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Building and Industrial Energy Systems Division
Lawrence Berkeley National Laboratory

Proposed Guidelines for Clearance Holes, Slots, and Washers

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Proposed Guidelines for Clearance Holes, Slots, and Washers in Solar PV Structures

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U.S. DOE Office of Energy Efficiency and Renewable Energy (EERE), Solar Energy
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Table of Contents

- Acknowledgements..... i
- Table of Contents ii
- Table of Figures..... iii
- List of Tables..... iii
- 1. Applicability and Relationship to the ASCE/SEI Solar PV Structures Manual of Practice 1
- 2. Guidelines for Round and Slotted Clearance Holes 2
 - 2.1 Traditional Structural Joints 2
 - 2.2 Alternative Structural Joints 3
- 3. Proposed Guidelines for Washers 3
 - 3.1 Traditional Structural Joints 3
 - 3.2 Alternative Structural Joints 4
 - 3.2.1 Round and Plate Washer Functional Requirements 4
 - 3.2.2 Common Washer Failure Mechanisms and Solutions 5
- 4. Design Checklist for Alternative Structural Joints: Clearance Holes, Slots, and Washers..... 12
- 5. References..... 13

Table of Figures

Figure 1: The bolt pretension is concentrated at the bolt and nut bearing surfaces, resulting in high contact stress.	5
Figure 2: Evidence of compressive yield of a 'soft' washer tightened on a standard, round clearance hole.....	5
Figure 3: Example of bending of a thin washer on an oversized slot.	6
Figure 4: Evidence of compressive yield at the edge of a slot due to bending of a thin washer. .	7
Figure 5: Plot showing von Mises stress in a bolted joint with a thin washer that does not cover the entire slot.....	7
Figure 6: Sketches of plain and plate washers with outside dimensions large enough to cover the slotted hole.....	9

List of Tables

Table 1: Table 3.1 Nominal Bolt Dimensions from Specification for Structural Joints Using High Strength Bolts (RCSC, 2020)	2
Table 2: Table 6.1 - Washer Requirements for Pretensioned Bolted Joints (RCSC, 2020).....	4
Table 3: Summary of the specified maximum hardness of common bolt/screw materials. Washers should be specified with a hardness equal to or greater than that of the bolt/screw.	10
Table 4: Proposed minimum washer thicknesses as a function of clearance (D-d for round holes, W-d for slots), fastener size, and assumed pretension.....	11

1. Applicability and Relationship to the ASCE/SEI Solar PV Structures Manual of Practice

This specification is intended to provide interim, practical guidance for the specification of clearance holes and washers in solar PV mounting structures, with particular emphasis on alternative structural joints commonly used in PV racking and module mounting hardware. The forthcoming ASCE Solar PV Structures Manual of Practice (MOP) establishes a clear framework for categorizing bolted joints in PV structures as either traditional structural joints or alternative structural joints. This specification is explicitly aligned with that framework and is intended to complement, not replace, the guidance in the MOP.

Under the MOP:

- **Traditional structural joints** are bolted connections using standard high-strength structural bolts (generally ½-inch diameter and larger) that fall within the scope of AISC 360 and the RCSC Specification for Structural Joints Using High-Strength Bolts. For these joints, the MOP requires full compliance with AISC and RCSC provisions, including prescribed requirements for clearance hole sizes, slot geometries, washer types, washer hardness, and washer thickness. Accordingly, this specification does not introduce new requirements for clearance holes or washers in traditional structural joints beyond those already established in AISC and RCSC (ANSI/ASCE, 2022) (RCSC, 2020).
- **Alternative structural joints** include the majority of PV-specific connections, such as module-through bolted joints, top-down clamp joints, torque-tube connections, and other joints using fasteners smaller than ½ inch or materials not addressed by RCSC. These joints fall outside the direct scope of AISC 360 and the RCSC Specification.

For alternative structural joints, the MOP places responsibility on the Engineer of Record (EOR) or the mounting system designer to rationally design the joint. This includes explicitly defining the geometry of clearance holes and slots, washer dimensions, washer thickness, and washer material properties based on mechanics, testing, or relevant consensus guidance.

Until the ASCE MOP is formally published, this document may be used as an interim reference. Following publication, it should be read as a companion document that elaborates on washer and clearance-hole considerations within the alternative structural joint framework defined by the MOP.

2. Guidelines for Round and Slotted Clearance Holes

Round clearance holes and slotted holes are necessary to accommodate misalignments between components arising from manufacturing tolerances, uneven terrain at the solar PV site, and expansion joints.

2.1 Traditional Structural Joints

Both AISC 360 and the RCSC Specification define design requirements for holes and slots.

- **AISC 360: Section J3** – This section provides guidance on the following topics for traditional structural bolted joints (1/2” and larger) (ANSI/ASCE, 2022).
 - Size and use of holes.
 - Minimum and maximum spacing
 - Minimum edge distance

- **RCSC Specification: Section 3.1** – This section of the specification defines the nominal dimensions for standard, oversized, short-slotted, and long-slotted holes for traditional structural bolted joints (1/2” and larger) in Table 1. The specification permits holes larger than shown in the table when specified or approved by the Engineer of Record (RCSC, 2020).

Table 3.1 Nominal Bolt Hole Dimensions				
Nominal Bolt Diameter, d_b , in.	Nominal Bolt Hole Dimensions ^{a,b} , in.			
	Standard (diameter)	Oversized (diameter)	Short-Slotted (width × length)	Long-Slotted (width × length)
1/2	9/16	5/8	9/16 × 1 1/16	9/16 × 1 1/4
5/8	1 1/16	1 3/16	1 1/16 × 7/8	1 1/16 × 1 9/16
3/4	1 3/16	1 5/16	1 3/16 × 1	1 3/16 × 1 7/8
7/8	1 5/16	1 1/4	1 5/16 × 1 1/8	1 5/16 × 2 3/16
1	1 1/8	1 1/4	1 1/8 × 1 5/16	1 1/8 × 2 1/2
≥ 1 1/8	$d_b + 1/8$	$d_b + 5/16$	$(d_b + 1/8) \times (d_b + 3/8)$	$(d_b + 1/8) \times (2.5d_b)$

^a The detailed hole dimension shall not exceed the nominal. The fabricated hole dimension shall not exceed the nominal +1/32 in. Exception: In the width of slotted holes, gouges not more than 1/16 in. deep are permitted.

^b The slightly conical hole that naturally results from punching operations with properly matched punches and dies is acceptable.

Table 1: Table 3.1 Nominal Bolt Dimensions from Specification for Structural Joints Using High Strength Bolts (RCSC, 2020)

2.2 Alternative Structural Joints

Standard hole and slot sizes for alternative structural joints are specified in ASME/ISO. When practical, the mounting system designer should follow one of these standards.

- **ASME B18.2.8** – (Round) Clearance Holes for (imperial and metric) Bolts, Screws, and Studs: This Standard covers the recommended clearance hole sizes in three classes of clearance using close (tight), normal (standard), and loose-fit (oversized) categories (ASME, 2011).
- **ISO 273** – (Round) Clearance Holes for (metric) Bolts and Screws: Specifies diameters for general-purpose applications; tabulates the hole diameters for fine, medium, and coarse series for thread diameters (ISO, 2002).

Note: The clearance hole sizes listed in the ASME and ISO standards listed above are based on standard drill sizes. The solar PV mounting system designer has the latitude to deviate from these standards as necessary, since the holes in most mounting system components are thermally cut with a laser or plasma torch rather than drilled, as these standards imply.

3. Proposed Guidelines for Washers

Solar PV mounting system designers and EORs must balance multiple factors when specifying a washer for a particular bolted joint. The washer specification must be chosen to meet the functional requirements, avoid failure mechanisms, and, ideally, be readily available commercially.

3.1 Traditional Structural Joints

AISC 360 references the RCSC Specification for detailed requirements governing plain and plate washers. Under this specification, hardened washers manufactured in accordance with ASTM F436/F436M must be used with round standard holes, oversized holes, and short slots when clamping materials with a yield strength below 40 ksi (see Table 2) (ASTM, 2024). In addition, the RCSC Specification recognizes the use of plate washers in situations where a standard washer does not provide sufficient bearing area or coverage, such as over oversized or slotted holes, or where thin or slotted connected elements require additional reinforcement.

Table 6.1 Washer Requirements for Pretensioned and Slip-Critical Bolted Joints with Oversized and Slotted Holes in the Outer Ply				
Bolt Group	Nominal Bolt Diameter, d_b , in.	Hole Type in Outer Ply		
		Oversized	Short-Slotted	Long-Slotted
Group 120	$\frac{1}{2} - 1\frac{1}{2}$	ASTM F436 ^a		$\frac{5}{16}$ -in.-thick plate washer or continuous bar ^{b,c}
	≤ 1			
Group 144 and 150	> 1	ASTM F436 extra thick ^{a,b,d}		ASTM F436 washer with either a $\frac{3}{8}$ -in.-thick plate washer or continuous bar ^{b,c}

^a This requirement shall not apply at the head at round heads of ASTM F3125 Grades F1852 and F2280, or F3148 Grade 144 *bolting assemblies* with round heads that meet the requirements in Section 2.4 and provide a bearing circle diameter that meets the requirements of the relevant ASTM Standard.

^b See ASTM F436 Section 1.2. Multiple washers with a combined thickness of $\frac{5}{16}$ in. or larger do not satisfy this requirement.

^c The plate washer or bar shall be of structural-grade steel material, but need not be hardened.

^d Alternatively, a $\frac{3}{8}$ -in.-thick plate washer and an ordinary thickness F436 washer may be used. The plate washer need not be hardened.

Table 2: Table 6.1 - Washer Requirements for Pretensioned Bolted Joints (RCSC, 2020)

3.2 Alternative Structural Joints

Alternative structural joints used in solar PV mounting systems frequently fall outside the traditional bolt–hole–washer configurations covered by AISC 360 and the RCSC Specification. The EOR or mounting system designer should design them rationally. Because the hole geometry directly influences washer demands, the specification of clearance holes must be paired with washer designs that meet the functional requirements and avoid the failure mechanisms discussed below.

3.2.1 Round and Plate Washer Functional Requirements

1. Spread the compressive stress under the bolt (cap screw) head and nut over a larger area on the clamped components to prevent damage to the underlying surface.
2. Provide a hard surface for the nut or cap screws to rotate against during tightening to achieve consistent friction.

Factors such as the hole diameter (or slot width), fastener head size and pretension, and joint (clamped component) properties should be considered when specifying the washer size, material, and thickness to meet these requirements. Other factors must also be considered to

avoid the two common failure mechanisms summarized below.

3.2.2 Common Washer Failure Mechanisms and Solutions

1. **Compressive Yield in ‘Soft’ Washers:** When high-strength bolts are tightened, the pretension in the bolt results in high compressive stress at the relatively small bearing surfaces of the nut and cap screw (see Figure 1). This stress is often higher than what mild steel or 300-series stainless washers can sustain without yielding. Compressive yield (see Figure 2) in the washer typically causes a gradual loss of pretension (relaxation) and should be avoided.

Cap screw head and
nut bearing surfaces

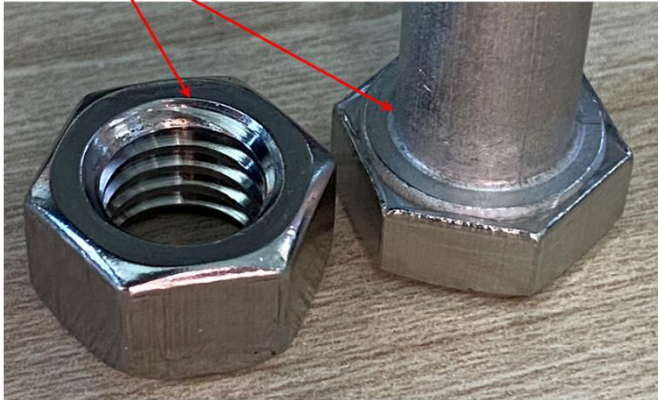


Figure 1: The bolt pretension is concentrated at the bolt and nut bearing surfaces, resulting in high contact stress.



Figure 2: Evidence of compressive yield of a ‘soft’ washer tightened on a standard, round clearance hole.

- **Solution for Compressive Yield in Washer:** A common best practice is to select a washer material with compressive yield strength greater than that of the adjoining

bolt or nut. A straightforward way to achieve this is to choose a washer whose hardness is equal to or greater than that of the adjoining bolt or nut.

- 2. Bending in Washers:** Oversized round and slotted clearance holes are commonly used in solar PV mounting system components. Although helpful for accommodating misalignments caused by manufacturing tolerances and terrain at the solar PV site, these oversized holes can be problematic if the washers do not fully cover them or are too thin.

Thin washers that do not cover the entire hole will bend (deflect) under the pretension developed during tightening (see Figure 3). The bending will also cause high compressive stress at the edge of the slot, which can result in compressive yield of the clamped component, especially if it is made of a lower-strength material like aluminum (see Figure 4).

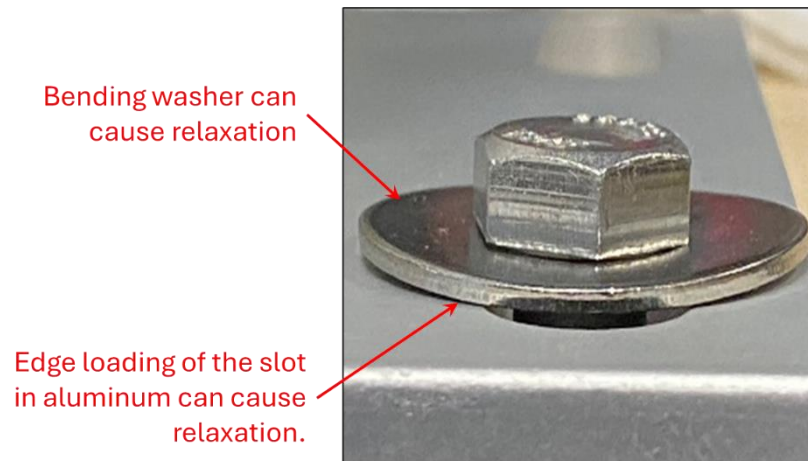


Figure 3: Example of bending of a thin washer on an oversized slot.

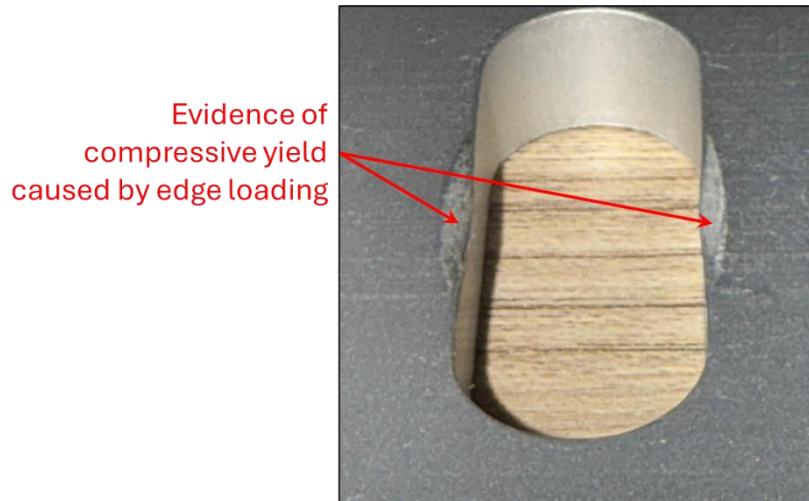


Figure 4: Evidence of compressive yield at the edge of a slot due to bending of a thin washer.

A finite element model of the example joint was created to illustrate the high bending stress in the washer and compressive stress at the washers on a slotted hole. The details and results of that analysis are shown in Figure 5.

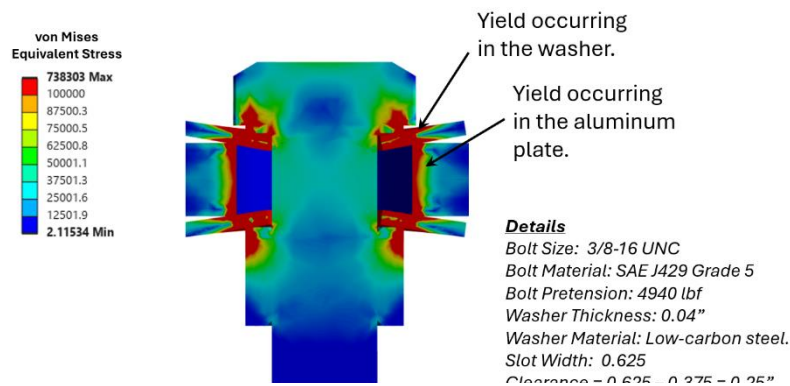


Figure 5: Plot showing von Mises stress in a bolted joint with a thin washer that does not cover the entire slot.

Yielding of the washer, or along the edge of a slot, can lead to significant joint loosening after initial tightening and should be avoided.

- **Solution for Washer Bending:** To prevent this, oversized holes and slot widths must be paired with washers thick enough to distribute the pretension evenly across the joint and remain flat once the nut or bolt is tightened. In addition, the washers should be large enough to completely cover the oversized hole or slot.

3.2.2.1 Washer Standards Applicable to Alternative Structural Joints

The following is a selection of standards applicable to the fastener size and materials commonly used in alternative structural joints.

ASTM Standards

- ASTM F436/F436M-24 Standard Specification for Hardened Steel Washers Inch and Metric Dimensions: This specification defines the chemical, mechanical, dimensional, and quality requirements for hardened steel washers in pretensioned and slip-critical bolted joints (ASTM, 2024).
- ASTM F844-00 Standard Specification for Washers, Steel, Plain (Flat), Unhardened for general use. Washers conforming to this standard are unhardened and would only be appropriate for alternative structural joints if the washer hardness matched the bolt or nut it's paired with (ASTM, 2000).

ASME Standard

- ASME B18.21.1-2009 Washers: Helical Spring-Lock, Tooth Lock, and Plain Washers (inch series): This specification defines the dimensional, materials, and quality requirements. The standard defines two types of plain washers, Type A and Type B. Type A refers to washers with a large tolerance, whereas Type B refers to flat washers with a tighter tolerance. Type B washers also feature narrow, regular, or wide outside diameters (ASME, 2011).
 - Note: Type A narrow washers are often referred to as 'SAE Washers', and Type A wide washers are referred to as 'USS Washers' even though they are not covered by SAE or USS standards.

European Standard

- EN 14399-5: 2005 Plain Washers: This standard specifies hardened and tempered plain washers intended for bolting assemblies with large series hexagon high-strength structural bolts and nuts with threads from M12 to M36 inclusive (EN, 2005).

ISO Standards

- ISO 7089 Plain washers – Normal series – Product grade A: Defines general-purpose flat washers, including standard thickness ranges. The specification defines the material specifications for carbon steel, alloy steel, and stainless steel (ISO, 2000).
- ISO 7093-1 Plain washers—Large series—Product grade A: This specification defines general-purpose flat washers, including standard thickness ranges. It allows materials (ISO, 2018) standard are intended for oversized round and slotted holes (ISO, 2000).
- ISO 898-3 Mechanical properties of fasteners made of carbon and alloy steel – Flat (ISO, 2012) properties of flat washers, designed to be used in bolted joints in combination with bolts, screws, studs, and nuts with a specified property class by ISO 898-1 and ISO 898-2 (ISO, 2020) (ISO, 2018) (ISO, 2012).

3.2.2.2 Guidelines for Alternative Structural Joints

The following guidelines provide basic guidance on specifying plain washers for alternative structural joints in solar PV structures. They are intended only as an initial reference for the PV mounting system designer or Engineer of Record to design round and plate washers rationally.

These guidelines draw on best practices from other industries and selected provisions of the RCSC Specification. When applied, they will generally satisfy the functional requirements defined earlier in this section and help avoid common failure mechanisms. This guidance is not a substitute for engineering judgment. Nothing in this section relieves the mounting system designer or Engineer of Record of their responsibility to apply engineering principles, supported by calculation, testing, or relevant consensus standards, when specifying washers.

1. **Plain and plate washers should be specified with outside dimensions large enough to span (completely cover) oversized round and slotted holes completely in all positions.** Plate washers should be used instead of round washers when it is impractical to cover a long slot with a round washer (see Figure 6). In such cases, designers should be aware that rectangular plate washers can introduce local stress risers at plate ends and corners, so appropriate corner radii/fillets and plate thickness should be specified to smooth load transfer and help avoid unintended stress concentrations.

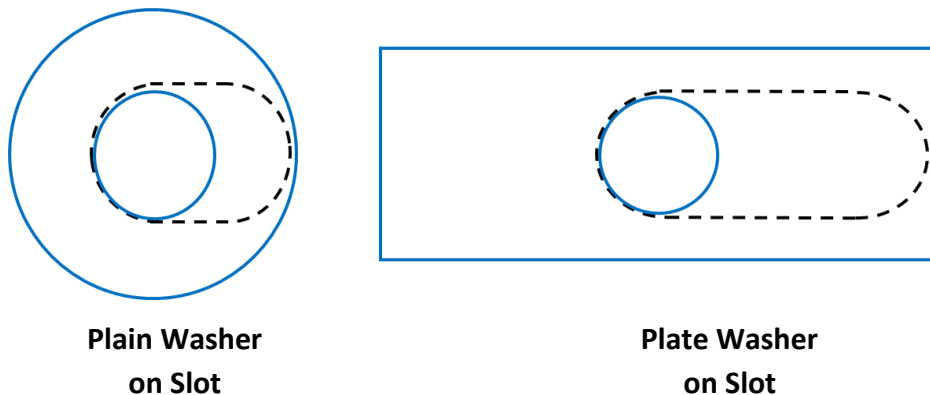


Figure 6: Sketches of plain and plate washers with outside dimensions large enough to cover the slotted hole.

- Why? This guideline aligns with the RCSC specification. In general, washers that span oversized round and slotted holes distribute the stress more uniformly across the clamped component, compared to washers that only partially cover the hole or slot.
2. **Plain washers should be specified with a hardness equal to or greater than that of the nut/bolt.** Washer hardness is an indicator of the tensile and yield strengths of steel washers. The harder the material, the higher the tensile strength. A designer only needs to

know the maximum hardness of the bolt or nut mated to the washer to know the ideal washer hardness. Table 3 summarizes the maximum specified hardness of common bolt/screw materials used in the solar PV industry (ASTM, 2022) (ASTM, 2023) (ASTM, 2022) (ISO, 2012) (ISO, 2020) (SAE, 2020). Note: The washers should be heat-treated utilizing a process that produces a through-hardened condition (not just surface-hardened).

- Why?
 - This specific guideline aligns with the RCSC specification.
 - Ensure that the washer does not yield when tightened. See Figure 2, which shows an example of compressive yield in a ‘soft’ washer.
 - Provide a hard surface for the nut or cap screws to rotate against during tightening to achieve consistent friction.
 - Through-hardened washers have a consistent strength through the thickness of the washer, not just the surface. Washers that are only surface-hardened are at risk of compressive yield in the subsurface when tightened.

Bolt/Screw Material	Specified Bolt/Screw Max Hardness
Alloy Steel Bolts/Screws	
SAE J425-Grade 1 or 2	HRB 100
ASTM A307A or B	HRB 100
ISO 898-1 Class 4.6	HRB 100
SAE J425-Grade 5	HRC 34
ASTM F3125 Grade A325	HRC 34
ISO 898-1 Class 8.8	HRC32
SAE J425-Grade 8	HRC 39
ASTM F3125 Grade A490	HRC 38
ISO 898-1 Class 10.9	HRC 39
Stainless Steel Bolts/Screws	
ASTM F593C or G	HRC 32
ISO 3506-1 A2-70	HRC 32

Table 3: Summary of the specified maximum hardness of common bolt/screw materials. Washers should be specified with a hardness equal to or greater than that of the bolt/screw.

3. Plain washers should be specified with sufficient thickness to remain flat under the expected load.

Washer bending (and whether the washer remains effectively flat) over oversized round holes or slots is fundamentally a stiffness problem governed primarily by the clearance geometry (unsupported span over the hole/slot), the washer section properties (washer thickness), Young’s modulus (E), and assumed pretension. Because the washer materials used in PV mounting systems are almost always low-carbon steel, heat-treated alloy steel, or austenitic stainless steel, E is approximately the same across these materials. As a result, washer bending behavior is primarily driven by geometry and thickness.

Table 4 provides recommended washer thicknesses for common solar PV joint hardware sizes. The values are based on the clearance between the nominal bolt diameter (d) and either the round clearance-hole diameter (D) or slot width (W) (see Figure 7).

Plain Washer Thickness Guidelines		
Nom. Bolt Diameter, d (in)	Clamp Component Hole Clearance = D-d or Slot Clearance = W-d (in)	Recommended Minimum Washer Thickness (in)
1/4 to 7/16"	Clearance $\leq 1/16$ "	0.063
	$1/16 < \text{Clearance} \leq 1/4$ "	0.125
$\geq 1/2$ "	See RCSC -Section 2.5, Table 6.1 ^a	
<i>Recommended washer thickness applicable to the following; Washer covers the clearance hole and slot completely. Maximum washer clearance hole = $d + 1/32$"</i>		

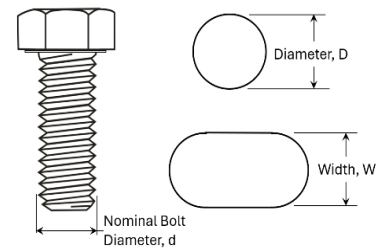


Table 4: Proposed minimum washer thicknesses as a function of clearance (D-d for round holes, W-d for slots), fastener size, and assumed pretension.

These recommendations were developed through an iterative 3D finite element analysis. Although a full FEA workflow is beyond the scope of this guideline, the essential approach is outlined here. The model represented the washer and the surrounding clamped region with solid elements, applied the appropriate bolt pretension and maximum service loads, and included nonlinear contact between the washer and the clamped surface. For each clearance scenario, the washer thickness was incrementally adjusted until the analysis confirmed that it remained flat, with only minor bending, and maintained full contact throughout loading.

- Why?
 - This specific guideline aligns with the RCSC specification.
 - Ensure that the washer does not yield when tightened. See Figures 3 & 4 for an example of the bending of a thin washer used on an oversized slot in an aluminum plate.
 - Ensure that the bolt pretension is transferred to the clamped component uniformly to avoid edge loading. See Figure 5 for an example of compressive yield at the edge of a slot due to the bending of a thin washer.

4. Design Checklist for Alternative Structural Joints: Clearance Holes, Slots, and Washers

Use this checklist as a minimum set of practical verifications when specifying hole/slot geometry and washers for alternative structural joints.

Clearance hole and slot specification checks

- Round holes: Hole diameter (D) should be specified. The selected clearance class should be intentional (tight/normal/loose) and consistent with manufacturing requirements and ASME B18.2.8 or ISO 273.
- Slots: Slot width (W), length (L), and end geometry (radiused ends vs. sharp) should be specified.
- Slots: Worst-case fit-up position should be considered (bolt may sit at the extreme of slot length plus tolerance stack-up).

Washer specification checks

- Round washer should fully cover the oversized hole or slot in all tolerance positions (including worst-case bolt position within a slot).
- For long slots where a round washer cannot reasonably cover the slot, a plate washer should be used, with dimensions sufficient to cover the slot at the extremes.
- Washer thickness should be specified considering the unsupported span: round holes based on $(D-d)$; slots based on $(W-d)$. Washer thickness should be sufficient to remain effectively flat under the specified preload (Table 4 may be used as a default basis where applicable).
- If deviating from the Table 4 conservative thickness guidance, the deviation should be supported by rational analysis or test evidence demonstrating the washer remains elastic/flat and maintains contact.
- Washer hardness should be specified to be greater than or equal to the hardness of the mating bolt/nut and should be through-hardened (not just surface-hardened).

Local contact and bearing checks

- Under-head/under-nut bearing pressures (through the washer) should be checked against the clamped material's permissible surface pressure.

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