. Two, the clearance hole must be large enough to accommodate the fastener and its radii but not so large as to allow the washer material to be pulled into the hole. Three, the diameter of the washer's internal hole and the mating clearances must be agreeable in dimension. One fact, before we begin; it has been proven many times that a flat washer spreads it loading over a diameter equal to the bearing face diameter (of the bolt) plus two times the thickness of the washer. This is an important fact to be used in calculations.

Using an M8 bolt and a hardened flat washer (values listed below) the joint stress is:

$$\text{Joint Stress (Sj)} = \frac{P}{A}$$

Where:

Minimum diameter of bearing face of bolt (Dwf) = 11.6mm

Maximum inside diameter of washer (IDw) = 9.12mm

Minimum outside diameter of washer (ODw) =17.6mm

Minimum washer thickness (T) = 1.9mm

Proof load of class 9.8 bolt (P9.8) = $2.38 \times 10^4$ N

Effective outside diameter of washer (Ode) = Dwf + 2T = 15.4mm

Effective surface area of washer

$$(\text{Ae}) = \frac{\pi(\text{Ode}^2\text{-IDw}^2)}{4} = 1.21 \times 10^{-4}\text{m}^2$$

Solving for joint stress:

$$\text{Sj } 9.8 = \frac{\text{P9.8}}{\text{Ae}} = \frac{2.38 \times 10^4\text{N}}{1.21 \times 10^{-4}\text{m}^2} = 197\text{MPa}$$

Assuming that the yield strength of the attached material is greater than the yield strength for this bolt-washer combination, this calculation shows that the washer will not pull down or embed itself in the attached material. For information's sake, the yield strength of standard grade 1008-1010 steel is about 283MPa.

As mentioned before, care should be taken to examine the clearance holes of all of the attached pieces. If a hole is larger than the inside diameter of the washer, pull through may occur, bringing with it joint loosening and torque loss. The following calculation can determine the maximum inside hole diameter which will support the joint stress.

Assume the mating material hole is as large as the effective outside diameter of the washer the clearance hole (Dc) can be found by:

$$\text{Ad} = \frac{\pi\,(\text{Ode2} - \text{Dc2})}{4} \text{ and AD} = \frac{P}{\text{Sy}}$$

Where Ad = Bearing surface area of mating part

Sy = Yield strength of mating part

Dc = Maximum diameter clearance hole

$$\text{Dc} = \sqrt{\text{Ode}} - \frac{4P}{\pi\text{Sy}}$$

For a class 9.8 grade bolt:

Dc= 11.4 mm to obtain 282MPa.

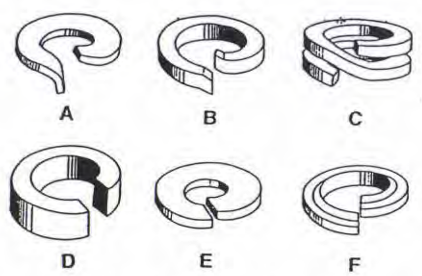
The standard clearance hole diameter for an M8 bolt is 8.55-8.82, therefore a larger clearance hole can be accommodated. Still, it is better engineering to keep the hole as small as practical.

## Lockers

Lock washers can be separated into three general types. One, the split, spring steel helical lock washer used from decades in wooden wagons and car bodies. Two, internal and/or external tooth lock washer used mainly for electrical grounding. And three, spring steel conical lock washers and variations. Lock washers are named as such because they are supposed to induce some degree on tension (locking) in the installed joint. However, the amount and how this happens varies widely with the type.

As **Figure 2** shows, the helical type adds tension to the joint as it is being installed until about 20% of the maximum joint load has been applied. After this point it is basically a flat washer. Since its diameter is less than the bolt bearing face it presents a smaller effective bearing surface (remember-the load is carried by an area equal to bearing face of bolt plus twice washer thickness). Another negative is that the washer tends to spread open during tightening. To prevent this condition many helical lock washers are made with the thickness at the periphery less than at the inner edge. This type of lock washer is a poor

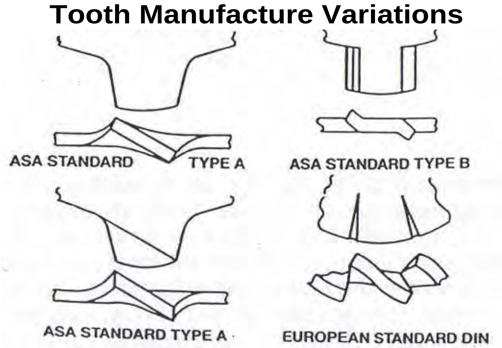
Figure 3. Helical Lock Washer Shapes




Helical spring lock washers for special applications: wood spring lock washer (A), positive type (B), double-coil type (C), Hy-Collar type (D), wide bearing lock washer (E), and ribbed type (F).

Figure 4.

Tooth Manufacture Variations




choice for any high strength loading application but it is usable in areas where the loads drop to below 20% of the joint's capacity (i.e. wood, soft plastics, and long length fasteners). It is often used where the appearance of a washer "peeking" out from under a fancy bolt head is not desired. See the washer selection chart at the end of this article for more selection considerations.

Helical lock washers come in thin, regular and thick series, with tabs to prevent rotation, multiple loops for increased tension, and even anti-tangling features to retard interlocking of parts in the shipping carton. Loading calculations are possible but difficult and are not usually done because of the many series of parts (thickness variations), shapes (trapezoidal vs. flat cross sections), and materials in use.

Internal/external tooth lock washers have been used for years as grounding contacts for electrical applications. The teeth prevent rotation as they "bite" into the substrate and offer a clean path for current. The fact that they cut the surface makes them a poor choice for cosmetic applications. They work best with under loaded applications, rigid materials and with both long and short screw lengths. They are poor performers when large holes are to be spanned. Loading them to high installation torques may cause them to crack as they are usually made of high hardness steel. Variations in design are based upon differences in manufacture and the way that the teeth are formed. However, the variations do not seem to have any effect upon their loading characteristics. They show a constant rate linear compression/deflection curve (see **Figure 2**).

The illustration shows the usual type of tooth formation. The type A style is available in two manufactured types. Both show substantial spring action and embed at little and no load conditions. The type B embeds well but has a limited amount of spring action. Both types are considered interchangeable in the United States. With global sourcing today, several other variations can be found. The most common one, the DIN part shown, although popular in Europe, has little "digging in" capacity.

Toothed lock washer come in the mentioned internal and external types a well as internal/ external variations. Since they are seldom used for anything besides grounding applications, calculations are an academic matter.

## Countersunk Washers

Countersunk washers are a small offshoot of standard parts which are manufactured into a cone shape. They are used to spread loads in materials such as plastics, copper and fiber compositions. They are good at preventing pull-through in fabric and fiber applications. Tooth styles add some spring action in metal joints.

## Finishing Washers

Finishing washers are small cone shaped parts through which a screw is driven. They are used cosmetically to fasten panel boards, aces covers, and fabrics.

Figure 5. Bolt And Ridged Ramp Washer

## Ramp Washers

A small group of lock washers known as "ramp" washers exists. Their salient feature is that they incorporate a radial ramp on the bearing face. These ridges are intended act as a stop to prevent loosening by forcing the washer away from the bearing face of the bolt as the bolt attempts to rotate under vibration. In other words, the washer jams itself tighter in the loosening direction. They are often used in pairs or matched against a ridged surface on the bolt bearing face. When designed into a conical washer they show advantageous torque retention and resistance to loosening.

Most of what work on washers has been done on the group known as conical spring washers. A small amount of data is available on wave types but since they are used with low load applications to maintain a small amount of "take-up expansion" to keep small shafts and such tighter, especially during rotational movements, the data is not of much use generally. While use in extremely small sizes (i.e., watches, electronic and micro-devices), may be interesting, space limitations require that it not be included here.

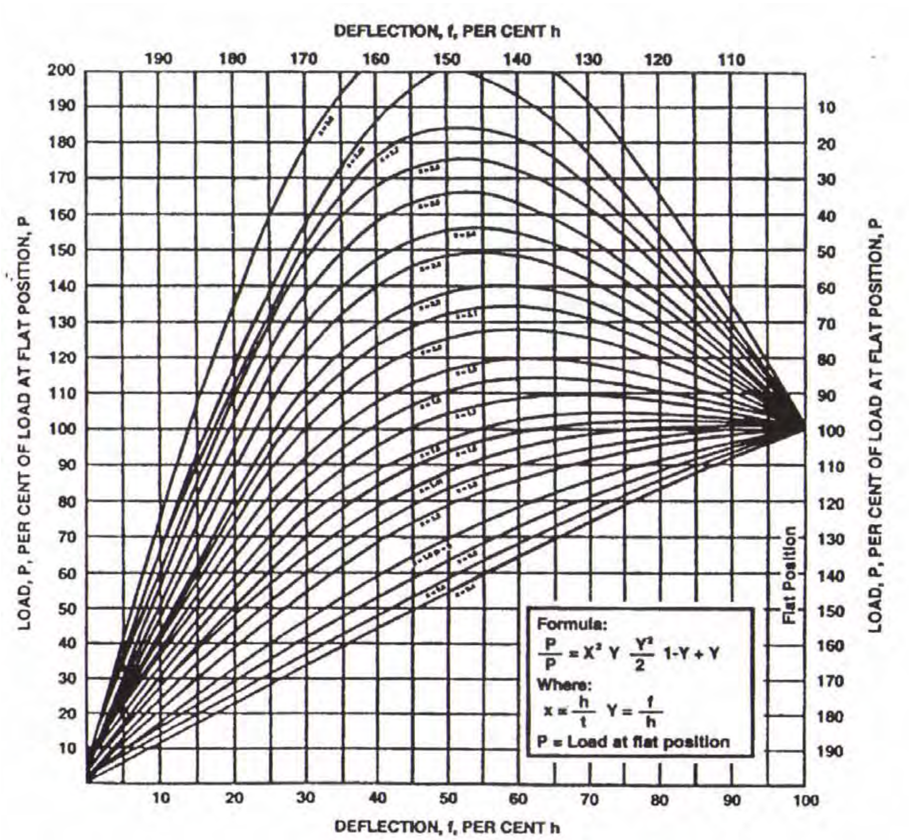
The familiar conical spring washer seen on bolt/screw assemblies is an outgrowth of the larger size parts used, Technology

in past years, as tension take-up assists in large military cannons and some heavy machinery (locomotives for one). Named for its inventor, Belleville, numerous rules for its functioning were worked out by him and further studied by Messrs.' Alman and Laszlo in the 1930's. A look at **Figure 2** shows that the conical washer contributes to the joint tension during the first 2/3 of the loading. After that point the washer crown has been compressed flat and it just functions as a flat washer. Proper design is necessary to allow the conical washer to function correctly. The most common mistake is to design in too much crown height, which does not add to spring effect. Due to the limited available return of the material and incomplete recovery after the first installation, failure may occur if a highly stressed permanent set of the washer occurs. A properly designed conical washer shows an almost linear rate of compression from its initial crown height to its flat position without a permanent set in height due to elastic limit overstress of the material.

Among the many rules for functioning of conical washers, as worked out by Messer's Belleville, Alman, and Laszlo, is a chart which allows the calculation of load at any deflection when the height and load at flat position is known.

This chart **(Figure 5)** does not depend upon any particular stress or ratio of diameters. As the ratio of height to thickness decreases, the load deflection curve approaches closer and closer to a straight line. With a ratio of about h=0.4t, the maximum error in linearity from a true straight line is about 2½%, which eliminates the need for smaller ratios to be calculated.

Figure 6.




Example: Using the chart, a washer with a crown height of 1.3 times its thickness and with a calculated flat load of 100 kilograms is examined. At 75% of its deflection (let's say that the joint has somehow loosened through vibration or some other mode) the chart shows that there will still be about 95% of its flat load in the joint (or 95 kilograms). At 50% deflection the load is 82% and so on. While it is possible to change the loading characteristics by changing the h/t ration, a correct answer may not always be generated. The reason behind this is the reason that most fastener calculations are approximations, at best. While the calculations would take up several pages here, the fact is that the load carrying capacity of a washer is dependent upon the cube of the stock thickness. This means that small changes in stock (washer) thickness produce large changes in loading. This is the reason that even testing parts from a "single lot manufacture" vary widely. Stock variations of as little as 5% (+/-0.075% on a 3mm thickness) can change the overall load values by 15% (i.e. 75kG on a total load of 500kG).

Several modifications to the basic design have been tried over the years. Washers with an asymmetrical cross section are made to produce an additional, off-center loading for increased spring action. Two stage washers (washers with a square or other shaped center section formed into a conical part) increase spring action also.

Wave washers come as a single curve (bowed) or with multiple waves in its body. Used in low load and maximum deflection applications, they take up endplay in motor spindles, reduce rattle in pins, and in soft materials (plastics) where anti-rattle prevention is needed without crushing of the base material. Design formulas for wave washers can be found in most engineering handbooks. Where the amount of space is limited, multiple wave washers are used. Any number of waves is possible, depending upon the load requirements but three, four, and six waves are common.

The chart above lists the performance of the various types of lock washers under various conditions. The major conditions are the initial tension on the joint, the nature of the clamped material, and the length of the screw/bolt. This should be of assistance in the selection of the proper type of lock washer.

Figure 7. Washer Usage Chart

## A GUIDE TO LOCKWASHER SELECTION

### BASIC APPLICATION CONSIDERATIONS

| FASTENING VARIABLES | | | | | | WASHER TYPE TO SELECT | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| INITIAL SCREW TENSION (1) | | CLAMPED MATERIAL (2) | | CLAMPED SCREW LENGTH (3) | | Tooth | | | | | Conical | | Helical Spring |
| Properly Loaded | Under Loaded | Rigid | Yieldable | Short | Long | External | Internal | Ext. Int. | Dished Conical | Counter-sunk | Plain | Ramp | |
| √ | | √ | | √ | | E | E | E | G | E | F | G | P |
| √ | | | √ | √ | | G | G | G | E | G | F | G | P |
| √ | | √ | | | √ | E | E | E | E | E | G | G | P |
| √ | | | √ | | √ | G | G | G | E | G | G | E | P |
| | √ | √ | | √ | | E | E | E | E | E | F | G | P |
| | √ | | √ | √ | | G | G | G | E | G | G | G | E |
| | √ | √ | | | √ | E | E | E | E | E | G | G | P |
| | √ | | √ | | √ | F | F | F | G | F | F | G | F |

### AUXILIARY CONSIDERATIONS

| | External | Internal | Ext. Int. | Dished Conical | Counter-sunk | Plain | Ramp | Helical Spring |
|---|---|---|---|---|---|---|---|---|
| Washers to span holes | | | x | x | | x | x | |
| Washers for flat & oval head screws | | | | | x | | | |
| Washers to distribute load over wide area | Some | Some | x | x | Some | x | x | |
| Washers to prevent shifting of work surfaces | x | x | x | x | x | | | |
| Appearance washers | | x | | Some | Some | x | x | x |
| Sems washers to certain maximum thread under washer | x | x | x | | x | | | |

(1) Estimate whether screw can be tightened to its optimum conditions.

(2) Is the clamped material rigid (steel) or yieldable (gasket, aluminum, brass, etc)

(3) Is the clamped thickness- spring stretch available in the screw: short (up to 1 1/2" approximate) or long (over 1 1/2" approximate).

√ - General Purpose Fastening Condition
E - Excellent
G - Good
F - Fair
P - Poor
X - Recommended

## Shoulder Washers

Shoulder washers are, as their name implies, washers with a shoulder section designed to space or insulate two components. Non-metallic parts are used in the electronic industry to keep two circuit boards from touching. When used with plastics and "honeycomb" material they prevent "pinching" while maintaining a degree of tightness. Often they are used as a locator in assembly.

## Alignment Washers

Alignment washers are used to level joints and take up irregularities in the joint. Most usage is in the construction industry where the lack of parallelism in steel construction beams and channels requires their use. They resemble a flat washer with a beveled cross section which matches the channel outer face which has an approximate slope of about 1:6 with respect to the bolt axis.

## Special Washers

The group known as "Special washers" is the "catch-all" category for whatever does not fit into any other classification. Generally they are unique to a single application and their singularity excludes them from much discussion. One group that has a wide range of use is the washers either made of or containing mastic. Mastic is any gummy dough-like substance which, when compressed during installation, seals the crevices of the adjacent areas it is in contact with. These are the hole clearances that are required for the fastener to pass through. They are sealants against liquid, chemicals, and gasses and are made of the specific material required for the application. The amount needed do follow some guidelines; it should be of sufficient quantity to flow into the spaces as needed without extruding excessively to form a non-acceptable visual dross. The hole in the clearance plate to be sealed should be kept as small as possible. The mastic should be as soft as possible for the design so that the excess can be squeezed out from under the head and be cut off by the shearing action as the bolt head mates against the mating surface. Use a closed cellular material where excess material can be compressed under pressure. And, if possible, undercut the bolt head to allow space for the sealer to be compressed.

To determine the minimum outside diameter of a sealing washer the following calculation may be used:

$$X = 2D - d + 0.8\text{mm}$$

Where X = minimum O.D. of washer

D = maximum diameter of clearance hole to be sealed

D = minimum major diameter of bolt

Washers, while considered lowly parts, are the horseshoe nails that could lose the horse, and so on. They are both extremely simple and extremely complex pieces of hardware. They have definite functions and, with a small amount of forethought, can be engineered to perform as required. Proper selection of material coupled with correct dimensions and the correct type of washer for the job should lead to a successful attachment.