Investigation of Steel Plate Washer Thickness for Column Anchor Rod Applications

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ABSTRACT

Since the 13th edition, the AISC *Steel Construction Manual* has included provisions regarding the recommended minimum plate washer thickness used in a column base plate and anchor rod assembly. Each plate washer must have sufficient strength and stiffness to fully develop the anchor rod to which it is fastened without succumbing to pull-through, flexural, or cracking failure. Laboratory tensile testing of an anchor rod, nut, and plate washer assembly was conducted at the University of Cincinnati to study plate washer performance. This testing investigated the capacity of ASTM A572/A572M Grade 50 (ASTM, 2021b) plate washers using the recommended minimum thicknesses as listed in Table 14-2 of the 15th edition of the AISC *Steel Construction Manual* (2017), with anchor rods having ¾, 1, 1½, 2, and 2½ in. diameter. A total of 94 tests were conducted, after which the plate washers were visually assessed for signs of failure, including measurement of permanent out-of-plane deformation. This assessment established that a 40% relative deformation in plate washers could reasonably be judged as a failure threshold due to excessive deformation. Testing and assessment revealed that while 10 plate washers exhibited relative deformations in excess of 40%, the recommended minimum plate washer thicknesses found in AISC *Manual* Table 14-2 were sufficient in fully developing most anchor rods. The notable exception to the current minimum thickness recommendations were for washers in use with anchor rods with diameters of ¾, 1, and 1½ in. made from Grade 105 steel. For these anchor rods, a thicker plate washer than that currently specified is recommended. Testing also found that the anchor rod orientation and the variations of ultimate strength in individual anchor rods did not appear to be significantly associated with the performance of plate washers in these tests.

Keywords: plate washers, pull-through failure, anchor rods, column baseplates, column base connections.

INTRODUCTION

The connection of a column baseplate to the foundation is critically important to the performance and behavior of the framing system. The anchor rods that extend through oversized holes in the steel baseplate are attached through hardened nuts and plate washers covering those holes. The column baseplate connection can be subjected to uplift forces due to high seismic or wind loading conditions that create an overturning moment, placing the anchor rods in tension as the steel baseplate is restrained by the plate washer (Figure 1). Excessive deformation of the plate washer resulting in pull-through failure would cause the actual behavior of the connection to be quite different from the anticipated behavior, which, in turn, could affect the design assumptions. Although the plate washer plays a significant role of the column base connection, there is a lack of experimental research on the behavior and appropriate thickness of plate washers. This lack of guidance regarding column base connections has motivated recent research conducted by Grilli and Kanvinde (2016) at the University of California–Davis, who investigated column base connections subjected to high seismic loads. This experimental study focused on anchor bolts connected by a plate embedded within a concrete footing to compare experimental strength to that predicted by various models. Enhancing knowledge surrounding the behavior of column base connections, including the behavior of plate washers, will help provide guidance in column base connection design and limit the variance between actual and anticipated frame behavior.

The stated purpose of AISC Design Guide 1, *Base Plate and Anchor Rod Design*, is to provide guidance for engineers and fabricators to design, detail, and specify column base plate and anchor rod connections (Fisher and Kloiber, 2006). This reference notes that plate washers can be rectangular, square, or circular, although square washers are the most commonly used because they are easily produced. Proper plate washer behavior should prevent pulling through the hole of the column base plate. Recommended minimum plate washer dimensions, based approximately

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Table 1. AISC Design Guide 1, Table 2.3 (Fisher and Kloiber, 2006)

Table 2.3. Recommended Sizes for Anchor Rod Holes in Base Plates

Anchor Rod Diameter, in.	Hole Diameter, in.	Min. Washer Dimension, in.	Min. Washer Thickness, in.
¾	1⁵⁄₁₆	2	¼
⅞	1⁹⁄₁₆	2½	⁵⁄₁₆
1	1¹³⁄₁₆	3	⅜
1¼	2¹⁄₁₆	3	½
1½	2⁵⁄₁₆	3½	½
1¾	2¾	4	⅝
2	3¼	5	¾
2½	3¾	5½	⅞

Notes: 1. Circular or square washers meeting the size shown are acceptable.
2. Adequate clearance must be provided for the washer size selected.
3. See discussion in Section 2.6 regarding the use of alternate 1¹⁄₁₆-in. hole size for ¾-in.-diameter anchor rods, with plates less than 1¼-in. thick.

on a 3:1 ratio of rod diameter to washer thickness, are given in Table 2.3 of Design Guide 1, shown here as Table 1. The values in Design Guide 1 are an exact match to those given in Table 14-2 of the 15th edition of the AISC *Steel Construction Manual* (2017) shown in Table 2.

Adequate performance of the column base connection depends on the plate washer, whose purpose is to cover the oversized hole in the base plate while transferring any tension forces developed in the anchor rods. Since the second edition of AISC Design Guide 1 was published, changes have occurred to the materials that are commonly specified in base plate design. While ASTM A36/A36M (ASTM, 2019a) steel has been the most common plate material specified in practice for decades, this grade is now becoming obsolete and is not explicitly addressed in the 16th edition of the AISC *Manual* (AISC, 2023). Anchor rods are standardized in ASTM F1554 (ASTM, 2020) and are most commonly specified as Grade 55, although Grades 36 and 105 are typically available (Carter, 1999; Tavarez, 2018). An investigation into the behavior of steel plate washers of varying thicknesses using anchor rods made from all three grades of ASTM F1554 steel is needed to provide further understanding of this critical element.

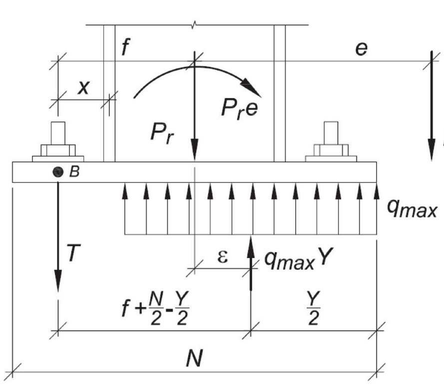


Fig. 1. Anchor rod tension created by large moment (Fisher and Kloiber, 2006).

EXPERIMENTAL TESTING

The main objective for this study was to experimentally evaluate a selected sample of ASTM A572/A572M Grade 50 (ASTM, 2021b) plate washers in conjunction with its appropriately sized ASTM F1554 Grades 36, 55, and 105 threaded rods. This included loading the assembly of specimens to failure, followed by a visual observation of the plate washer failure modes and measurement of the plate washer deformation normal to the tensile loading. A secondary objective was to observe the behavior of the F1554 anchor rods. This included noting discrepancies between the minimum yield criteria and observed yield points; any discrepancies between the minimum and maximum ultimate tensile strengths; and the observed tensile strengths for five diameters of anchor rod, ranging in size from ¾ in. to 2½ in. diameter.

Experimental testing consisted of the tensile loading of 90 sets of specimens, which included one plate washer and one 48-in.-long fully threaded anchor rod. Rods of five different diameters were tested (¾, 1, 1½, 2, and 2½ in.) to provide a representative sample of the diameters listed in AISC *Manual* Table 14-2 (2017). For each of these five

Table 2. AISC *Manual* Table 14-2 (AISC, 2017)

TABLE 14–2
Recommended Maximum Sizes for Anchor-Rod Holes in Base Plates

Anchor Rod Diameter, in.	Max. Hole Diameter, in.	Min. Washer Size, in.	Min. Washer Thickness	Anchor Rod Diameter, in.	Hole Diameter, in.	Min. Washer Size, in.	Min. Washer Thickness
¾	1⁵⁄₁₆	2	¼	1½	2⁵⁄₁₆	3½	½
⅞	1⁹⁄₁₆	2½	⁵⁄₁₆	1¾	2¾	4	⅝
1	1¹³⁄₁₆	3	⅜	2	3¼	5	¾
1¼	2¹⁄₁₆	3	½	2½	3¾	5½	⅞

Notes: 1. Circular or square washers meeting the washer size are acceptible.
2. Clearance must be considered when choosing an appropriate anchor rod hole location, noting effects such as the position of the rod in the hole with respect to the column, weld size and other interferences.
3. When base plates are less than 1¼ in. thick, punching of holes may be an economical option. In this case, ¾-in. anchor rods and 1¹⁄₁₆-in. diameter punched holes may be used with ASTM F844 (USS Standard) washers in place of fabricated plate washers.

anchor rod diameters, a total of 18 plate washers were tested using combinations of three grades of steel for the anchor rods (ASTM F1554 Grades 36, 55, and 105), two anchor rod orientations (centered in the hole and offset in the hole), and three plate washer thicknesses based on proximity to the value given in Table 14-2. The anchor rod orientation variable was used to study the potential effect that rod orientation relative to the plate washer hole (centered versus offset) may have on plate washer performance. In total, six plate washers were tested per grade and rod diameter, corresponding to 18 washers per rod diameter, and overall, 90 specimens were tested. Due to the lack of experimental testing data, the plate washer thicknesses tested using various combinations of anchor rods and steel grades always used plate washer thicknesses, as well as thicknesses greater than, and sometimes less than, those currently recommended in the 15th edition of the AISC *Manual* in Table 14-2, in order to explore the testing space. At the conclusion of this phase of testing, it was noted that five anchor rods had not achieved their ultimate tensile strength as specified in the ASTM standard. All five rods were Grade 105, and three of those five were 1½ in. diameter. For this reason, four more 1½-in.-diameter Grade 105 threaded rods were acquired along with four accompanying plate washers, with ½ in. and ⅝ in. thicknesses, resulting in a total of 94 sets of specimens tested.

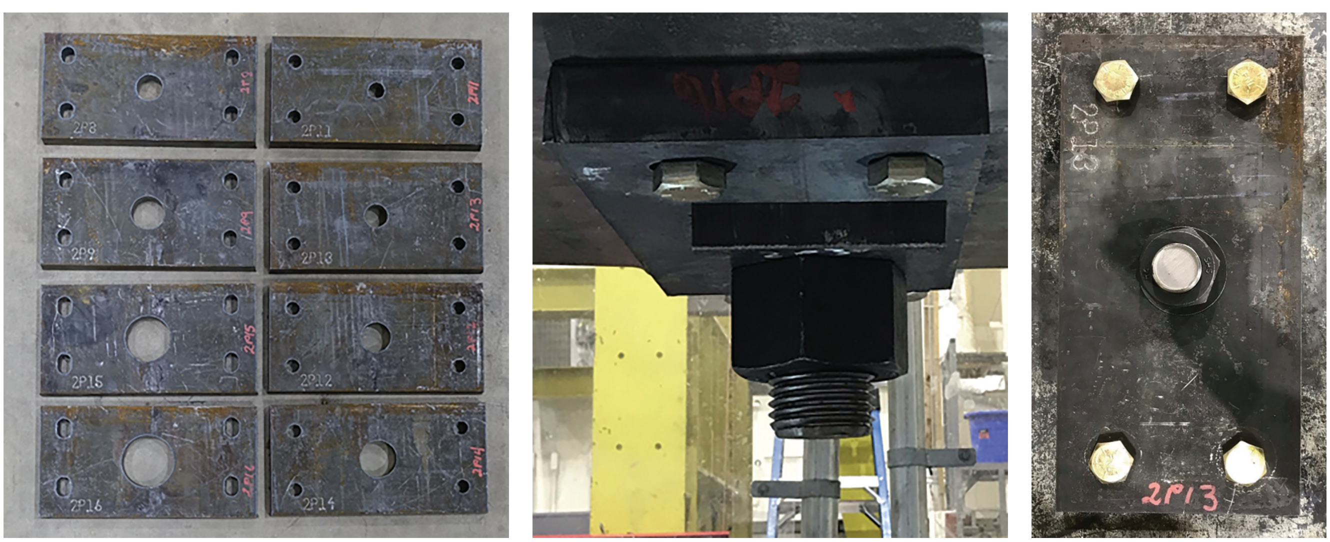
All testing occurred in the High Bay Structural Research Laboratory at the University of Cincinnati. Testing was conducted using a Tinius-Olsen Super L universal testing machine shown in Figure 2. This testing apparatus has top and bottom crosshead plates that are responsible for applying tension force to the assembly using a servo-controlled hydraulic cylinder.

The experimental set-up consisted of two 1½-in.-thick ASTM A572/A572M Grade 50 reaction plates affixed to the testing apparatus using four ¾ in. high-strength bolts—one to the top surface of the top crosshead and one to the bottom surface of the middle crosshead. The bottom plate represented the configuration of a base plate in the anchor rod assembly and had a hole diameter as found in AISC *Manual* Table 14-2. Neither top nor bottom plate deformed significantly during testing. To ensure that these plates did not incur excessive damage during testing, while also fulfilling the provisions regarding base plate hole sizes, the reaction plates were changed for each rod diameter to a plate with an appropriately sized hole. For the top reaction plate, the hole was fabricated ¹⁄₁₆ in. larger in diameter than the anchor rods for the ¾ in. rod, and ⅛ in. larger in diameter for all other rod sizes. The bottom reaction plate was fabricated with a central hole of the diameter given in AISC *Manual* Table 14-2. The top and bottom reaction plates are shown in Figure 3. Additionally, the bottom plates were detailed with short-slotted mounting holes to allow the installation of the plates so that the effect that anchor rod orientation (centered versus offset) may have on plate washer behavior could be investigated (Figure 4).

Each test included one ASTM F1554 anchor rod and one ASTM A572/A572M Grade 50 plate washer with ASTM A563/A56M (ASTM, 2021a) Grade DH nuts fastening the plate washer to the anchor rod and the reaction plates. An ASTM F436/436M (ASTM, 2019b) washer was placed between the top nut and reaction plate.

Once the test specimens were set in place, testing commenced with force and displacement measured over time. The specimens were loaded at a predetermined rate of displacement to ensure that only static force effects were

Fig. 2. Tinius Olsen Super-L universal testing apparatus.



(a) Before testing *(b) Bottom during testing* *(c) Top during testing*

Fig. 3. Reaction plates.

considered. These rates were 0.1, 0.25, 0.5, and 1.0 in./s. Each test began at the lowest rate of displacement, with the rate being increased after yielding was deemed to have occurred, dependent on the stiffness and ductility of each member. The specimens were loaded either to failure of the anchor rod, or to the full capacity of the Tinius-Olsen Super L universal testing apparatus, which has a maximum load capacity of 400 kips. The only anchor rods that exceeded this 400-kip capacity were those rods having a 2½ in. diameter and composed of Grade 105 steel. Once all test data was recorded, it was compiled into force-displacement curves.

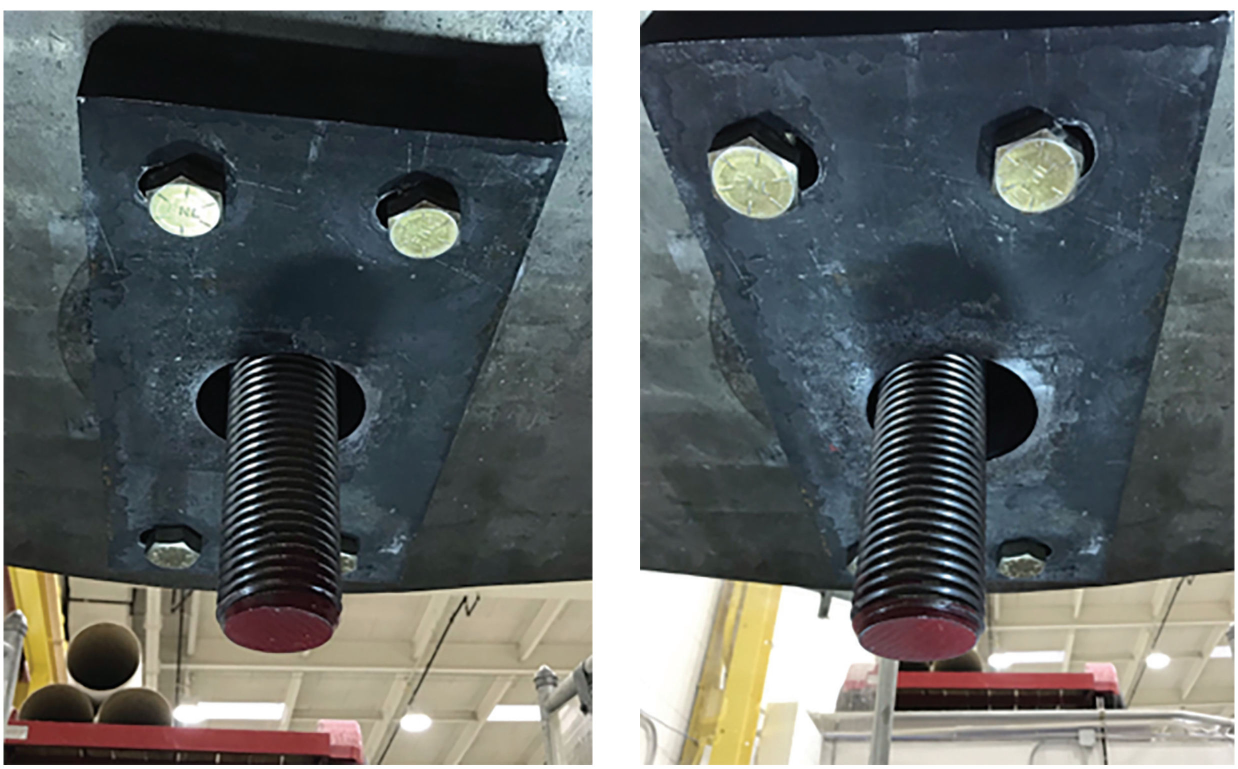
DEFORMATION AND VISUAL ASSESSMENT OF PLATE WASHERS

Because there is no direct way during testing to measure the deformation of the plate washers normal to the plane of loading, the measurement of plate washer deformation occurred after the tensile testing had been completed. The deformation for each washer was measured using an electronic dial gauge having a 1 in. stroke affixed to a handcrafted wooden stage. The stage had a dowel rod that held the dial gauge and was fastened to vertical posts at each corner. A top brace was used to ensure the plumbness of the posts and that the stage was horizontal. The apparatus was inspected using a bubble level before each measurement of tested plate washers as shown in Figure 5.

Prior to measuring the plate washer deformation, the thickness of each washer was measured using a digital dial caliper at the mid-point of all four sides, and the average of these four thicknesses was recorded as the average thickness of the washer after the test (Figure 6). In general, this average thickness was found to be within 3% of the nominal washer thickness and averaged less than a 1% deviation from the nominal value in the 94 plate washers measured.

Once the average measured thickness of the washer had been determined, the washer was placed on the stage to determine the location of the absolute minimum elevation on the face of the plate washer. When the location of minimum elevation had been found, the dial gauge was zeroed, and the plate washer was moved along the stage, maintaining contact between the stage and washer at all four corners. This allowed the point of maximum deformation on the plate to be captured by the dial gauge and recorded.

Because the experimental testing in this study used plate washer thicknesses ranging from ¼ in. to 1½ in., a relative deformation was used as a plate washer performance metric. The relative deformation of each washer was calculated as the percentage of absolute maximum deformation to the average thickness of each plate washer tested. Figure 7



(a) Centered *(b) Offset*

Fig. 4. Anchor rod orientations.

Fig. 5. Assembly of stage and affixed dial gauge.

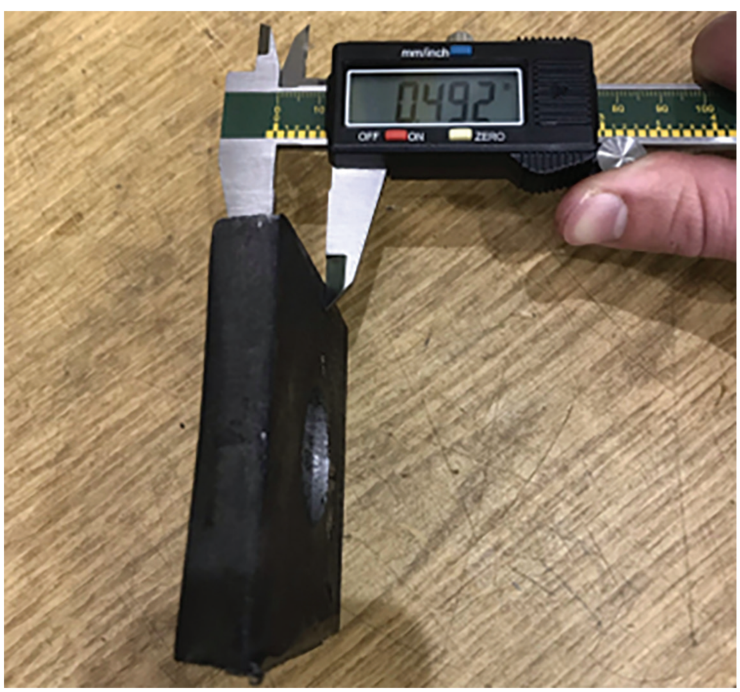


Fig. 6. Measurement of thickness using dial caliper.

shows this data distributed across the entire dataset, which is found in the testing report prepared for the AISC (Cozzens et al., 2021). Further information is provided in the Appendix. Most plate washers exhibited minor to moderate relative deformation. Over half of those tested experienced less than 10% relative deformation, and over three-quarters exhibited less than 20% relative deformation. Of the 10 plate washers that deformed over 40%, nine of those were the thinnest tested, with nominal thicknesses of ¼ or ⅜ in.

To establish the amount of deformation that constitutes failure in a plate washer, a visual assessment of each plate washer was conducted. Those plate washers with only a light amount of deformation were placed in Category 0—Did Not Fail. Plate washers that were judged to have sustained severe deformation were assigned to Category 3—Clear Failure. Two other categories were created (1—No Likely Failure and 2—Likely Failure), and 92 plate washers were visually assessed and placed into one of these categories. Two tests that were at least three standard deviations away from the visual classification's mean were removed. Examples of plate washers assigned to each of these four categories are shown in Figures 8 through 11.

Coupling the visual assessment of plate washers with the physical measurement and determination of relative deformation established a lower bound of relative deformation associated with failure. The results in Figure 12 show a clear delineation appearing between plate washers assigned to Category 1 and those assigned to Category 2. Considering the array of plate washer thicknesses evaluated, the grades of steel anchor rods used, and the various anchor rod orientations, there seems to be sufficient evidence that a threshold for likely failure is apparent when the relative deformation of a plate washer exceeds 40%.

ANCHOR ROD STRENGTH AND ORIENTATION

Based on the design principles established in the AISC *Specification for Structural Steel Buildings* (AISC, 2016b), plate washers are responsible for transferring the design load of the anchor rods through the assembly. However, because the anchor rods have significantly more ductility than the plate washers, it is in the best interest of the structure to ensure the failure of the anchor rods occurs before the failure of the plate washers. To establish a safe and conservative hierarchy of failure for the structure, the performance of each plate washer was evaluated with respect to the ultimate strength of the rod it was responsible for developing, not its design strength. As previously mentioned, the testing in this study has established that a failure threshold involving a plate washer can reasonably be associated with a relative deformation exceeding 40%. The relative deformation of the plate washers in this study were determined after the anchor rods had exceeded their ultimate strength, revealing that 10 plate washers were considered to have failed.

Because inherent variation exists within all groups of test specimens, this study considered the possibility that plate

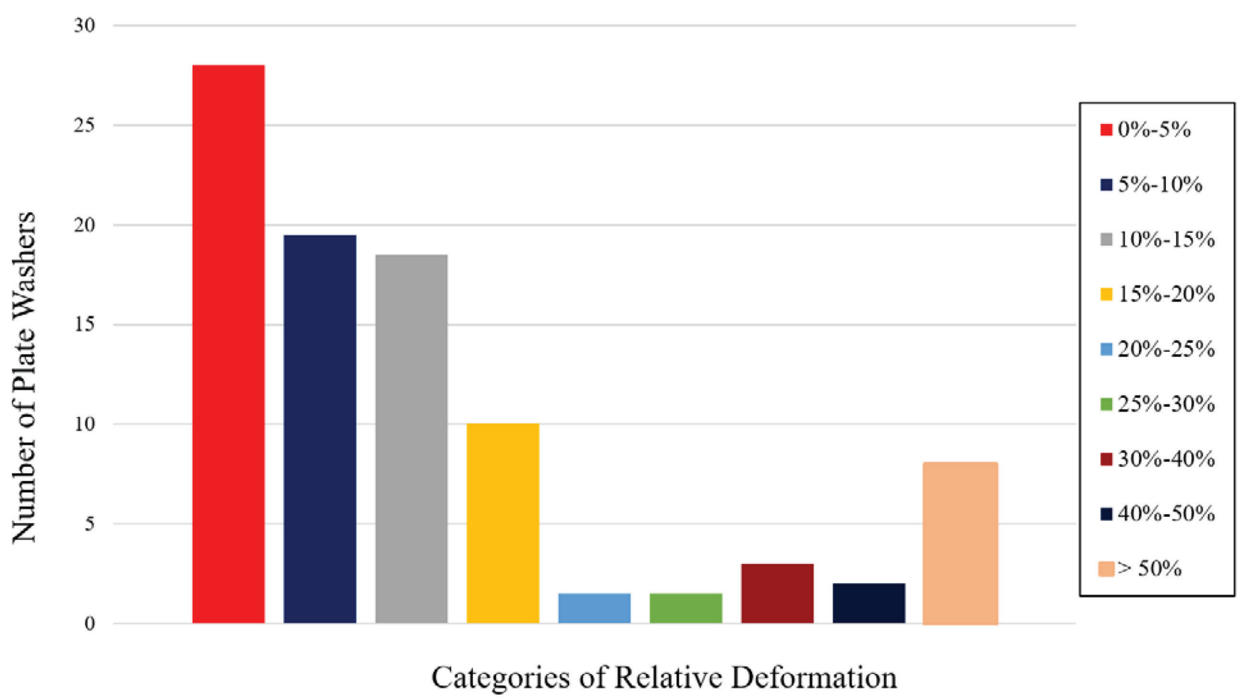


Fig. 7. Distribution of relative deformation of plate washers.

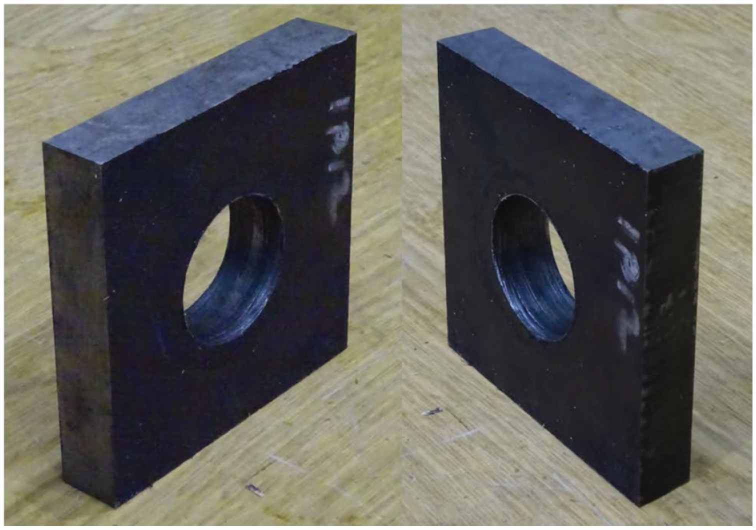


Fig 8. ¾ in. plate washer, centered orientation visual Category 0—did not fail.

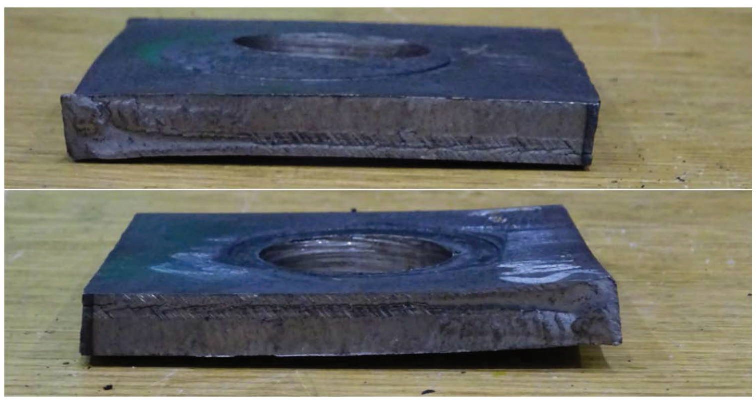


Fig. 9. ½ in. plate washer, centered visual Category 1—no likely failure.

Fig. 10. ¼ in. plate washer, offset orientation visual Category 2—likely failure.

Fig. 11. ¼ in. plate washer, offset orientation visual Category 3—clear failure.

Fig. 12. Visual failure categories and measured relative deformation.

Table 3. ANOVA Results Ratio of Ultimate Rod Capacity to Design Strength				
Groups	**Average Ultimate-to-Design Strength Ratio of the Anchor Rods (%)**	**ANOVA Statistics**		
Relative deformation < 40%	154.62	F_{test}	$F_{critical}$	Probability, p
Relative deformation > 40%	154.98	0.004	3.957	0.953

Table 4. ANOVA Results—Orientation of Anchor Rods				
Orientation Groups	**Average Relative Deformation of Plate Washer (%)**	**ANOVA Statistics**		
Centered	16.49	F_{test}	$F_{critical}$	Probability, p
Offset	20.71	0.495	3.957	0.484

washer failure may have resulted from an unusual variation between the ultimate strength of individual anchor rods in the group of anchor rods tested. To investigate this possibility, a metric of experimental ultimate strength to design strength of each anchor rod was calculated. This ratio was then compared to the relative deformation of the associated plate washer. A single-factor analysis of variance (ANOVA) was performed on the specimens tested to evaluate the mean ultimate strength to design strength ratio of each anchor rod among two groups—the group of plate washers with a relative deformation greater than 40% (i.e., plate washers that failed) and the group of plate washers with a relative deformation less than 40% (i.e., plate washers that had not failed). This tested a null hypothesis that there was no significant difference in the mean value between the groups using a level of significance of 0.05. The analysis revealed that the mean value of the ratio of ultimate strength to design strength of the failed group versus the nonfailed group were almost identical (154.98 versus 154.62) as was the coefficient of variation (8.1% versus 12%). Not surprisingly, the ANOVA test revealed that the difference in the mean value of the two groups was not significant, with the probability, p, of observing sample results equal to 0.953, which exceeds the stated level of significance. The ANOVA results are shown in Table 3. This suggests that variations in the ultimate strength of individual anchor rods, varying by size and grade of steel, did not appear to have a significant influence on plate washer performance.

Another aspect of this study considered the orientation of the anchor rod relative to the plate washer. The experimental setup allowed for the installation of the plates so that the anchor rod could be placed in a "centered" orientation or an "offset" orientation (i.e., the rod placed to the edge of the plate washer hole). Variations in the designed versus actual location of anchor bolts are an anticipated occurrence and the tolerances governing these variations are found in the AISC *Code of Standard Practice* (AISC, 2016a). As noted earlier, each plate washer was systematically measured after testing to determine its relative deformation.

The anchor rods that were loaded until failure were studied to determine if orientation of the anchor rod (centered versus offset) had any apparent effect on the relative deformation exhibited. Results showed that the mean value of relative deformation for the offset specimens was higher than the group of plate washers having the centered orientation (20.71% versus 16.49%). A single-factor ANOVA was performed to statistically test a null hypothesis that there was no significant difference in the mean value of the centered and offset groups using a level of significance of 0.05. This test revealed that the difference in the mean value of relative deformation for the two groups was not significant, with the probability, p, of observing sample results equal to 0.484, which exceeds the stated level of significance (Table 4). Interestingly, of the 10 plate washers whose relative deformation exceeded the failure threshold of 40%, seven of those were tested in the offset orientation. However, the average relative deformation of those seven specimens having an offset orientation averaged 74.2%, while the relative deformation of washers having the centered orientation was 100.8%. This also supports the statistical finding that anchor rod orientation is not significantly associated with the relative deformation experienced by plate washers.

While the ultimate capacity and orientation of the anchor rods seemed to lack significant association with plate washer performance in this study, a review of the results indicates that stiffness and thickness of the plate washers are influential. As noted previously, only 10 plate washers of the 94 tested exhibited relative deformation above the 40% failure threshold. Of the 10 considered to have failed, six had thicknesses less than the minimum thickness

Table 5. Recommended Plate Washer Thickness—By Rod Diameter Only

Anchor Rod Diameter (in.)	Recommended Plate Washer Thickness (in.)	AISC *Manual* 15th Ed. Specified Plate Washer Thickness (in.)
¾	⅜	¼
⅞	½	5⁄16
1	½	⅜
1¼	⅝	½
1½	⅝	½
1¾	¾	⅝
2	¾	¾
2½	⅞	⅞

found in AISC *Manual* Table 14-2. Of the remaining four plate washers that were judged to have failed, all had plate thicknesses matching the minimum thickness found in Table 14-2, but all were part of an assembly using Grade 105 anchor rods. This finding would appear to support the concept of minimum plate washer thickness being associated with the specified grade of steel for anchor rods.

RECOMMENDATIONS

This experimental study considered the behavior of plate washers in a column base connection using anchor rods of various sizes and grades of steel. No plate washers ruptured during testing, but 10 plate washers were unable to effectively develop the ultimate strength of the anchor rods without incurring significant deformations. No clear standard exists currently that would define how much out-of-plane deformation would constitute failure of a plate washer in column base assembly. Based on post-test measurements of the plate washers coupled with visual assessment, it can be reasonably asserted that plate washers experiencing more than 40% out-of-plane deformation relative to its original average thickness can be judged to have failed.

Of the 94 plate washers tested, 10 showed significant out-of-plane deformation exceeding the 40% relative deformation threshold. Of these failed plate washers, six had thicknesses less than that required in the 15th edition of the AISC *Manual* Table 14-2, while the other four plate washers all were coupled with anchor rods using Grade 105 steel. All minimum thicknesses of plate washers in AISC *Manual* Table 14-2 are recommended based on the diameter of the anchor rod only. Because anchors rods made from Grade 105 steel are designed to develop high tensile forces, if minimum plate washer thickness continues to be recommended only based on anchor rod diameter, then the results of this testing support the changes found in Table 5.

The washer thickness recommended for the 2½-in.-diameter rod is ⅞ in. because the ultimate strength of the 2½ in. Grade 105 anchor rod specimens could not be fully developed due to limitations of the testing equipment. This recommendation of ⅞ in. is given tentatively until further testing yields more information.

Although Grade 36 and Grade 55 are more common, anchor rods made from Grade 105 steel may be necessary when conditions warrant the need to develop large tensile forces. As previously noted, 40% of the plate washers that failed in this study had a thickness in line with the minimum thickness specified in AISC *Manual* Table 14-2, but were tested with Grade 105 anchor rods. Given the considerable difference between loads carried by anchor rods of the same diameter, but of different steel grades, it may be valuable to include recommendations by the steel grade of the anchor rod as well as the diameter. The recommended minimum plate washer thickness given in such a format is shown in Table 6.

CONCLUSION

In summary, this study has produced the first experimentally developed values for the thicknesses of plate washers used in column baseplate and anchor rod applications. The results have shown that ASTM F1554 Grade 36 and Grade 55 anchor rods having diameters of ¾, 1, 1½, 2, and 2½ in. can be adequately developed using the currently specified minimum plate washer thicknesses found in Table 14-2 of the 15th edition of the AISC *Steel Construction Manual* (2017). The results also found that for ASTM F1554 Grade 105 anchor rods, the minimum plate washer thicknesses specified in the 15th edition of the AISC *Manual* were not sufficient to develop the rods' ultimate strength without excessive deformations for anchor rods having ¾, 1, and 1½ in., diameters. For anchor rods having ¾, 1, and

Table 6. Recommended Plate Washer Thicknesses—By Diameter and Grade			
Anchor Rod Diameter (in.)	**Grade of Steel**	**Recommended Plate Washer Thickness (in.)**	**AISC *Manual* 15th Ed. Specified Plate Washer Thickness (in.)**
¾	Gr. 36	¼	¼
	Gr. 55	¼	
	Gr. 105	⅜	
⅞	Gr. 36	⅜	5⁄16
	Gr. 55	⅜	
	Gr. 105	½	
1	Gr. 36	⅜	⅜
	Gr. 55	⅜	
	Gr. 105	½	
1¼	Gr. 36	⅜	½
	Gr. 55	½	
	Gr. 105	⅝	
1½	Gr. 36	⅜	½
	Gr. 55	½	
	Gr. 105	⅝	
1¾	Gr. 36	¾	⅝
	Gr. 55	¾	
	Gr. 105	¾	
2	Gr. 36	¾	¾
	Gr. 55	¾	
	Gr. 105	¾	
2½	Gr. 36	¾	⅞
	Gr. 55	¾	
	Gr. 105	⅞	

1½ in., diameters and made of Grade 105 steels, a plate washer ⅛ in. greater in thickness than that currently given in AISC *Manual* Table 14-2 was needed to develop the ultimate strength of the rod without incurring a 40% relative deformation or greater. The currently specified plate washer thickness was found to be sufficient for the 2-in.-diameter Grade 105 anchor rod, and the testing was inconclusive for the 2½-in.-diameter Grade 105 rod. Recommended minimum plate washer thicknesses are provided for anchor rods with ⅞, 1¼, and 1¾ in. diameters using conservative estimates based on the testing conducted. Additionally, it was found that the anchor rod orientation and the potential variations of ultimate strength in individual anchor rods did not appear to be significantly associated with the performance of plate washers in these tests.

Future studies could investigate the performance of plate washers under various conditions including the use of welds, field modification of baseplate holes, and the effect of the combination of shear and tension forces.

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APPENDIX

In this Appendix, tables reporting the measured plate washer deformation data, the statistical distribution of relative deformation of the plate washers, and the measured strengths of the threaded rods are presented.

Specifically, Table A-1 summarizes the deformation data of the plate washers tested, reporting the nominal thickness, the measured thicknesses at the mid-points of all four sides, the maximum measured deformation, the average measured thickness, and the percent deformation with respect to both nominal and average measured thickness. Table A-2 contains the binned relative deformation data that was used to produce Figure 7.

Table A-3 summarizes measured data on the threaded rods used during the tests, reporting plate washer orientation (1 = centered, 2 = offset) and its nominal thickness, the rod diameter and grade, its minimum and maximum tensile strength from ASTM F1554, the measured ultimate strength, the minimum yield strength from ASTM F1554, the calculated yield strength (using the 0.2% offset method), and the calculated design strength. Values highlighted in red do not meet some of the ASTM F1554 given limits. Note that the threaded rods used in tests 73 through 78 are consistently above maximum tensile strength, while those in tests 79 through 82 are very close to the minimum tensile strength. It is posited that the rods were mismarked (rod ends are routinely color coded to indicate grade), and thus, the Grade 36 set was really a Grade 55 (and, in this case, the measured values would all be acceptable), and the Grade 55 set was really a Grade 36 (and, in this case, the measured values would be closer to maximum tensile strength, without surpassing it, as would be routinely expected).

The full set of data can be found in the testing report submitted to AISC (Cozzens et al., 2021).

Table A-1. Plate Washer Deformation Data									
Test Number	Nominal t	t_1	t_2	t_3	t_4	Δ_{max}	t_{avg}	% $Deformed_{nominal}$	% $Deformed_{ave}$
1	0.500	0.505	0.495	0.505	0.491	—	0.499	—	—
2	0.500	0.490	0.490	0.489	0.500	—	0.492	—	—
3	0.375	0.375	0.376	0.380	0.370	0.024	0.375	6.32%	6.32%
4	0.375	0.375	0.376	0.372	0.372	0.016	0.374	4.19%	4.20%
5	0.250	0.245	0.246	0.247	0.255	0.062	0.248	24.88%	25.06%
6	0.250	0.242	0.244	0.248	0.254	0.027	0.247	10.76%	10.89%
7	0.500	0.490	0.491	0.502	0.510	0.015	0.498	2.96%	2.97%
8	0.500	0.492	0.501	0.491	0.510	0.086	0.499	17.16%	17.21%
9	0.375	0.369	0.376	0.377	0.375	0.025	0.374	6.67%	6.68%
10	0.375	0.375	0.375	0.369	0.379	0.018	0.375	4.85%	4.86%
11	0.250	0.263	0.248	0.248	0.245	0.051	0.251	20.52%	20.44%
12	0.250	0.242	0.266	0.248	0.249	0.069	0.251	27.64%	27.50%
13	0.500	0.505	0.495	0.505	0.491	0.025	0.499	5.02%	5.03%
14	0.500	0.490	0.490	0.489	0.500	0.046	0.492	9.22%	9.37%
15	0.375	0.375	0.376	0.372	0.376	0.047	0.375	12.53%	12.54%
16	0.375	0.375	0.375	0.374	0.376	0.046	0.375	12.16%	12.16%
17	0.250	0.250	0.252	0.242	0.240	0.177	0.246	70.68%	71.83%
18	0.250	0.241	0.239	0.246	0.248	0.169	0.244	67.44%	69.24%
19	0.500	0.490	0.499	0.493	0.493	0.058	0.494	11.58%	11.73%
20	0.500	0.492	0.492	0.492	0.495	0.059	0.493	11.70%	11.87%
21	0.375	0.374	0.492	0.374	0.375	0.038	0.404	10.11%	9.39%
22	0.375	0.369	0.370	0.368	0.370	0.045	0.369	11.92%	12.11%
23	0.250	0.239	0.245	0.252	0.245	0.240	0.245	96.12%	97.98%
24	0.250	0.248	0.243	0.250	0.253	0.271	0.249	108.36%	109.01%
25	0.500	0.488	0.489	0.493	0.501	0.044	0.493	8.88%	9.01%
26	0.500	0.490	0.492	0.491	0.490	0.053	0.491	10.60%	10.80%
27	0.375	0.371	0.373	0.368	0.370	0.063	0.371	16.80%	17.00%
28	0.375	0.372	0.366	0.372	0.369	0.039	0.370	10.32%	10.47%
29	0.250	0.249	0.250	0.245	0.245	0.342	0.247	136.80%	138.32%
30	0.250	0.245	0.245	0.245	0.241	0.339	0.244	135.48%	138.81%

(Table A-1 continues on the next page)

Table A-1. Plate Washer Deformation Data (continued)									
Test Number	Nominal t	t_1	t_2	t_3	t_4	Δ_{max}	t_{avg}	% Deformed$_{nominal}$	% Deformed$_{ave}$
31	0.750	0.741	0.744	0.737	0.746	0.020	0.742	2.72%	2.75%
32	0.750	0.739	0.736	0.737	0.747	0.014	0.740	1.85%	1.88%
33	0.500	0.494	0.495	0.498	0.492	0.070	0.495	13.96%	14.11%
34	0.500	0.495	0.491	0.503	0.500	0.068	0.497	13.54%	13.61%
35	0.375	0.373	0.373	0.374	0.375	0.132	0.374	35.07%	35.18%
36	0.375	0.375	0.374	0.375	0.373	0.233	0.374	62.16%	62.28%
37	0.750	0.749	0.749	0.750	0.749	0.023	0.749	3.03%	3.03%
38	0.750	0.751	0.751	0.750	0.749	0.029	0.750	3.91%	3.91%
39	0.500	0.496	0.490	0.486	0.498	0.076	0.493	15.24%	15.47%
40	0.500	0.490	0.491	0.490	0.496	0.078	0.492	15.60%	15.86%
41	0.375	0.372	0.370	0.370	0.378	0.063	0.373	16.77%	16.89%
42	0.375	0.372	0.374	0.374	0.381	0.196	0.375	52.37%	52.34%
43	0.750	0.757	0.749	0.749	0.752	0.027	0.752	3.57%	3.57%
44	0.750	0.750	0.750	0.750	0.751	0.017	0.750	2.24%	2.24%
45	0.500	0.499	0.501	0.493	0.496	0.074	0.497	14.86%	14.94%
46	0.500	0.497	0.497	0.500	0.493	0.096	0.497	19.28%	19.41%
47	0.375	0.372	0.375	0.373	0.373	0.168	0.373	44.85%	45.06%
48	0.375	0.372	0.374	0.370	0.376	0.068	0.373	18.00%	18.10%
49	1.000	1.000	1.005	0.999	0.999	0.022	1.001	2.18%	2.18%
50	1.000	1.001	1.001	1.000	0.999	0.017	1.000	1.68%	1.68%
51	0.750	0.752	0.752	0.751	0.750	0.036	0.751	4.79%	4.78%
52	0.750	0.752	0.752	0.750	0.751	0.043	0.751	5.73%	5.72%
53	0.500	0.490	0.490	0.492	0.501	0.178	0.493	35.52%	36.01%
54	0.500	0.488	0.487	0.498	0.491	0.189	0.491	37.72%	38.41%
1A	0.500	0.498	0.495	0.497	0.495	0.210	0.496	41.94%	42.26%
2A	0.500	0.495	0.495	0.497	0.496	0.069	0.496	13.70%	13.82%
3A	0.625	0.624	0.625	0.625	0.625	0.069	0.625	10.96%	10.96%
4A	0.625	0.624	0.623	0.626	0.625	0.067	0.625	10.72%	10.73%
55	1.000	0.998	0.997	0.991	0.998	0.010	0.996	0.96%	0.96%
56	1.000	1.000	1.000	1.001	1.001	0.014	1.001	1.40%	1.40%
57	0.875	0.880	0.881	0.880	0.886	0.017	0.882	1.93%	1.92%

(Table A-1 continues on the next page)

Table A-1. Plate Washer Deformation Data (continued)									
Test Number	Nominal t	t_1	t_2	t_3	t_4	Δ_{max}	t_{avg}	% Deformed$_{nominal}$	% Deformed$_{ave}$
58	0.875	0.885	0.880	0.880	0.883	0.019	0.882	2.13%	2.11%
59	0.750	0.753	0.754	0.756	0.754	0.011	0.754	1.40%	1.39%
60	0.750	0.755	0.756	0.753	0.752	0.047	0.754	6.32%	6.29%
61	1.000	1.000	1.000	0.998	0.998	0.017	0.999	1.69%	1.69%
62	1.000	1.002	0.999	0.999	1.002	0.060	1.001	5.98%	5.98%
63	0.875	0.883	0.884	0.880	0.881	0.033	0.882	3.73%	3.70%
64	0.875	0.881	0.881	0.882	0.879	0.059	0.881	6.72%	6.68%
65	0.750	0.753	0.753	0.754	0.757	0.051	0.754	6.73%	6.70%
66	0.750	0.753	0.753	0.753	0.757	0.051	0.754	6.81%	6.78%
67	1.250	1.253	1.252	1.253	1.262	0.040	1.255	3.22%	3.20%
68	1.250	1.253	1.256	1.253	1.263	0.044	1.256	3.53%	3.51%
69	1.000	1.003	1.000	1.000	0.998	0.080	1.000	7.96%	7.96%
70	1.000	0.997	0.960	0.999	0.999	0.055	0.989	5.45%	5.51%
71	0.750	0.752	0.753	0.754	0.752	0.122	0.753	16.20%	16.14%
72	0.750	0.754	0.754	0.755	0.756	0.140	0.755	18.68%	18.56%
73	1.000	1.000	1.000	0.999	1.002	0.061	1.000	6.11%	6.11%
74	1.000	1.000	0.999	0.998	1.001	0.046	1.000	4.59%	4.59%
75	0.875	0.883	0.886	0.889	0.887	0.102	0.886	11.61%	11.46%
76	0.875	0.883	0.883	0.883	0.882	0.078	0.883	8.94%	8.86%
77	0.875	0.882	0.882	0.880	0.886	0.075	0.883	8.58%	8.51%
78	0.875	0.882	0.883	0.886	0.882	0.108	0.883	12.33%	12.22%
79	1.000	1.000	0.999	1.001	1.003	0.032	1.001	3.22%	3.22%
80	1.000	1.003	1.002	1.000	1.000	0.044	1.001	4.39%	4.38%
81	0.750	0.755	0.755	0.755	0.757	0.055	0.756	7.36%	7.31%
82	0.750	0.753	0.755	0.757	0.756	0.090	0.755	12.03%	11.94%
83	1.500	1.516	1.515	1.510	1.518	0.017	1.515	1.11%	1.10%
84	1.500	1.507	1.514	1.512	1.514	0.034	1.512	2.26%	2.24%
85	1.250	1.251	1.257	1.253	1.256	0.046	1.254	3.64%	3.63%
86	1.250	1.253	1.253	1.252	1.257	0.043	1.254	3.42%	3.41%
87	0.875	0.882	0.883	0.884	0.882	0.111	0.883	12.66%	12.55%
88	0.875	0.882	0.883	0.883	0.882	0.076	0.883	8.67%	8.60%
89	0.750	0.752	0.755	0.754	0.753	0.075	0.754	9.95%	9.90%
90	0.750	0.755	0.755	0.753	0.754	0.125	0.754	16.71%	16.61%

Table A-2. Statistical Distribution of Relative Deformation											
Stat.	**0%–5%**			**5%–10%**			**10%–15%**			**15%–20%**	
Min	**0.96%**	**0.96%**		**5.02%**	**5.03%**		**10.11%**	**10.47%**		**15.24%**	**15.47%**
Avg.	**2.88%**	**2.87%**		**7.23%**	**7.33%**		**12.00%**	**11.74%**		**17.04%**	**17.13%**
Median	**2.99%**	**3.00%**		**6.73%**	**6.74%**		**11.92%**	**12.02%**		**16.79%**	**16.94%**
Max	**4.85%**	**4.86%**		**9.95%**	**9.90%**		**14.86%**	**13.61%**		**19.28%**	**19.41%**
28	0.96%	0.96%	19.5	5.02%	5.03%	18.5	10.11%	10.47%	10	15.24%	15.47%
	1.11%	1.10%		5.45%	5.51%		10.32%	10.73%		15.60%	15.86%
	1.40%	1.39%		5.73%	5.72%		10.60%	10.80%		16.20%	16.14%
	1.40%	1.40%		5.98%	5.98%		10.72%	10.89%		16.71%	16.61%
	1.68%	1.68%		6.11%	6.11%		10.76%	10.96%		16.77%	16.89%
	1.69%	1.69%		6.32%	6.29%		10.96%	11.46%		16.80%	17.00%
	1.85%	1.88%		6.32%	6.32%		11.58%	11.73%		17.16%	17.21%
	1.93%	1.92%		6.67%	6.68%		11.61%	11.87%		18.00%	18.10%
	2.13%	2.11%		6.72%	6.68%		11.70%	11.94%		18.68%	18.56%
	2.18%	2.18%		6.73%	6.70%		11.92%	12.11%		19.28%	19.41%
	2.24%	2.24%		6.81%	6.78%		12.03%	12.16%			
	2.26%	2.24%		7.36%	7.31%		12.16%	12.22%			
	2.72%	2.75%		7.96%	7.96%		12.33%	12.54%			
	2.96%	2.97%		8.58%	8.51%		12.52%	12.55%			
	3.03%	3.03%		8.67%	8.60%		12.66%	13.61%			
	3.22%	3.20%		8.88%	8.86%		13.54%	13.82%			
	3.22%	3.22%		8.94%	9.01%		13.70%	14.11%			
	3.42%	3.41%		9.22%	9.37%		13.96%	14.94%			
	3.53%	3.51%		9.95%	9.39%		14.86%				
	3.57%	3.57%			9.90%						
	3.64%	3.63%									
	3.73%	3.70%									
	3.91%	3.91%									
	4.19%	4.20%									
	4.39%	4.38%									
	4.59%	4.59%									
	4.79%	4.78%									
	4.85%	4.86%									

Table A-2. Statistical Distribution of Relative Deformation (continued)														
Stat.	**20%–25%**			**25%–30%**			**30%–40%**			**40%–50%**			**>50%**	
Min	20.52%	20.44%		27.64%	25.06%		35.07%	35.18%		41.94%	15.47%		52.37%	52.34%
Avg.	22.70%	20.44%		27.64%	26.28%		36.10%	36.53%		43.40%	17.13%		91.18%	92.48%
Median	22.70%	20.44%		27.64%	26.28%		35.52%	36.01%		43.40%	16.94%		83.40%	84.91%
Max	24.88%	20.44%		27.64%	27.50%		37.72%	38,41%		44.85%	19.41%		136.80%	1338.81%
1.5	20.52%	20.44%	1.5	27.64%	25.06%	3	35.07%	35.18%	2	41.94%	15.47%	8	52.37%	52.34%
	24.88%				27.50%		35.52%	36.01%		44.85%	15.86%		62.16%	62.28%
							37.72%	38.41%					67.44%	69.24%
													70.68%	71.83%
													96.12%	97.98%
													108.36%	109.01%
													135.48%	138.32%
													136.80%	138.81%

Table A-3. Performance of Threaded Rods										
					ASTM Specified		Measured	ASTM Specified	Measured	
Test Number	Orientation	Nominal *t* (in.)	Diameter (in.)	Grade (ksi)	Minimum Tensile (kips)	Maximum Tensile (kips)	Ultimate Tensile (kips)	Minimum Yield (kips)	Yield (kips)	Design Strength (kips)
1	1	0.500	0.750	36	19.4	26.7	23.05	12.00	15.8	14.55
2	2	0.500					22.97		15.8	
3	1	0.375					22.96		15.8	
4	2	0.375					23.02		15.8	
5	2	0.250					23.05		15.8	
6	1	0.250					23.17		16.0	
7	1	0.500	0.750	55	25.0	31.7	29.69	18.40	21.8	18.75
8	2	0.500					29.51		21.6	
9	2	0.375					29.62		22.0	
10	1	0.375					29.65		21.9	
11	1	0.250					29.39		21.5	
12	2	0.250					29.48		21.7	
13	2	0.500	0.750	105	41.8	50.1	48.14	35.10	41.9	31.35
14	1	0.500					47.52		42.2	
15	1	0.375					47.63		41.9	
16	2	0.375					47.54		41.6	
17	2	0.250					48.40		41.5	
18	1	0.250					48.03		41.5	
19	1	0.500	1.000	36	35.2	48.5	47.27	21.80	34.0	26.40
20	2	0.500					47.10		35.2	
21	2	0.375					47.21		35.2	
22	1	0.375					47.17		35.1	
23	1	0.250					46.74		34.5	
24	2	0.250					46.99		35.4	
25	2	0.500	1.000	55	45.4	57.6	51.74	33.30	36.2	34.05
26	1	0.500					51.79		34.0	
27	1	0.375					51.71		35.7	
28	2	0.375					51.73		36.0	
29	2	0.250					51.66		35.7	
30	1	0.250					51.23		35.5	
31	1	0.750	1.000	105	75.8	90.9	76.77	63.60	67.2	56.85
32	2	0.750					84.54		61.8	
33	2	0.500					81.53		70.5	
34	1	0.500					84.41		66.7	
35	1	0.375					76.49		61.8	
36	2	0.375					81.65		70.0	

(Table A-3 continues on the next page)

Table A-3. Performance of Threaded Rods (continued)										
					ASTM Specified		Measured	ASTM Specified	Measured	
Test Number	Orientation	Nominal *t* (in.)	Diameter (in.)	Grade (ksi)	Minimum Tensile (kips)	Maximum Tensile (kips)	Ultimate Tensile (kips)	Minimum Yield (kips)	Yield (kips)	Design Strength (kips)
37	1	0.750	1.500	36	81.5	112.4	104.10	50.60	71.7	81.50
38	2	0.750					113.85		81.8	
39	2	0.500					104.35		82.2	
40	1	0.500					113.66		71.8	
41	1	0.375					103.67		72.8	
42	2	0.375					113.66		81.4	
43	2	0.750	1.500	55	105.0	133.0	119.61	77.30	84.3	78.75
44	1	0.750					119.63		84.5	
45	1	0.500					119.58		83.2	
46	2	0.500					119.82		84.0	
47	2	0.375					119.72		84.0	
48	1	0.375					119.95		83.3	
49	1	1.000	1.500	105	176.0	216.0	190.61	148.00	184.4	132.00
50	2	1.000					174.63		143.0	
51	2	0.750					191.50		143.6	
52	1	0.750					174.27		168.1	
53	1	0.500					191.58		166.1	
54	2	0.500					174.14		143.5	
1A	2	0.500	1.500	105.0	176.0	216.0	197.84	148.00	158.0	132.00
2A	1	0.500					196.87		157.0	
3A	1	0.625					197.45		157.2	
4A	2	0.625					198.42		156.0	
55	1	1.000	2.000	36	145.0	200.0	184.16	90.00	112.0	108.75
56	2	1.000					184.18		113.0	
57	2	0.875					182.86		113.5	
58	1	0.875					184.39		113.5	
59	1	0.750					183.58		114.8	
60	2	0.750					182.89		115.5	
61	2	1.000	2.000	55	188.0	238.0	214.68	138.00	141.0	141.00
62	1	1.000					214.62		141.0	
63	1	0.875					213.97		141.5	
64	2	0.875					213.06		139.5	
65	2	0.750					214.43		140.0	
66	1	0.750					214.79		141.0	

(Table A-3 continues on the next page)

Table A-3. Performance of Threaded Rods (continued)										
					ASTM Specified		Measured	ASTM Specified	Measured	
Test Number	Orientation	Nominal *t* (in.)	Diameter (in.)	Grade (ksi)	Minimum Tensile (kips)	Maximum Tensile (kips)	Ultimate Tensile (kips)	Minimum Yield (kips)	Yield (kips)	Design Strength (kips)
67	1	1.250	2.000	105	312.0	375.0	325.24	262.00	276.5	234.00
68	2	1.250					309.77		271.0	
69	2	1.000					312.46		284.0	
70	1	1.000					323.59		273.0	
71	1	0.750					316.23		284.0	
72	2	0.750					311.86		284.0	
73	1	1.000	2.500	36	232.0	320.0	340.31	144.00	321.0	174.00
74	2	1.000					336.91		318.0	
75	2	0.875					355.52		297.5	
76	1	0.875					357.61		313.0	
77	1	0.875					355.98		315.0	
78	2	0.875					354.39		298.0	
79	2	1.000	2.500	55	300.0	380.0	312.10	220.00	214.0	225.00
80	1	1.000					311.32		217.0	
81	1	0.750					314.29		211.5	
82	2	0.750					312.40		214.5	
83	2	1.500	2.500	105	500.0	600.0	399.41	420.00	—	375.00
84	1	1.500					399.01		—	
85	1	1.250					400.35		—	
86	2	1.250					398.98		—	
87	2	0.875					397.17		—	
88	1	0.875					388.71		—	
89	1	0.750					389.34		—	
90	2	0.750					385.88		—	