Pull-Through Testing of Plate Washers for Column Anchor Rod Applications

A Technical Report Submitted to the American Institute of Steel Construction

by

Paul A. Cozzens, E.I.T.
Bachelor of Science in Civil Engineering
University of Evansville, 2020

And

Gian Andrea Rassati, Ph.D.
Associate Professor of Structural Engineering
University of Cincinnati

James A. Swanson, Ph.D.
Associate Professor of Structural Engineering
University of Cincinnati

University of CINCINNATI
COLLEGE OF ENGINEERING AND APPLIED SCIENCE

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University of Cincinnati

Abstract

In the 13th and 14th Editions of the American Institute of Steel Construction's (AISC) *Manual of Steel Construction* (the *Manual* herein), provisions have been included that recommend appropriate sizes and thicknesses of steel plate washers to be used in the column base plate and anchor rod assembly. Each washer must have sufficient strength and stiffness to fully develop the anchor rod to which it is fastened without succumbing to pull-through failure, flexural failure, or cracking. Questions received by AISC's Solution Center spurred some interest in further investigating the values provided in the *Manual*.

The enclosed report presents the results from the laboratory tensile testing of the anchor rod and nut, plate washer and base plate assembly, specifically with regard to the performance of the plate washers in the pull-through failure condition. This testing investigated the capacity of ASTM A572 Gr. 50 plate washers using the *Manual's* recommended thicknesses, as well as other thickness values. Threaded rods having 0.75", 1", 1.5", 2", and 2.5" diameter, as listed in Table 14-2 of the *Manual*, were developed fully in tension, and the aforementioned plate washers were examined for signs of failure. The permanent out-of-plane deformation of the plate washers was measured after testing as a means of determining if a given washer had failed under tensile loading to the assembly. The testing procedure and the measured results are included herein.

Chapter 1: Introduction and Literature Review

To date, no direct testing has been conducted on plate washers in column base plate applications, or on plate washers in general. The most significant research in the area of steel column baseplates and anchor rods in recent years was that conducted by Grilli and Kanvinde (2016) at the University of California Davis. They investigated shear transfer in steel column baseplates, and contributed to the update of AISC's *Design Guide 1*. Again in 2017, Grilli and Kanvinde and Grilli et al. studied Embedded Column Base connections (ECB) when being subjected to axial and flexural loads. Shear transfer deals with lateral loads, and ECBs do not utilize anchor rods and therefore plate washers. So, while these studies were integral to the current understanding of the column base plate assembly, they were included in this review as they were considered tangential to this topic. Because of the novelty of this testing, the literature review herein will discuss the relevant guides for the design of these assemblies as well as some related experimental and analytical research studies. Some material properties and characteristics of these assemblies will also be discussed with regard to their effect on the plate washer under tensile loading. This introduction will serve to describe the conditions in which the anchor rod assembly undergoes tensile loading and how it distributes the force from the column into the foundation, as well as to underscore the importance of the plate washer in the assembly.

1.1. Need for Testing

This testing project was conducted for the American Institute of Steel Construction (AISC) to evaluate whether or not the values for plate washer thickness on anchor rods listed in the *Manual* are adequate for uplift conditions. This is a necessary consideration as all steel structures must be designed for uplift loading (ASCE 7-16, 2016). Many structures may never experience full reversal of gravity loads due to wind or seismic activity, but steel buildings are especially susceptible to uplift forces during construction when most of the dead and live gravity loads are yet to be applied to the structure. In this condition, the column can be put in tension, forcing the anchor rods to follow suit. However, the case of an overturning moment about the base of the column is more common and is generally due to lateral forces on the structure (AISC, 2006). When this happens, all anchor bolts located to one side of the neutral axis of the column may be put in tension once the compressive forces in the column are overcome. AISC's *Design Guide 1* explores this loading condition in significant detail and provides several pertinent design examples.

1.2. *AISC Design Guide 1*

This design guide, first released by AISC in 1990 is "*intended to provide guidelines for engineers and fabricators to design, detail and specify column-base-plate and anchor rod connections in a manner that avoids common fabrication and erection problems*" (AISC, 2006). Generally speaking, it expounds on the *Manual*, provides design recommendations for cases that are not specifically addressed, and offers solutions to various design problems. While this is a very useful design aid for a structural engineer, it provides very little direct information on plate washers. That information and some tangentially relevant provisions will be discussed in this section.

Section 2.6 of the *Design Guide* states, "*The washer may be either a plain circular washer or a rectangular plate washer as long as the thickness is adequate to prevent pulling through the hole.*" Recommended washer dimensions are then listed in Table 2.3 and the thicknesses are based approximately on a 3:1 ratio of rod diameter to washer thickness. The values in this table match exactly those given in Table 14-2 of the *Manual* (AISC, 2017). These plate thicknesses were first included in the *Design Guide* and in the *Manual* in 2006, while the anchor rod diameter and hole diameters have been appearing since 1990 (AISC, 1990). It should be noted that this testing will only examine the case of square plate washers as they are the most commonly used and most easily produced form of these washers.

Table 1.1:AISC Design Guide 1 - Table 2.3 (AISC, 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	1$^{5}/_{16}$	2	¼
⅞	1$^{9}/_{16}$	2½	$^{5}/_{16}$
1	1$^{13}/_{16}$	3	⅜
1¼	2$^{1}/_{16}$	3	½
1½	2$^{5}/_{16}$	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 1$^{1}/_{16}$-in. hole size for ¾-in.-diameter anchor rods, with plates less than 1¼-in. thick.

Table 1.2: 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
$^{3}/_{4}$	1$^{5}/_{16}$	2	$^{1}/_{4}$	1$^{1}/_{2}$	2$^{5}/_{16}$	3$^{1}/_{2}$	$^{1}/_{2}$
$^{7}/_{8}$	1$^{9}/_{16}$	2$^{1}/_{2}$	$^{5}/_{16}$	1$^{3}/_{4}$	2$^{3}/_{4}$	4	$^{5}/_{8}$
1	1$^{13}/_{16}$	3	$^{3}/_{8}$	2	3$^{1}/_{4}$	5	$^{3}/_{4}$
1$^{1}/_{4}$	2$^{1}/_{16}$	3	$^{1}/_{2}$	2$^{1}/_{2}$	3$^{3}/_{4}$	5$^{1}/_{2}$	$^{7}/_{8}$

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 1$^{1}/_{4}$ in. thick, punching of holes may be an economical option. In this case, $^{3}/_{4}$-in. anchor rods and 1$^{1}/_{16}$-in. diameter punched holes may be used with ASTM F844 (USS Standard) washers in place of fabricated plate washers.

When *Design Guide 1* was developed and last updated, ASTM A36 steel plate was the most common plate material in use; however, this material is now becoming obsolete and will not be included in the 16th edition of the *Manual*. For this reason, ASTM A572 Gr. 50 steel was used for plate washers in this testing project as it is the more common grade of plate and will be used throughout in the 16th edition of the *Manual*.

It is also noted in AISC *Design Guide 1* that ASTM F436 washers are not to be used as plate washers in column base plate applications as they do not have a sufficient size and are susceptible to pull-through failure. It is stated that ASTM F844 steel plate washers may be used in cases where uplift is not a consideration (AISC, 2006). This further confirms the selection of A572 Gr. 50 steel as the most appropriate material to test. Most of the plate washer provisions in AISC *Design Guide 1* refer to the shear transfer behavior of the washers when welded to the column base plate, but two statements are made that are important to this project. In Section 2.7 of the *Design Guide*, it is stated that ASTM F1554 Gr. 36 anchor rods should be used up to 2" in diameter before increasing the grade of steel to increase the capacity of the rod. This provision was included in 2006 because of material availability and possibly because the Gr. 36 steel provides considerably more ductility to delay catastrophic failure under seismic or cyclic loading. Whatever the case, this testing will examine all three grades of ASTM F1554 steel anchor rods as all three grades are widely used in the U.S. industry today (Carter, 1999). Also, in Section 2.7 of the *Design Guide*, it is mentioned that if the anchor rods are not set in the concrete foundation such that they fit in the holes of the column base plate, those holes should be slotted, and plate washers should be used to cover the gaps in the hole (AISC, 2006). However, the hole sizes given in the *Manual* and in *Design Guide 1* are both already oversized due to an expected lack of centricity of the anchor rods in the column base plate holes. This provision, referring to rods which do not fit in these oversized holes, is vague and presents a potential danger to the structure given that the size of the slot and the dimensions of the plate washer are not addressed here. This should be carefully considered by the engineer of record, but the results of this testing will not apply to this case.

Lastly, AISC *Design Guide 1* presents detailed sets of calculations in the case of both small and large overturning moments about the column base plate in Sections 3.3 and 3.4, respectively. These are used to guide the design of the column base plate itself, based on the allowable bearing pressure of the concrete foundation and the section properties of the column, given information about the tensile and compressive capacities of the anchor rods. These calculations could be reversed and used to calculate the tensile demand on the anchor rods if a particular lateral displacement or force is calculated from an appropriate design procedure. However, this is outside the scope of this testing as all rod and washer assemblies were tested to failure.

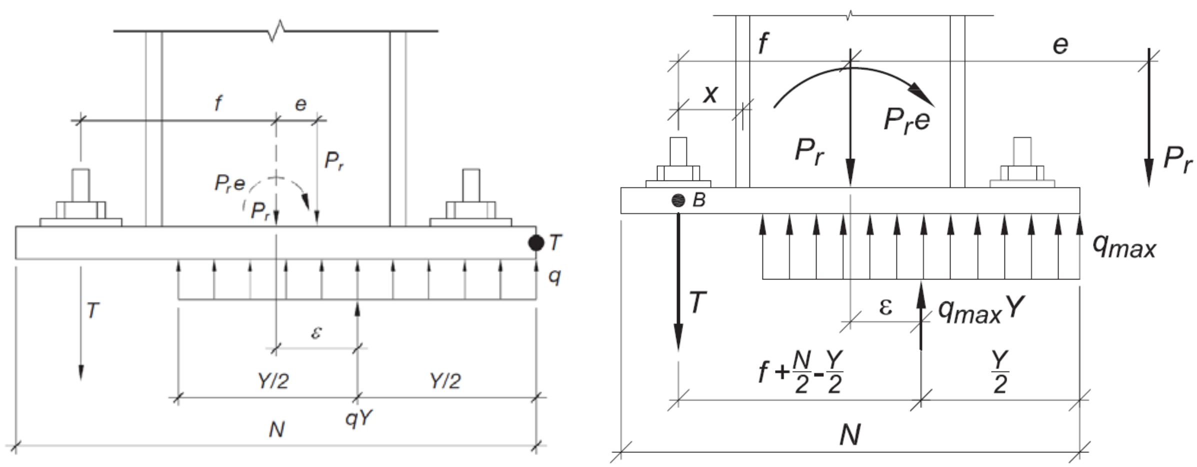

Figure 1.1: Small (left) and Large Moment Schematics (AISC, 2006)

1.3. *Practical Design and Detailing of Steel Column Base Plates*

An issue of *Steel Tips* was released by the Structural Steel Education Council in 1999 and was intended to "*provide practical guidelines for engineers, fabricators and contractors regarding the design and detailing of steel column base plates*" (Honeck & Westphal, 1999). The first section of this resource aims to inform the reader of current fabrication best practices and material preferences for engineers and contractors. It tackles the issue of how to manage common erection problems such as how to ensure that anchor rods are properly set and what size holes should be specified (Honeck & Westphal, 1999). The *Manual* is referenced in this section of the resource and the same hole sizes are given as in Table 14.2 of the *Manual*. The following section outlines guidelines for designing these assemblies and discusses loading conditions, including uplift and moment. In the case of uplift or moment, this design aid heavily emphasizes the need for ductility of the anchor rods as the most common cause for uplift or overturning moments is cyclic wind or seismic loads (Honeck & Westphal, 1999). This may substantiate the recommendation made in AISC *Design Guide 1* that F1554 Gr. 36 be used up to 2” diameter rods before increasing the grade. This publication also affirms that plate washers should only be welded to the column base plate if the system is being designed to transfer shear forces from the column into the foundation. Otherwise, flexure is then added to the anchor rod, creating a combined axial/flexural effect on the rod (Honeck & Westphal, 1999). This design and detailing guide included more information on fabrication and erection than design, but it did help to elaborate on some of the issues discussed in AISC *Design Guide 1*.

1.4. *Experimental and Analytical Investigation of Steel Column Bases*

This combined experimental and analytical research study from the University of Athens, Greece attempted to establish a mathematical relationship between the bending moment in the column baseplate and the displacement angle of the column in its strong direction. It also set out to observe the stresses experienced by the base plate when the column undergoes uniaxial bending (Stamatopoulos & Ermopoulos, 2011). As with most studies, this research did not directly analyze the plate washers, but it did establish some general understanding of the behavior of the column base plate and anchor rod assembly. In the experimental portion of this study, a small steel column was bolted to a sample concrete foundation, and two pistons were used: one to add compressive force to the member, and one to introduce a strong axis rotational displacement. See Figure 1.2.

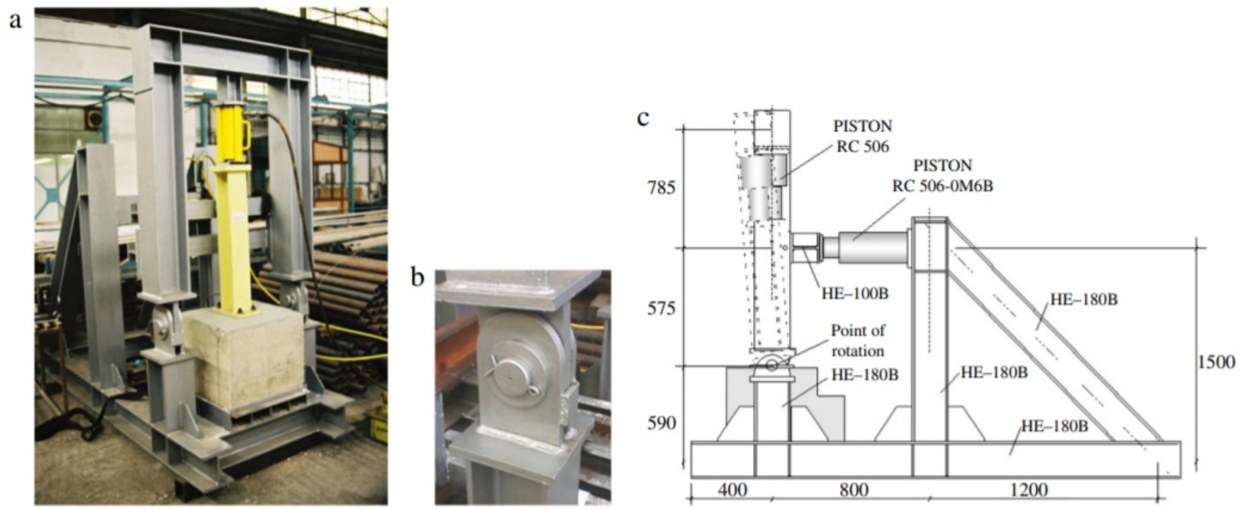

Figure 1.2: University of Athens Test Setup (Stamatopoulos & Ermopoulos, 2011)

From these test results, curves were created to plot the relationship between the moment about the column base plate vs. the rotational displacement of the column. These curves showed the plate yielding behavior which was confirmed by the finite element analysis, and both were used to develop the numerical model, seen in Figure 1.3, used for calculating the plastic moment in the base plate, based on the angle of rotation of the column.

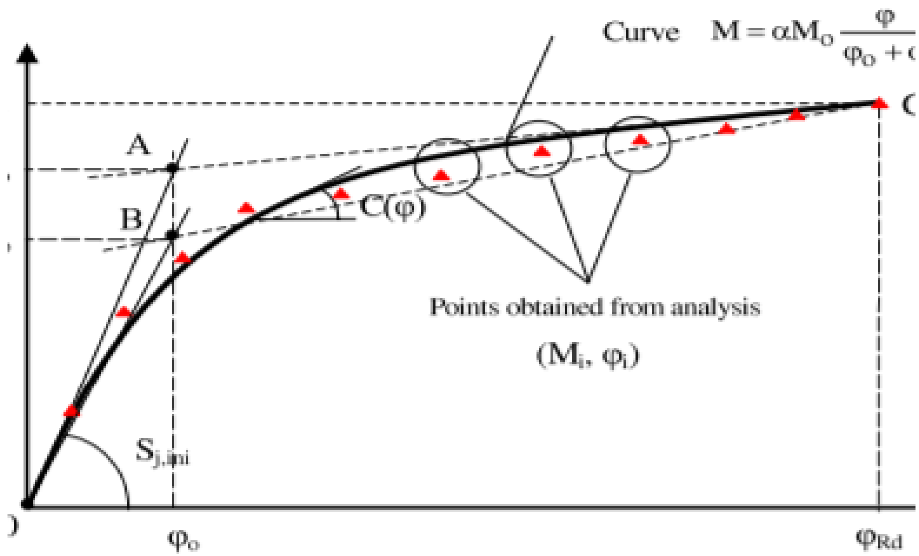

Figure 1.3: Relationship Derived for Moment vs. Rotation (Stamatopoulos & Ermopoulos, 2011)

However, more relevant to this testing is the supplementary information given in the appendices of the report which showed the ultimate failure modes for each specimen. The failure mode of all column base plate/anchor rod assemblies which experienced rupture was tensile failure of the anchor rods. While the plate washers used were of greater thickness than those recommended by the *Manual*, it is still worthy of note that when these specimens were loaded to failure, anchor rod tension was the controlling mode of failure (Stamatopoulos & Ermopoulos, 2011). This highlights the importance of this testing – that when steel columns undergo rotation about the base plate, its anchor rods have to be capable of achieving their full tensile strength to avoid catastrophic failure of the structure.

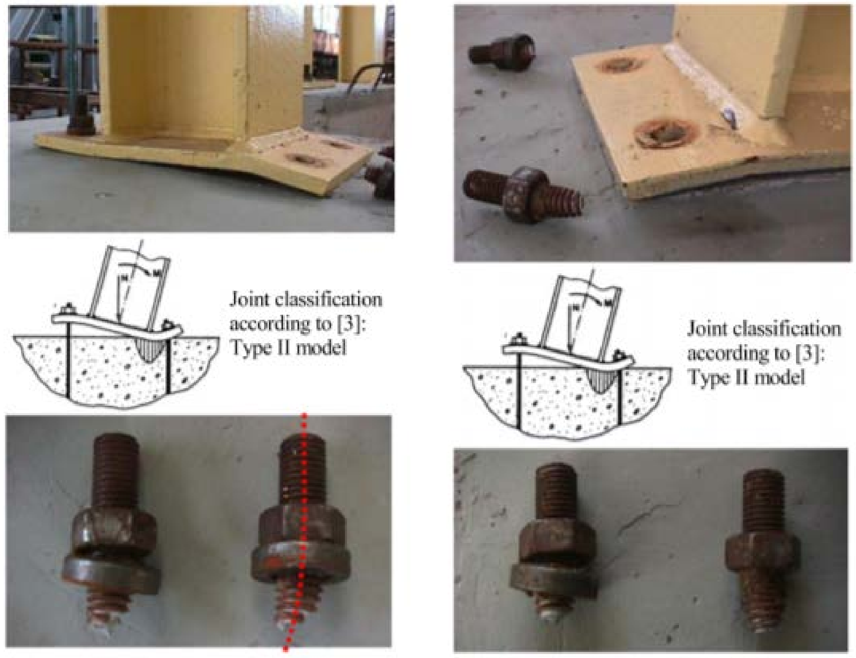

Figure 1.4: Tensile Rupture of Anchor Rods at Base Plate (Stamatopoulos & Ermopoulos, 2011)

1.5. *Analytical Approach of Anchor Rod Stiffness and Steel Base Plate etc.*

This article published by the *Research Journal of the Institution of Structural Engineers* is largely based on the research done by the University of Athens in the previously described study. It explores in great detail the distribution of stresses in a column baseplate under tensile loading and under uniaxial and biaxial moments. This research was conducted using the finite element analysis software packages SAP2000 and ABAQUS to model the behavior of steel column bases and anchor rods in bending and to observe the stresses created in the plate (Tsavdaridis et al., 2016). Primarily considering conventional base plates with four anchor rod holes but also analyzing more complicated bolt patterns, the consideration of biaxial moments created complicated patterns of tensile forces in the anchor rods in each base plate, depending on the location of the anchor rod on the column base plate. Figure 1.5 shows an example of the distribution of tensile force among anchor rods developed using finite element analysis.

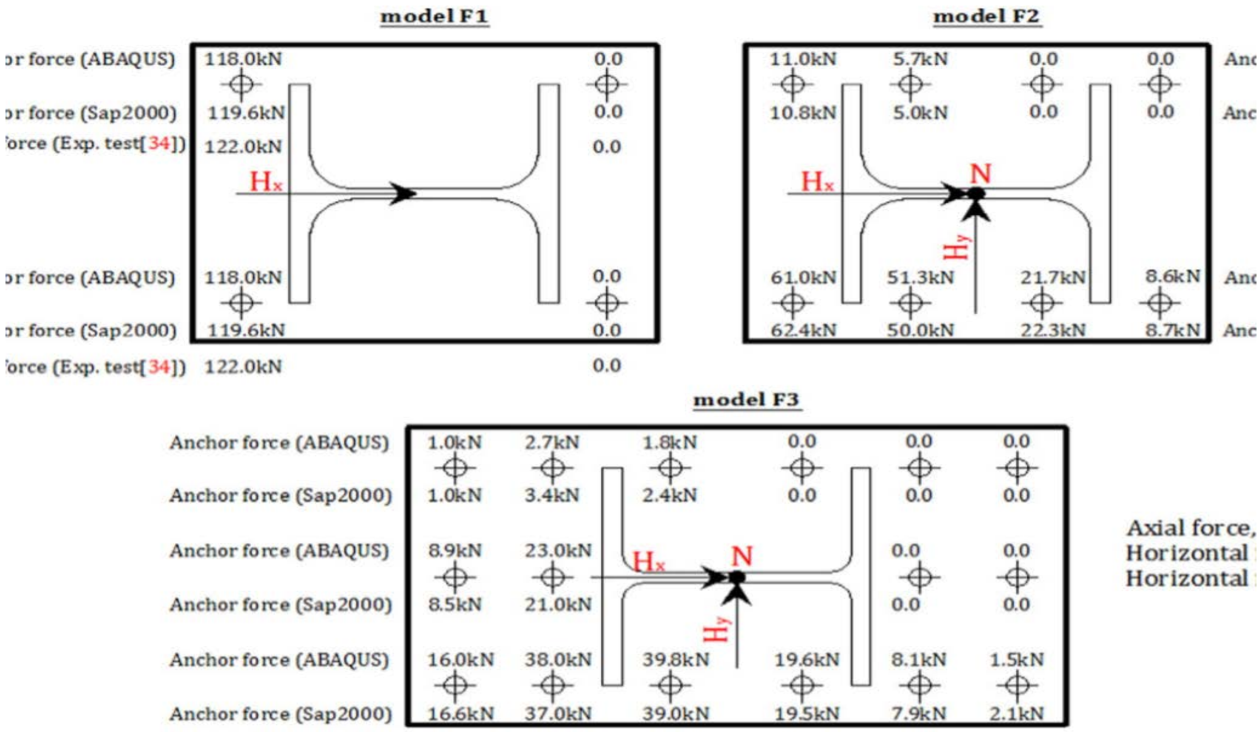

Figure 1.5: Variation of Tension in Anchor Rods, Biaxial Moment (Tsavdaridis et al., 2016)

While this research did not directly explore the stresses occurring in the plate washers – as the washers were modeled as entirely rigid, perfectly transferring all force from the rod into the base plate – it does convey important information about the stresses in the base plate around the anchor rod holes. It is noted in this article that two separate finite element analyses were completed for each base plate considered: one with a plate washer at each anchor rod, supporting the rod and nut in tension, and one with no plate washer at each rod, the nut bearing directly onto the base plate (Tsavdaridis et al., 2016). The results of these analyses showed clearly that the plate washers created a more even stress distribution from the anchor rod into the base plate, while the models without the plate washers created high stress concentrations around the anchor rod holes in the column base plates (Tsavdaridis et al., 2016). This further confirms the importance of this testing considering that strength of both the anchor rod – as indicated by the University of Athens - and column base plate are dependent on the presence of an adequate plate washer.

Chapter 2: Project Objectives and Methodology

The main objective for this testing project was to experimentally evaluate a selected sample of ASTM A572 Gr. 50 plate washers in conjunction with its appropriately sized ASTM F1554 Gr. 36, Gr. 50, and Gr. 105 threaded rod. This included loading the assembly of specimens to failure, observing, and visually observing the modes of failure of the plate washers and rods, along with measuring the deformation of the plate washers in the plane 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 and noting any discrepancies between the minimum and maximum ultimate tensile strengths and the observed tensile strengths for all three grades of steel in all five diameters of rod.

2.1.Plan for Testing

Experimental testing consisted of the tensile loading of 90 sets of specimens which included one plate washer and one 48” long fully threaded anchor rod. Rods of five different diameters were tested: 0.75”, 1”, 1.5”, 2” and 2.5”, in order to provide a representative sample of the diameters in Table 14-2 of the *Manual*. Three grades of steel were tested for each diameter rod: ASTM F1554 Gr. 36, Gr. 55, and Gr. 105. One additional variable was considered. Significantly different stresses are felt in the plate washer and anchor rod when the rod is offset in the base plate hole rather than centered, although either condition is acceptable during erection. For this reason, two plate washers per grade of steel rod and diameter were tested, one centered in the baseplate hole, and one set up so that the rod is as close to the hole’s edge as possible. This provision also allowed for the consideration of variation between specimens and mitigated the effects of fabrication defects or testing irregularities. Three plate washer thicknesses per combination of rod diameter and grade were selected based on proximity to the value given in Table 14-2 of the *Manual*. In total, six plate washers were tested per grade and rod diameter, corresponding to 18 washers per rod diameter, and overall 90 tests were performed in Phase 1, reported herein. 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 Gr. 105, and three of those five were 1.5” in diameter. For this reason, four more 1.5” diameter Gr. 105 threaded rods were acquired along with four accompanying plate washers - two ½” thick plate washers and two ⅝” thick plate washers.

2.2. Physical Test Setup

All testing occurred in the High Bay Structural Research Laboratory in Rhodes Hall on the campus of the University of Cincinnati. Specimen testing was carried out using a Tinius-Olsen Super L universal testing machine (Figure 2.1). This testing apparatus has top and bottom crosshead plates which are connected by four round steel posts, as well as a central stationary crosshead plate which is controlled by an electric motor. The top and bottom crossheads are responsible for applying tension force to the assembly using a servo-controlled hydraulic cylinder.

Figure 2.1: Tinius Olsen Super-L Universal Testing Apparatus

To ensure adequate protection of the testing machinery, two 1-½” thick ASTM A572 Gr. 50 reaction plates were affixed to the testing apparatus using four ¾” high strength bolts: one to the top surface of the top crosshead and one to the bottom surface of the middle crosshead where they were both compressed functioning as reaction plates. The bottom plate mimicked the configuration of a base plate in the anchor rod assembly and had a hole diameter as required in Table 14-2 of the *Manual*. 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” larger in diameter than the anchor rods for the ¾” rod, and ⅛” larger in diameter for all other rods. The bottom reaction plate was fabricated with a central hole of the diameter given in Table 14-2 of the *Manual*. Additionally, the bottom plates were detailed with short-slotted mounting holes, to allow the installation of the plates in both a centric and an offset configuration.

Figure 2.2: Bottom (left) and Top (right) Reaction Plates

As was indicated in the above section, *Plan for Testing*, each test specimen included one ASTM F1554 anchor rod and one ASTM A572 Gr. 50 plate washer. ASTM A563 Gr. DH nuts were used to fasten the plate washer to the anchor rod and bottom reaction plate, as well as to fasten the anchor rod to the top reaction plate, and an ASTM F436 washer was placed between the top nut and reaction plate.

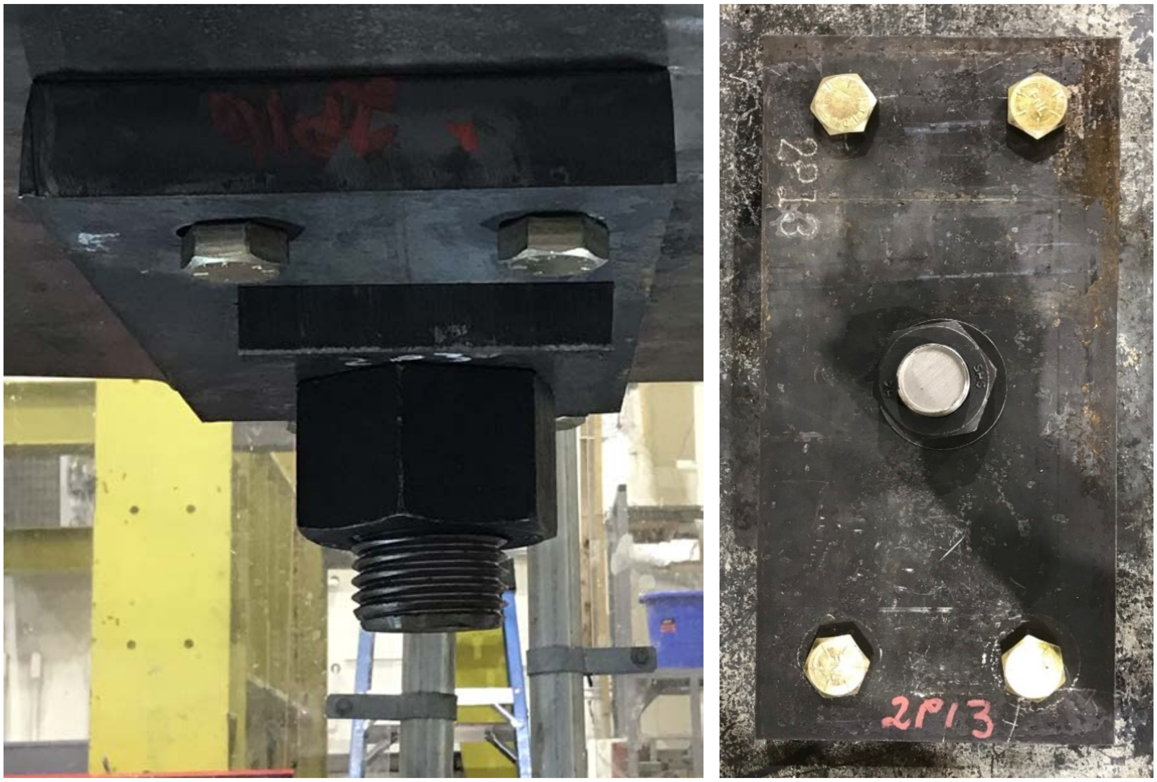

Figure 2.3: Bottom (left) and Top Reaction Plates During Testing

Figure 2.4: Plate Washers Prior to Testing

Figure 2.5: Anchor Rods Prior to Testing

Figure 2.6: Anchor Rod in Centered (left) and Offset (right) Orientations

Another ASTM A563 Gr. DH nut was used with an ASTM F436 washer to install a safety plate to the section of the threaded rod between the crossheads as close to the top crosshead as possible to prevent most of the rod from being projected through the top crosshead of the testing machine after fracture (see Figure 2.7). When the rod fractured below the safety plate, it was stopped on its way up, but when the rod fractured above the safety plate, a much smaller portion of the anchor rod was launched up and out of the testing machine. For this reason, a heavy-duty tarp was secured above the testing apparatus to prevent this smaller section from potentially damaging the ceiling and equipment nearby or harming any persons in the laboratory (see Figure 2.8).

Figure 2.7: Fastening of Safety Plate to Anchor Rod

Figure 2.8: Heavy Tarp Affixed to Top Crosshead

Once the test specimens were set in place, cameras were set up to record the action and deformation of the plate washer during loading, and the Tinius-Olsen data acquisition system was activated by the test operator to record force and displacement over time. The operator then began loading the specimens at a predetermined rate of displacement to ensure that only static force effects were considered. These rates were 0.1 in./s, 0.25 in./s, 0.5 in./s and 1.0 in./s. Each test began at the lowest rate of deformation; the rate was 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 testing machine. The Tinius-Olsen Super L universal testing apparatus has a maximum load capacity of 400 kips, which exceeds the maximum specified ultimate strength for all anchor rods tested, with the exception of the 2.5” diameter Gr. 105 rods. These anchor rods were loaded to the full capacity of the machine, then unloaded. Multiple plate washers were tested for this case, but because the anchor rod did not undergo any appreciable yielding, the rod was reused for all of its tests. Once all test data was recorded, it was compiled into force-displacement curves.

Figure 2.9: Tinius Olsen Controller

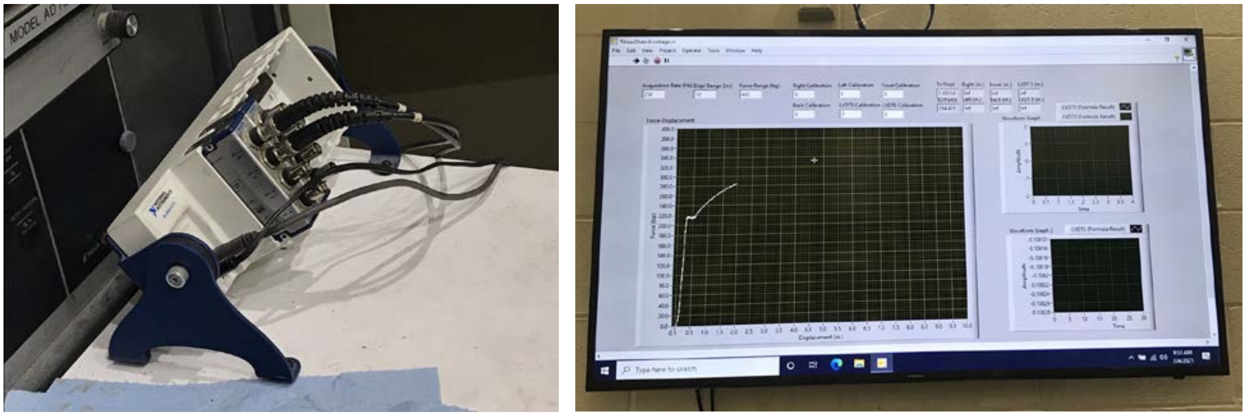

Figure 2.10: Data Acquisition System and Live Readout

Chapter 3: Results and Presentation of Data

This chapter will serve to outline and summarize all test data recorded with regard to the performance of the specified plate washers and threaded rods. Because there is no direct way to measure the deformation of the plate washers in the direction normal to the plane of loading during the test process, these measurements were taken following testing. The final out-of-plane deformation of each washer and comparisons to nominal and measured plate thickness are enclosed. The test data for yield and ultimate tensile strength of each rod is also presented herein along with the minimum allowable yield strength and minimum and maximum allowable ultimate strengths. These required strength values were taken entirely from the ASTM F1554 Standard.

3.1. Plate Washer Measurement and Data

A total of 94 plate washers were tested in the anchor rod assemblies. The deformations of each washer were measured using a 1” dial gauge affixed to a wooden dowel rod. The dowel was embedded in wooden runners and fastened to a flat stage. A top brace was used to ensure that the structure was vertical and the stage was horizontal. Both elements were inspected using a bubble level before the measurement of tested plate washers (see Figures 3.1 and 3.2).

Figure 3.1: Assembly of Stage, Dowels and Affixed Dial Gauge

Figure 3.2: Close-up of Affixed Dial Gauge

Before measurement of the deformation was taken, the thickness of each washer was measured using a digital dial caliper at the mid-point of all 4 sides, and the average value of the four thicknesses was assumed to be the average thickness of the washer after the test. In general, this average thickness was found to be within 3% of the nominal washer thickness in all cases, averaging less than a 1% deviation from the nominal value (see Figure 3.3).

Figure 3.3: Measurement of Thickness Using Dial Caliper

Once the average measured thickness of the washer had been determined, the washer was placed on the stage and the dial gauge's "HOLD MIN." function was used to determine the location of the absolute minimum elevation on the face of the plate washer. In general, this point was in the corner of the plate washer at the farthest point from the maximum deformation. When the location of minimum elevation had been found, the dial gauge was cleared to a value of 0.000" at that location, and the plate washer was slid across the stage, maintaining contact between the stage and washer at all four corners. It was ensured that the point of maximum deformation of the plate washer was captured by the dial gauge using its "HOLD MAX" function. Once the absolute maximum value of deformation was determined, it was recorded. These values are presented in Table 3.1. Fabrication defects and sheared edges were systematically excluded from these measurements.

Table 3.1: Plate Washer Deformation Data

Test #	Orientation	Nominal t	t_1	t_2	t_3	t_4	Δ_{max}	t_{avg}	% $Deformed_{nominal}$	% $Deformed_{average}$
1	1	0.500	0.505	0.495	0.505	0.491	-	0.499	-	-
2	2	0.500	0.490	0.490	0.489	0.500	-	0.492	-	-
3	1	0.375	0.375	0.376	0.380	0.370	0.024	0.375	6.32%	6.32%
4	2	0.375	0.375	0.376	0.372	0.372	0.016	0.374	4.19%	4.20%
5	2	0.250	0.245	0.246	0.247	0.255	0.062	0.248	24.88%	25.06%
6	1	0.250	0.242	0.244	0.248	0.254	0.027	0.247	10.76%	10.89%
7	1	0.500	0.490	0.491	0.502	0.510	0.015	0.498	2.96%	2.97%
8	2	0.500	0.492	0.501	0.491	0.510	0.086	0.499	17.16%	17.21%
9	2	0.375	0.369	0.376	0.377	0.375	0.025	0.374	6.67%	6.68%
10	1	0.375	0.375	0.375	0.369	0.379	0.018	0.375	4.85%	4.86%
11	1	0.250	0.263	0.248	0.248	0.245	0.051	0.251	20.52%	20.44%
12	2	0.250	0.242	0.266	0.248	0.249	0.069	0.251	27.64%	27.50%
13	2	0.500	0.505	0.495	0.505	0.491	0.025	0.499	5.02%	5.03%
14	1	0.500	0.490	0.490	0.489	0.500	0.046	0.492	9.22%	9.37%
15	1	0.375	0.375	0.376	0.372	0.376	0.047	0.375	12.53%	12.54%
16	2	0.375	0.375	0.375	0.374	0.376	0.046	0.375	12.16%	12.16%
17	2	0.250	0.250	0.252	0.242	0.240	0.177	0.246	70.68%	71.83%
18	1	0.250	0.241	0.239	0.246	0.248	0.169	0.244	67.44%	69.24%
19	1	0.500	0.490	0.499	0.493	0.493	0.058	0.494	11.58%	11.73%
20	2	0.500	0.492	0.492	0.492	0.495	0.059	0.493	11.70%	11.87%
21	2	0.375	0.374	0.492	0.374	0.375	0.038	0.404	10.11%	9.39%
22	1	0.375	0.369	0.370	0.368	0.370	0.045	0.369	11.92%	12.11%
23	1	0.250	0.239	0.245	0.252	0.245	0.240	0.245	96.12%	97.98%
24	2	0.250	0.248	0.243	0.250	0.253	0.271	0.249	108.36%	109.01%
25	2	0.500	0.488	0.489	0.493	0.501	0.044	0.493	8.88%	9.01%
26	1	0.500	0.490	0.492	0.491	0.490	0.053	0.491	10.60%	10.80%
27	1	0.375	0.371	0.373	0.368	0.370	0.063	0.371	16.80%	17.00%
28	2	0.375	0.372	0.366	0.372	0.369	0.039	0.370	10.32%	10.47%
29	2	0.250	0.249	0.250	0.245	0.245	0.342	0.247	136.80%	138.32%
30	1	0.250	0.245	0.245	0.245	0.241	0.339	0.244	135.48%	138.81%
31	1	0.750	0.741	0.744	0.737	0.746	0.020	0.742	2.72%	2.75%
32	2	0.750	0.739	0.736	0.737	0.747	0.014	0.740	1.85%	1.88%
33	2	0.500	0.494	0.495	0.498	0.492	0.070	0.495	13.96%	14.11%
34	1	0.500	0.495	0.491	0.503	0.500	0.068	0.497	13.54%	13.61%
35	1	0.375	0.373	0.373	0.374	0.375	0.132	0.374	35.07%	35.18%
36	2	0.375	0.375	0.374	0.375	0.373	0.233	0.374	62.16%	62.28%

37	1	0.750	0.749	0.749	0.750	0.749	0.023	0.749	3.03%	3.03%
38	2	0.750	0.751	0.751	0.750	0.749	0.029	0.750	3.91%	3.91%
39	2	0.500	0.496	0.490	0.486	0.498	0.076	0.493	15.24%	15.47%
40	1	0.500	0.490	0.491	0.490	0.496	0.078	0.492	15.60%	15.86%
41	1	0.375	0.372	0.370	0.370	0.378	0.063	0.373	16.77%	16.89%
42	2	0.375	0.372	0.374	0.374	0.381	0.196	0.375	52.37%	52.34%
43	2	0.750	0.757	0.749	0.749	0.752	0.027	0.752	3.57%	3.57%
44	1	0.750	0.750	0.750	0.750	0.751	0.017	0.750	2.24%	2.24%
45	1	0.500	0.499	0.501	0.493	0.496	0.074	0.497	14.86%	14.94%
46	2	0.500	0.497	0.497	0.500	0.493	0.096	0.497	19.28%	19.41%
47	2	0.375	0.372	0.375	0.373	0.373	0.168	0.373	44.85%	45.06%
48	1	0.375	0.372	0.374	0.370	0.376	0.068	0.373	18.00%	18.10%
49	1	1.000	1.000	1.005	0.999	0.999	0.022	1.001	2.18%	2.18%
50	2	1.000	1.001	1.001	1.000	0.999	0.017	1.000	1.68%	1.68%
51	2	0.750	0.752	0.752	0.751	0.750	0.036	0.751	4.79%	4.78%
52	1	0.750	0.752	0.752	0.750	0.751	0.043	0.751	5.73%	5.72%
53	1	0.500	0.490	0.490	0.492	0.501	0.178	0.493	35.52%	36.01%
54	2	0.500	0.488	0.487	0.498	0.491	0.189	0.491	37.72%	38.41%
1A	2	0.500	0.498	0.495	0.497	0.495	0.210	0.496	41.94%	42.26%
2A	1	0.500	0.495	0.495	0.497	0.496	0.069	0.496	10.96%	10.96%
3A	1	0.625	0.624	0.625	0.625	0.625	0.069	0.625	13.70%	13.82%
4A	2	0.625	0.624	0.623	0.626	0.625	0.067	0.625	10.72%	10.73%
55	1	1.000	0.998	0.997	0.991	0.998	0.010	0.996	0.96%	0.96%
56	2	1.000	1.000	1.000	1.001	1.001	0.014	1.001	1.40%	1.40%
57	2	0.875	0.880	0.881	0.880	0.886	0.017	0.882	1.93%	1.92%
58	1	0.875	0.885	0.880	0.880	0.883	0.019	0.882	2.13%	2.11%
59	1	0.750	0.753	0.754	0.756	0.754	0.011	0.754	1.40%	1.39%
60	2	0.750	0.755	0.756	0.753	0.752	0.047	0.754	6.32%	6.29%
61	2	1.000	1.000	1.000	0.998	0.998	0.017	0.999	1.69%	1.69%
62	1	1.000	1.002	0.999	0.999	1.002	0.060	1.001	5.98%	5.98%
63	1	0.875	0.883	0.884	0.880	0.881	0.033	0.882	3.73%	3.70%
64	2	0.875	0.881	0.881	0.882	0.879	0.059	0.881	6.72%	6.68%
65	2	0.750	0.753	0.753	0.754	0.757	0.051	0.754	6.73%	6.70%
66	1	0.750	0.753	0.753	0.753	0.757	0.051	0.754	6.81%	6.78%
67	1	1.250	1.253	1.252	1.253	1.262	0.040	1.255	3.22%	3.20%
68	2	1.250	1.253	1.256	1.253	1.263	0.044	1.256	3.53%	3.51%
69	2	1.000	1.003	1.000	1.000	0.998	0.080	1.000	7.96%	7.96%
70	1	1.000	0.997	0.960	0.999	0.999	0.055	0.989	5.45%	5.51%
71	1	0.750	0.752	0.753	0.754	0.752	0.122	0.753	16.20%	16.14%
72	2	0.750	0.754	0.754	0.755	0.756	0.140	0.755	18.68%	18.56%
73	1	1.000	1.000	1.000	0.999	1.002	0.061	1.000	6.11%	6.11%
74	2	1.000	1.000	0.999	0.998	1.001	0.046	1.000	4.59%	4.59%
75	2	0.875	0.883	0.886	0.889	0.887	0.102	0.886	11.61%	11.46%
76	1	0.875	0.883	0.883	0.883	0.882	0.078	0.883	8.94%	8.86%
77	1	0.875	0.882	0.882	0.880	0.886	0.075	0.883	8.58%	8.51%
78	2	0.875	0.882	0.883	0.886	0.882	0.108	0.883	12.33%	12.22%

79	2	1.000	1.000	0.999	1.001	1.003	0.032	1.001	3.22%	3.22%
80	1	1.000	1.003	1.002	1.000	1.000	0.044	1.001	4.39%	4.38%
81	1	0.750	0.755	0.755	0.755	0.757	0.055	0.756	7.36%	7.31%
82	2	0.750	0.753	0.755	0.757	0.756	0.090	0.755	12.03%	11.94%
83	2	1.500	1.516	1.515	1.510	1.518	0.017	1.515	1.11%	1.10%
84	1	1.500	1.507	1.514	1.512	1.514	0.034	1.512	2.26%	2.24%
85	1	1.250	1.251	1.257	1.253	1.256	0.046	1.254	3.64%	3.63%
86	2	1.250	1.253	1.253	1.252	1.257	0.043	1.254	3.42%	3.41%
87	2	0.875	0.882	0.883	0.884	0.882	0.111	0.883	12.66%	12.55%
88	1	0.875	0.882	0.883	0.883	0.882	0.076	0.883	8.67%	8.60%
89	1	0.750	0.752	0.755	0.754	0.753	0.075	0.754	9.95%	9.90%
90	2	0.750	0.755	0.755	0.753	0.754	0.125	0.754	16.71%	16.61%

Deformations based on percentage of the measured and nominal thicknesses of the plate washer are given in Table 3.1. Table 3.2 summarizes the deformation data with regard to these percentages and Figure 3.4 shows this data distributed across the entire set of tests. More than 75% of plate washers exhibited less than 20% relative deformation, and more than 50% of washers experienced less than 10% relative deformation, as can be seen in Figure 3.4.

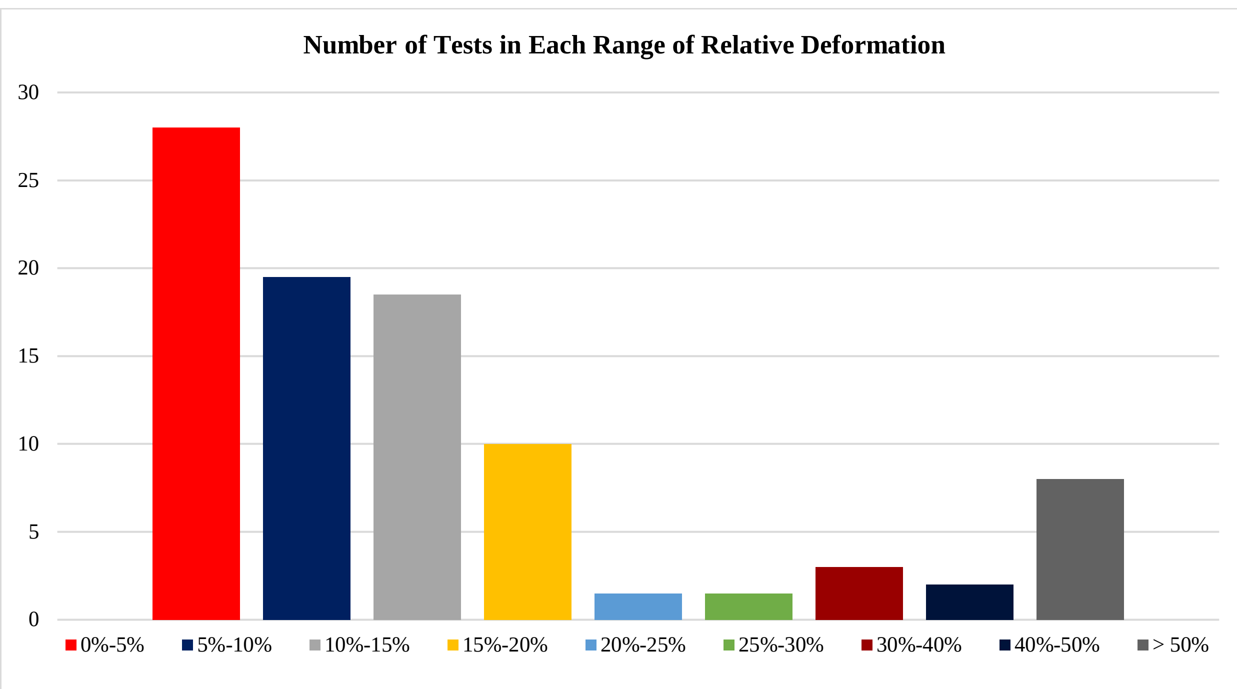

Figure 3.4: Distribution of Relative Deformation of Plate Washers

Table 3.2: 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%		12.53%	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%									

	20%-25%			25%-30%			30%-40%			40%-50%			> 50%	
	20.52%	**20.44%**		**27.64%**	**25.06%**		**35.07%**	**35.18%**		**41.94%**	**42.26%**		**52.37%**	**52.34%**
	22.70%	**20.44%**		**27.64%**	**26.28%**		**36.10%**	**36.53%**		**43.40%**	**43.66%**		**91.18%**	**92.48%**
	22.70%	**20.44%**		**27.64%**	**26.28%**		**35.52%**	**36.01%**		**43.40%**	**43.66%**		**83.40%**	**84.91%**
	24.88%	**20.44%**		**27.64%**	**27.50%**		**37.72%**	**38.41%**		**44.85%**	**45.06%**		**136.80%**	**138.81%**
1.5	20.52%	20.44%	1.5	27.64%	25.06%	3	35.07%	35.18%	2	41.94%	42.26%	8	52.37%	52.34%
	24.88%				27.50%		35.52%	36.01%		44.85%	45.06%		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%

3.2. Behavior and Performance of Threaded Rods

A total of 94 threaded anchor rods were tested in axial tension, and the results of that testing are included herein. A summary of the performance of each threaded rod can be found in Table 3.3. This includes the ultimate tensile strength and yield strength of all 94 rods, as well as the specified yield strength, specified minimum and maximum ultimate tensile strength, and design strength.

Table 3.3: Summary of Performance of Threaded Rods

Test #	Orientation	Nominal t	Diameter (in.)	Grade (ksi)	Min. Tensile (k)	Max. Tensile (k)	Ultimate Tensile (k)	Min. Yield (k)	Yield (k)	Design Strength (k)
1	1	0.500	0.750	36	19.4	26.7	23.047	12.00	15.8	14.55
2	2	0.500					22.974		15.8	
3	1	0.375					22.955		15.8	
4	2	0.375					23.017		15.8	
5	2	0.250					23.047		15.8	
6	1	0.250					23.170		16.0	
7	1	0.500	0.750	55	25.0	31.7	29.686	18.40	21.8	18.75
8	2	0.500					29.510		21.6	
9	2	0.375					29.622		22.0	
10	1	0.375					29.649		21.9	
11	1	0.250					29.391		21.5	
12	2	0.250					29.477		21.7	
13	2	0.500	0.750	105	41.8	50.1	48.137	35.10	41.9	31.35
14	1	0.500					47.519		42.2	
15	1	0.375					47.625		41.9	
16	2	0.375					47.536		41.6	
17	2	0.250					48.403		41.5	
18	1	0.250					48.034		41.5	
19	1	0.500	1.000	36	35.2	48.5	47.270	21.80	34.0	26.40
20	2	0.500					47.103		35.2	
21	2	0.375					47.210		35.2	
22	1	0.375					47.171		35.1	
23	1	0.250					46.737		34.5	
24	2	0.250					46.993		35.4	
25	2	0.500	1.000	55	45.4	57.6	51.742	33.30	36.2	34.05
26	1	0.500					51.788		34.0	
27	1	0.375					51.713		35.7	
28	2	0.375					51.734		36.0	
29	2	0.250					51.656		35.7	
30	1	0.250					51.234		35.5	

31	1	0.750	1.000	105	75.8	90.9	76.770	63.60	67.2	56.85
32	2	0.750					84.544		61.8	
33	2	0.500					81.529		70.5	
34	1	0.500					84.409		66.7	
35	1	0.375					76.485		61.8	
36	2	0.375					81.653		70.0	
37	1	0.750	1.500	36	81.5	112.4	104.103	50.60	71.7	81.50
38	2	0.750					113.846		81.8	
39	2	0.500					104.351		82.2	
40	1	0.500					113.660		71.8	
41	1	0.375					103.673		72.8	
42	2	0.375					113.660		81.4	
43	2	0.750	1.500	55	105.0	133.0	119.606	77.30	84.3	78.75
44	1	0.750					119.634		84.5	
45	1	0.500					119.577		83.2	
46	2	0.500					119.820		84.0	
47	2	0.375					119.720		84.0	
48	1	0.375					119.949		83.3	
49	1	1.000	1.500	105	176.0	216.0	190.607	148.00	184.4	132.00
50	2	1.000					174.629		143.0	
51	2	0.750					191.498		143.6	
52	1	0.750					174.272		168.1	
53	1	0.500					191.579		166.1	
54	2	0.500					174.143		143.5	
1A	2	0.500	1.500	105.0	176.0	216.0	197.844	148.00	158.0	132.00
2A	1	0.500					196.865		157.0	
3A	1	0.625					197.445		157.2	
4A	2	0.625					198.423		156.0	
55	1	1.000	2.000	36	145.0	200.0	184.162	90.00	112.0	108.75
56	2	1.000					184.176		113.0	
57	2	0.875					182.861		113.5	
58	1	0.875					184.390		113.5	
59	1	0.750					183.576		114.8	
60	2	0.750					182.890		115.5	
61	2	1.000	2.000	55	188.0	238.0	214.675	138.00	141.0	141.00
62	1	1.000					214.617		141.0	
63	1	0.875					213.974		141.5	
64	2	0.875					213.060		139.5	
65	2	0.750					214.432		140.0	
66	1	0.750					214.789		141.0	
67	1	1.250	2.000	105	312.0	375.0	325.236	262.00	276.5	234.00
68	2	1.250					309.772		271.0	
69	2	1.000					312.459		284.0	
70	1	1.000					323.592		273.0	
71	1	0.750					316.232		284.0	
72	2	0.750					311.859		284.0	

73	1	1.000	2.500	36	232.0	320.0	340.314	144.00	321.0	174.00
74	2	1.000					336.912		318.0	
75	2	0.875					355.520		297.5	
76	1	0.875					357.607		313.0	
77	1	0.875					355.978		315.0	
78	2	0.875					354.391		298.0	
79	2	1.000	2.500	55	300.0	380.0	312.102	220.00	214.0	225.00
80	1	1.000					311.316		217.0	
81	1	0.750					314.288		211.5	
82	2	0.750					312.402		214.5	
83	2	1.500	2.500	105	500.0	600.0	399.410	420.00	-	375.00
84	1	1.500					399.010		-	
85	1	1.250					400.354		-	
86	2	1.250					398.982		-	
87	2	0.875					397.167		-	
88	1	0.875					388.706		-	
89	1	0.750					389.335		-	
90	2	0.750					385.876		-	

These values are taken from the ASTM F1554 Standard Specification, and the design strength is calculated as specified by AISC in the *Manual.* Values which fall below the minimum strength or exceed the maximum strengths designated by ASTM and AISC are in red. When appropriate, yield strengths were determined based on a 0.2% offset on the load vs. displacement diagram as can be seen in Figure 3.5. A line was drawn on the summary graph parallel to the elastic region of the load-displacement curves, and the value of load at which each curve crossed this line marking the 0.2% offset was taken as the yield strength for that specimen.

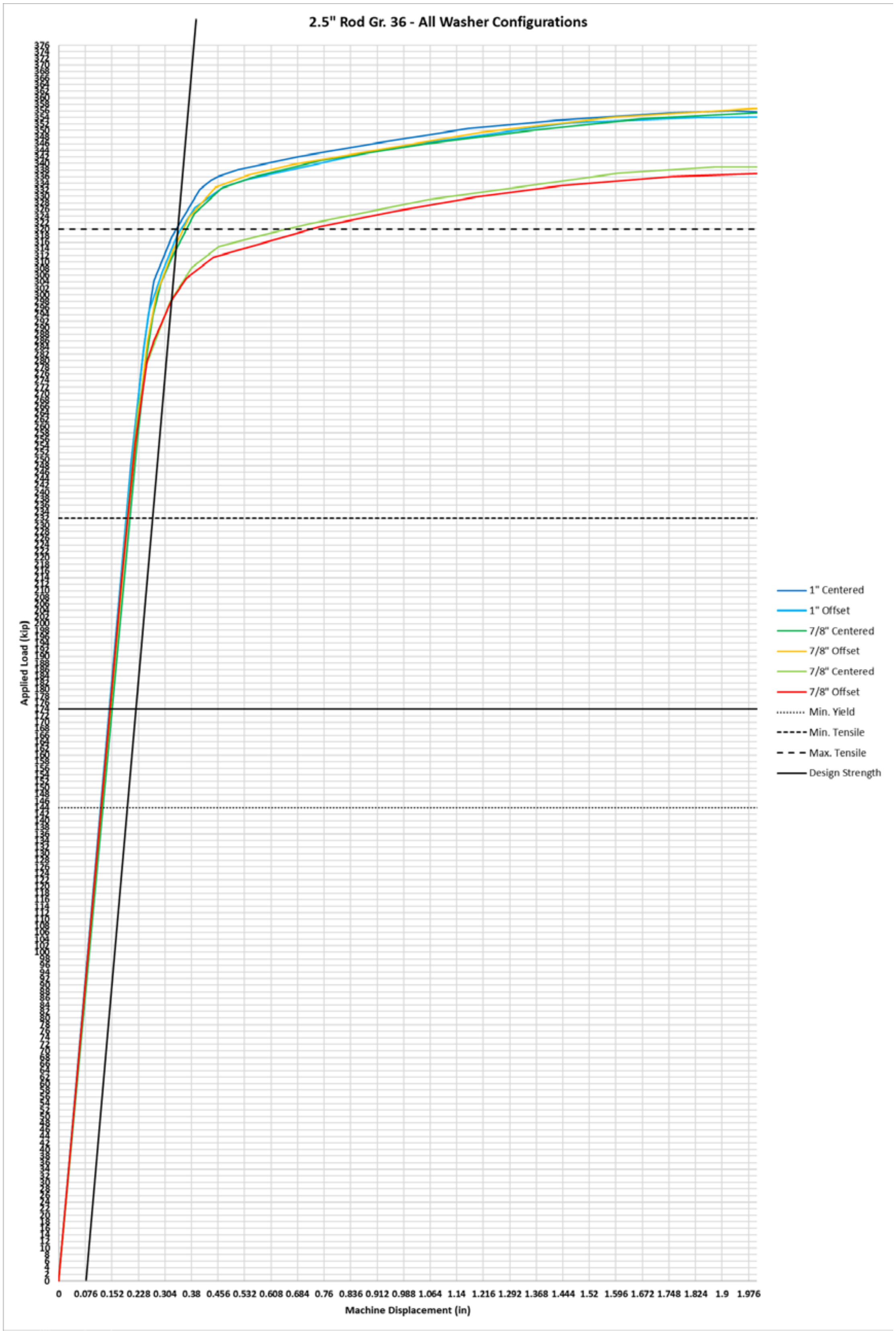

Figure 3.5: Determination of Yield Strength Using 0.2% Offset

All load and displacement data presented were acquired from the universal testing machine voltage output. However, during several of the tension tests, the testing apparatus was unable to maintain a constant instantaneous rate of displacement. While the average rate of displacement was maintained, the instantaneous changes in displacement rate caused the raw output data to be very difficult to directly interpret. To overcome this issue, the load vs. displacement plots were digitized, and the smoothed curves that were thus obtained were used. Figure 3.6 shows an example of a raw load-displacement curve, and its final digitized curve is shown in Figure 3.7.

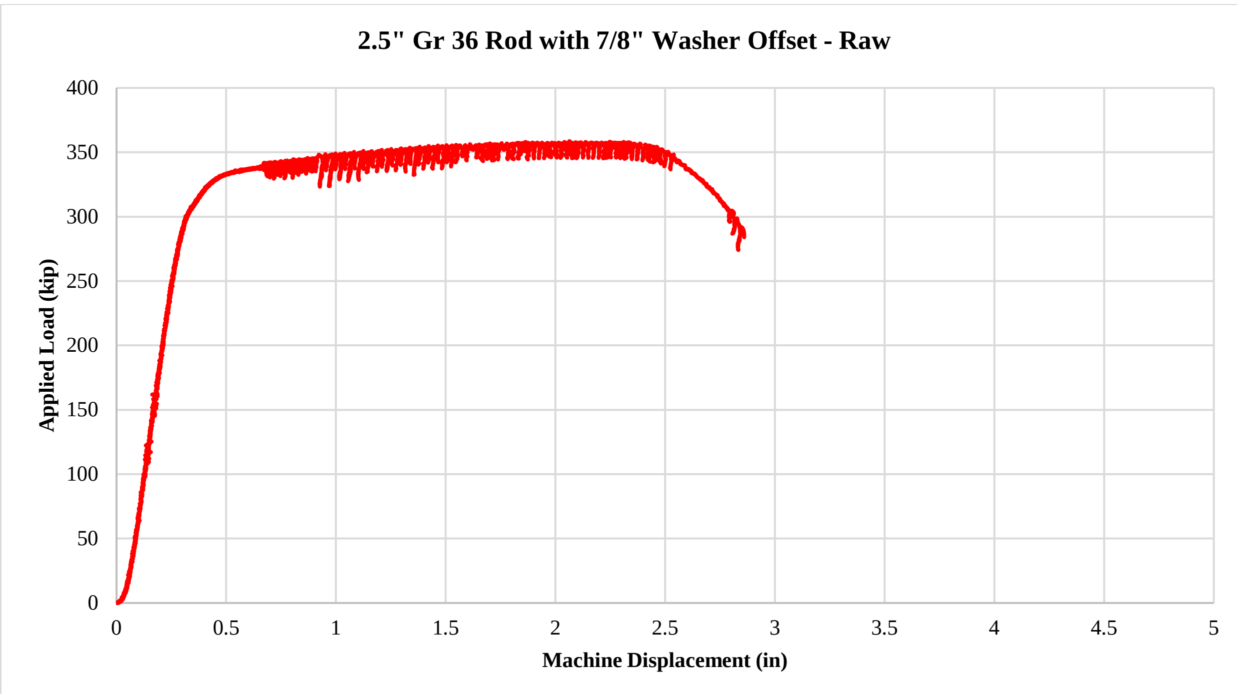

Figure 3.6: Example of Raw Load-Displacement Curve

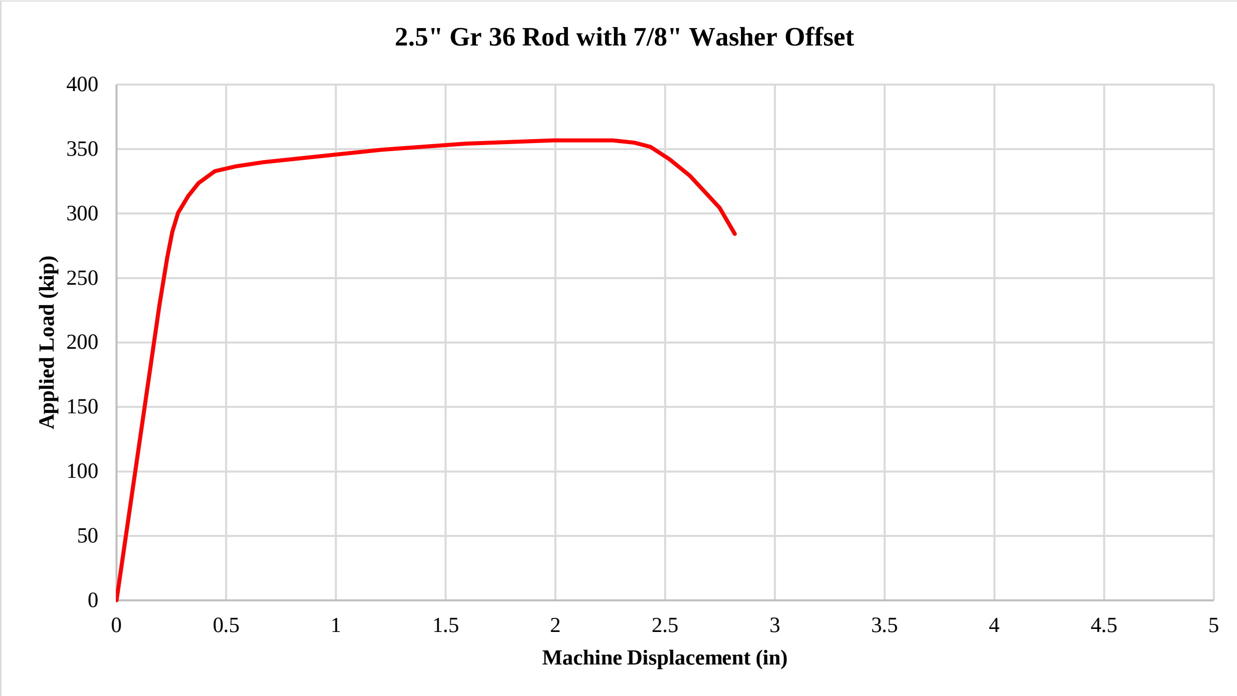

Figure 3.7: Example of Digitized Load-Displacement Curve

Aside from more clearly defining the points of the curve where the testing machine was unable to regulate the instantaneous rate of displacement, digitizing the load-displacement curves also made it possible to eliminate other imperfections. The most important of these was the initial settlement of the assembled test specimens. At the beginning of each test, the bottom nut was finger tightened to the plate washer in contact with the reaction plate. However, some small initial deformation of the assembly occurred in nearly every test which presented as a short near-parabolic curve. This was easily corrected in the digitizing process to show a more accurate curve with a more exact final displacement and ductility. The digitized plots are shown in the following summary graphs, and the individual raw data can be found in Appendix A.

3.2.1. Results of 0.75” Diameter Gr. 36 Rod Tension Tests

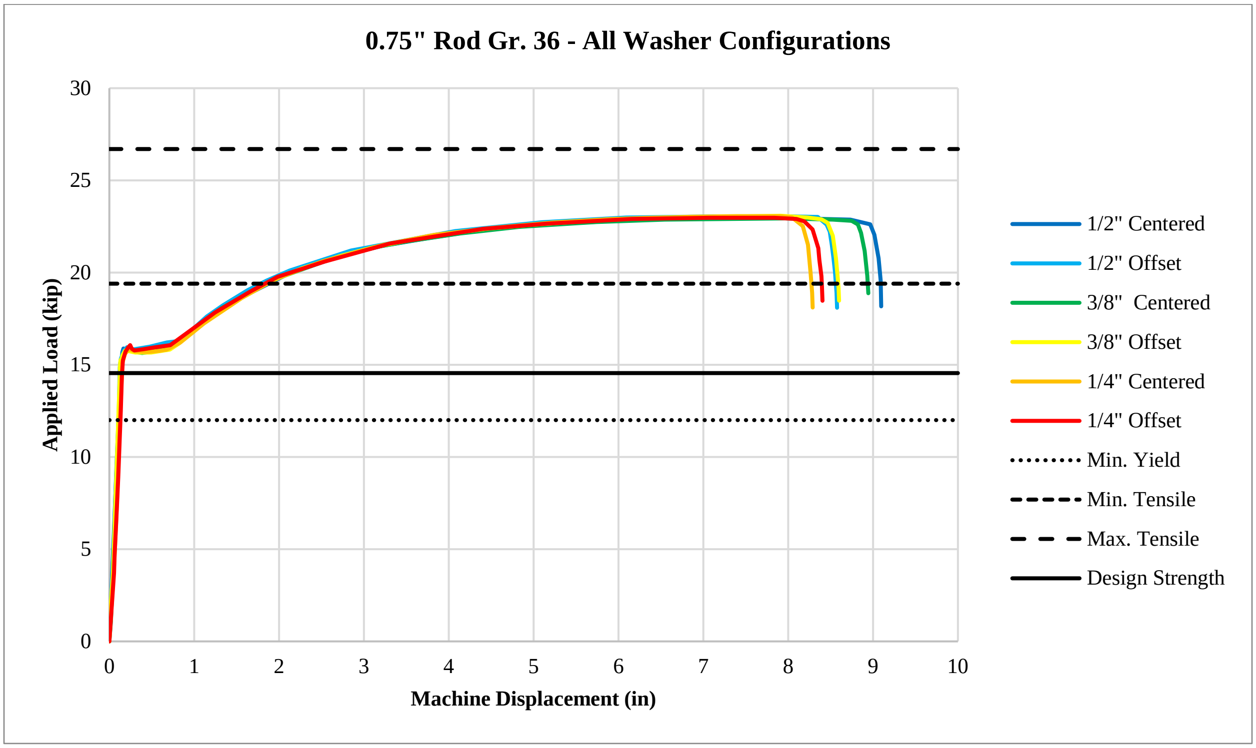

Figure 3.8: Load-Displacement Graph 0.75” Gr.36 Rod

The 0.75” diameter Gr. 36 specimens performed almost exactly as specified. Each specimen’s ultimate strength fell evenly between the minimum and maximum ultimate strength and its yield strength was markedly greater than the minimum. Every rod also exhibited a clear yield plateau and significant ductility as was expected. No clear correlation between the performance of the plates washers and the performance of the rods could be determined from the data shown.

Figure 3.9: 1/4" Plate Washer, Offset - 0.75" Gr. 36 Rod

In general, the plate washers in this group performed well. The plate washer shown in figure 3.9 had a relative deformation of 25% of its initial thickness. The minimum required plate washer thickness for 0.75" diameter anchor rods is 1/4" as specified in *the Manual*.

1.1.1. Results of 0.75” Diameter Gr. 55 Rod Tension Tests

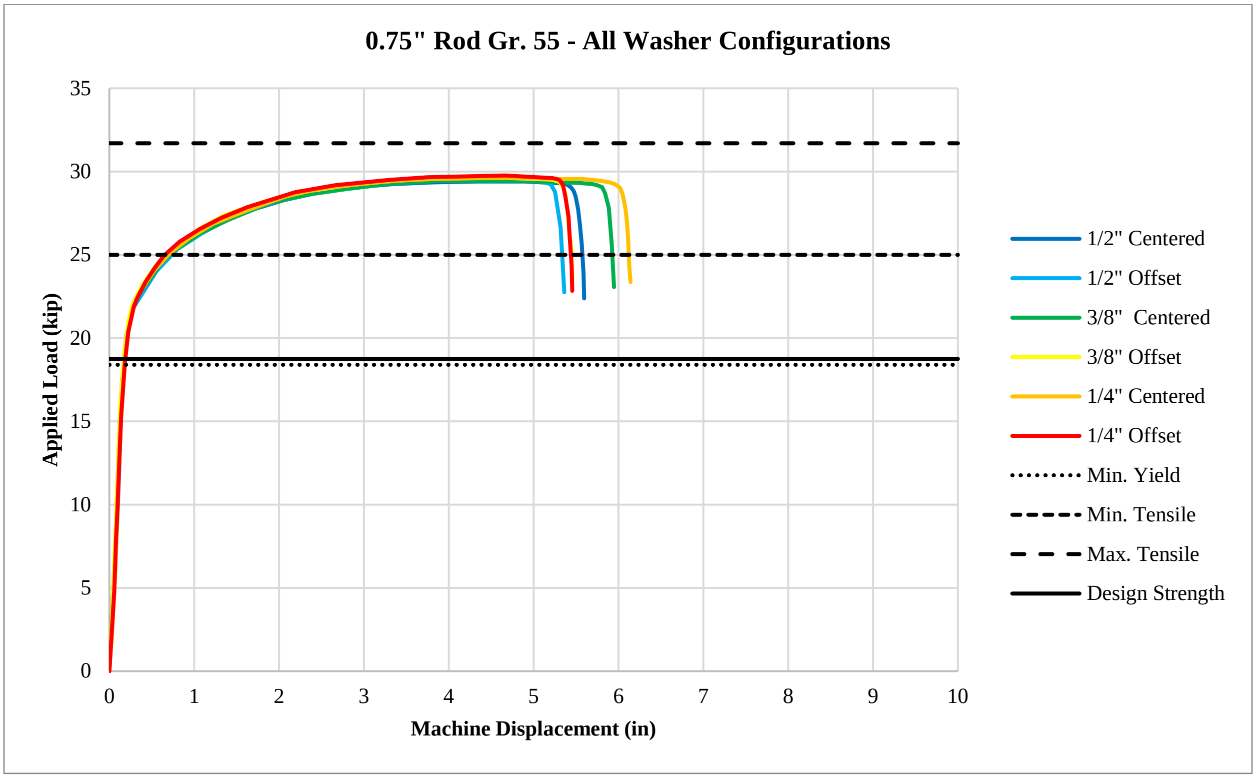

Figure 3.10: Load-Displacement Graph 0.75” Gr. 55 Rod

As expected, the 0.75” Gr. 55 anchor rods had more strength and somewhat less ductility than the Gr. 36 rods. These curves lack substantive yield plateaus which can be present in rods of all three grades, but each performed above the minimum yield strength, and between the bounds for ultimate strength. Notably, all of the 0.75” Gr. 55 anchor rods yielded and failed within 1 kip of each other showing material reliability.

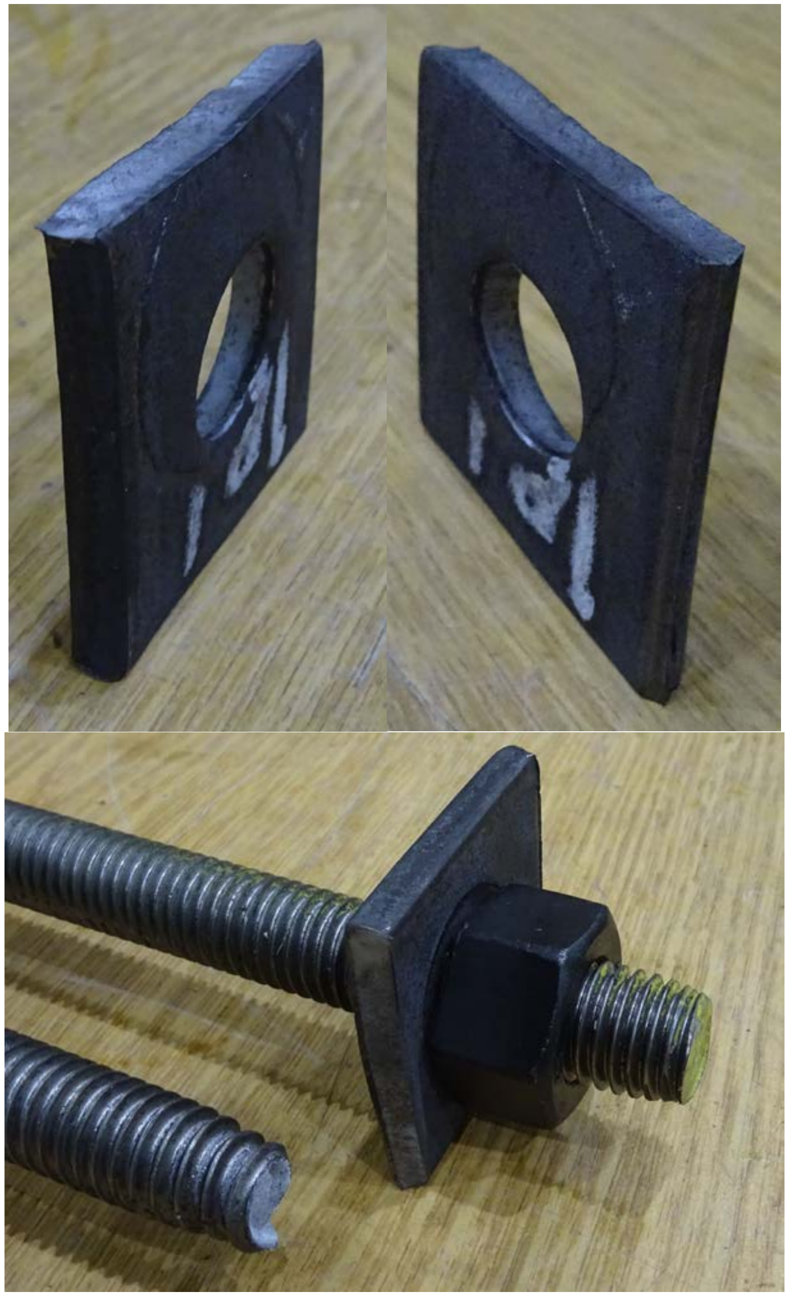

Figure 3.11: 1/4" Plate Washer, Offset – 0.75" Gr. 55 Rod

None of the six plate washers in this group had severe relative deformation or were visually classified as failed, but both of the 1/4" plate washers deformed more than 20% of their initial thickness. Figure 3.11 shows Test #12 which had a relative deformation of 28%.

1.1.2. Results of 0.75” Diameter Gr. 105 Rod Tension Tests

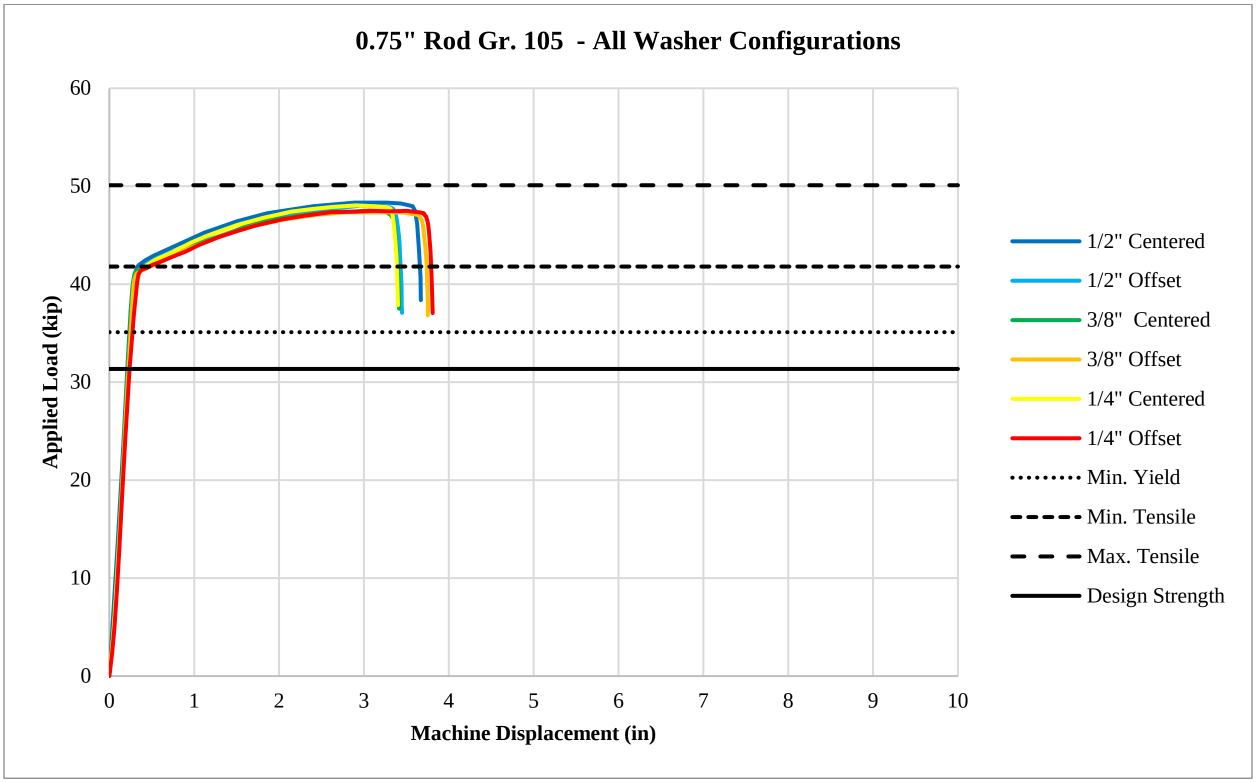

Figure 3.12:Load-Displacement Graph 0.75” Gr. 105 Rod

The 0.75” diameter Gr. 105 anchor rods all performed reliably and met the minimum yield strength and ultimate tensile strength bounds criteria. Predictably, the Gr.105 specimens displayed much higher strength and markedly lower ductility than the Gr. 36 or Gr. 55 specimens. In addition to fulfilling the ASTM requirements, these specimens also displayed a very short, if sloped, yield plateau.

Figure 3.13: 1/4" Plate Washer, Offset - 0.75" Gr. 105 Rod

This group of washers included a significant deviation from the expected results. The washer shown in Figure 3.13 deformed 71% relative to its initial thickness. The centered 1/4" washer incurred a relative deformation of 68% during testing. According to the *Manual*, all 0.75” diameter anchor rods can be fully developed by a 1/4" thick plate washer. This was the case, however the deformation was visually deemed to be excessive. These results will be discussed further in Chapter 4.

1.1.3. Results of 1” Diameter Gr. 36 Rod Tension Tests

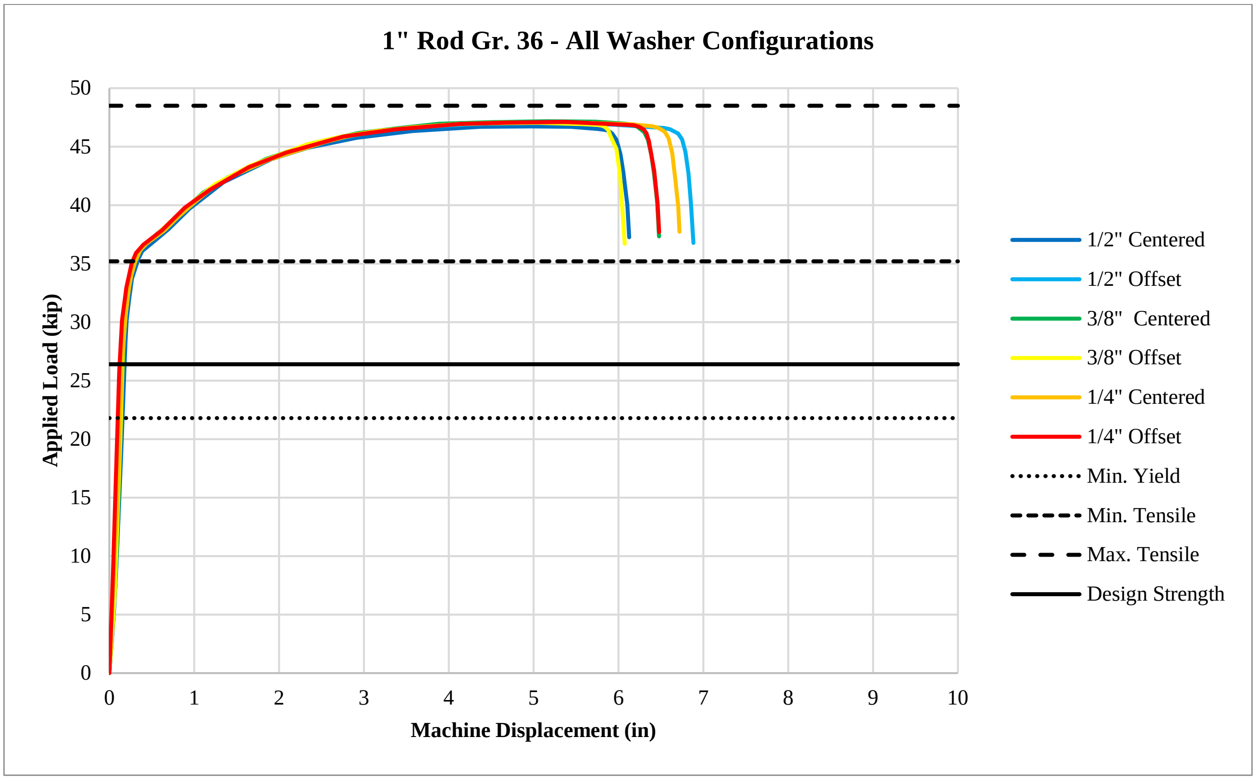

Figure 3.14: Load-Displacement Graph 1” Gr.36 Rod

The 1” diameter Gr. 36 anchor rods yielded approximately 50% higher than the minimum yield strength for Gr. 36 and also reached their ultimate strength in the top 20% of the allowable range. However, all six specimens met both strength requirements and would have met all the requirements for Gr. 55 steel as well. A very small yield plateau can be seen forming but is not as prominent as the 0.75” diameter rods. This shows that the Gr. 36 steel is performing similarly to the Gr. 55 steel.

Figure 3.15: 1/4" Plate Washer, Offset - 1" Gr. 36 Rod

Of this group of plate washers, the two 1/4" thick plate washers were measured to have failed at 97% and 109% relative deformation. Figure 3.15 shows Test #24 and its severe deformation in the direction of loading. It should be noted that the current recommended plate washer for 1” diameter anchor rods is 3/8” thick. A 1/4” thick plate washer would not meet the minimum requirement. The 3/8” thick washers tested in this group both deformed 10% relative to their original thickness.

1.1.4. Results of 1” Diameter Gr. 55 Rod Tension Tests

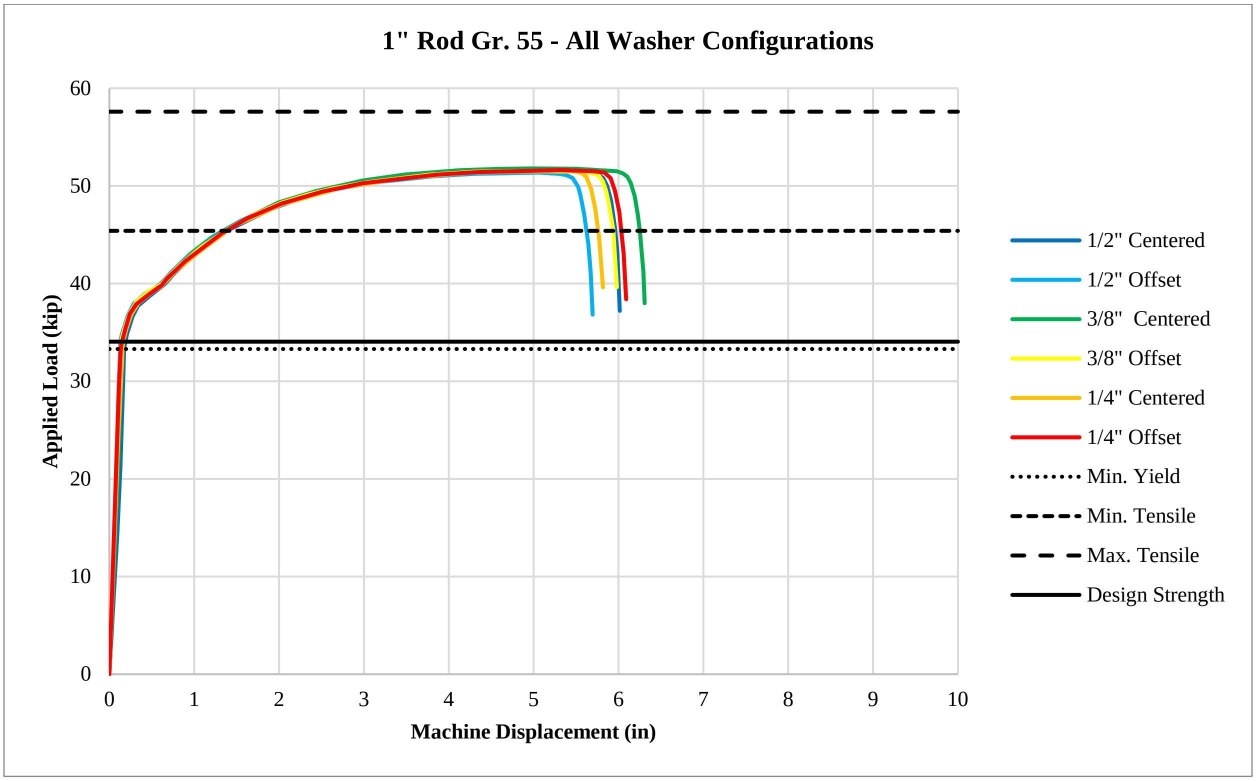

Figure 3.16: Load-Displacement Graph 1” Gr. 55 Rod

The 1” diameter Gr. 55 rods performed at adequate strengths for all strength requirements, falling directly between the maximum and minimum ultimate strength requirements on all six tests. A small yield plateau can be seen, similar to that of the Gr. 36 specimens of the same diameter.

Figure 3.17: 1/4" Plate Washer, Offset - 1" Gr. 55 Rod

Like the previous group of washers, all washers in this group which met the minimum requirement provided in *the Manual* performed adequately. The specimen from Test #29 in Figure 3.17 displays clear failure in pull-through with 138% relative displacement. However, the anchor rod also experienced notable bending at the interface with the plate washer as seen at the bottom of Figure 3.17.

1.1.5. Results of 1” Diameter Gr. 105 Rod Tension Tests

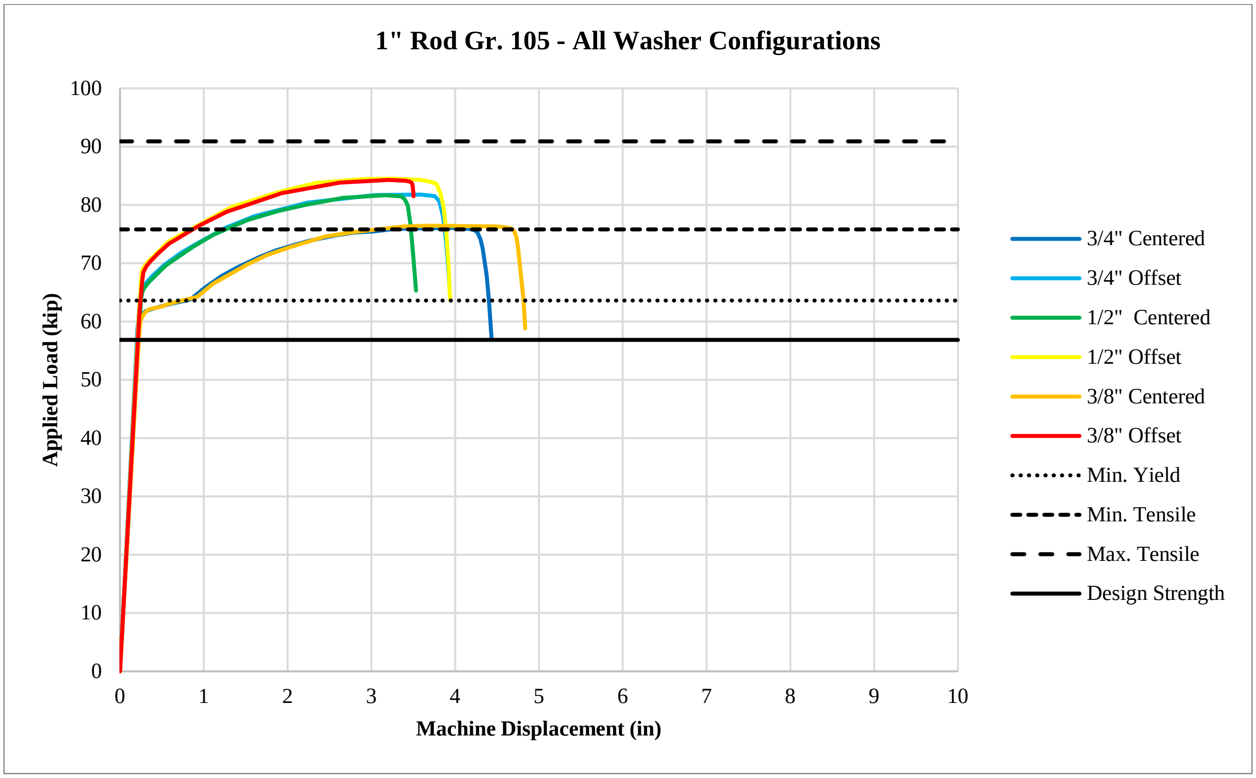

Figure 3.18: Load-Displacement Graph 1” Gr. 105 Rod

The 1” diameter Gr. 105 anchor rod specimens did not perform reliably. As Figure 3.18 indicates, two specimens did not meet the minimum yield strength criterion and met the minimum ultimate strength criterion by less than 1,000 pounds. Also, these two specimens produced load-displacement curves which did not match the general shape of the other four specimens’ curves. The two rods which failed to meet the minimum yield strength criterion produced distinctive yield plateaus while the other four specimens did not. The lack of reliability of these Gr. 105 rods will be further discussed in the following chapter.

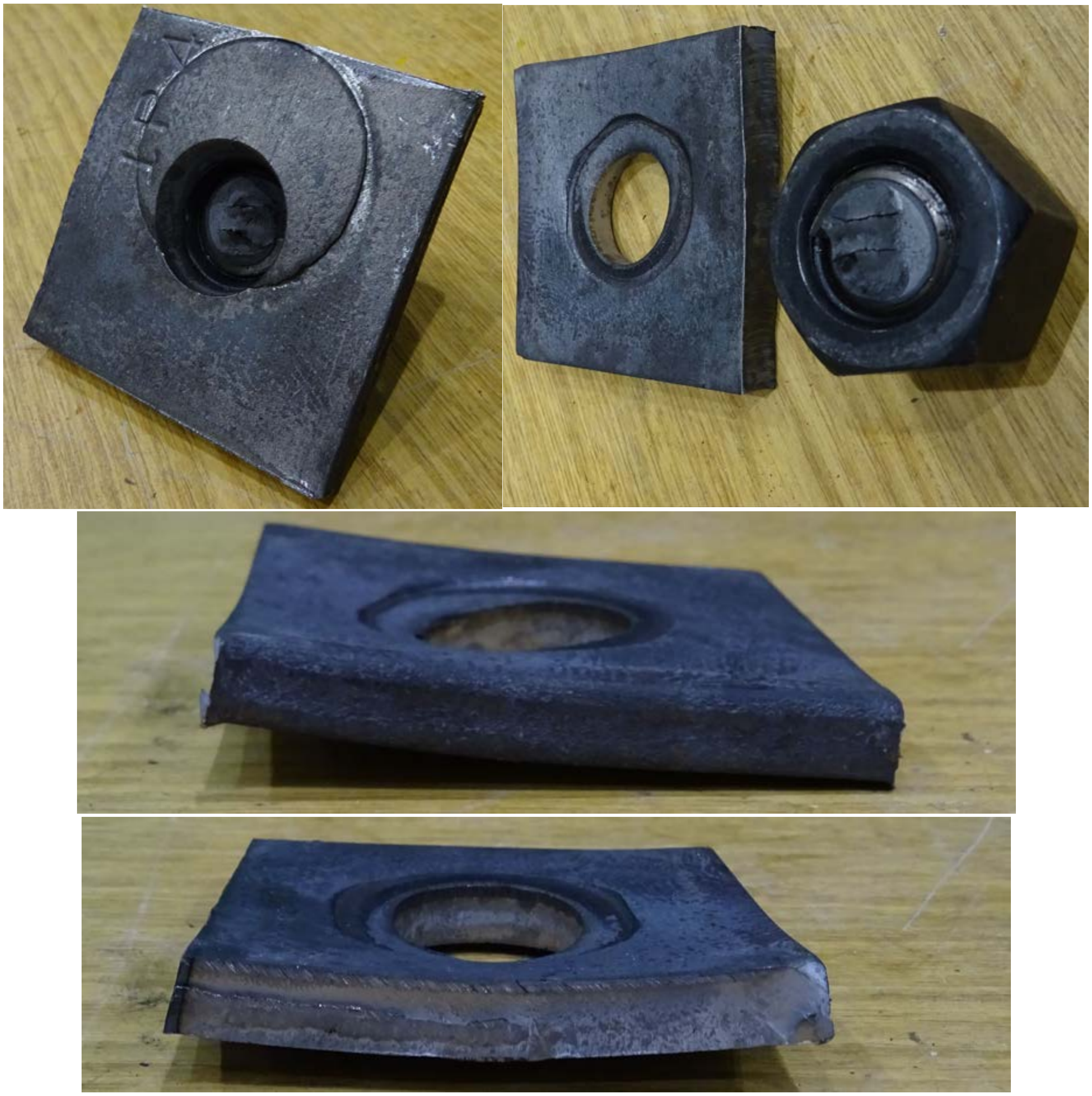

Figure 3.19: 3/8" Plate Washer, Offset - 1" Gr. 105 Rod

The 3/8” washer in the offset orientation deformed 62% relative to its initial thickness. This washer met the minimum requirement for thickness, and it was deemed to have failed in pull-through. In addition, the anchor rod appears to have failed in combined tension and bending. This can be seen in Figure 3.19 (top right) where the fracture surface in the anchor rod is shown to have occurred within the thickness of the plate washer, likely due to local bending.

1.1.6. Results of 1.5” Diameter Gr. 36 Rod Tension Tests

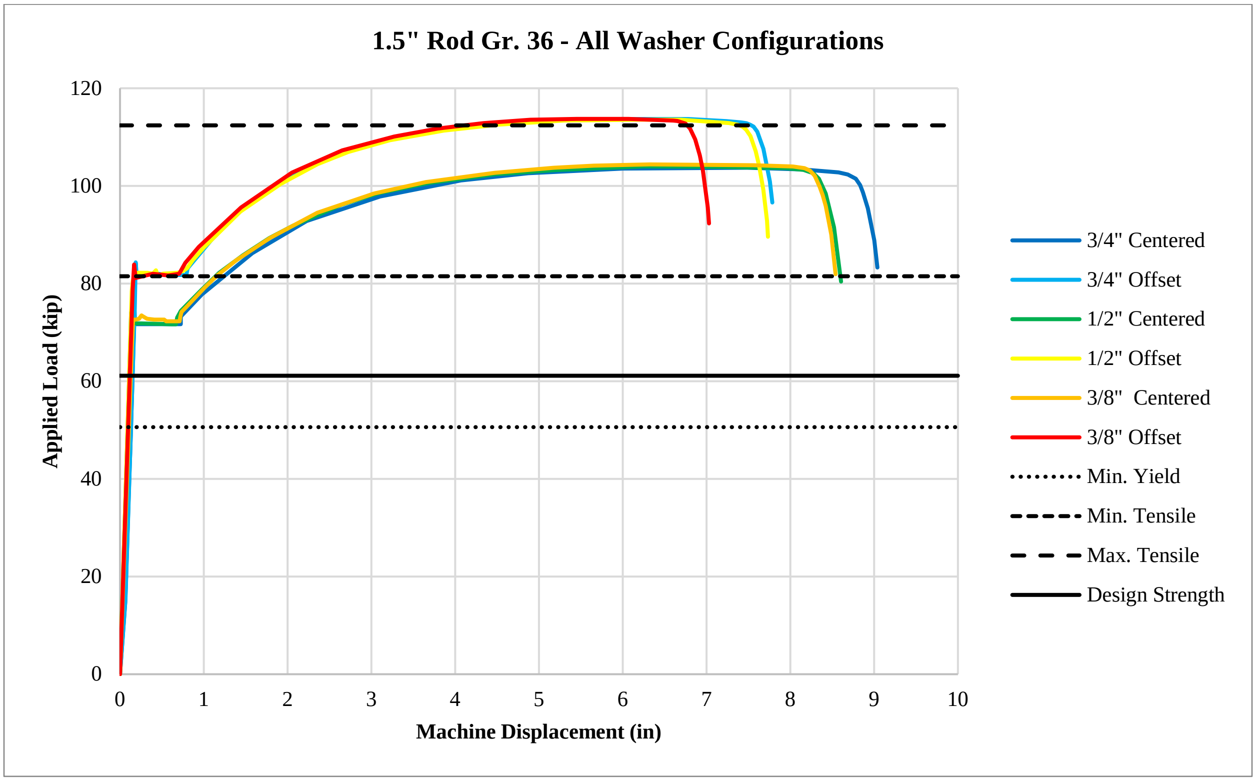

Figure 3.20: Load-Displacement Graph 1.5” Gr.36 Rod

The 1.5” diameter Gr. 36 anchor rod specimens did not perform reliably. As Figure 3.20 indicates, three specimens exceeded the maximum ultimate tensile strength limit by more than 1,000 pounds. Also, these three specimens produced load-displacement curves which matched the general shape of the other four specimens’ curves, but with strengths aligning much more closely with what would be expected of Gr. 55 rods. The questionable reliability of these Gr. 36 rods will be further discussed in the following chapter.

Figure 3.21: 3/8” Plate Washer, Offset – 1.5” Gr. 36 Rod

The minimum required thickness for plate washers with 1.5” diameter anchor rods is 1/2". The only plate washer in this group with a relative deformation greater than 17% was test #42, seen in Figure 3.21. This washer deflected 52% of its original thickness, but these results will not impact the final recommendations because its thickness was less than the minimum required washer thickness.

1.1.7. Results of 1.5” Diameter Gr. 55 Rod Tension Tests

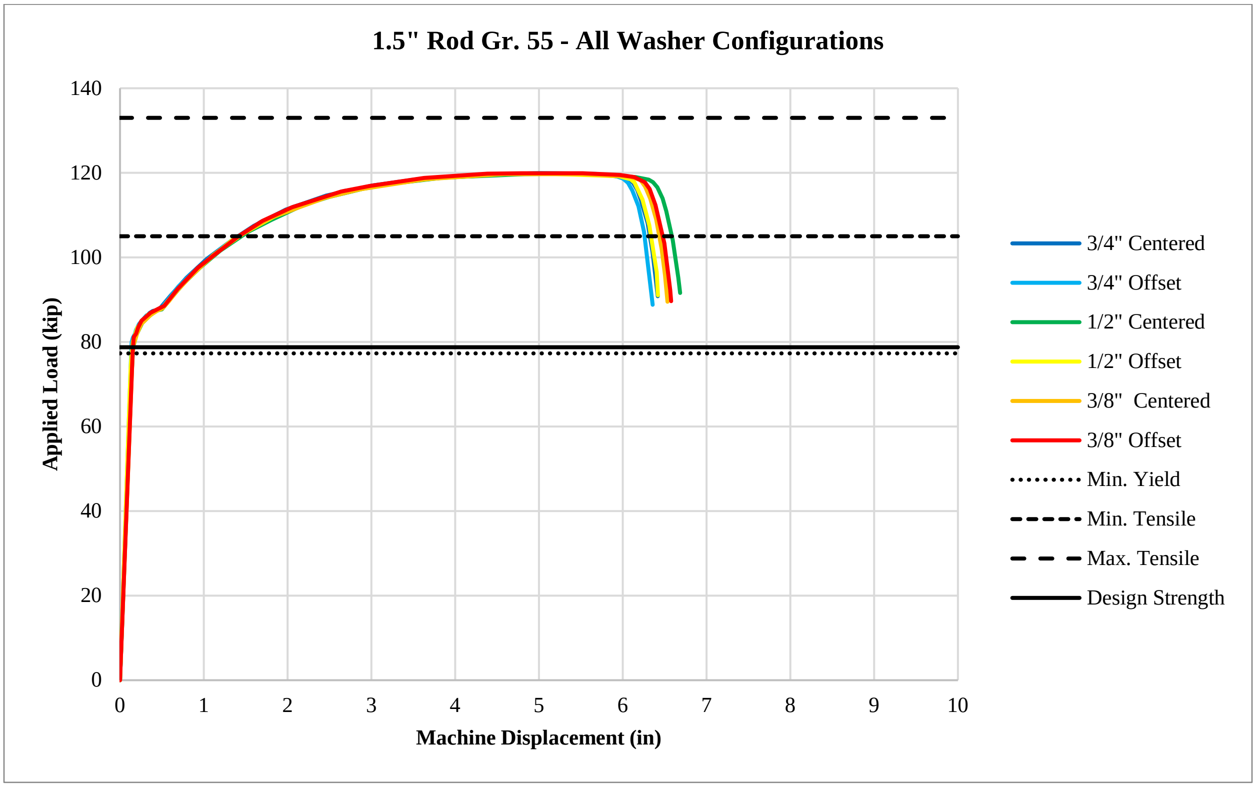

Figure 3.22: Load-Displacement Graph 1.5” Gr.55 Rod

The 1.5” diameter Gr. 55 anchor rods performed as expected, met all necessary criteria, and performed reliably across all six specimens. A very small yield plateau could be noted at the base of the strain hardening region. Each specimen displayed adequate strength and ductility.

Figure 3.23: 3/8" Plate Washer, Offset - 1.5" Gr. 55 Rod

The plate washer in Test #47, seen in Figure 3.23 deformed 45% relative to its thickness. This constituted visual failure, and it was the only washer in this group to have failed in pull-through. Again, the minimum required washer thickness given by AISC is 1/2", so this group met the requirements found in *the Manual*.

1.1.8. Results of 1.5” Diameter Gr. 105 Rod Tension Tests

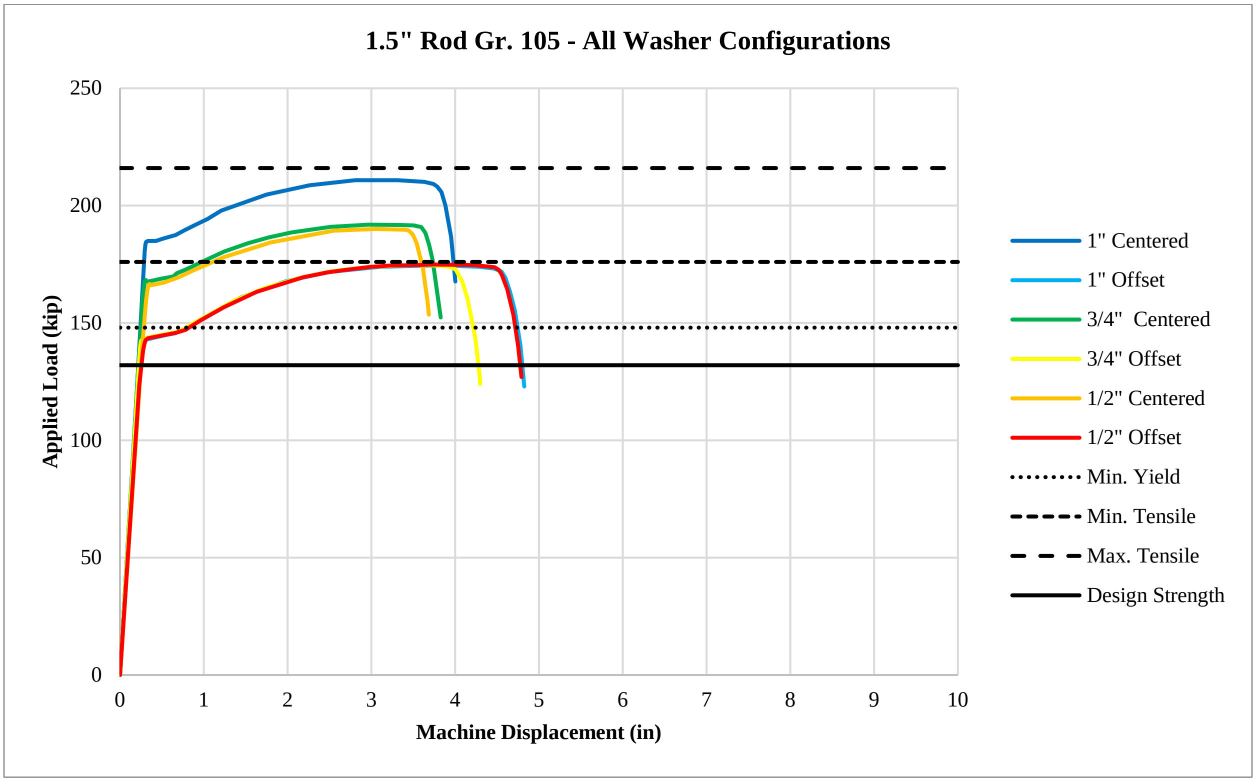

Figure 3.24: Load-Displacement Graph 1.5” Gr.105 Rod

The 1.5” Gr. 105 anchor rod specimens performed the least reliably of any group of specimens. Three anchor rods failed to meet the minimum yield strength and minimum ultimate strength requirements. Two anchor rods performed safely between the bounds, but one specimen exhibited an ultimate strength very close to the upper bound of the allowable tensile strength. Although each curve had the same general shape, the final results of each test were disparate enough to necessitate repetition of testing for this group of rods.

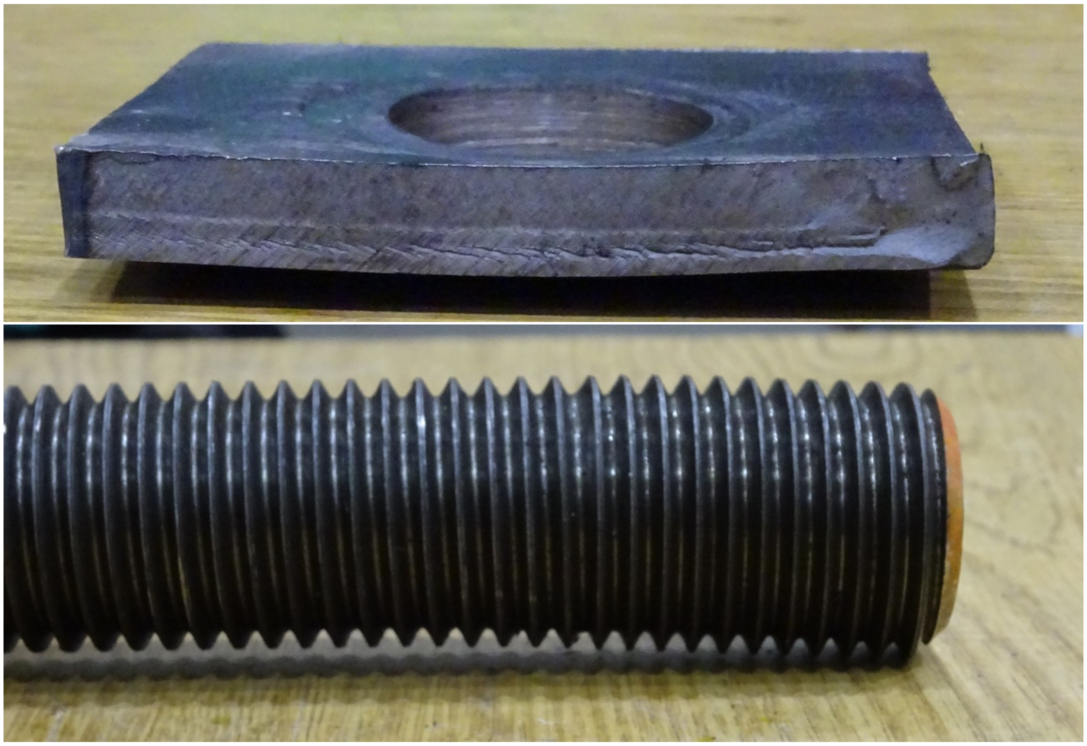

Figure 3.25: 1/2" Plate Washer, Offset - 1.5" Gr. 105 Rod

The washer in this group which deformed the most can be seen in Figure 3.25 and was found to have deformed 38% relative to its thickness. This did not constitute visual failure, but the anchor rod was tested below the minimum ultimate tensile strength. This will be discussed further in the following section. In addition to its moderate deformation in the direction of loading, the offset orientation of this washer caused the anchor rod to undergo significant bending at the interface with the plate washer.

1.1.9. Results of 1.5” Diameter Gr. 105 Additional Rod Tension Tests

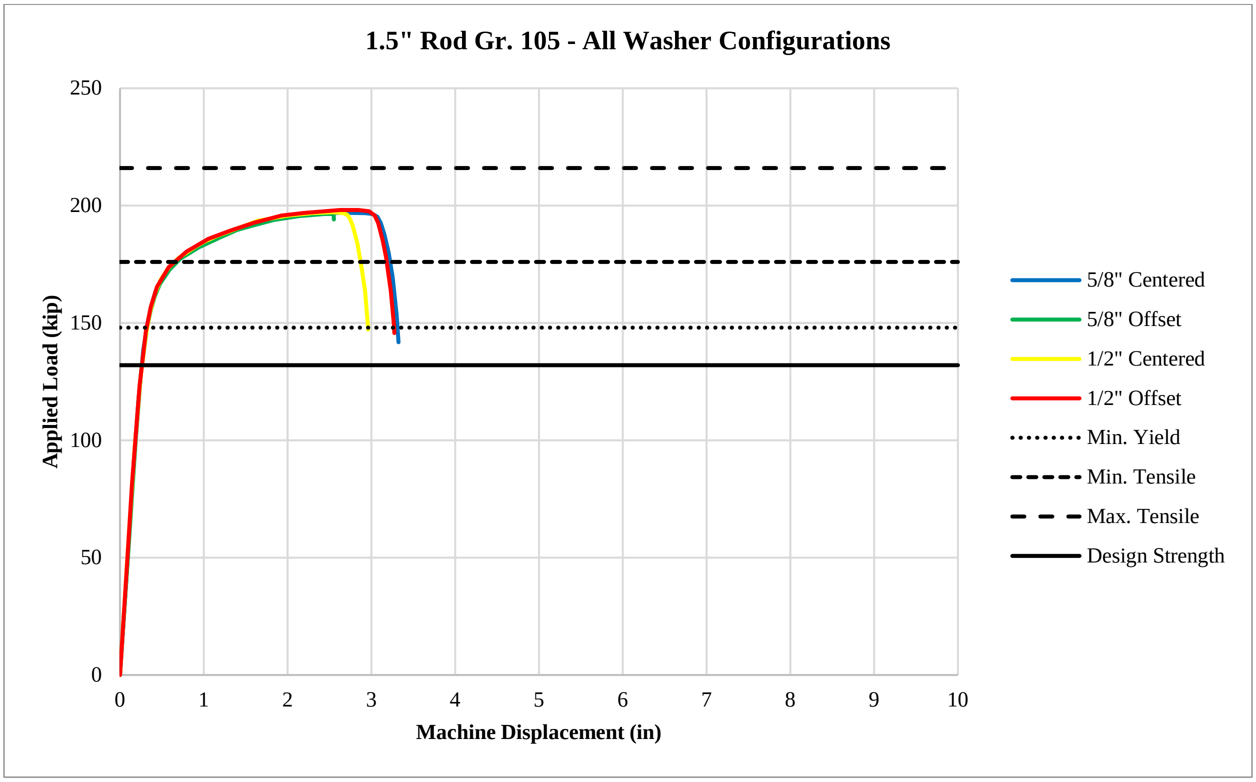

Figure 3.26: Load-Displacement Graph 1.5” Gr.105 Rod

Due to the inadequacy of the previous set of 1.5” diameter Gr. 105 anchor rod tests, four more specimens were acquired and tested following the completion of the first phase of testing. As can be seen in Figure 3.26, all four specimens yielded above the minimum yield strength and reached their ultimate strength evenly between the bounding criteria. These four specimens behaved reliably in general. However, the specimen with a 5/8” thick plate washer in the offset orientation experienced a considerably less ductile failure. This specimen failed without any visible necking. No evidence of bending of the anchor rod was discovered, and the reason for this unexpected failure is unknown.

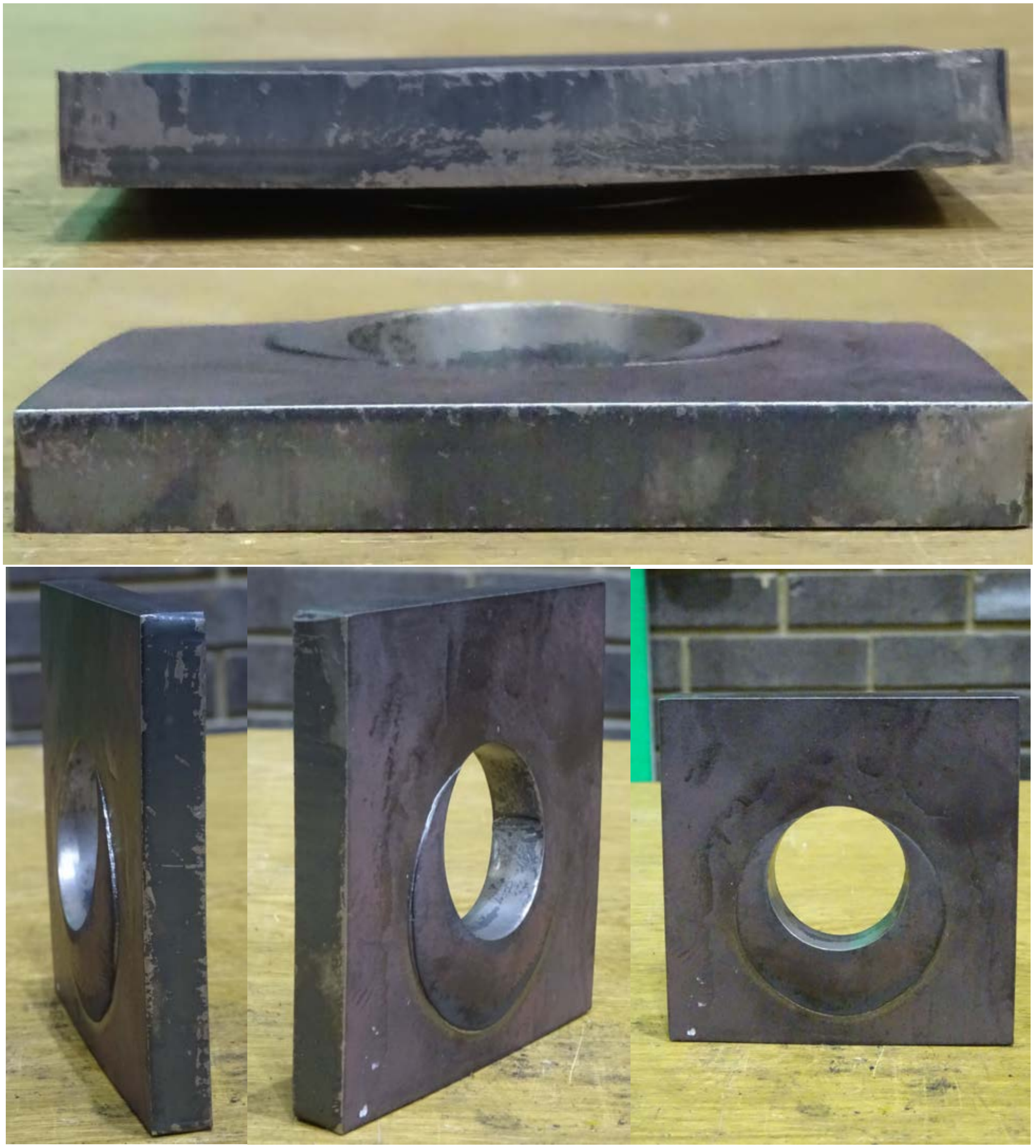

Figure 3.27: Additional 1/2" Plate Washer, Offset - 1.5" Gr. 105 Rod

Figure 3.28: Additional 5/8" Plate Washer, Offset - 1.5" Gr. 105 Rod

The plate washer shown in Figure 3.28 deformed 42% of its initial thickness in the direction of loading. This washer meets the current recommendation for thickness found in table 14-2 of *the Manual*. The other washers in this group tested between 10% and 15% relative deformation. The last test in this group, using a 5/8” plate washer in the offset orientation, underwent a shearing failure of the threads of the nut as shown in Figure 3.28. When the nut failed, the anchor rod had reached the average ultimate tensile strength of the other three rods in the group, and its washer had deformed comparably to the other washer at that load and thickness. It is suspected that this nut was incidentally subjected to multiple loadings in multiple tests before failing due to thread stripping.

1.1.10. Results of 2.00” Diameter Gr. 36 Rod Tension Tests

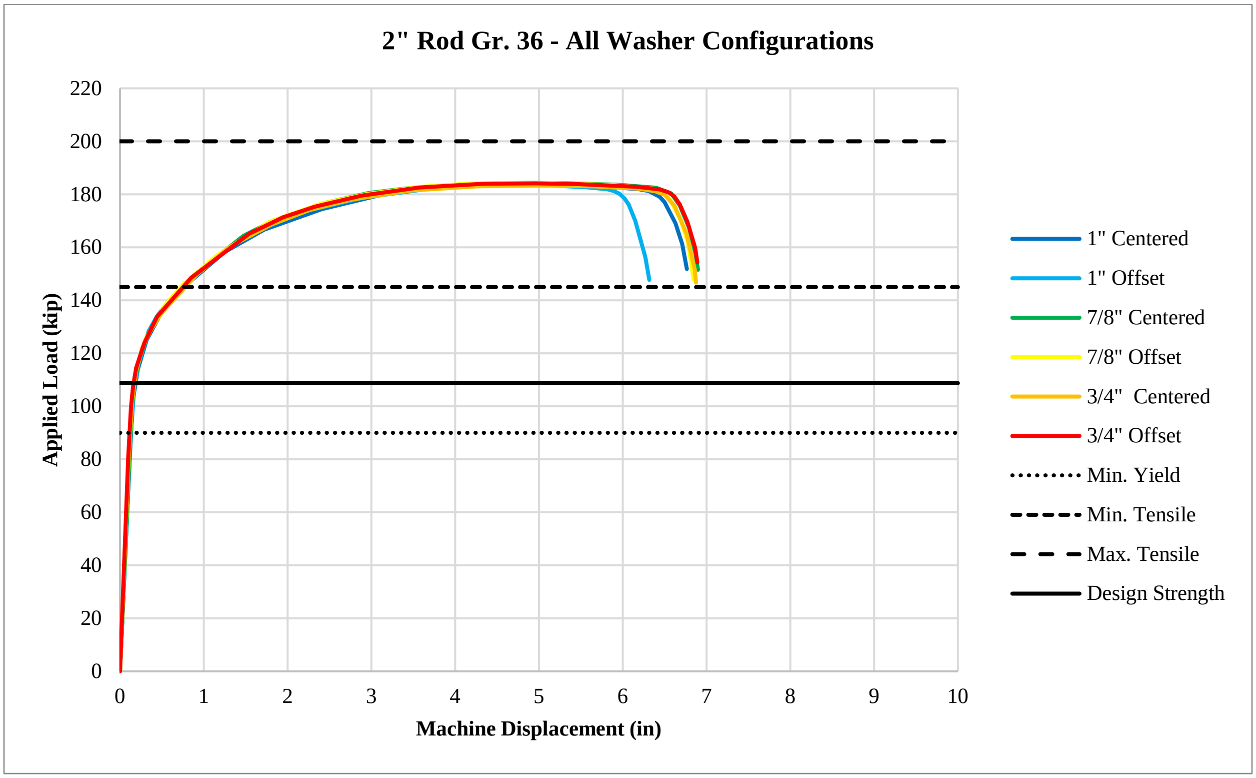

Figure 3.29: Load-Displacement Graph 2” Gr.36 Rod

The 2” diameter Gr. 36 rods performed at adequate strengths for all strength requirements, falling well between the maximum and minimum ultimate strength requirements on all six tests. No discernible yield plateau can be seen, similar to that of the Gr. 55 specimens of the same diameter.

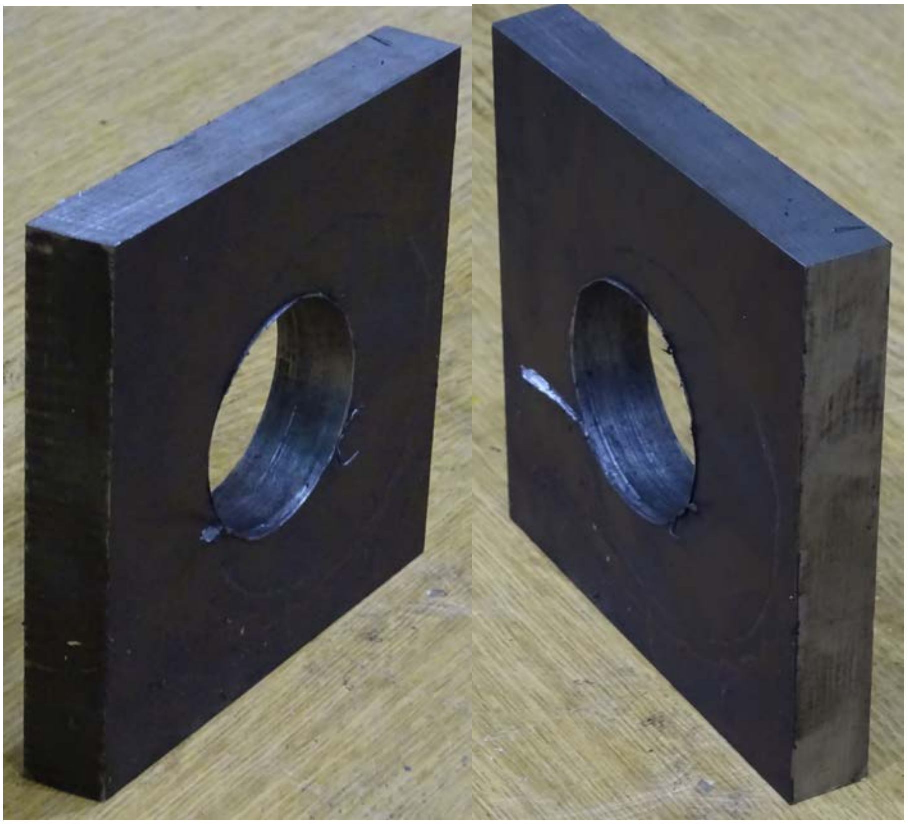

Figure 3.30: 3/4" Plate Washer, Offset - 2" Gr. 36 Rod

All plate washers in this group performed adequately and were not considered to have failed by visual inspection. The washer with the largest relative deformation in this group can be seen in Figure 3.30 and had a measured deformation of 6%.

1.1.11. Results of 2.00” Diameter Gr. 55 Rod Tension Tests

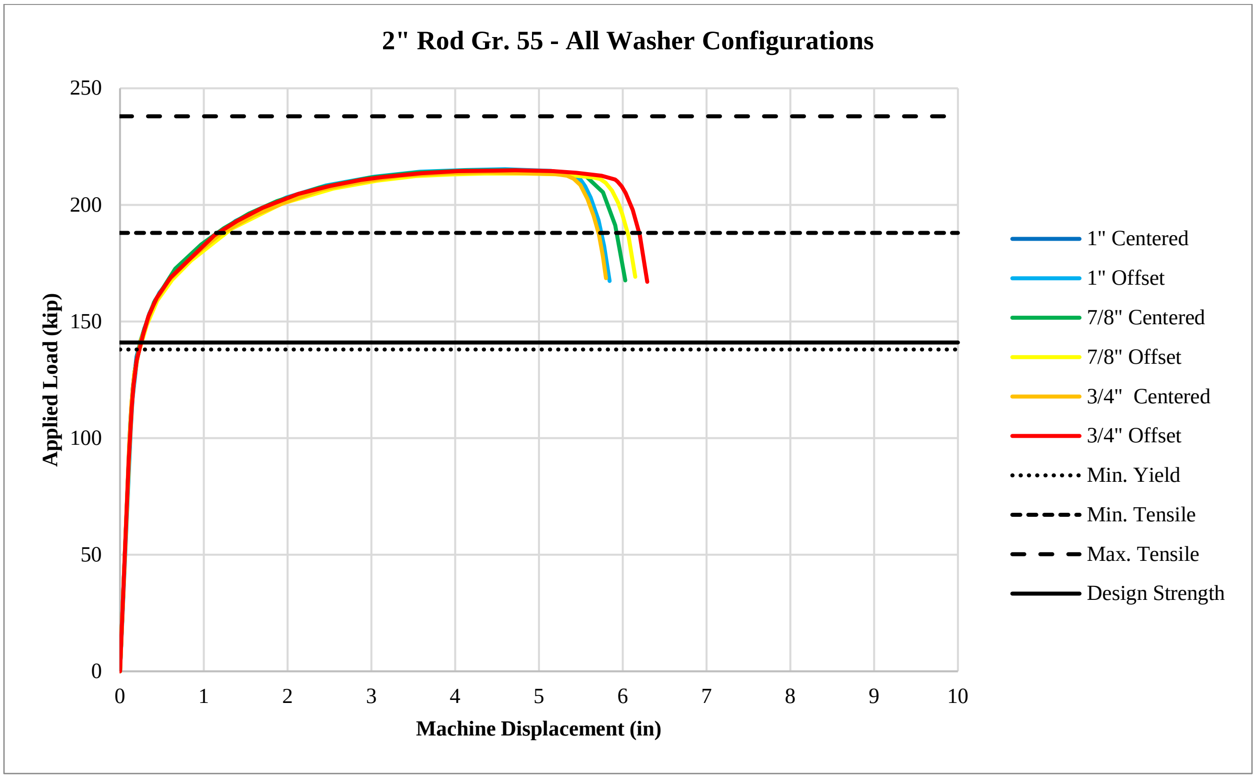

Figure 3.31: Load-Displacement Graph 2” Gr.55 Rod

The 2” diameter Gr. 55 rods performed at adequate strengths for all strength requirements, falling directly between the maximum and minimum ultimate strength requirements on all six tests. No discernible yield plateau can be seen, similar to that of the Gr. 36 specimens of the same diameter.

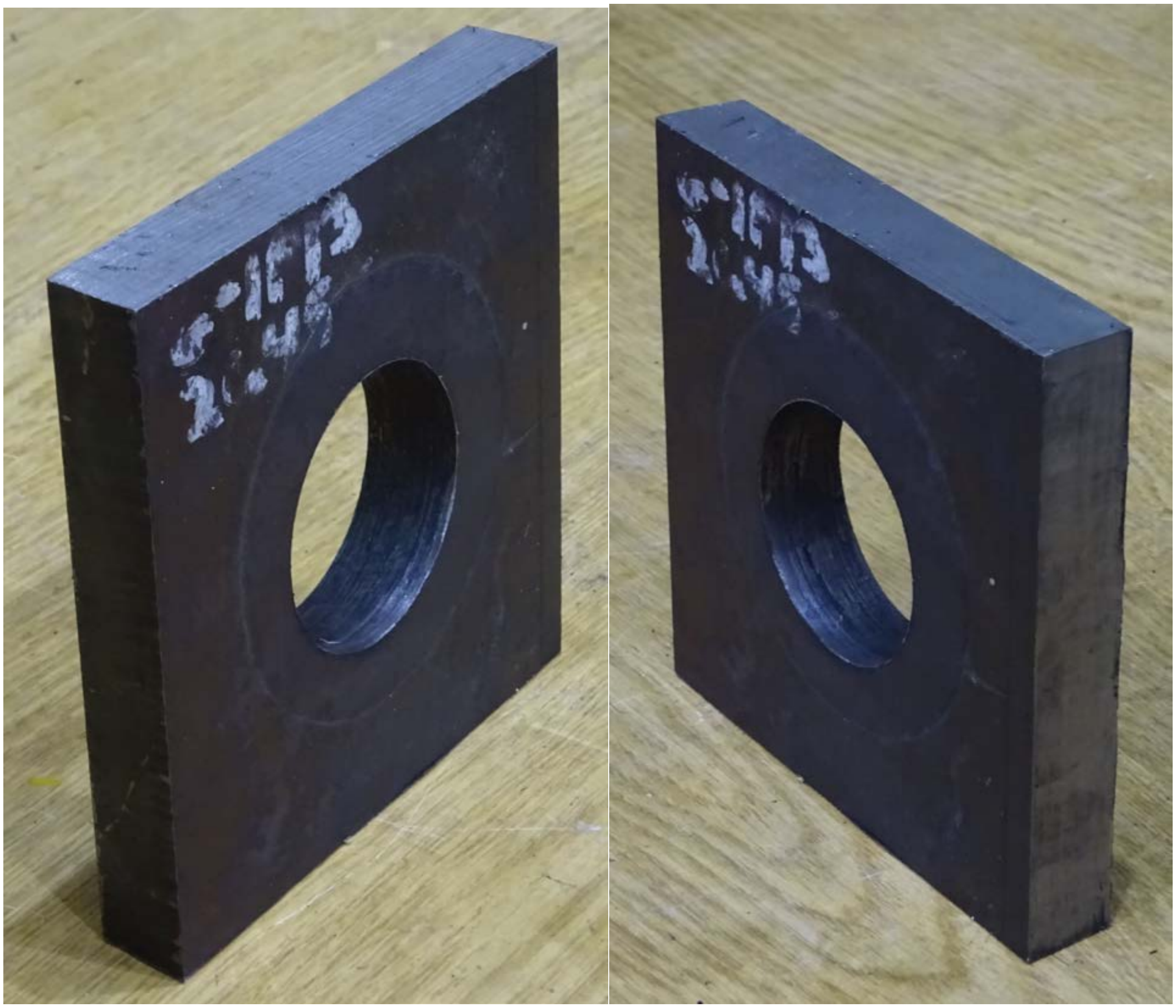

Figure 3.32: 3/4" Plate Washer, Offset - 2" Gr. 55 Rod

All plate washers in this group performed adequately and were not considered to have failed by visual inspection. The washer with the largest relative deformation in this group can be seen in Figure 3.32 and had a measured deformation of 7%.

1.1.12. Results of 2.00” Diameter Gr. 105 Rod Tension Tests

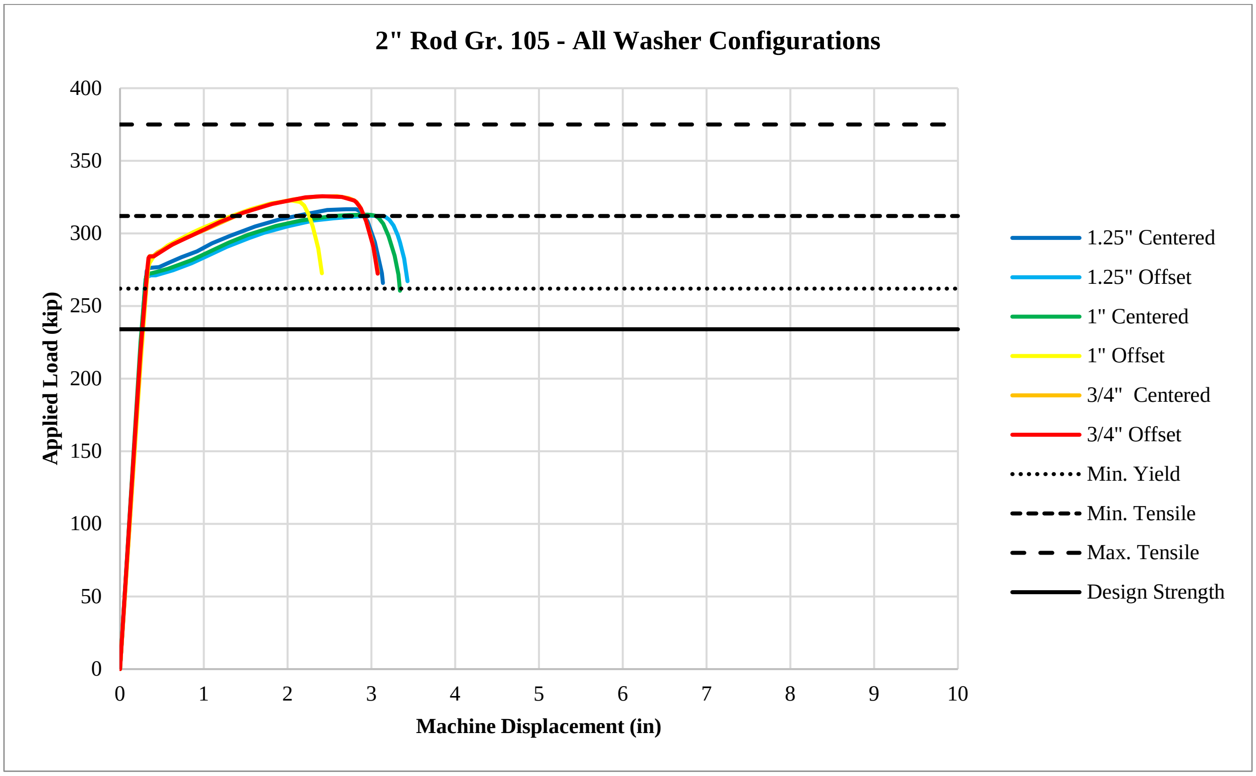

Figure 3.33: Load-Displacement Graph 2” Gr.105 Rod

The 2” diameter Gr. 105 rods did not perform as expected, just as was noted for the 1” and 1.5” diameter Gr. 105 rods. All six specimens met the minimum yield criteria for ASTM F1554 Gr. 105, but two specimens did not quite reach the minimum ultimate tensile strength for the material. All six specimens exhibited similar yielding and strain hardening behavior but did not display reliability with regard to ultimate strength.

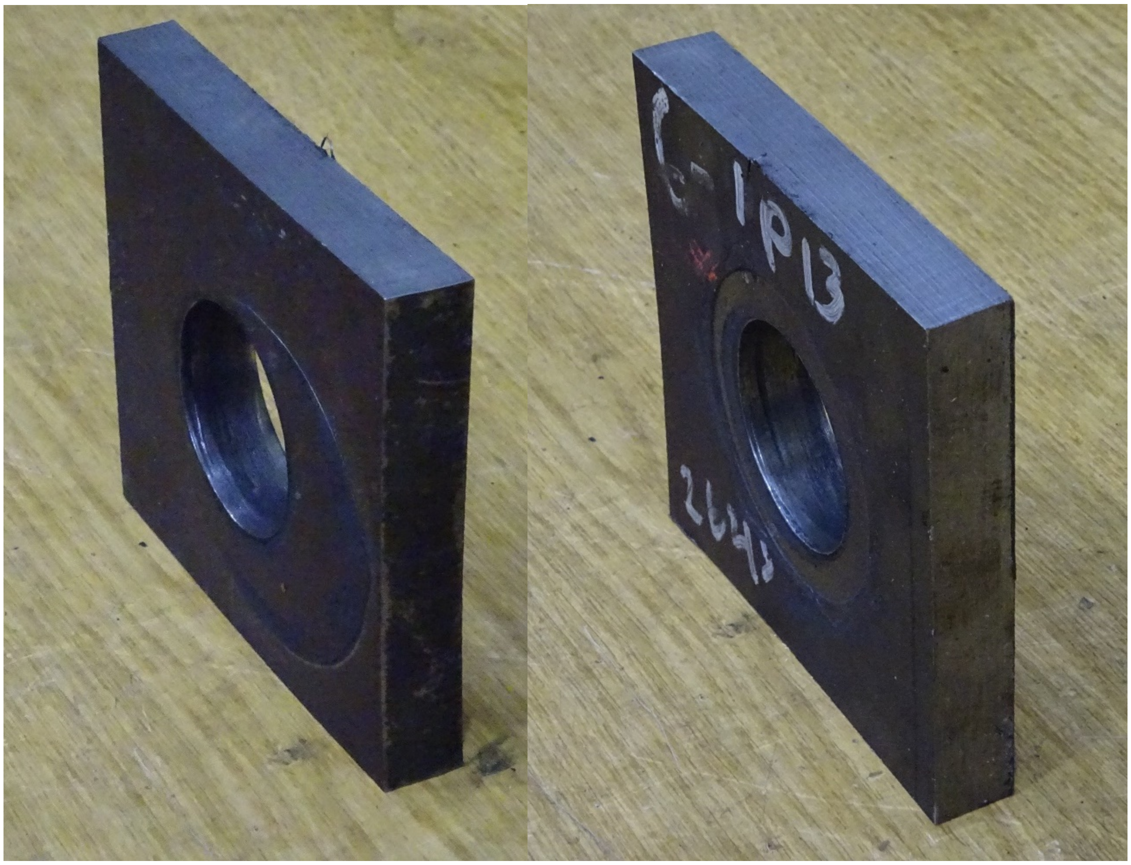

Figure 3.34: 3/4" Plate Washer, Offset - 2" Gr. 105 Rod

All plate washers in this group performed adequately and were not considered to have failed by visual inspection. The washer with the largest relative deformation in this group can be seen in Figure 3.34 and had a measured deformation of 19%. For the 3/4” thick plate washers, the increase in ultimate load was proportional to the increase in deformation for the Gr. 55 and Gr. 105 rods.

1.1.13. Results of 2.50" Diameter Gr. 36 Rod Tension Tests

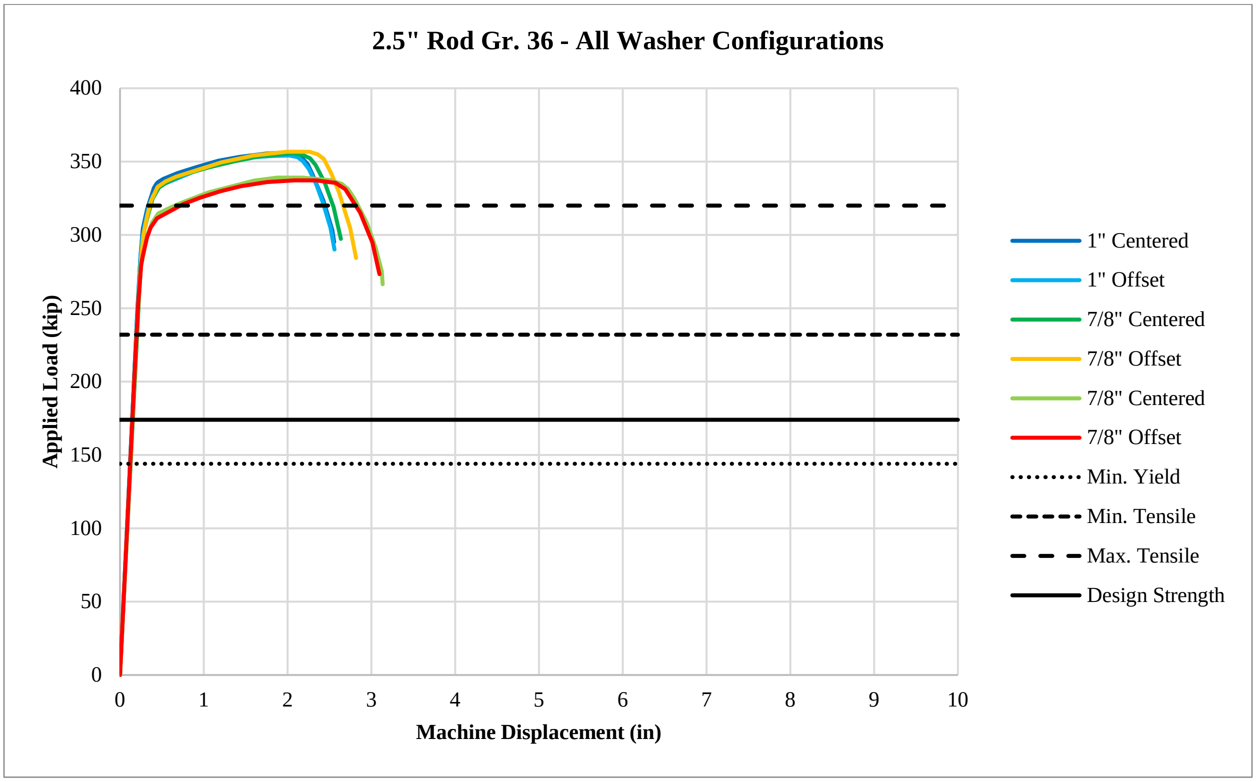

Figure 3.35: Load-Displacement Graph 2.5" Gr.36 Rod

All the 2.5" diameter Gr. 36 anchor rods reached their ultimate strength well above the maximum ultimate tensile strength requirement. All six 2.5" Gr. 36 rods displayed a higher ultimate tensile strength than all six 2.5" Gr. 55 rods. Aside from being well over-strength, the rods did not perform too reliably. Four rods reached a significantly higher ultimate tensile strength than the other two. Aside from discrepancies between the expected and tested strengths, these specimens also showed lower ductility when compared to that of the 2.5" Gr. 55 specimens. It is suspected that these were Gr. 55 material and were erroneously marked as Gr. 36.

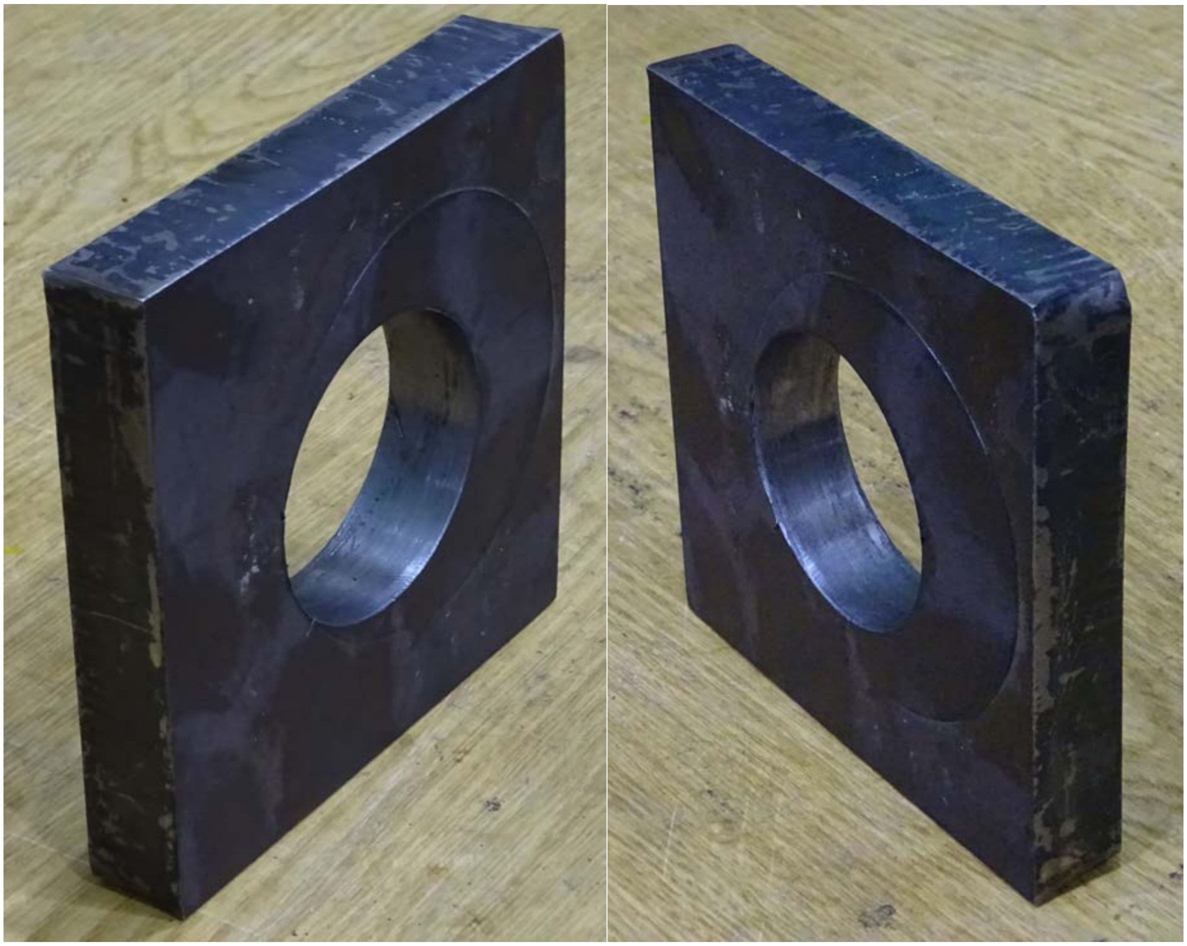

Figure 3.36: 7/8" Plate Washer, Offset - 2.5" Gr. 36 Rod

All plate washers in this group performed adequately and were not considered to have failed by visual inspection. The washer with the largest relative deformation in this group can be seen in Figure 3.36 and had a measured deformation of 12% of its initial thickness.

1.1.14. Results of 2.50” Diameter Gr. 55 Rod Tension Tests

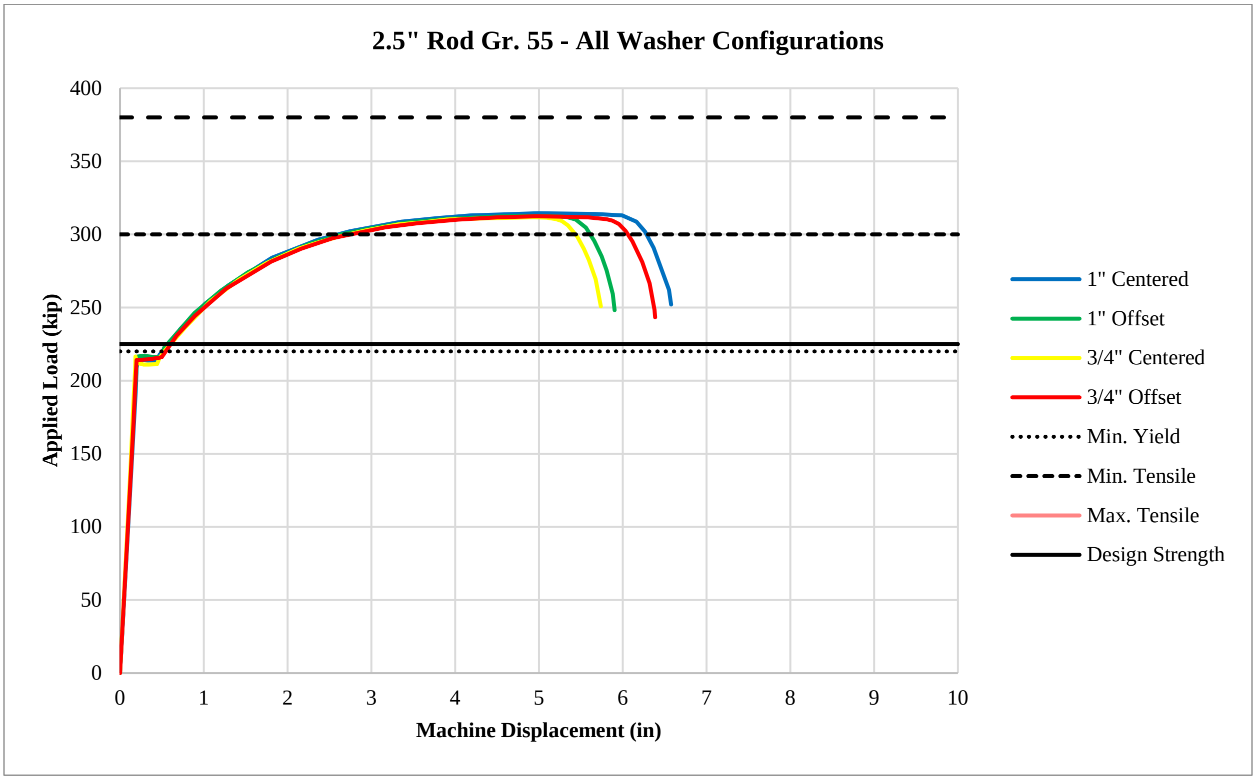

Figure 3.37: Load-Displacement Graph 2.5” Gr.55 Rod

The 2.5” Gr. 55 anchor rods performed reliably and met the minimum and maximum ultimate strength criteria. However, all six anchor rod specimens failed to meet the minimum yield strength criterion. The yielding and strain hardening behavior of these six specimens much more closely matches that of the Gr. 36 specimens of all diameters but the 2.5” Gr. 36. All specimens were inspected to ensure that the Gr. 36 and Gr. 55 threaded rods were not accidentally tested in the wrong groups. It is suspected that these rods may have been Gr. 36 material and may have accidentally been marked as Gr. 55 (see previous subsection).

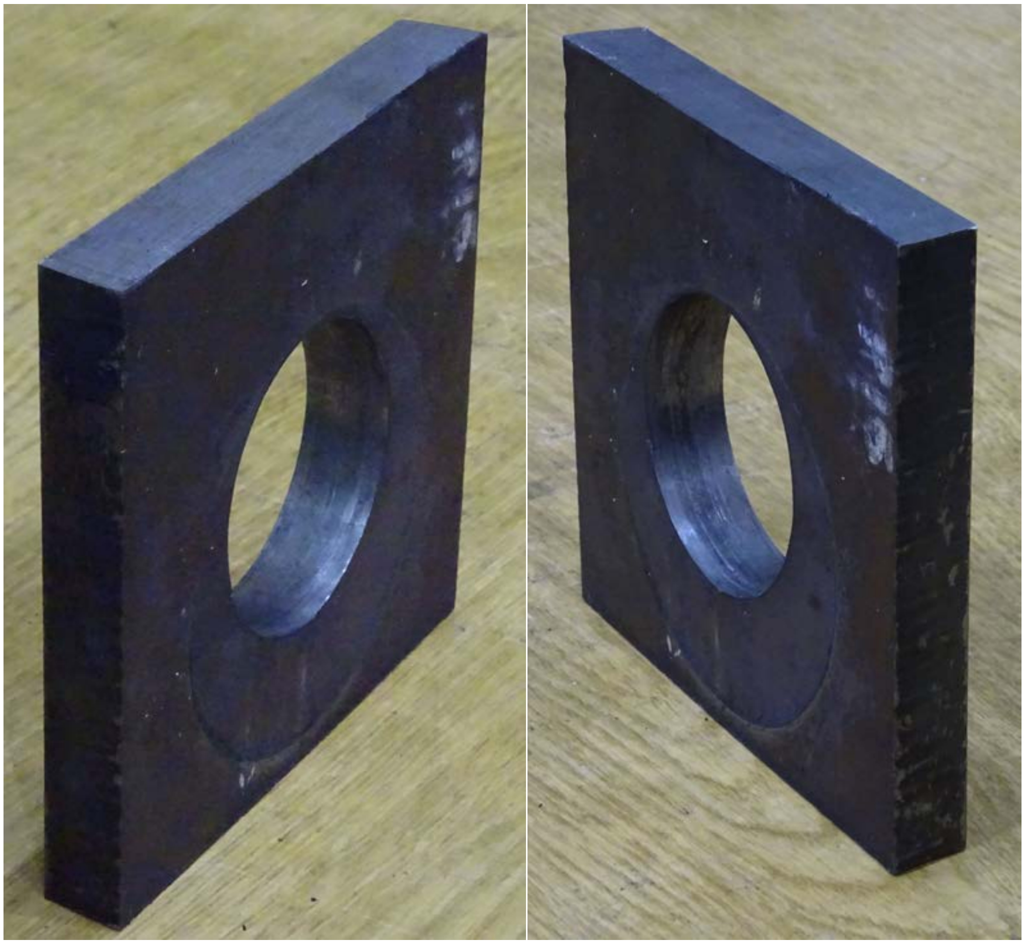

Figure 3.38: 3/4" Plate Washer, Offset - 2.5" Gr. 55 Rod

All plate washers in this group performed adequately and were not considered to have failed by visual inspection. The washer with the largest relative deformation in this group can be seen in Figure 3.38 and had a measured deformation of 12% of its initial thickness.

1.1.15. Results of 2.50” Diameter Gr. 105 Rod Tension Tests

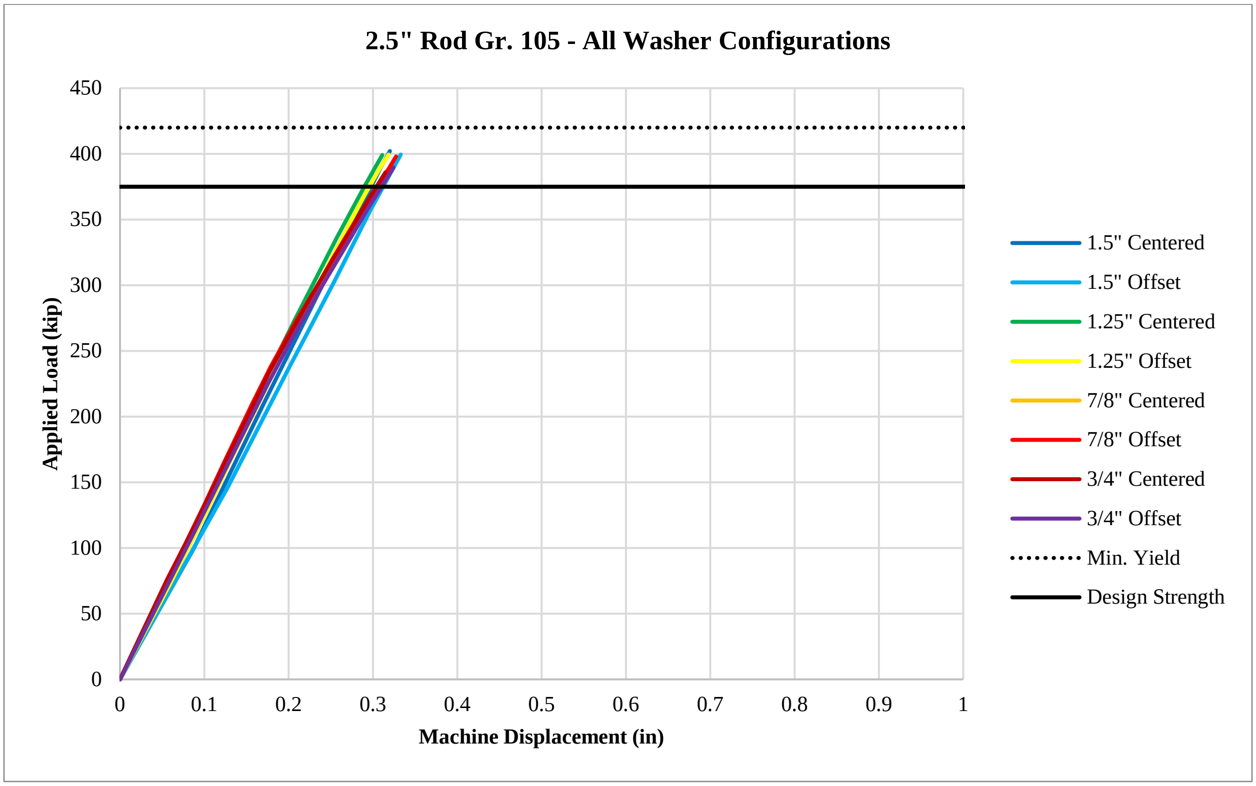

Figure 3.39: Load-Displacement Graph 2.5” Gr. 105 Rod

The maximum capacity of the Tinius Olsen Super-L Universal Testing Machine is approximately 400 kips. The minimum yield strength of the 2.5” diameter Gr. 105 anchor rods is 420 kips. For this reason, only one anchor rod specimen was used to test eight plate washers. In each case, the plate washer permitted the development of the design strength of the anchor rod before testing had to be terminated. No conclusions can be drawn about the behavior of these specimens beyond their design strength.

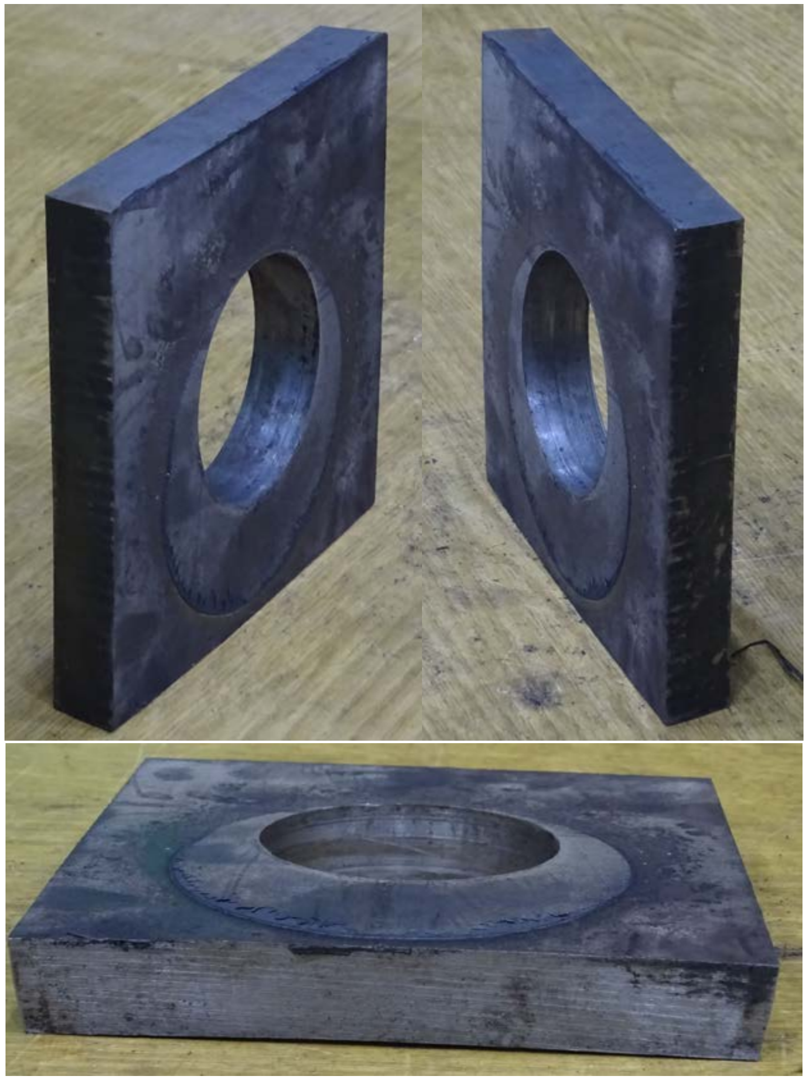

Figure 3.40: 3/4" Plate Washer, Offset - 2.5" Gr. 105 Rod

All plate washers in this group performed adequately and were not considered to have failed by visual inspection. The washer with the largest relative deformation in this group can be seen in Figure 3.40 and had a measured deformation of 17% of its initial thickness. It should be noted that the testing machine was not able to develop the full capacity of the 2.5” Gr. 105 rods. For this reason, the relative deformations recorded were measured are presumably lower than if the rods had been fully developed. This will be discussed further in the following chapter.

3.3. Visual Failure

The most convenient starting point for determining failure in the washers was to categorize all 94 specimens into four groups based on a visual assessment of their behavior in testing. The first category was the lightest deformation, indicated with the digit 0 – Did Not Fail. The last category was labeled 3 – Clear Failure. Two intermediate groups were created, and the 94 plate washers were visually classified according to their deformations relative to the other washers and best judgment, as shown in Table 3.4.

Table 3.4: Visual Classification of Failure Categories

Test #	Nominal t	P/F 0-3	Test #	Nominal t	P/F 0-3	Test #	Nominal t	P/F 0-3
1	0.500	0	31	0.750	0	55	1.000	0
2	0.500	0	32	0.750	0	56	1.000	0
3	0.375	0	33	0.500	0	57	0.875	0
4	0.375	0	34	0.500	0	58	0.875	0
5	0.250	1	35	0.375	0	59	0.750	0
6	0.250	1	36	0.375	2	60	0.750	0
7	0.500	0	37	0.750	0	61	1.000	0
8	0.500	0	38	0.750	0	62	1.000	0
9	0.375	0	39	0.500	0	63	0.875	0
10	0.375	0	40	0.500	0	64	0.875	0
11	0.250	1	41	0.375	1	65	0.750	0
12	0.250	1	42	0.375	1	66	0.750	0
13	0.500	0	43	0.750	0	67	1.250	0
14	0.500	0	44	0.750	0	68	1.250	0
15	0.375	0	45	0.500	0	69	1.000	0
16	0.375	0	46	0.500	0	70	1.000	0
17	0.250	2	47	0.375	2	71	0.750	0
18	0.250	3	48	0.375	1	72	0.750	1
19	0.500	0	49	1.000	0	73	1.000	0
20	0.500	0	50	1.000	0	74	1.000	0
21	0.375	0	51	0.750	0	75	0.875	1
22	0.375	0	52	0.750	0	76	0.875	0
23	0.250	2	53	0.500	1	77	0.875	0
24	0.250	3	54	0.500	1	78	0.875	0
25	0.500	0	1A	0.500	2	79	1.000	0
26	0.500	0	2A	0.500	1	80	1.000	0
27	0.375	1	3A	0.625	1	81	0.750	0
28	0.375	0	4A	0.625	1	82	0.750	0
29	0.250	3				83	1.500	0
30	0.250	3				84	1.500	0
						85	1.250	0
						86	1.250	0
						87	0.875	0
						88	0.875	0
						89	0.750	0
						90	0.750	0

3.4. Distribution of Washer Deformations

After visual failure groups had been populated, all plate washers were measured as described in Chapter 2. Relative deformations were calculated, and results of this calculation were correlated to the results of the visual assessment, as summarized in Figure 4.1 where the results of this analysis are shown.

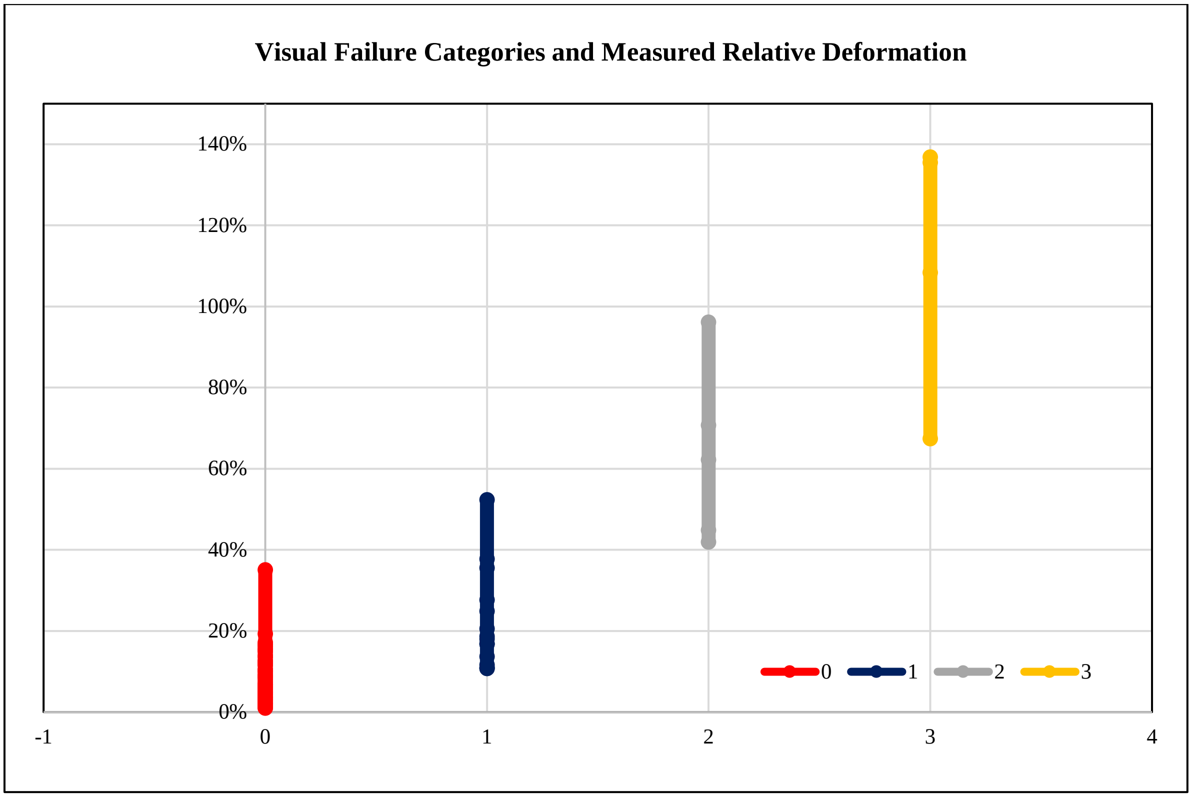

Figure 3.41: Visual Failure Categories and Measured Relative Deformation

Given the nature of any visual assessment, some outliers were expected in the data. A total of two points were removed that were at least three standard deviations away from the visual classification's mean. Once these statistical outliers were removed, a clear delineation appeared between Category 1 and Category 2 at approximately 40% relative deformation, as shown in Figure 3.42.

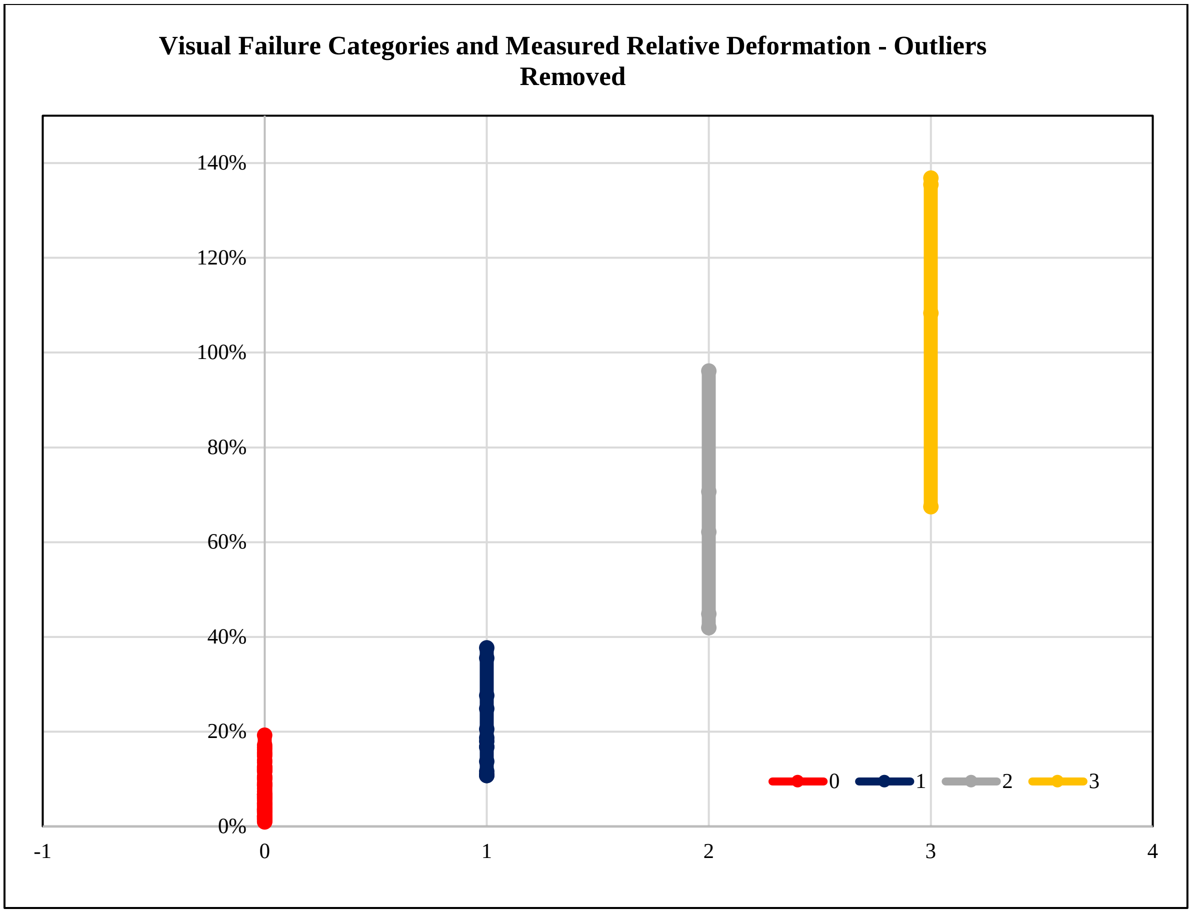

Figure 3.42: Visual Failure Categories and Measured Relative Deformation - Outliers Removed

3.5.Consideration of Design Strength

During the design life of a column anchor rod, the highest load the rod and plate washer will see is the design strength of the rod, taken conservatively as three quarters of the lower bound ultimate strength of the anchor rod as designated by ASTM F1554. However, during testing the assembly underwent the full ultimate strength of the individual anchor rod, with the exception of the 2.5" diameter Gr. 105 rods. In order to determine if the failure of any given plate washer came as the result of a disparity between the ultimate strength of its rod and the ultimate strength of the group, a comparison was made between the ratio of ultimate strength to design strength and the relative deformation of the washer, shown in Table 3.5. Deformations greater than 40% of the initial thickness of the washer are listed in red.

Table 3.5: Comparison of Design Strength vs. Ultimate Strength and Washer Performance

Test #	Nom. t	Orientation	Diameter (in.)	Grade (ksi)	Ultimate Tensile (k)	Design Strength (k)	Ultimate/Design (%)	Average Relative Deflection (%)
1	0.500	1	0.750	36	23.047	14.55	158.4%	-
2	0.500	2			22.974		157.9%	-
3	0.375	1			22.955		157.8%	6.3%
4	0.375	2			23.017		158.2%	4.2%
5	0.250	2			23.047		158.4%	25.0%
6	0.250	1			23.170		159.2%	10.8%
7	0.500	1	0.750	55	29.686	18.75	158.3%	3.0%
8	0.500	2			29.510		157.4%	17.2%
9	0.375	2			29.622		158.0%	6.7%
10	0.375	1			29.649		158.1%	4.9%
11	0.250	1			29.391		156.8%	20.5%
12	0.250	2			29.477		157.2%	27.6%
13	0.500	2	0.750	105	48.137	31.35	153.5%	5.0%
14	0.500	1			47.519		151.6%	9.3%
15	0.375	1			47.625		151.9%	12.5%
16	0.375	2			47.536		151.6%	12.2%
17	0.250	2			48.403		154.4%	71.3%
18	0.250	1			48.034		153.2%	68.3%
19	0.500	1	1.000	36	47.270	26.40	179.1%	11.7%
20	0.500	2			47.103		178.4%	11.8%
21	0.375	2			47.210		178.8%	9.7%
22	0.375	1			47.171		178.7%	12.0%
23	0.250	1			46.737		177.0%	97.1%
24	0.250	2			46.993		178.0%	108.7%
25	0.500	2	1.000	55	51.742	34.05	152.0%	8.9%
26	0.500	1			51.788		152.1%	10.7%
27	0.375	1			51.713		151.9%	16.9%
28	0.375	2			51.734		151.9%	10.4%
29	0.250	2			51.656		151.7%	137.6%
30	0.250	1			51.234		150.5%	137.1%
31	0.750	1	1.000	105	76.770	56.85	135.0%	2.7%
32	0.750	2			84.544		148.7%	1.9%
33	0.500	2			81.529		143.4%	14.0%
34	0.500	1			84.409		148.5%	13.6%
35	0.375	1			76.485		134.5%	35.1%
36	0.375	2			81.653		143.6%	62.2%

37	0.750	1	1.500	36	104.103	81.50	127.7%	3.0%
38	0.750	2			113.846		139.7%	3.9%
39	0.500	2			104.351		128.0%	15.4%
40	0.500	1			113.660		139.5%	15.7%
41	0.375	1			103.673		127.2%	16.8%
42	0.375	2			113.660		139.5%	52.4%
43	0.750	2	1.500	55	119.606	78.75	151.9%	3.6%
44	0.750	1			119.634		151.9%	2.2%
45	0.500	1			119.577		151.8%	14.9%
46	0.500	2			119.820		152.2%	19.3%
47	0.375	2			119.720		152.0%	45.0%
48	0.375	1			119.949		152.3%	18.0%
49	1.000	1	1.500	105	190.607	132.00	144.4%	2.2%
50	1.000	2			174.629		132.3%	1.7%
51	0.750	2			191.498		145.1%	4.8%
52	0.750	1			174.272		132.0%	5.7%
53	0.500	1			191.579		145.1%	35.8%
54	0.500	2			174.143		131.9%	38.1%
1A	0.500	2	1.500	105.0	197.844	132.00	149.9%	42.1%
2A	0.500	1			196.865		149.1%	13.8%
3A	0.625	1			197.445		149.6%	11.0%
4A	0.625	2			198.423		150.3%	10.7%
55	1.000	1	2.000	36	184.162	108.75	169.3%	1.0%
56	1.000	2			184.176		169.4%	1.4%
57	0.875	2			182.861		168.1%	1.9%
58	0.875	1			184.390		169.6%	2.1%
59	0.750	1			183.576		168.8%	1.4%
60	0.750	2			182.890		168.2%	6.3%
61	1.000	2	2.000	55	214.675	141.00	152.3%	1.7%
62	1.000	1			214.617		152.2%	6.0%
63	0.875	1			213.974		151.8%	3.7%
64	0.875	2			213.060		151.1%	6.7%
65	0.750	2			214.432		152.1%	6.7%
66	0.750	1			214.789		152.3%	6.8%
67	1.250	1	2.000	105	325.236	234.00	139.0%	3.2%
68	1.250	2			309.772		132.4%	3.5%
69	1.000	2			312.459		133.5%	8.0%
70	1.000	1			323.592		138.3%	5.5%
71	0.750	1			316.232		135.1%	16.2%
72	0.750	2			311.859		133.3%	18.6%

73	1.000	1	2.500	36	340.314	174.00	195.6%	6.1%
74	1.000	2			336.912		193.6%	4.6%
75	0.875	2			355.520		204.3%	11.5%
76	0.875	1			357.607		205.5%	8.9%
77	0.875	1			355.978		204.6%	8.5%
78	0.875	2			354.391		203.7%	12.3%
79	1.000	2	2.500	55	312.102	225.00	138.7%	3.2%
80	1.000	1			311.316		138.4%	4.4%
81	0.750	1			314.288		139.7%	7.3%
82	0.750	2			312.402		138.8%	12.0%
83	1.500	2	2.500	105	399.410	375.00	106.5%	1.1%
84	1.500	1			399.010		106.4%	2.3%
85	1.250	1			400.354		106.8%	3.6%
86	1.250	2			398.982		106.4%	3.4%
87	0.875	2			397.167		105.9%	12.6%
88	0.875	1			388.706		103.7%	8.6%
89	0.750	1			389.335		103.8%	9.9%
90	0.750	2			385.876		102.9%	16.7%

While some notable discrepancies can be found in the ultimate strength of rods of the same grade and diameter, only one such abnormality seems to have caused the failure of a plate washer. In the group of 1.5” diameter Gr. 105 plate washers, the 0.5” thick plate washer in the offset condition was tested under the minimum ultimate strength of the anchor rod during initial testing. This plate washer deformed approximately 38% relative to its initial thickness. However, during subsequent testing, the plate washer of the same thickness and orientation was subjected to the full, specified ultimate strength of the rod and deformed approximately 42% relative to its initial thickness. This takes this thickness across the threshold of 40% and also resulted in its visual classification in Group 2 – Likely Failure. Plate washer thickness and orientation were generally more influential on the behavior of the washer than ultimate strength of the rod, but this was a notable exception.

Chapter 4: Recommendations

This chapter will discuss the final applied results of this study and will provide the basis for the recommendations given herein. Based on the design principles established in the AISC *Manual*, the 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. In order to establish a safe 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. No plate washers ruptured during testing, but many were unable to effectively develop the ultimate strength of the anchor rods without incurring severe deformations. No clear standard exists currently that would define how much out of plane deformation would constitute failure in a plate washer in an anchor rod assembly. For this reason, the following section will describe the criterion developed for determination of failure using visual assessments and statistical correlations.

4.1. Final Recommendations

Given the strong correlation between the visual failure groups and the relative deformations of the washers in those groups, as well as the consideration of the safest reasonable failure hierarchy, the failure criterion recommended is as follows. The plate washer is considered to have failed if it has experienced greater than 40% permanent out-of-plane deformation relative to its original thickness. All current thicknesses of plate washers in Table 14-2 of the *Manual* are recommended based on the diameter of the anchor rod only. Intermediate anchor rod diameters which were not directly tested were assigned the plate washer thickness of the group of anchor rods smaller than them in the table. The results of this testing are presented in that format in Table 4.1.

Table 4.1: 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.)
0.75	3/8	1/4
0.875	1/2	5/16
1	1/2	3/8
1.25	5/8	1/2
1.5	5/8	1/2
1.75	3/4	5/8
2	3/4	3/4
2.5	7/8	7/8

The washer thickness recommended by this testing for the 2.5” diameter rod is 7/8”, even though the 3/4” thick plate washer did not deform 40% relative to its initial thickness. The 7/8” thick washer is recommended because the ultimate strength of the 2.5” Gr. 105 anchor rod specimens was not developed. These rods only experienced 2%-7% more load than their design strengths. So, this recommendation of 7/8” is given tentatively, and a 1” thick plate washer was considered as well. No reliable statistical conclusion could be drawn based on the existing data, so the existing recommended washer thickness was taken as the more likely alternative. Considering the difference between loads carried by rods of different grades of the same diameter, it seems valuable to include recommendations by rod grade and diameter. This data is included in Table 4.2.

Table 4.2: 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.)
0.75	Gr. 36	1/4	1/4
	Gr. 55	1/4	
	Gr. 105	3/8	
0.875	Gr. 36	3/8	5/16
	Gr. 55	3/8	
	Gr. 105	1/2	
1	Gr. 36	3/8	3/8
	Gr. 55	3/8	
	Gr. 105	1/2	
1.25	Gr. 36	3/8	1/2
	Gr. 55	1/2	
	Gr. 105	5/8	
1.5	Gr. 36	3/8	1/2
	Gr. 55	1/2	
	Gr. 105	5/8	
1.75	Gr. 36	3/4	5/8
	Gr. 55	3/4	
	Gr. 105	3/4	
2	Gr. 36	3/4	3/4
	Gr. 55	3/4	
	Gr. 105	3/4	
2.5	Gr. 36	3/4	7/8
	Gr. 55	3/4	
	Gr. 105	7/8	

Chapter 5: Conclusions

In summary, this testing and subsequent analysis has served to produce the first experimentally developed values for the thicknesses of plate washers used in column baseplate and anchor rod applications. The results have shown that in the case of ASTM F1554 Gr. 36 and Gr. 55 anchor rods 0.75”, 1”, 1.5”, 2”, and 2.5” in diameter, all currently specified thicknesses are sufficient for developing the ultimate strength of the anchor rod. However, it was also found that for ASTM F1554 Gr. 105 anchor rods, the plate washer thicknesses specified in the AISC *Manual* were not sufficient to develop the rods ultimate strength without excessive permanent deformations for rods 0.75”, 1”, and 1.5” in diameter. In each case, a plate washer 1/4” greater in thickness was found to be adequate based on the assumption that the washers should be able to develop the ultimate strength of the rods without incurring 40% relative deformation or greater. The currently specified plate washer thickness was found to be sufficient for the 2” diameter Gr. 105 anchor rod, and the data was inconclusive for the 2.5” diameter Gr. 105 rod. In the absence of direct testing of 0.875”, 1.25”, and 1.75” diameter anchor rods, the recommended plate washer thicknesses established for the 1”, 1.5”, and 2” diameter anchor rods were provided conservatively.

With regard to the behavior of the anchor rods, notable inconsistency was found between both Gr. 36 and Gr. 105 for rods of the same diameter. The Gr. 36 rods experienced both overstrength and understrength, while the Gr. 105 rods only experienced understrength. No such phenomenon was found in the Gr. 55 anchor rods. During additional testing, the 1.5” diameter Gr. 105 anchor rod specimens performed with adequate reliability. Additionally, it was found that the plate washer thickness and orientation have more significant effects on the performance of the plate washer than the marginal differences between the tested ultimate strength of rods with the same diameter and grade of steel.

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Appendix A: Raw Load vs. Displacement Curves

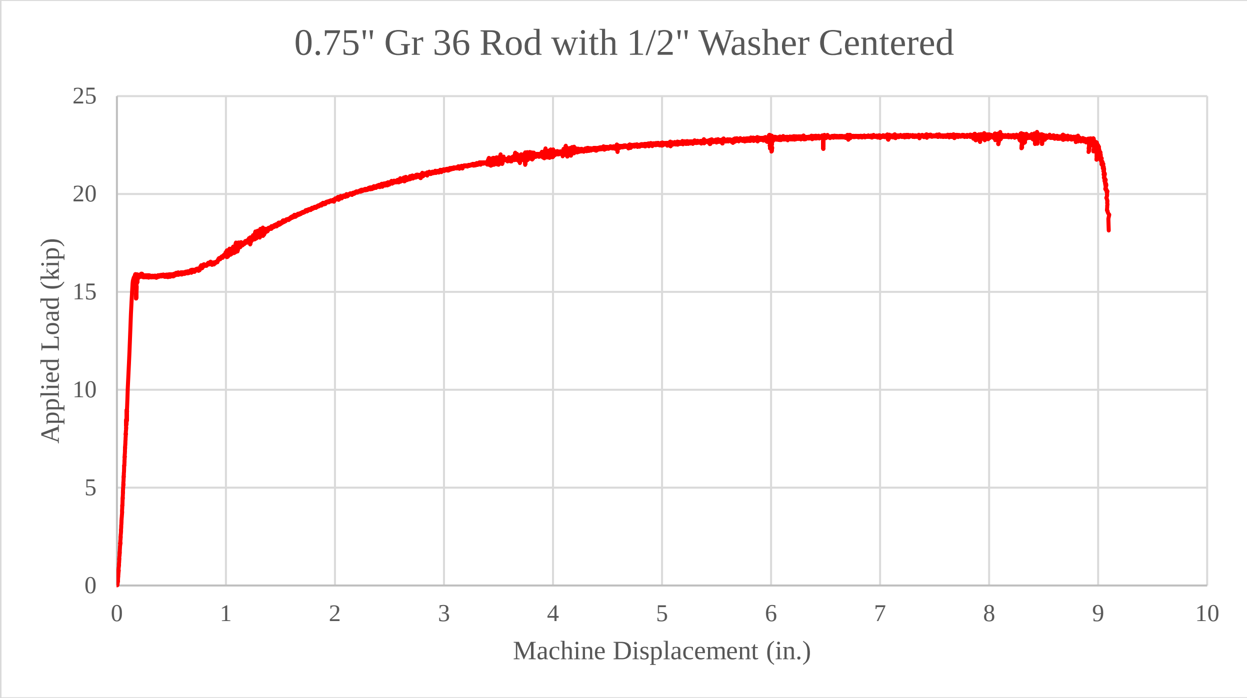

Figure A.1: 0.75" Gr 36 Rod with 1/2" Washer Centered

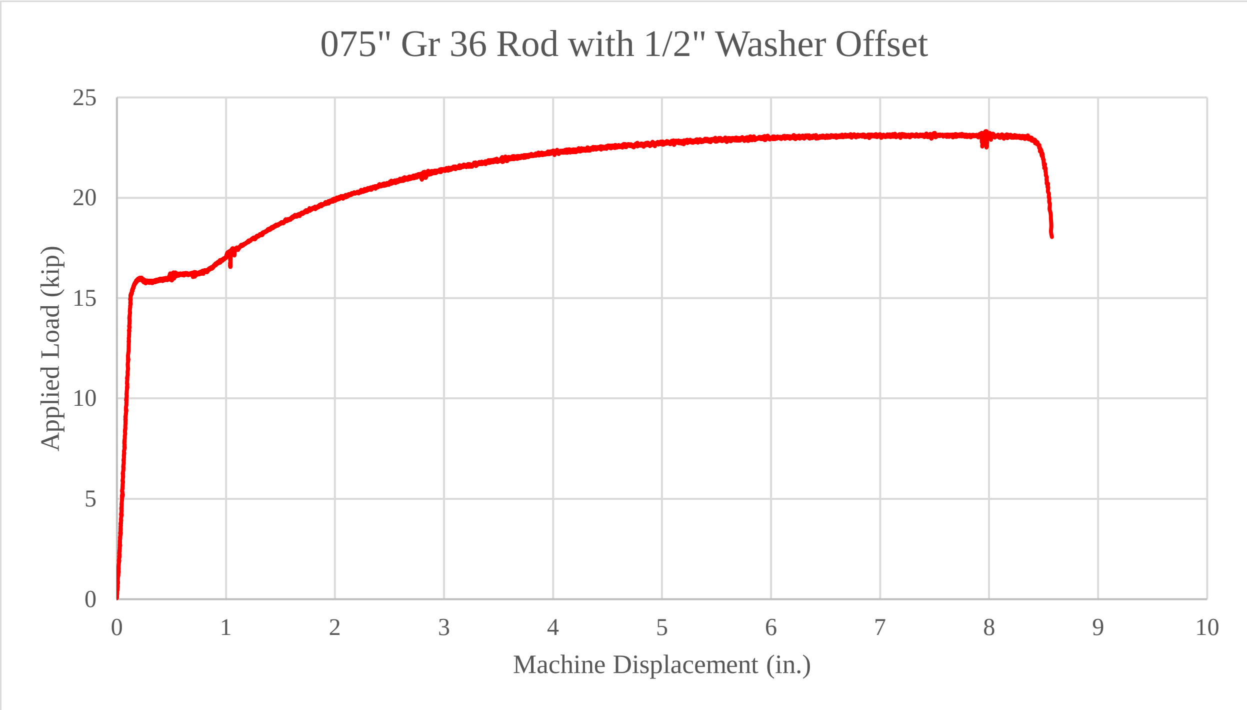

Figure A.2: 0.75" Gr 36 Rod with 1/2" Washer Offset

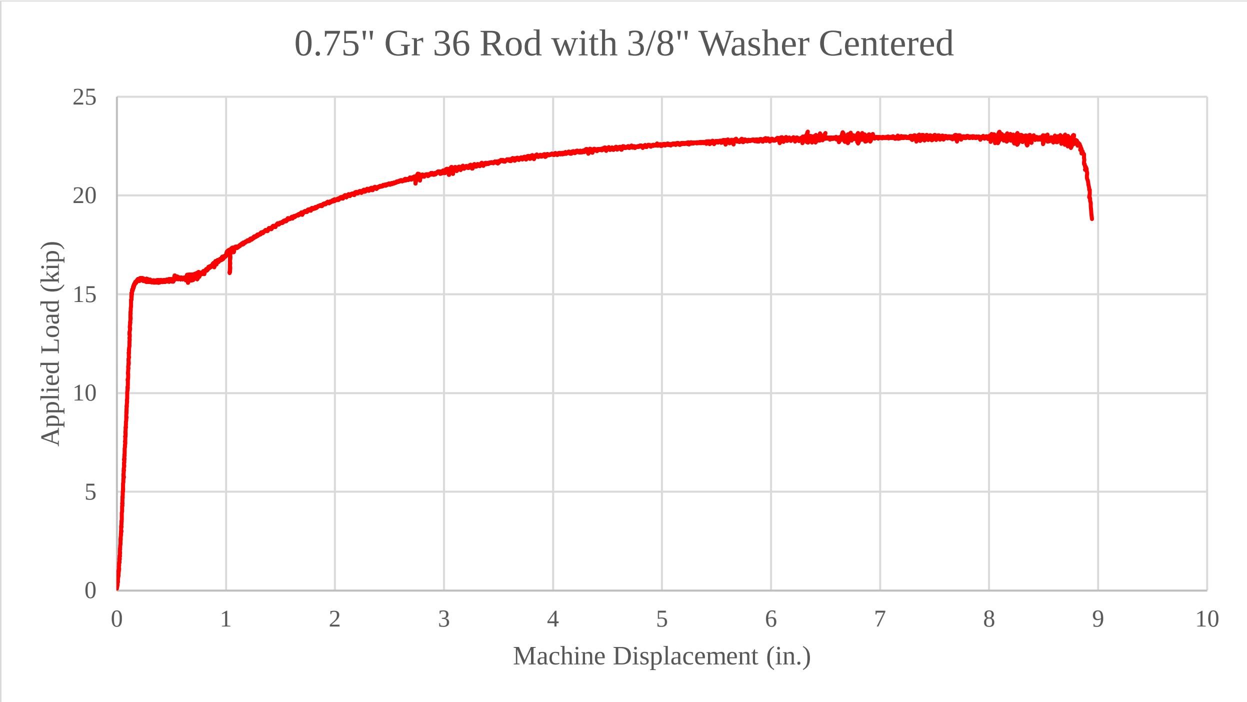

Figure A.3: 0.75" Gr 36 Rod with 3/8" Washer Centered

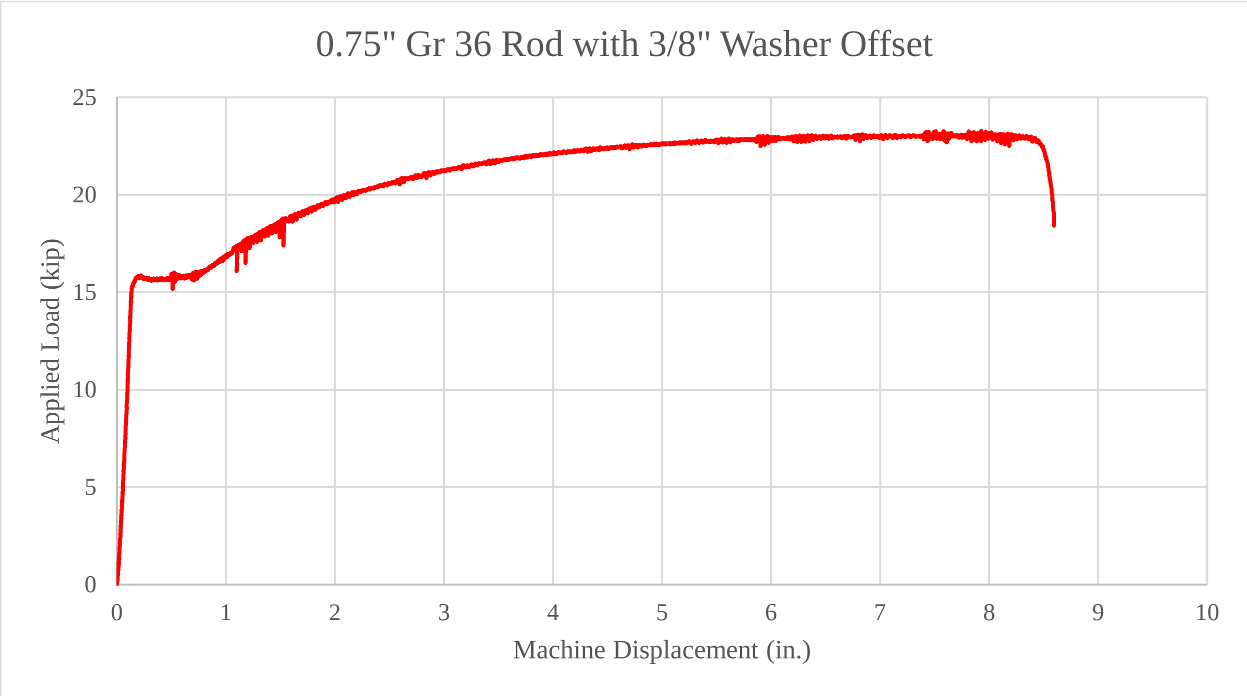

Figure A.4: 0.75" Gr 36 Rod with 3/8" Washer Offset

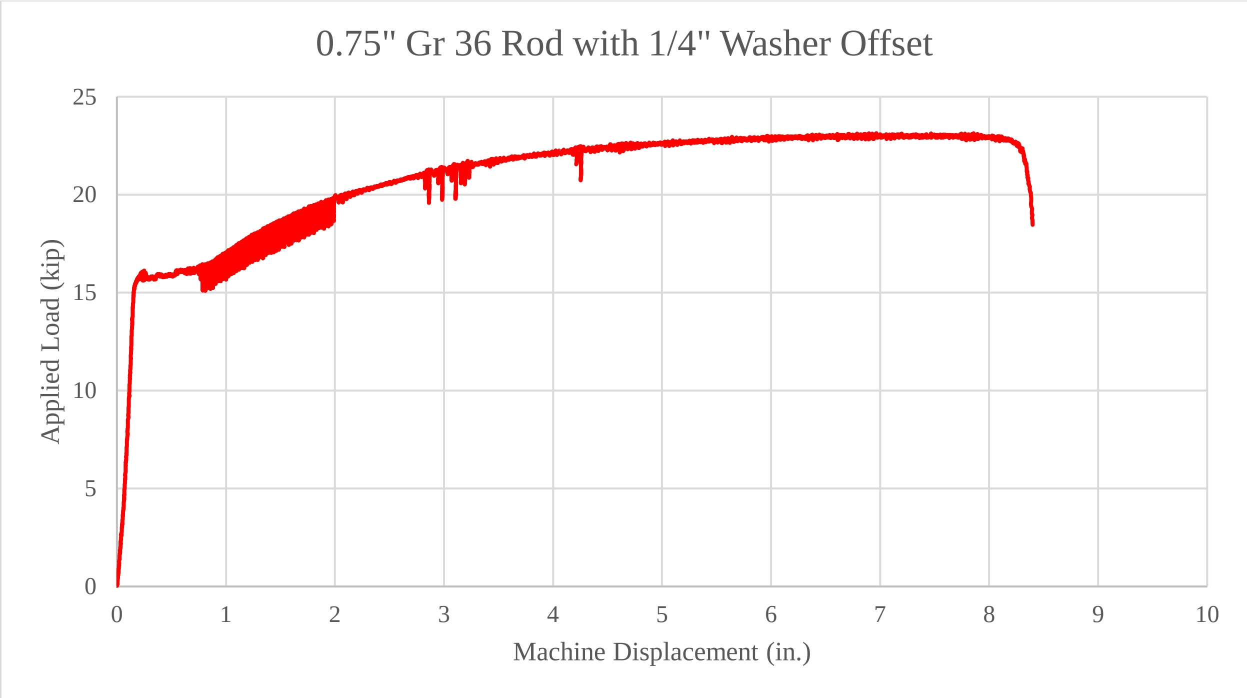

Figure A.5: 0.75" Gr 36 Rod with 1/4" Washer Offset

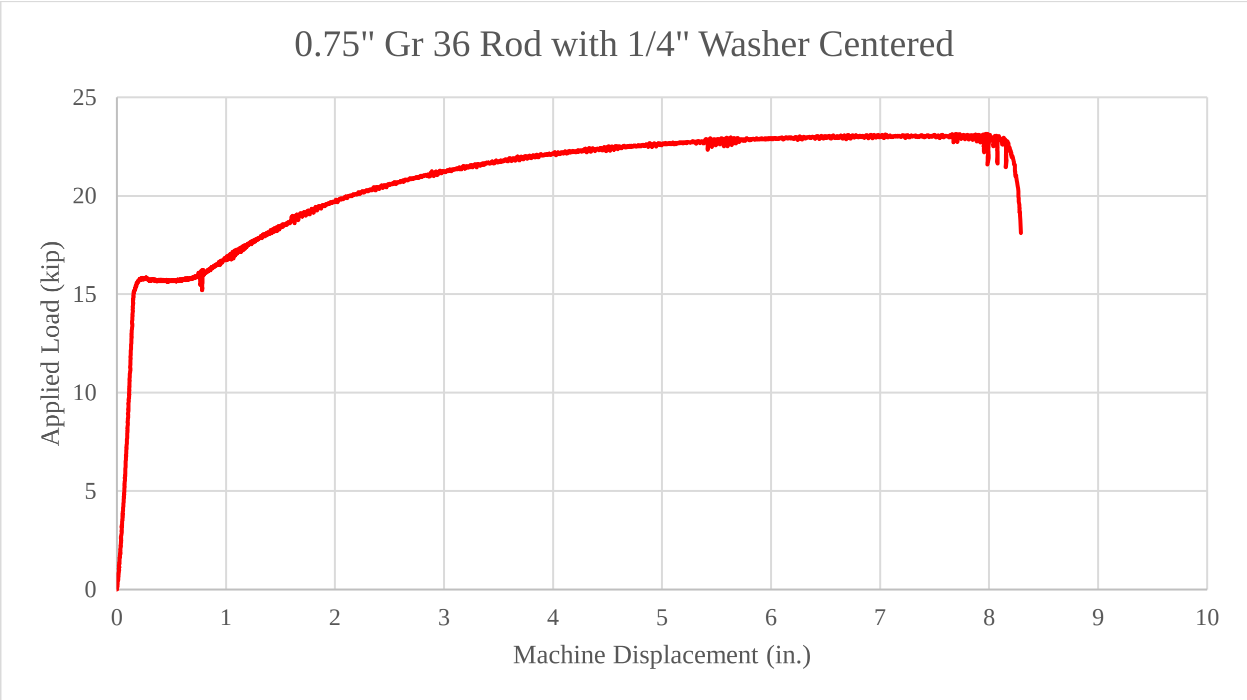

Figure A.6: 0.75" Gr 36 Rod with 1/4" Washer Centered

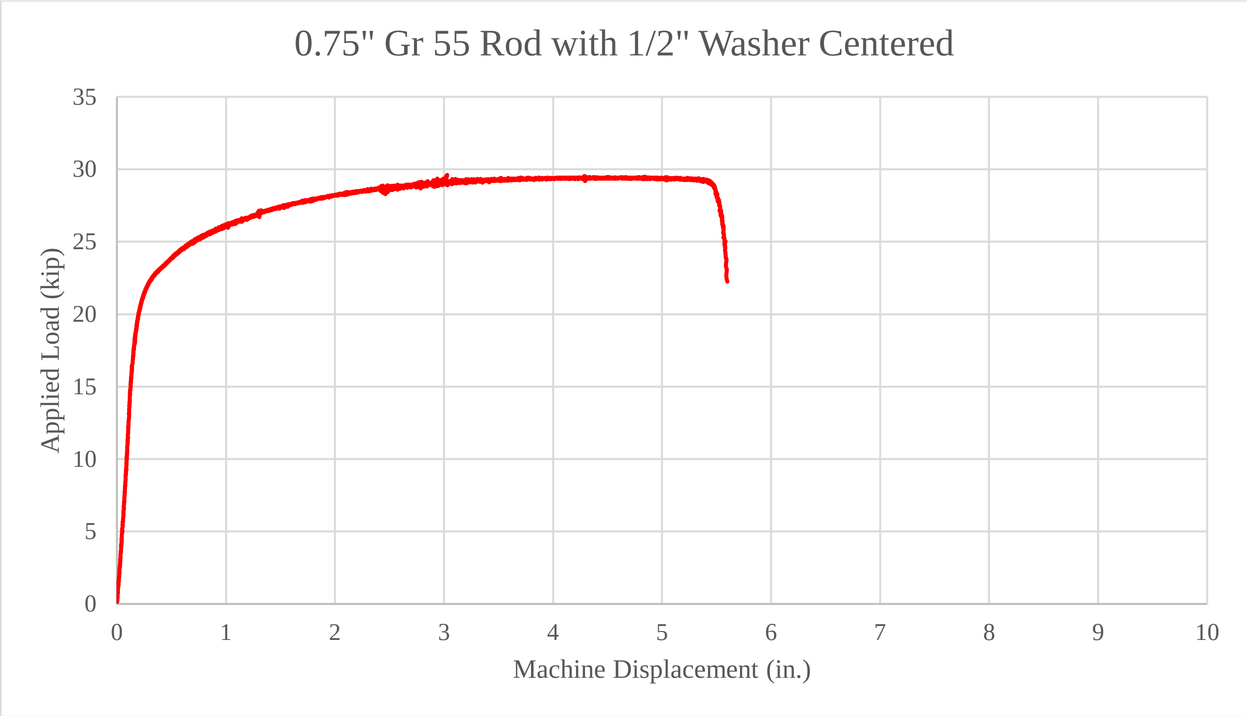

Figure A.7: 0.75" Gr 55 Rod with 1/2" Washer Centered

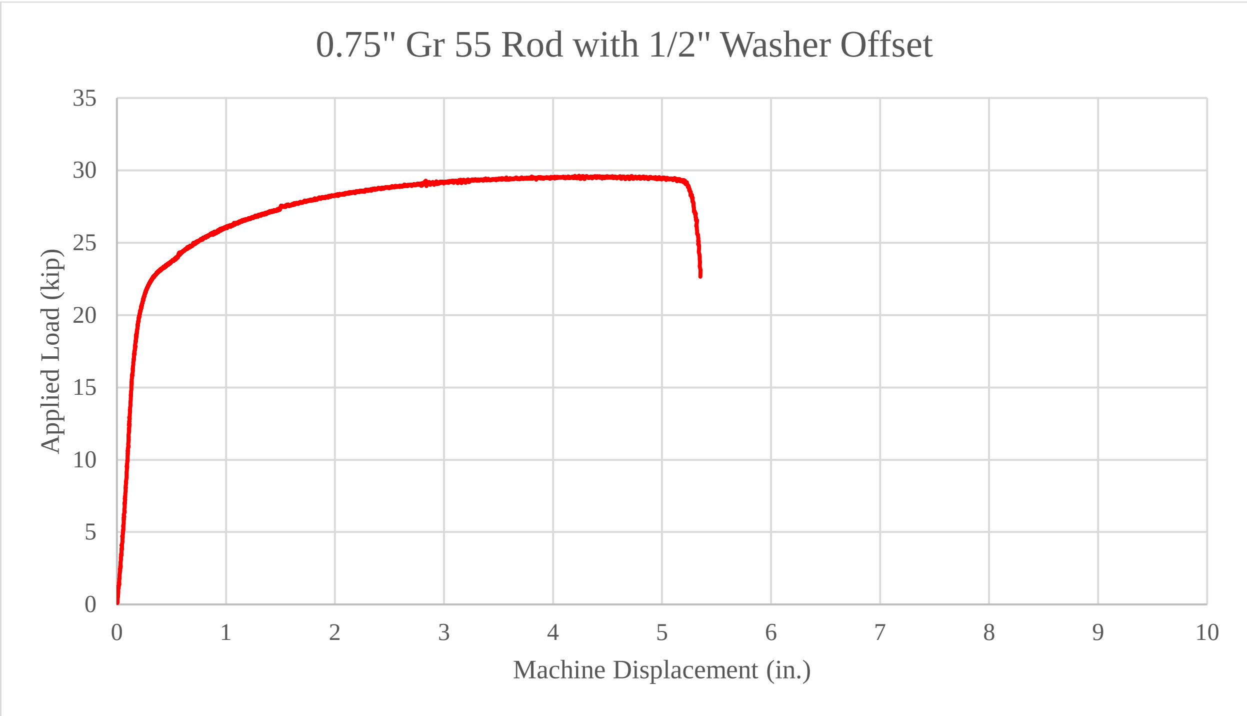

Figure A. 8: 0.75" Gr 55 Rod with 1/2" Washer Offset

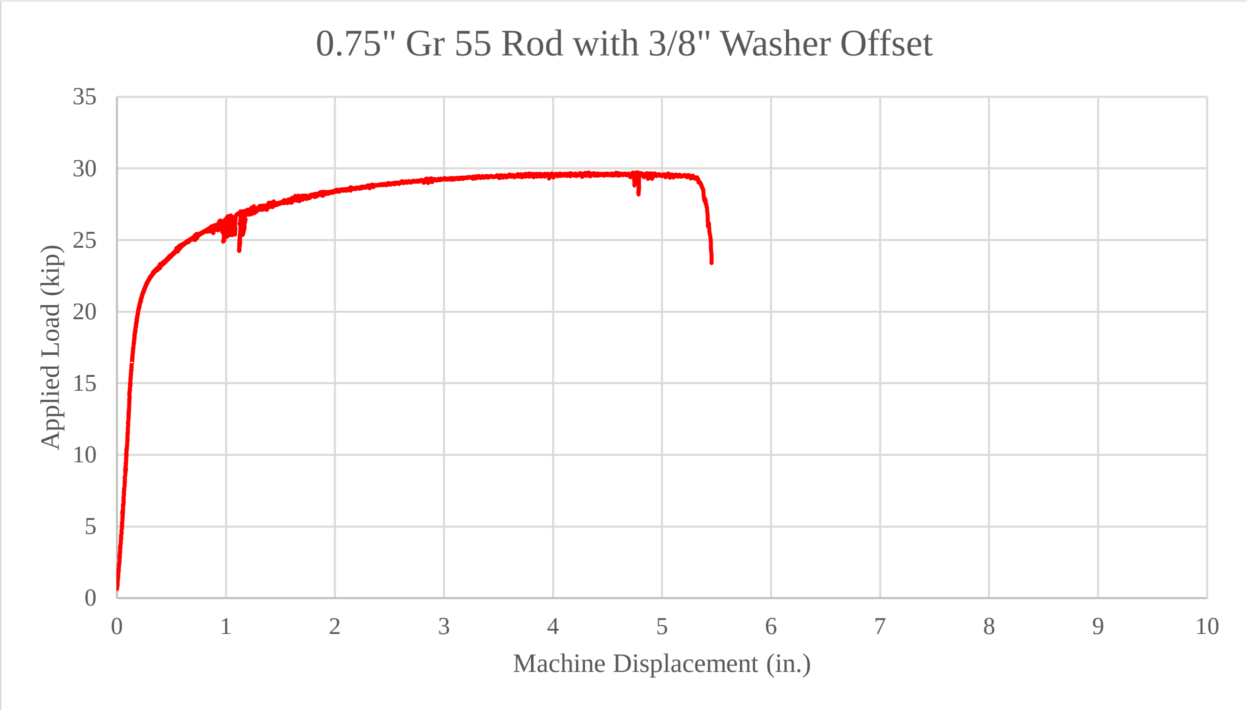

Figure A.9: 0.75" Gr 55 Rod with 3/8" Washer Offset

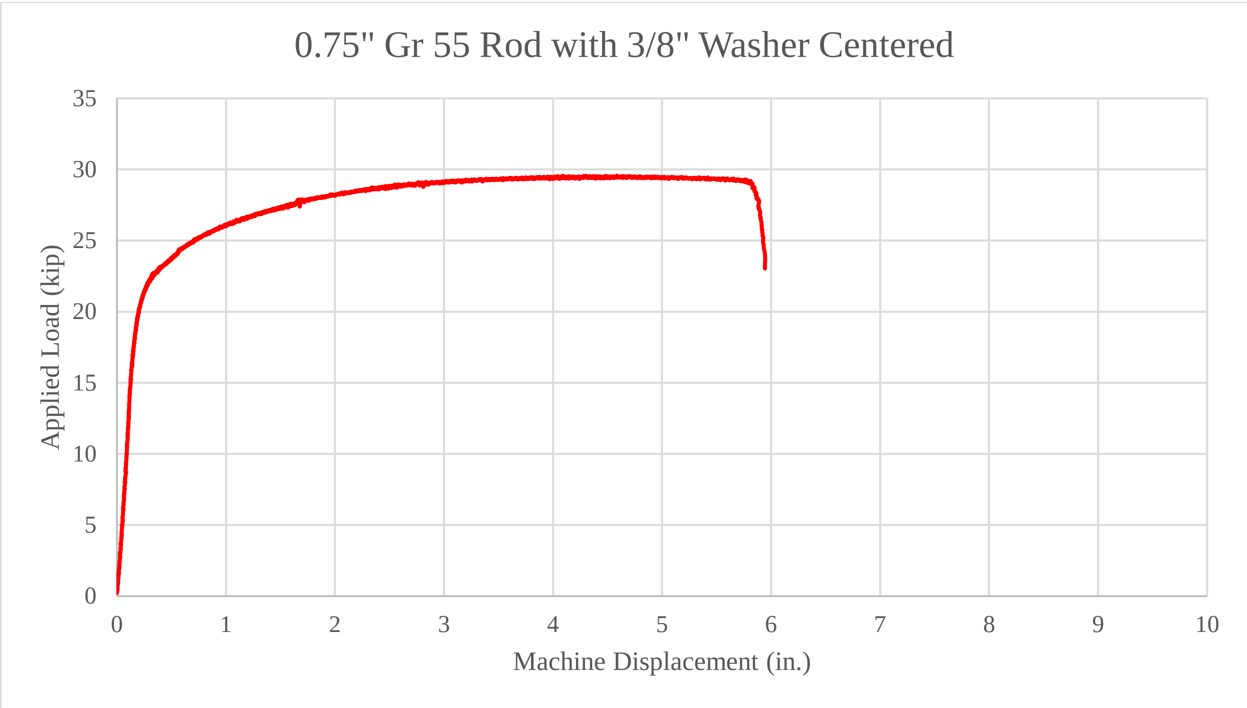

Figure A.10: 0.75" Gr 55 Rod with 3/8" Washer Centered

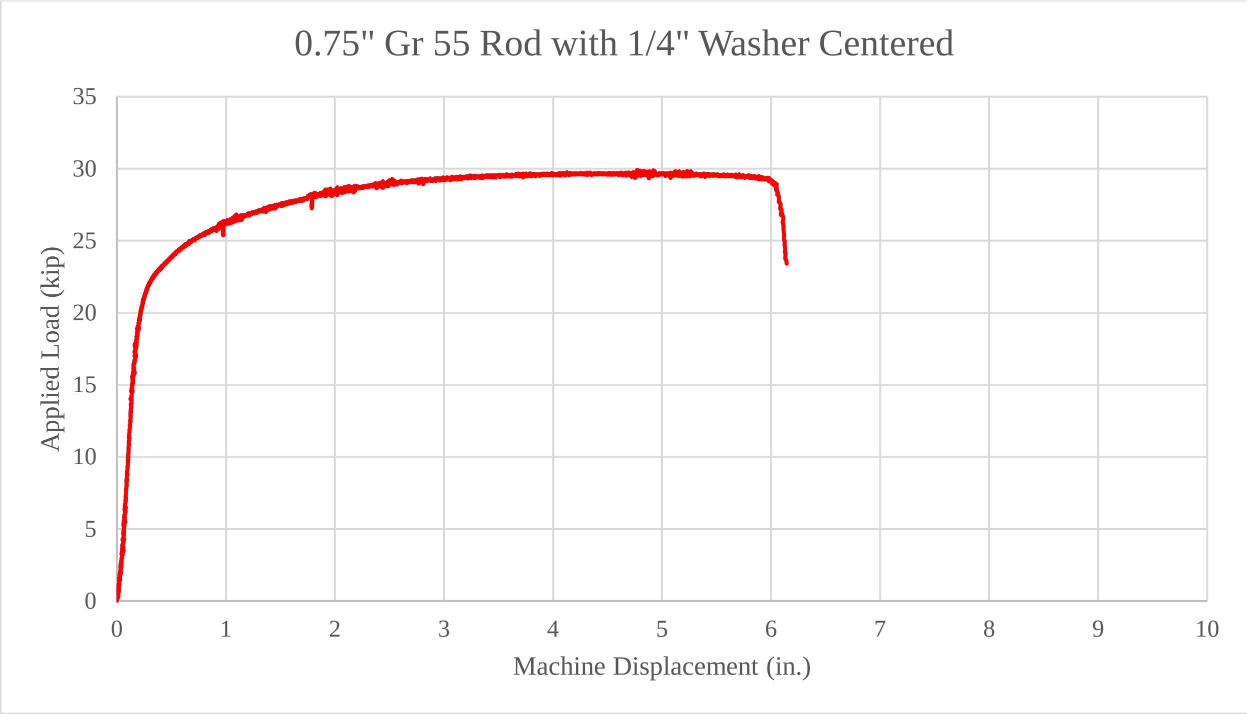

Figure A.11: 0.75" Gr 55 Rod with 1/4" Washer Centered

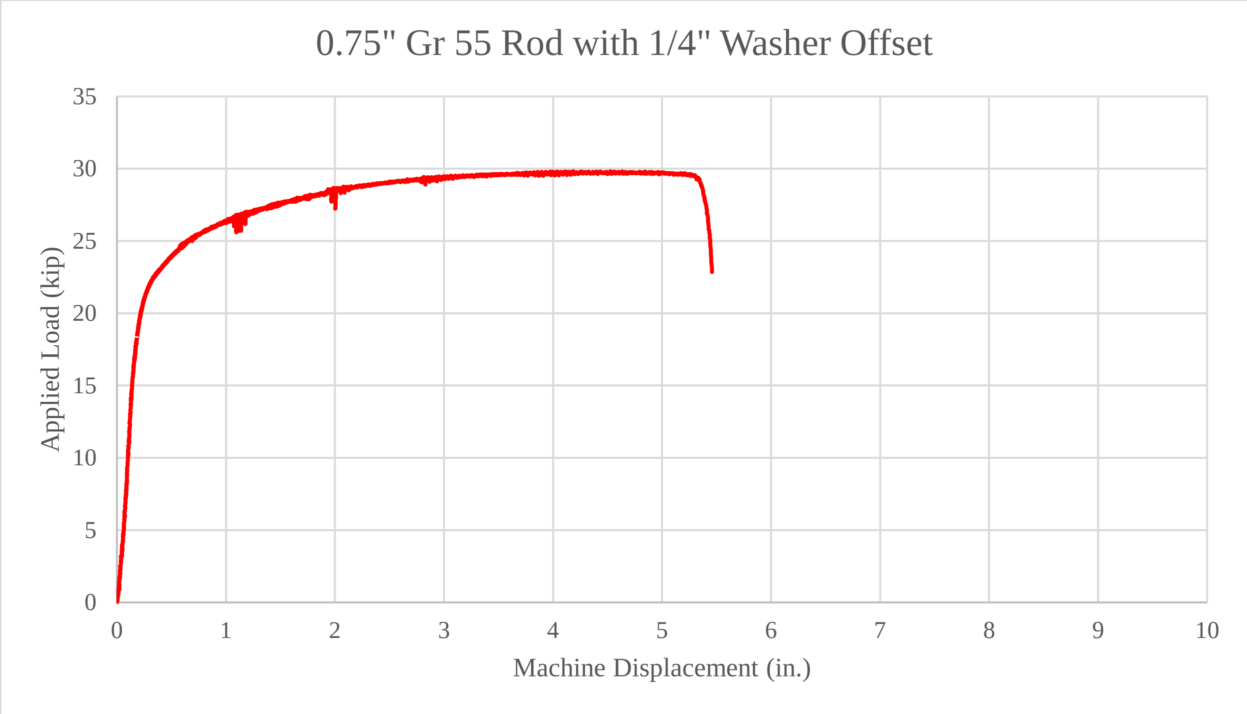

Figure A.12: 0.75" Gr 55 Rod with 1/4" Washer Offset

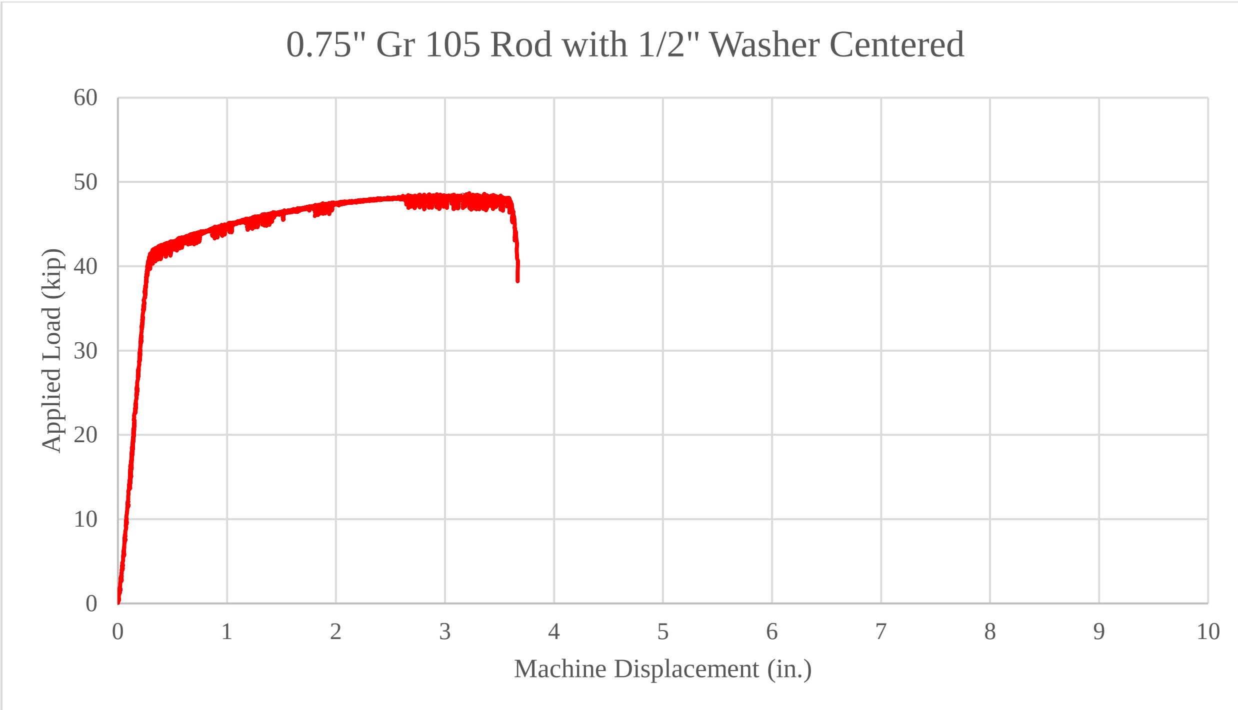

Figure A.13: 0.75" Gr 105 Rod with 1/2" Washer Centered

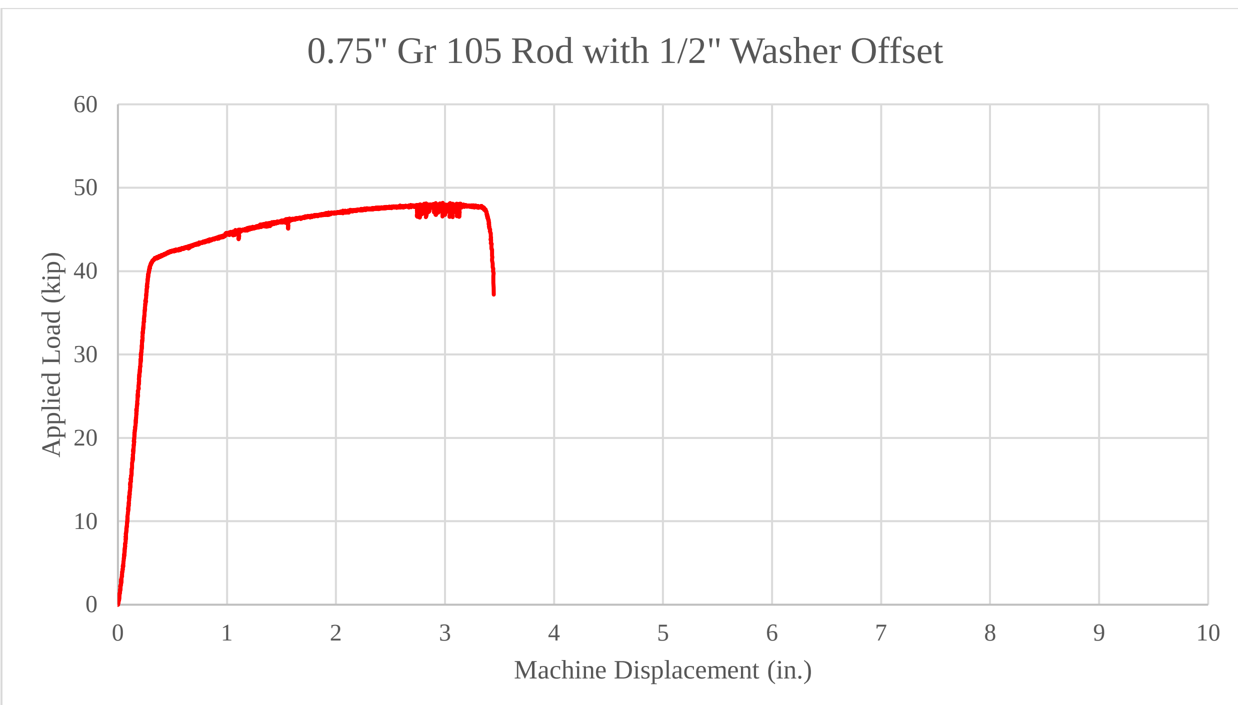

Figure A.14: 0.75" Gr 105 Rod with 1/2" Washer Offset

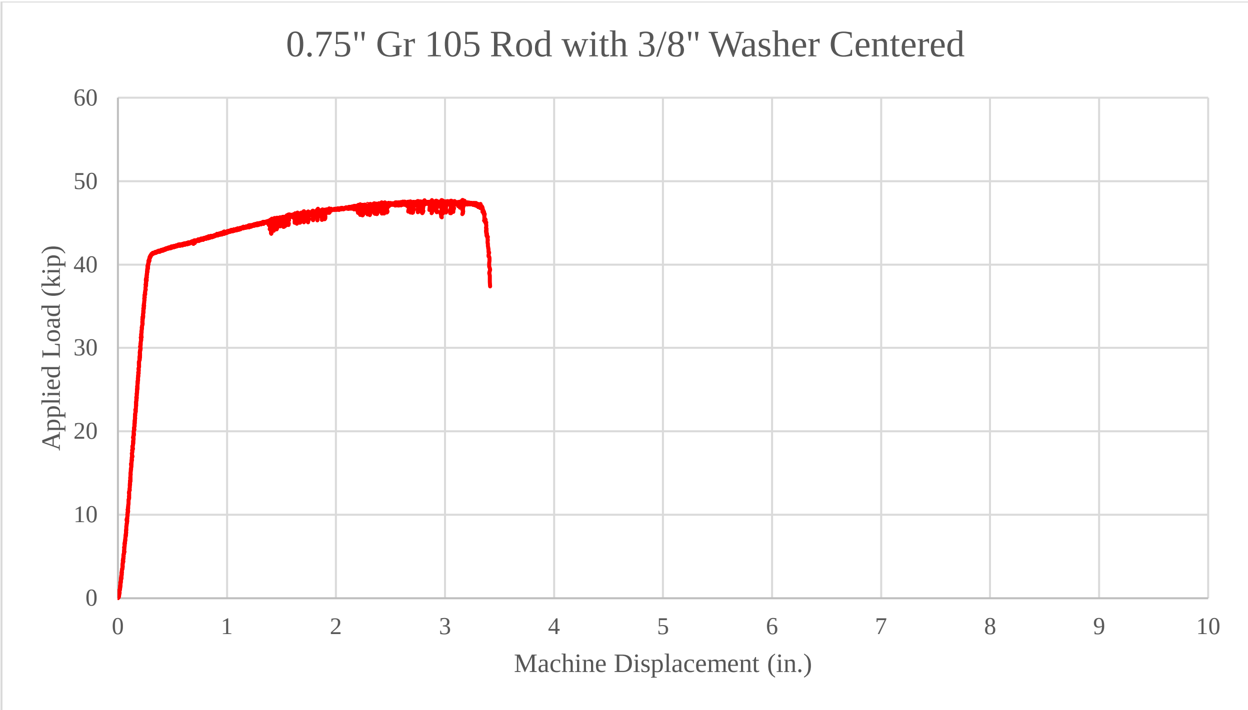

Figure A.15: 0.75" Gr 105 Rod with 3/8" Washer Centered

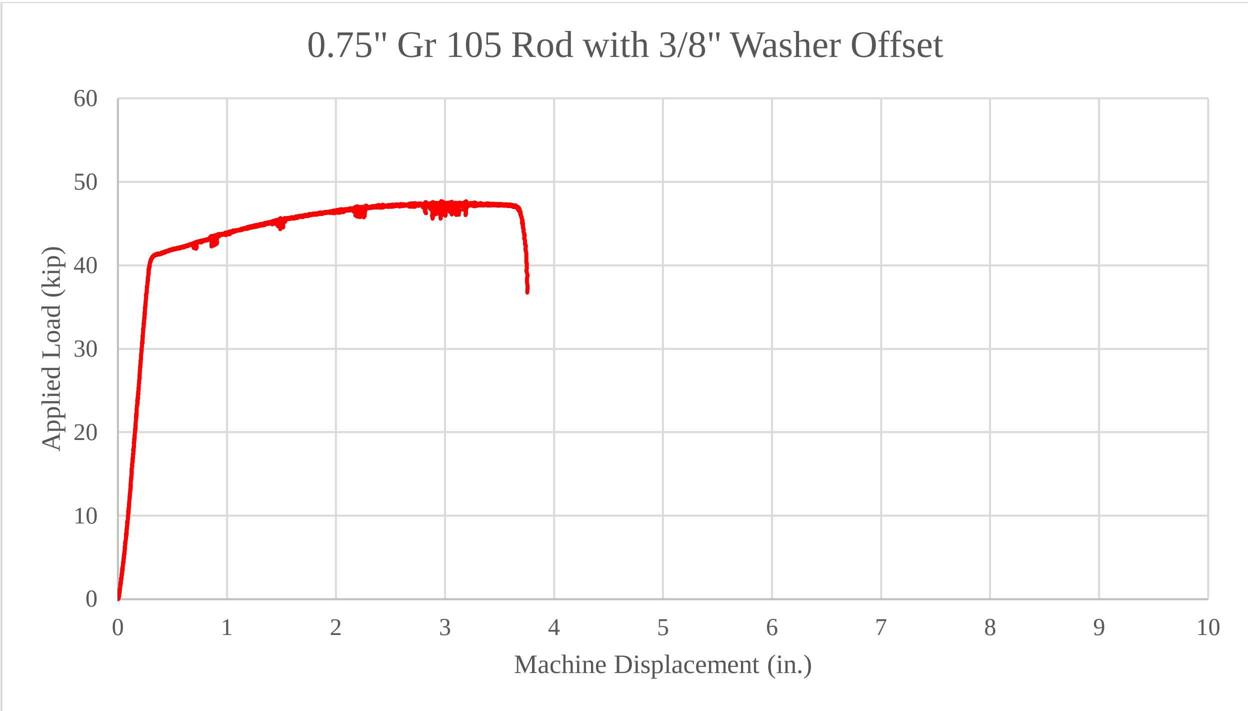

Figure A.16: A.75" Gr 105 Rod with 3/8" Washer Offset

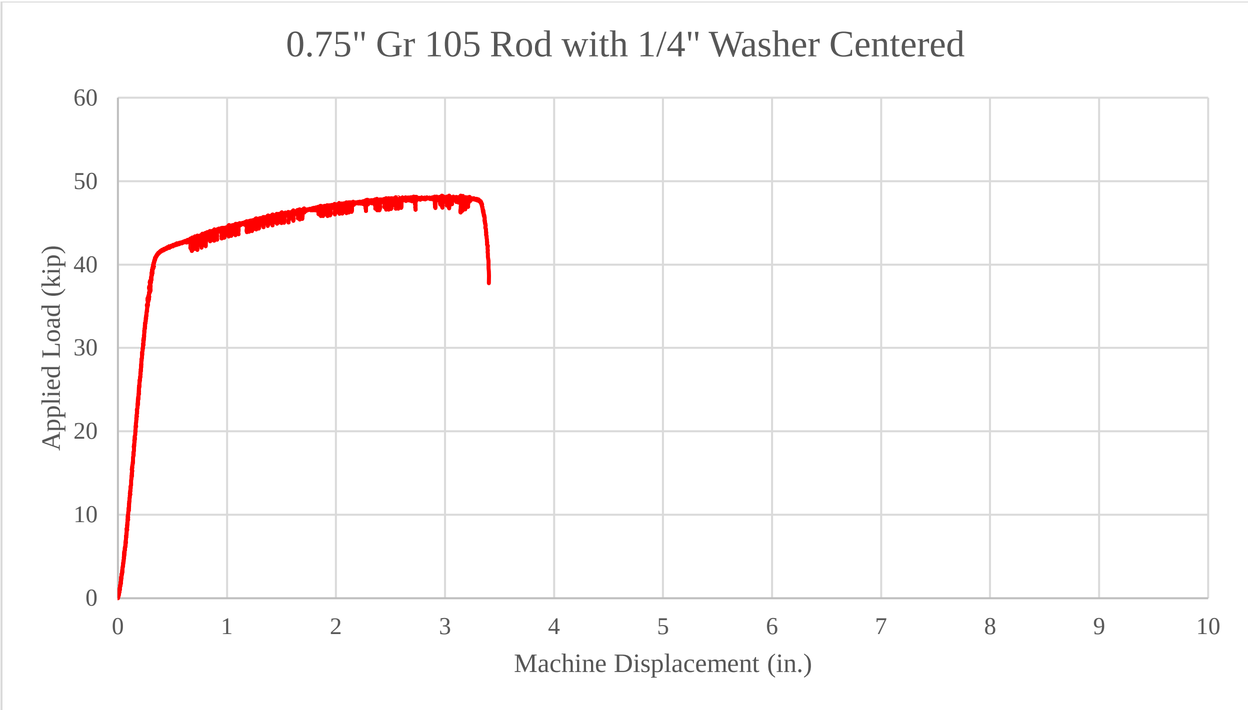

Figure A.17: A.75" Gr 105 Rod with 1/4" Washer Centered

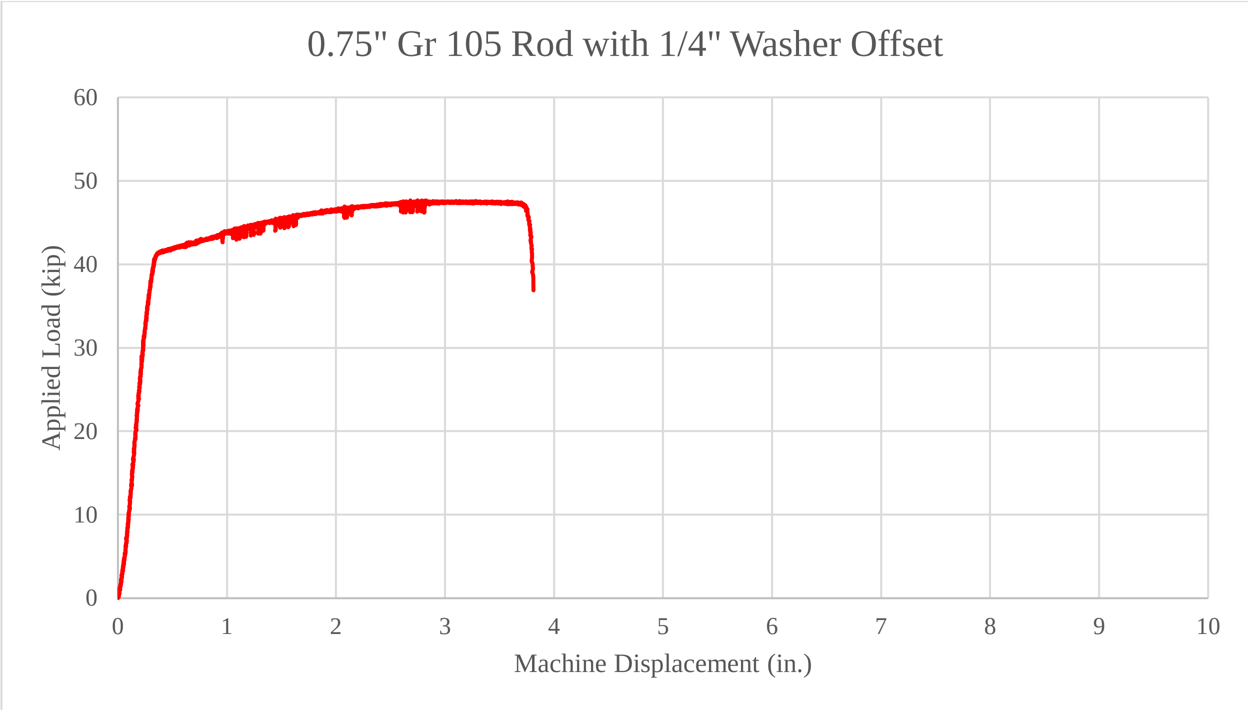

Figure A.18: A.75" Gr 105 Rod with 1/4" Washer Offset

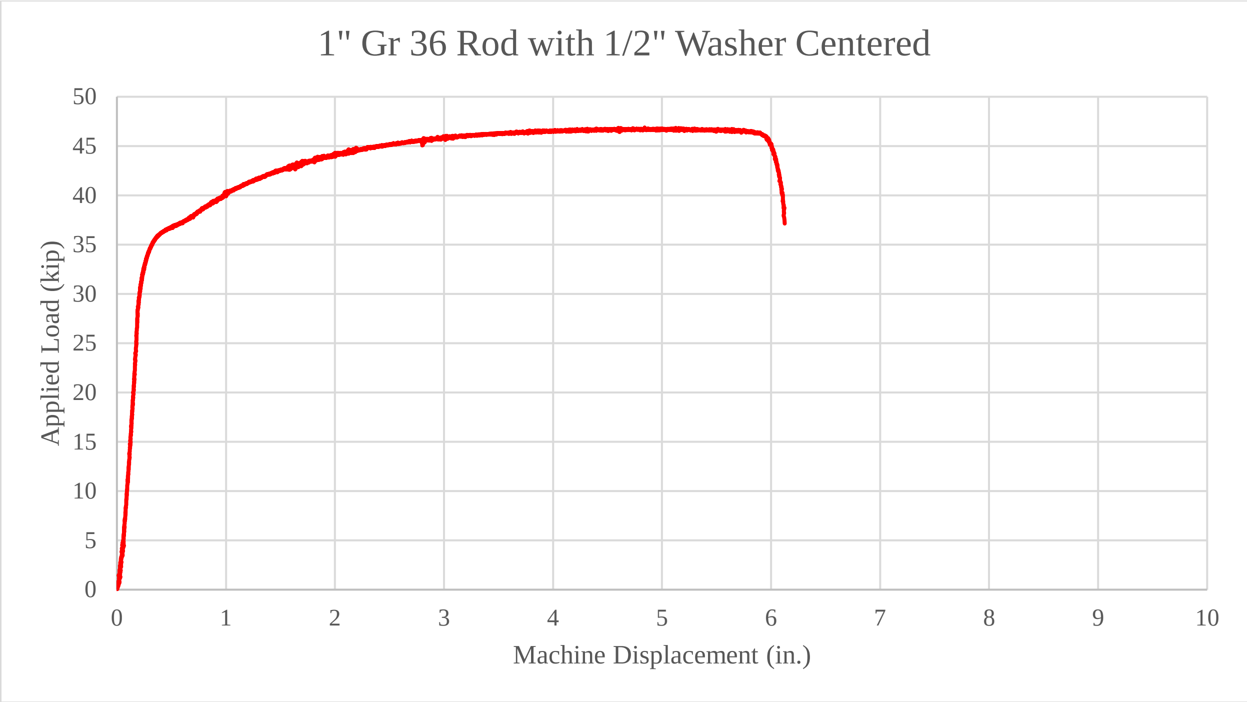

Figure A.19: 1" Gr 36 Rod with 1/2" Washer Centered

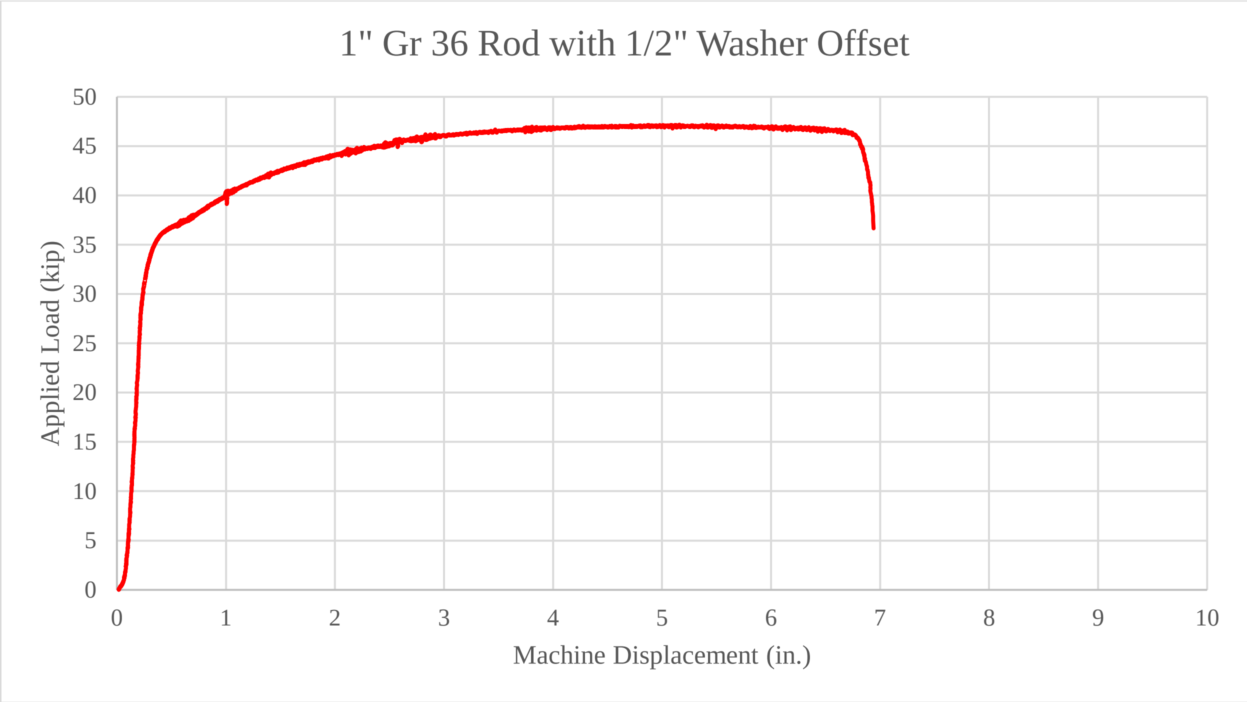

Figure A.20: 1" Gr 36 Rod with 1/2" Washer Offset

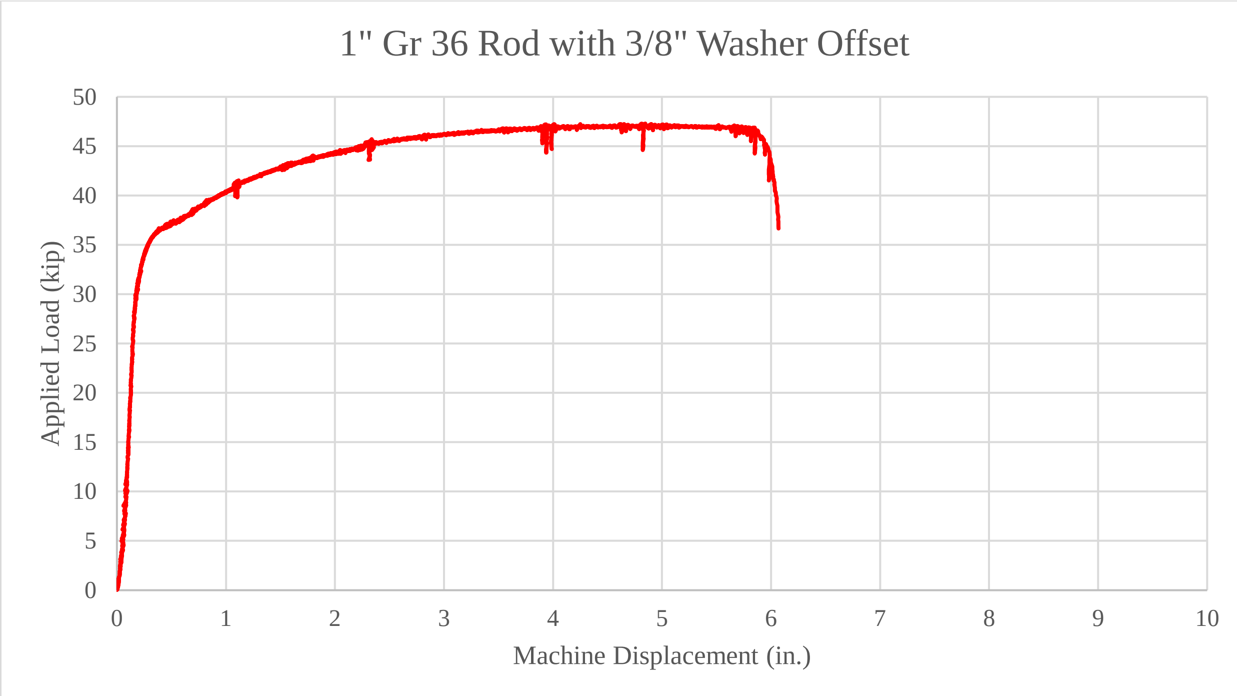

Figure A.21: 1" Gr 36 Rod with 3/8" Washer Offset

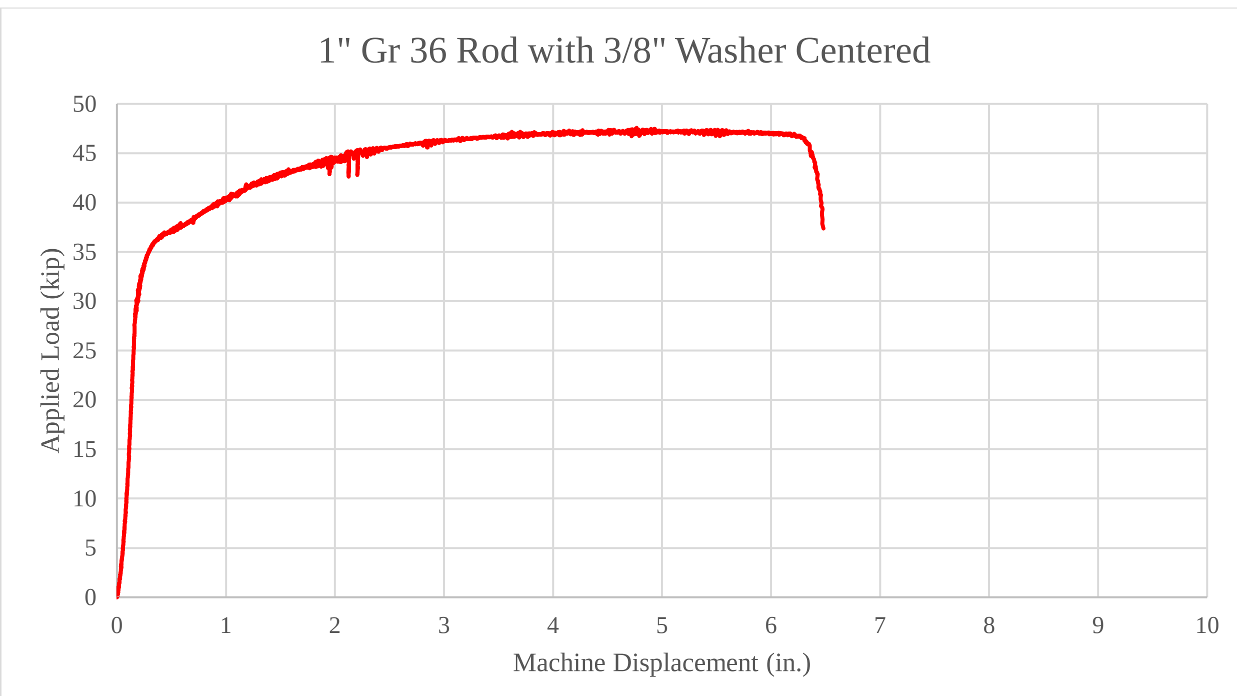

Figure A.22: 1" Gr 36 Rod with 3/8" Washer Centered

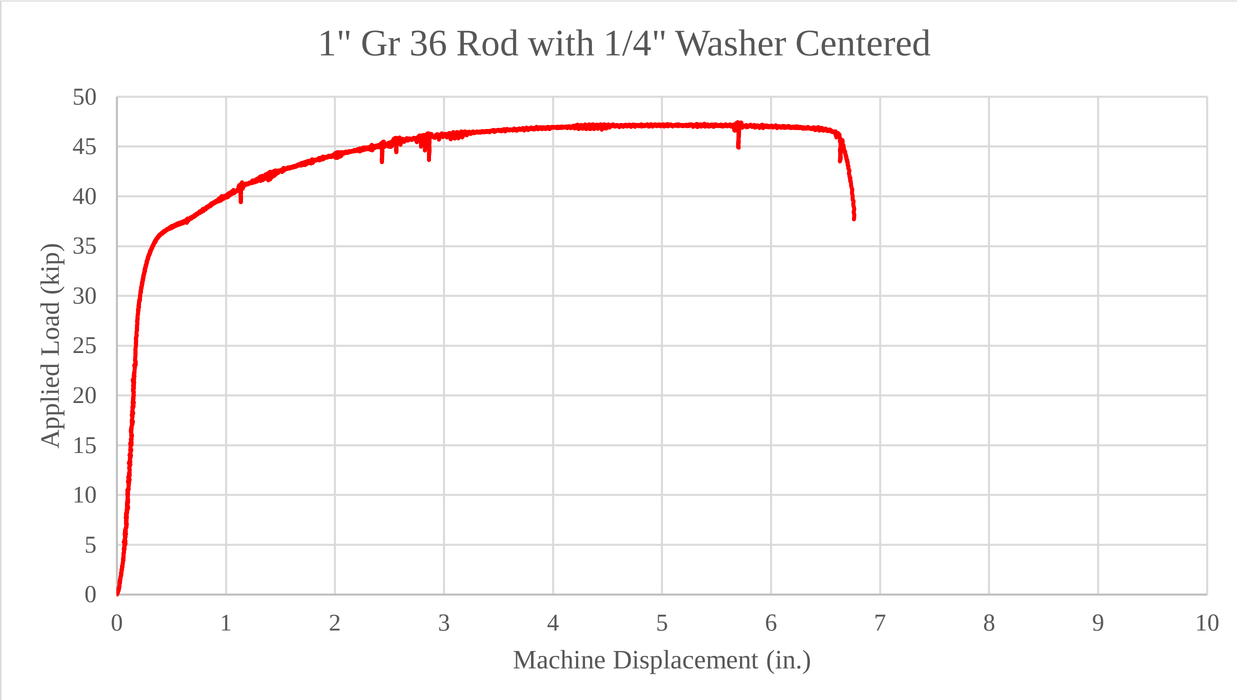

Figure A.23: 1" Gr 36 Rod with 1/4" Washer Centered

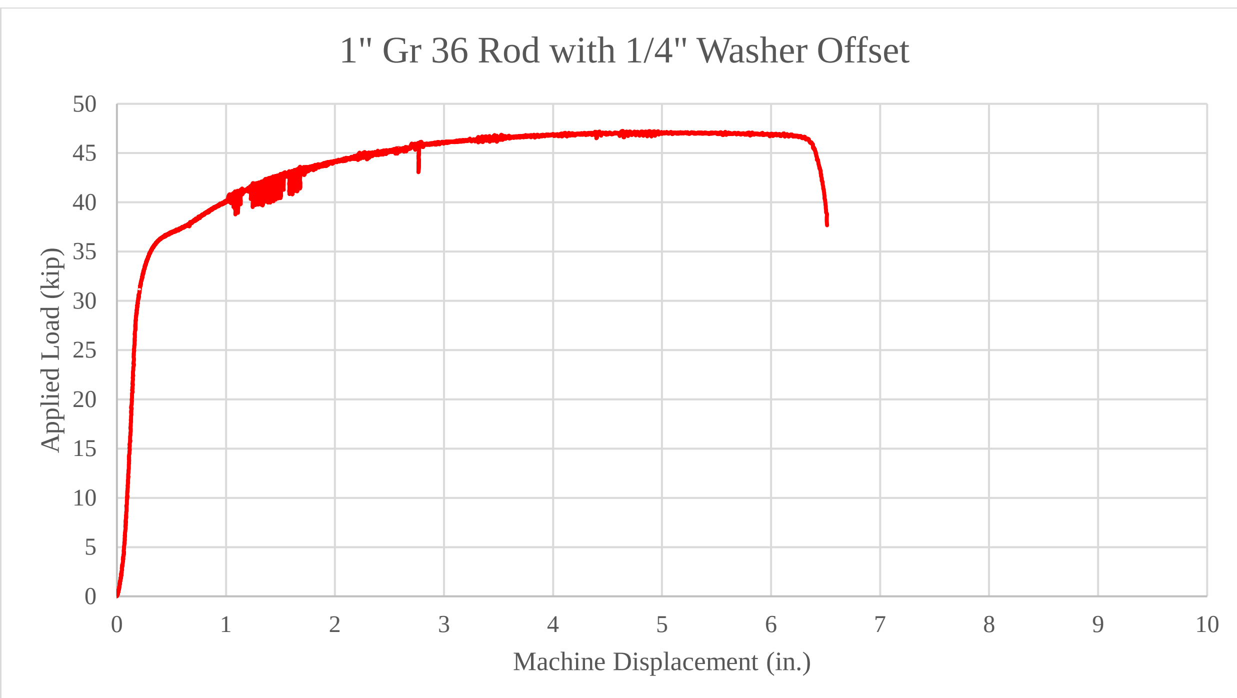

Figure A.24: 1" Gr 36 Rod with 1/4" Washer Offset

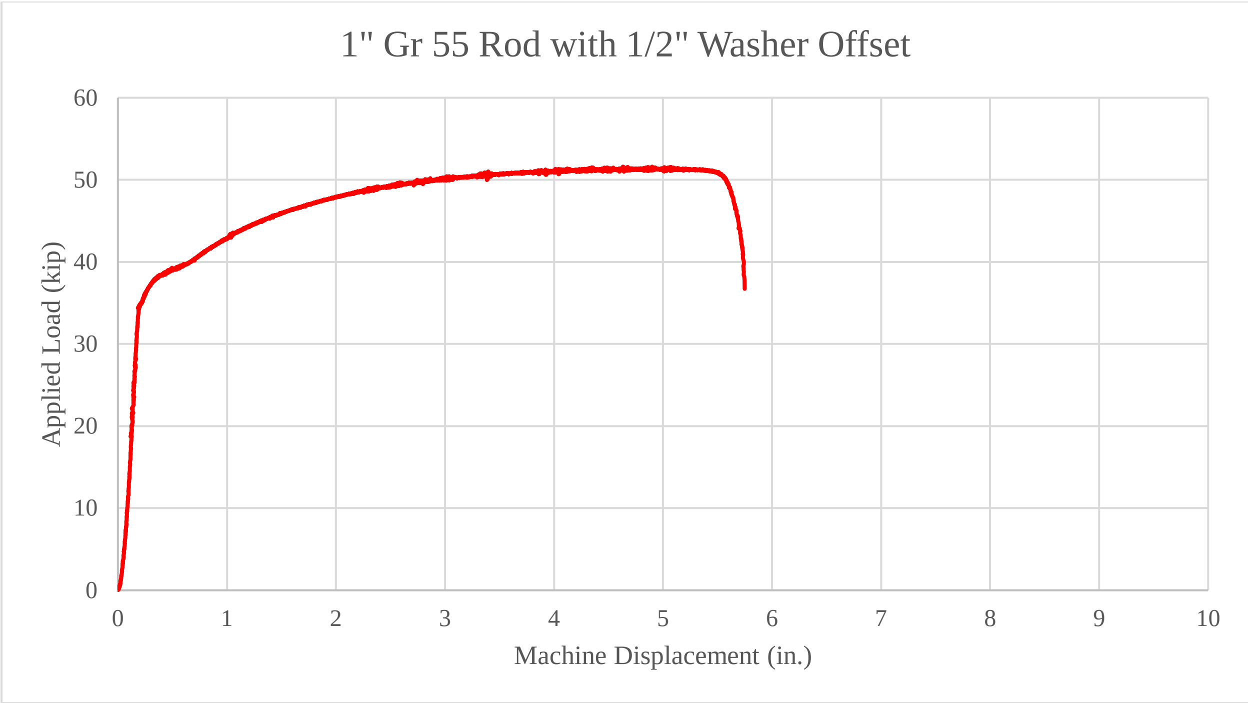

Figure A.25: 1" Gr 55 Rod with 1/2" Washer Offset

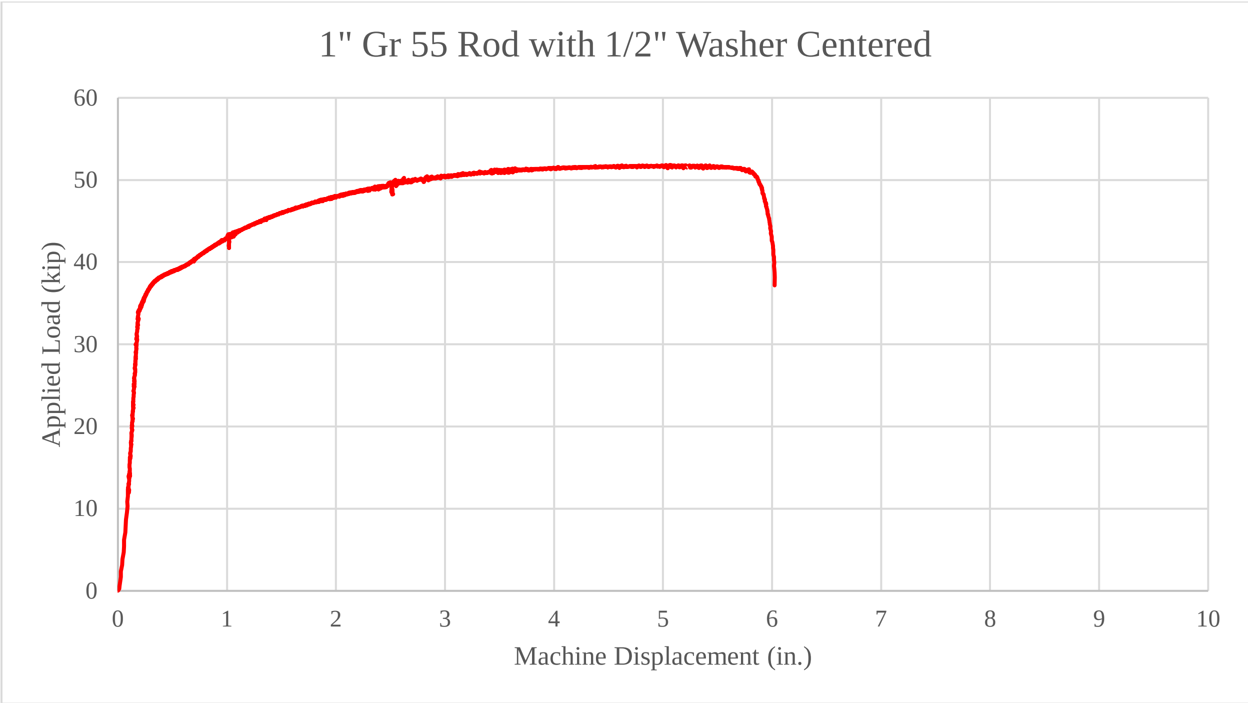

Figure A.26: 1" Gr 55 Rod with 1/2" Washer Centered

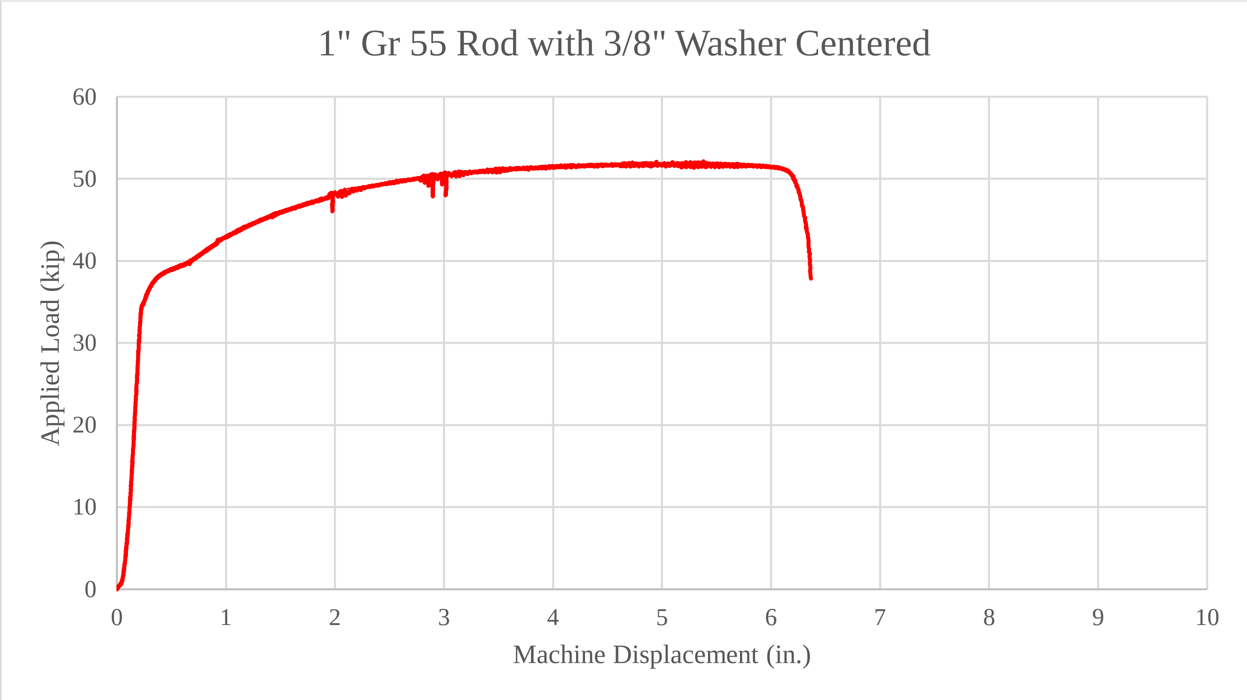

Figure A.27: 1" Gr 55 Rod with 3/8" Washer Centered

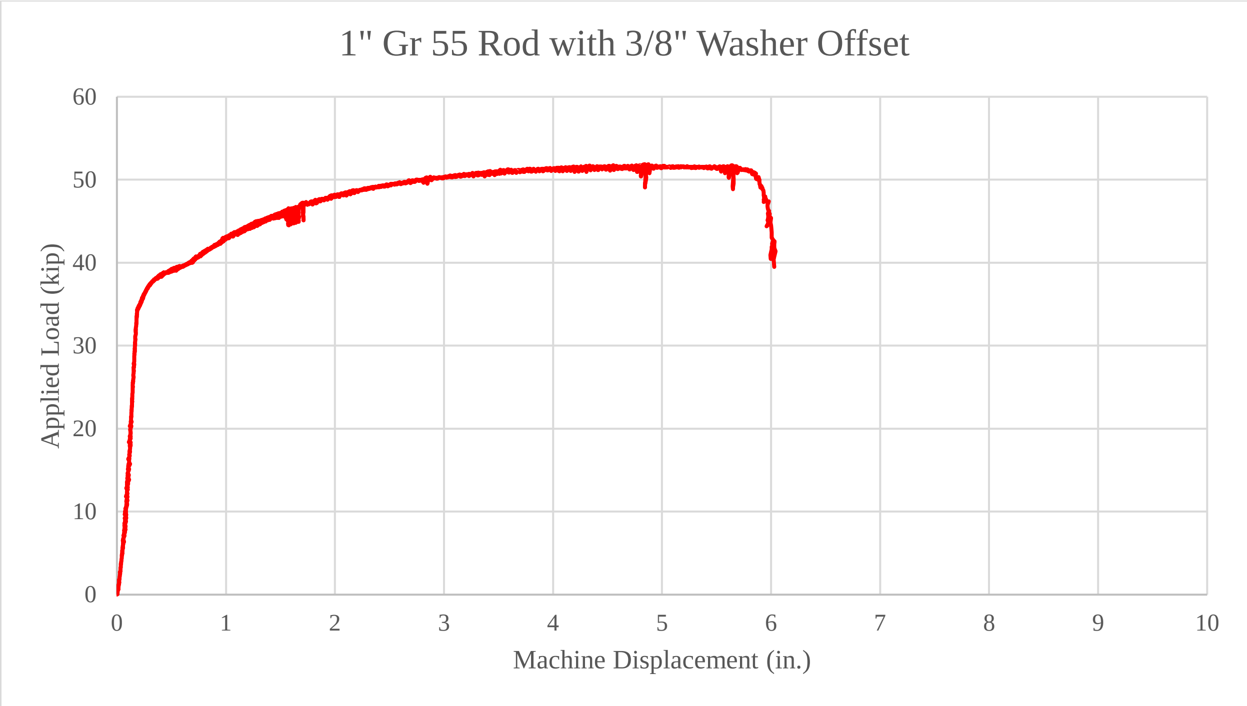

Figure A.28: 1" Gr 55 Rod with 3/8" Washer Centered

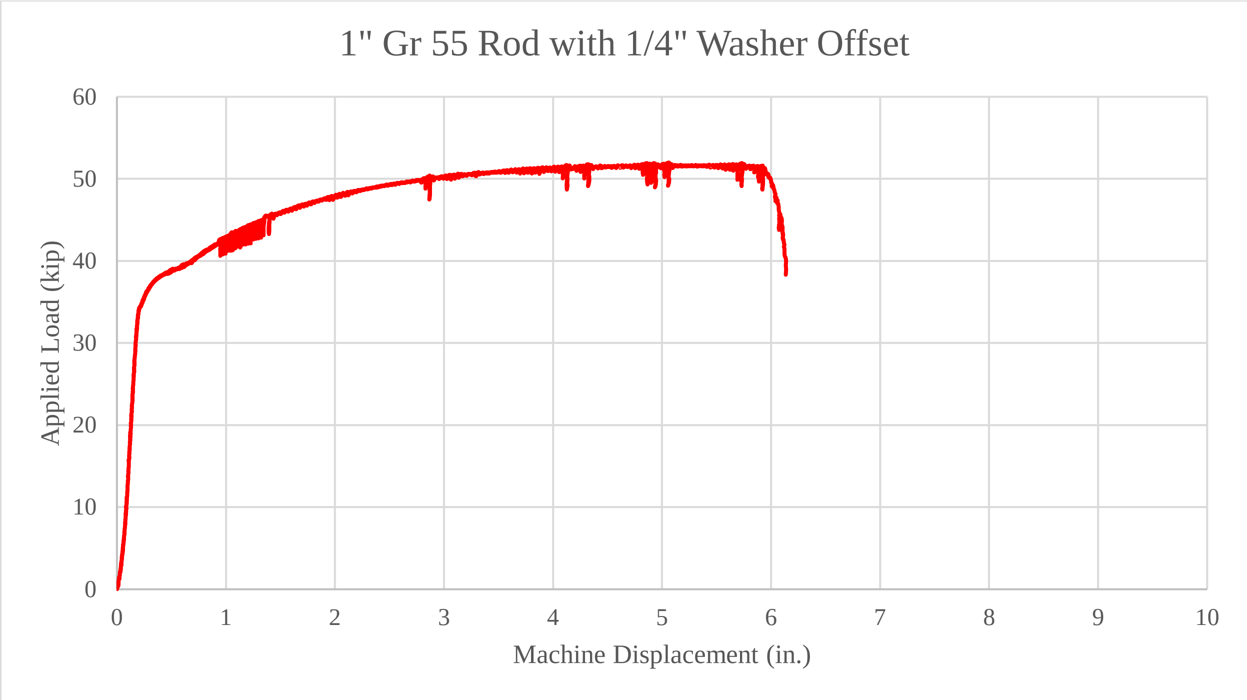

Figure A.29: 1" Gr 55 Rod with 1/4" Washer Offset

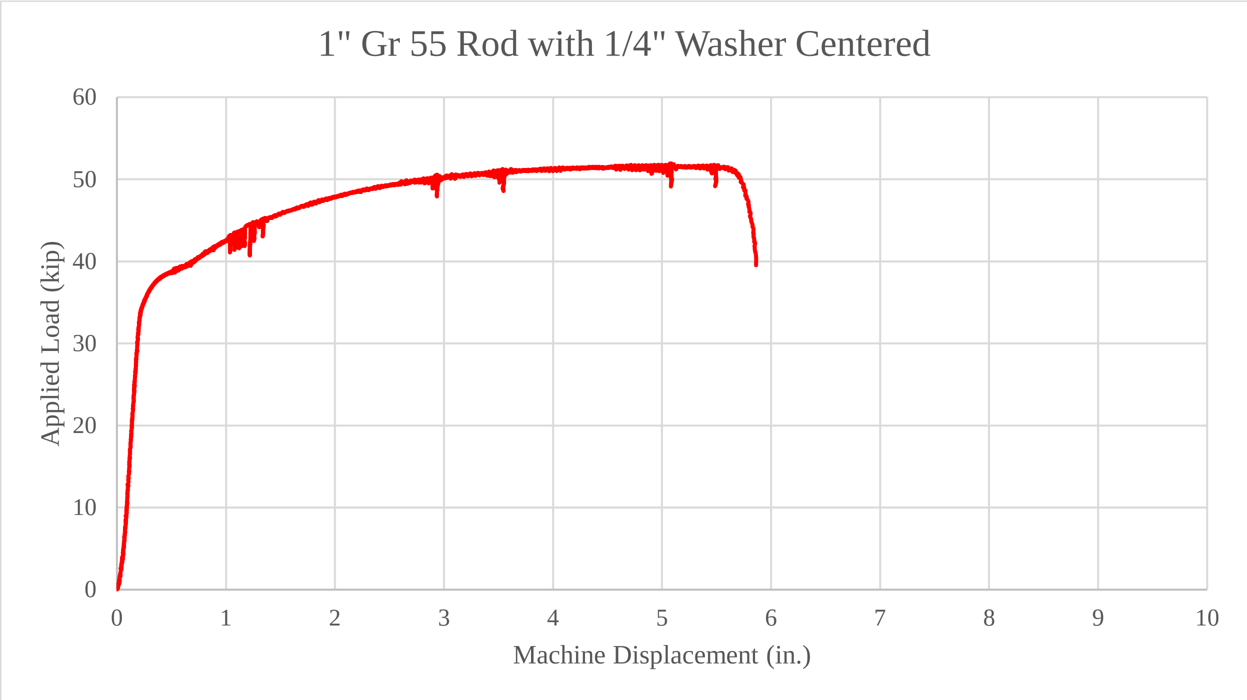

Figure A.30: 1" Gr 55 Rod with 1/4" Washer Centered

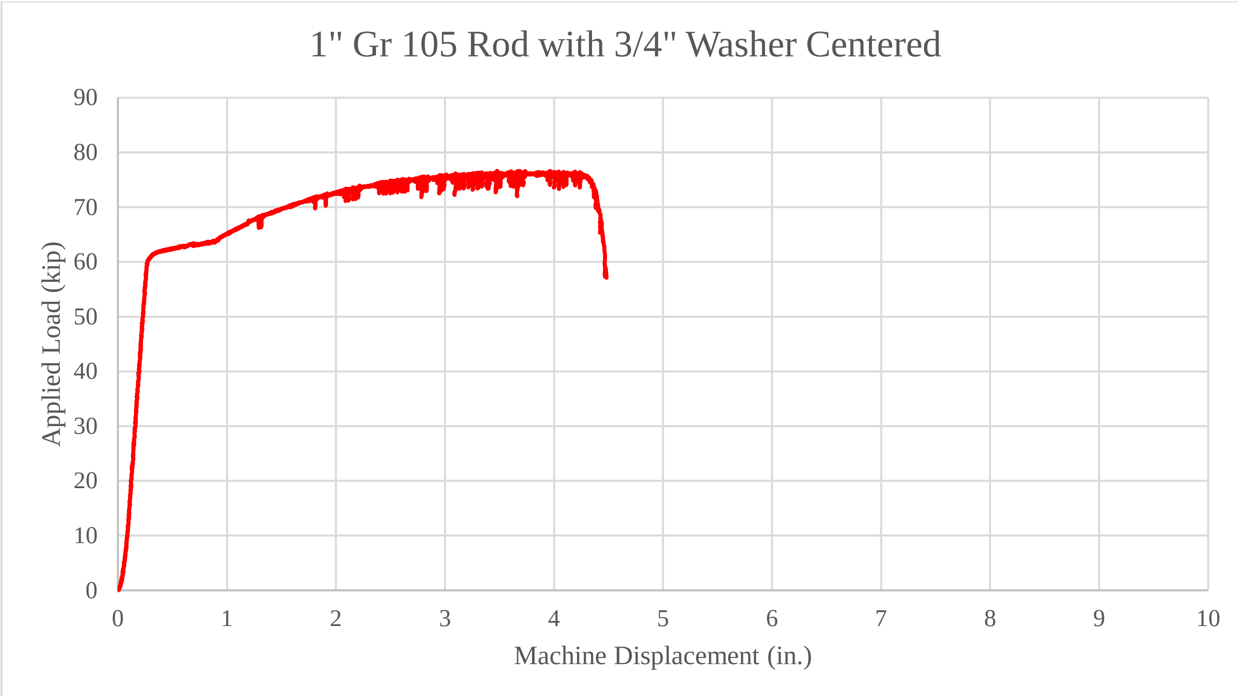

Figure A.31: 1" Gr 105 Rod with 3/4" Washer Centered

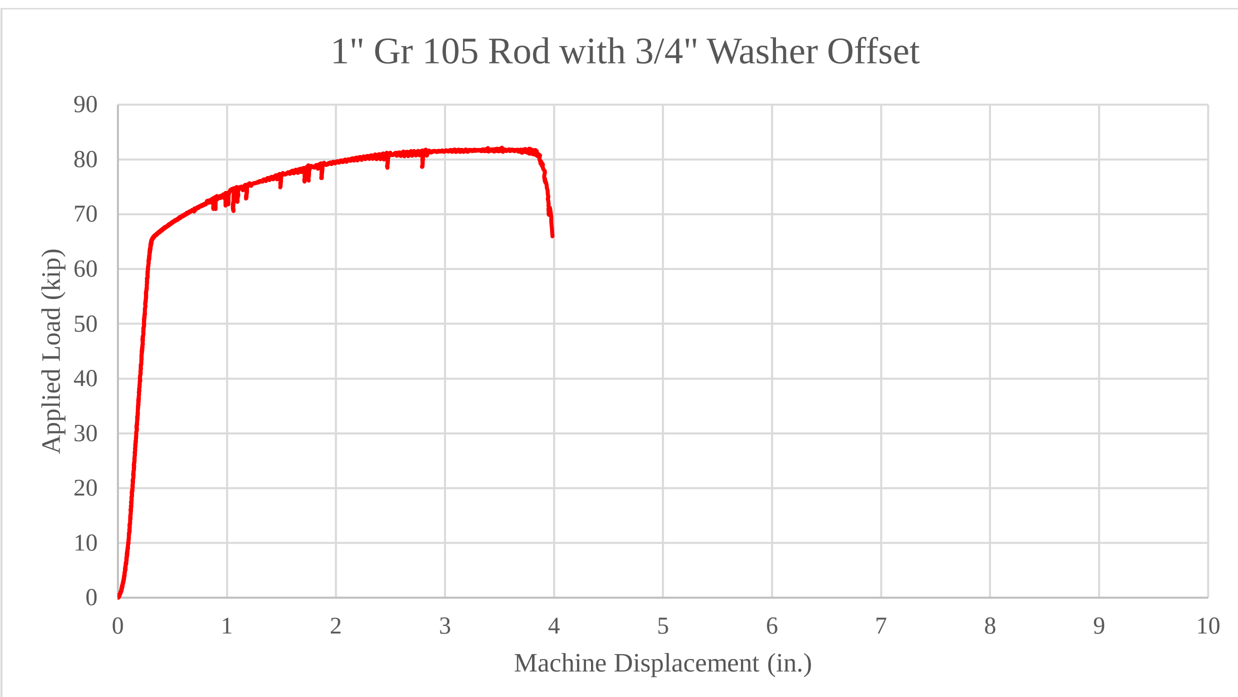

Figure A.32: 1" Gr 105 Rod with 3/4" Washer Offset

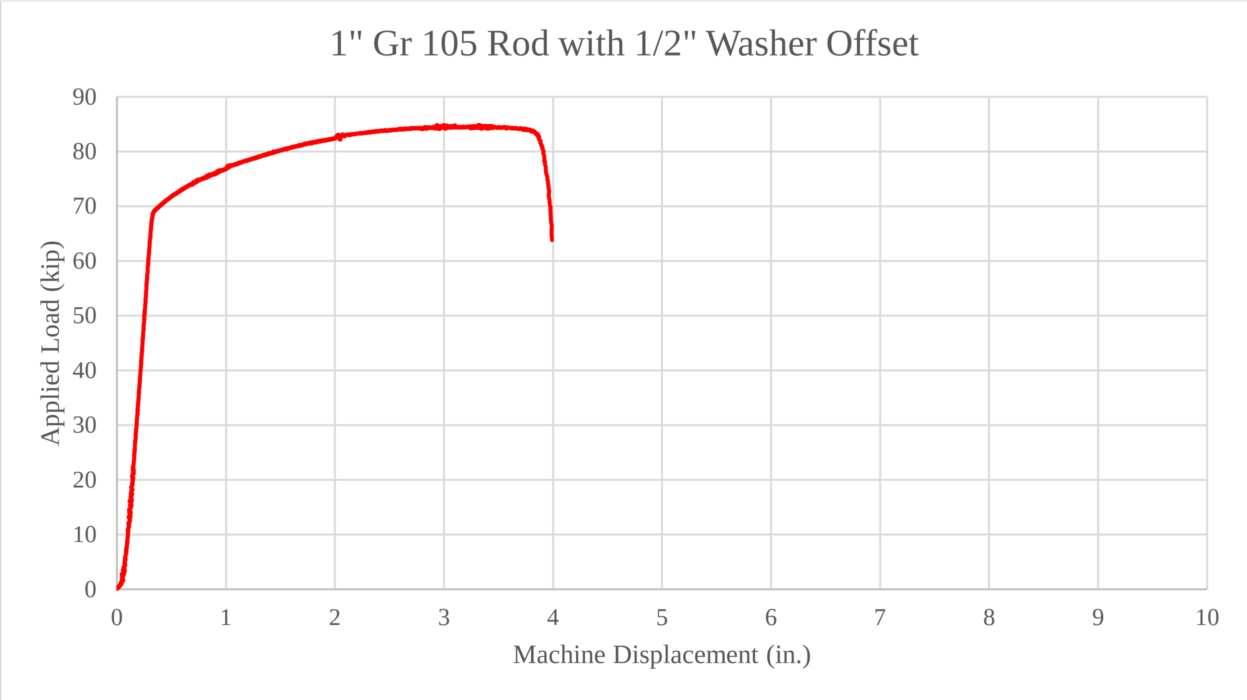

Figure A.33: 1" Gr 105 Rod with 1/2" Washer Offset

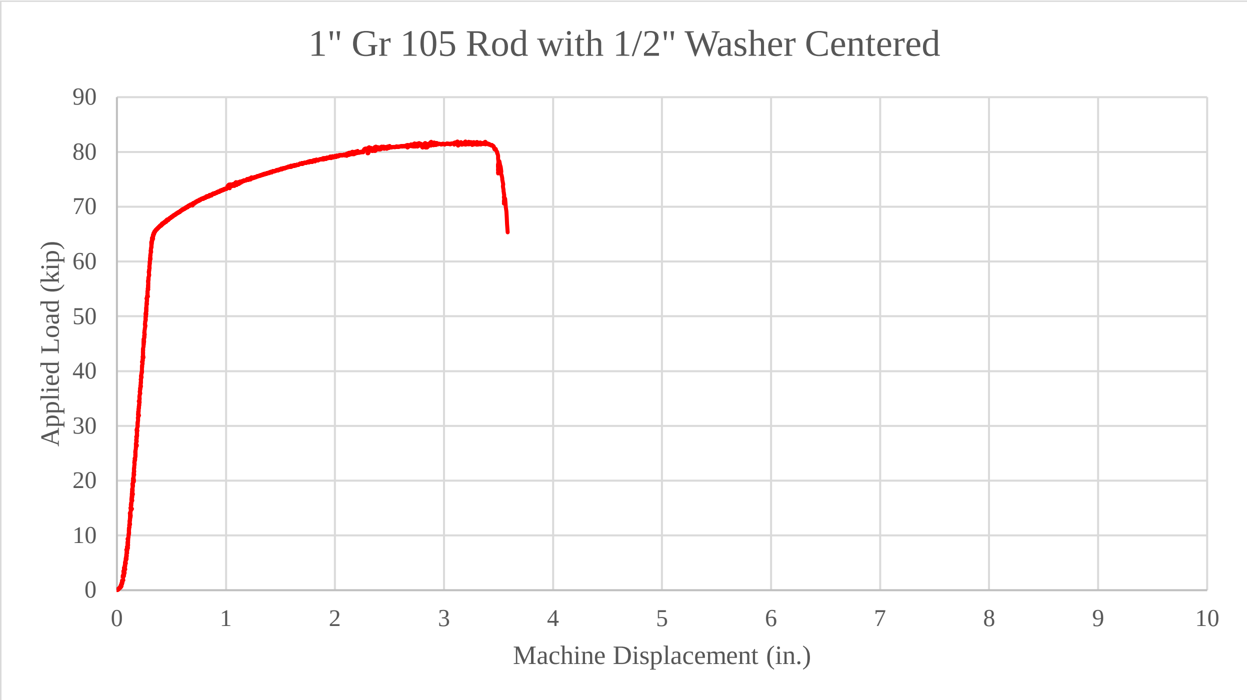

Figure A.34: 1" Gr 105 Rod with 1/2" Washer Centered

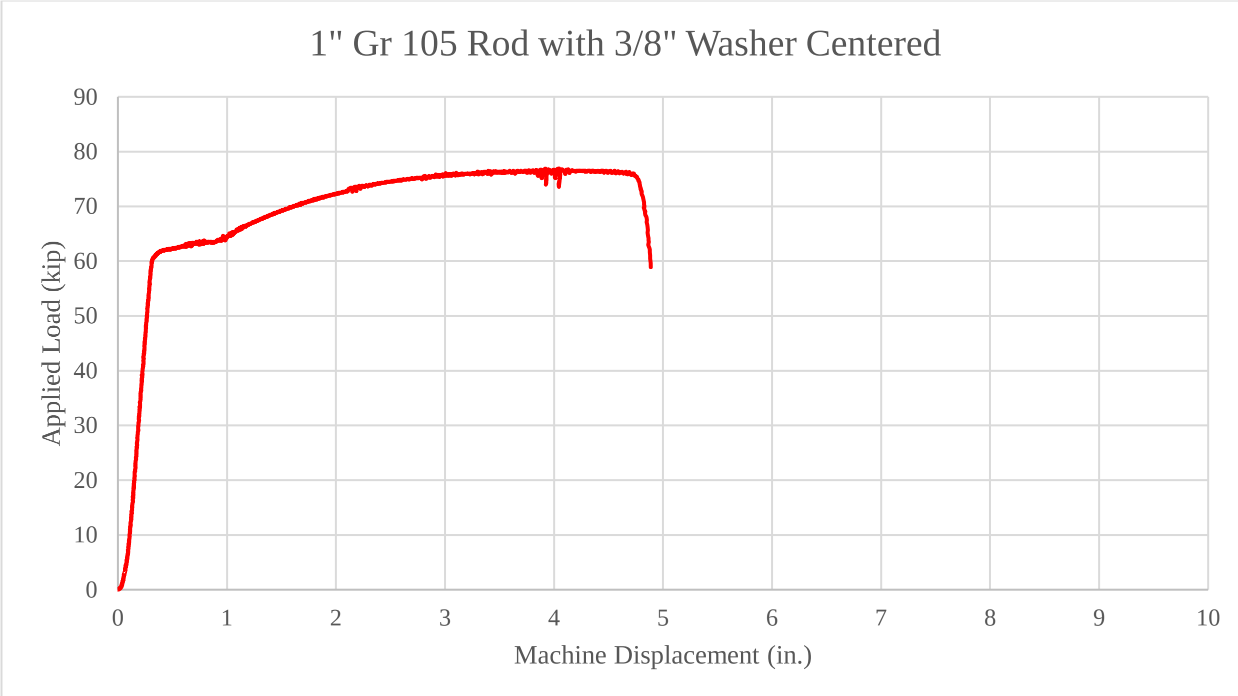

Figure A.35: 1" Gr 105 Rod with 3/8" Washer Centered

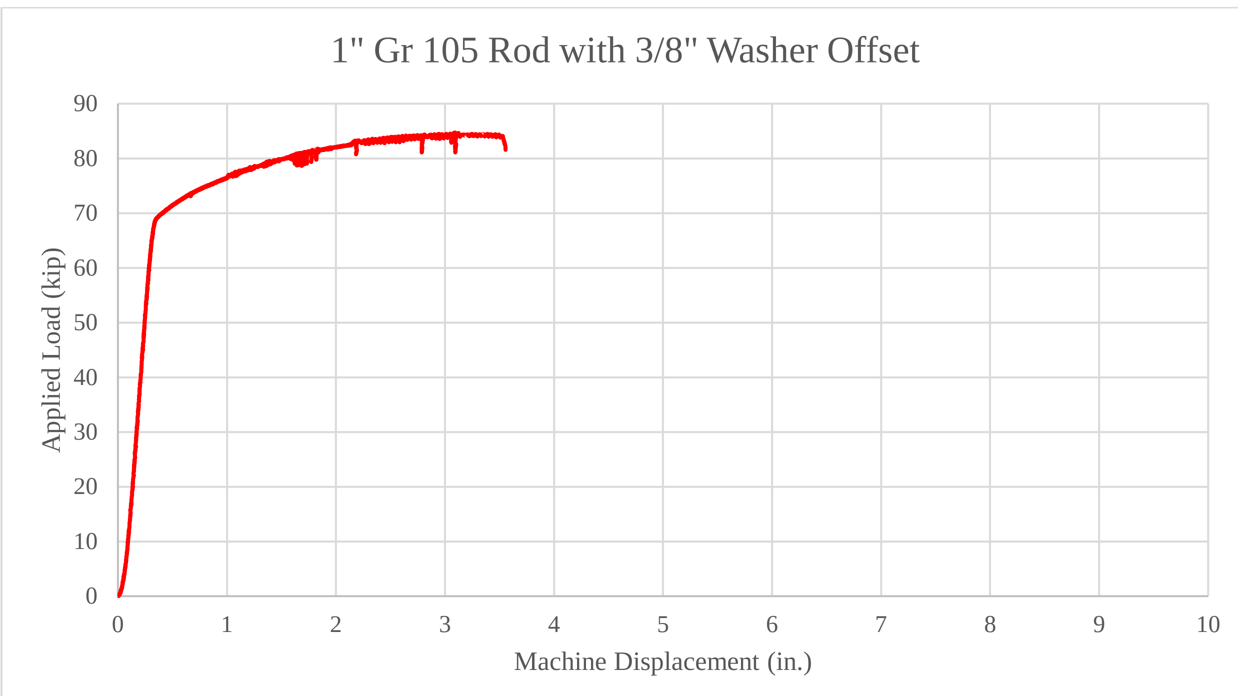

Figure A.36: 1" Gr 105 Rod with 3/8" Washer Offset

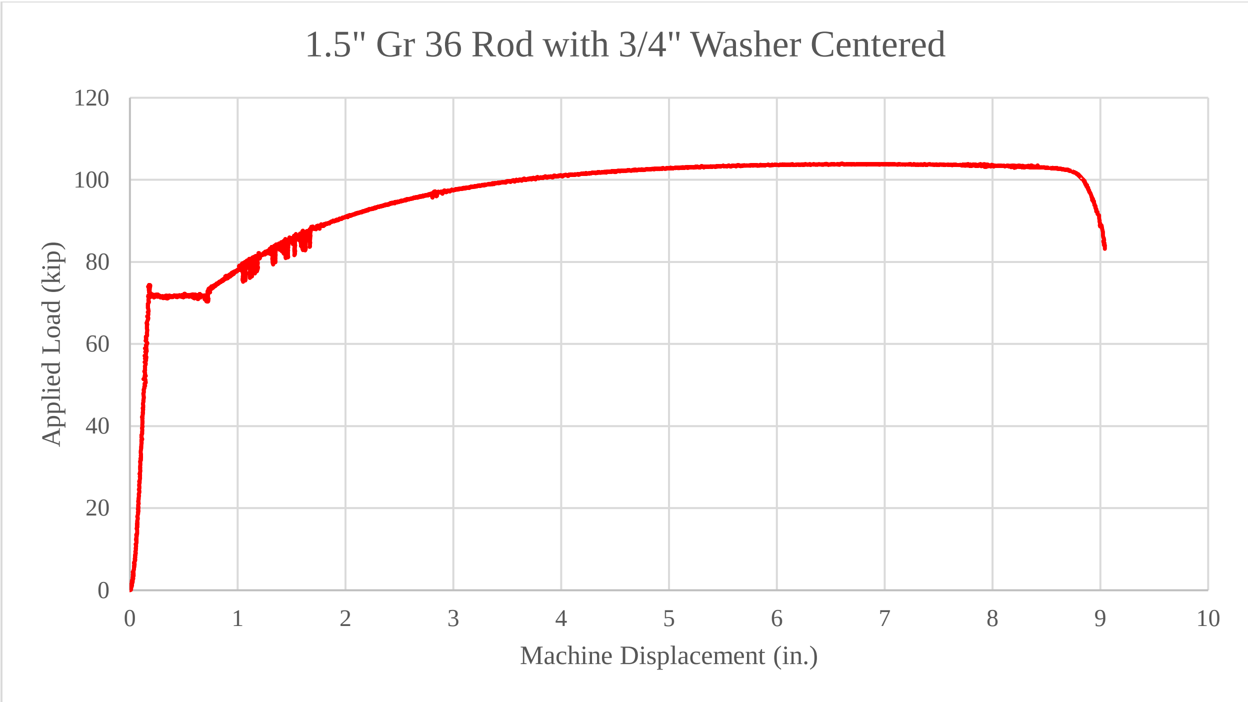

Figure A.37: 1.5" Gr 36 Rod with 3/4 " Washer Centered

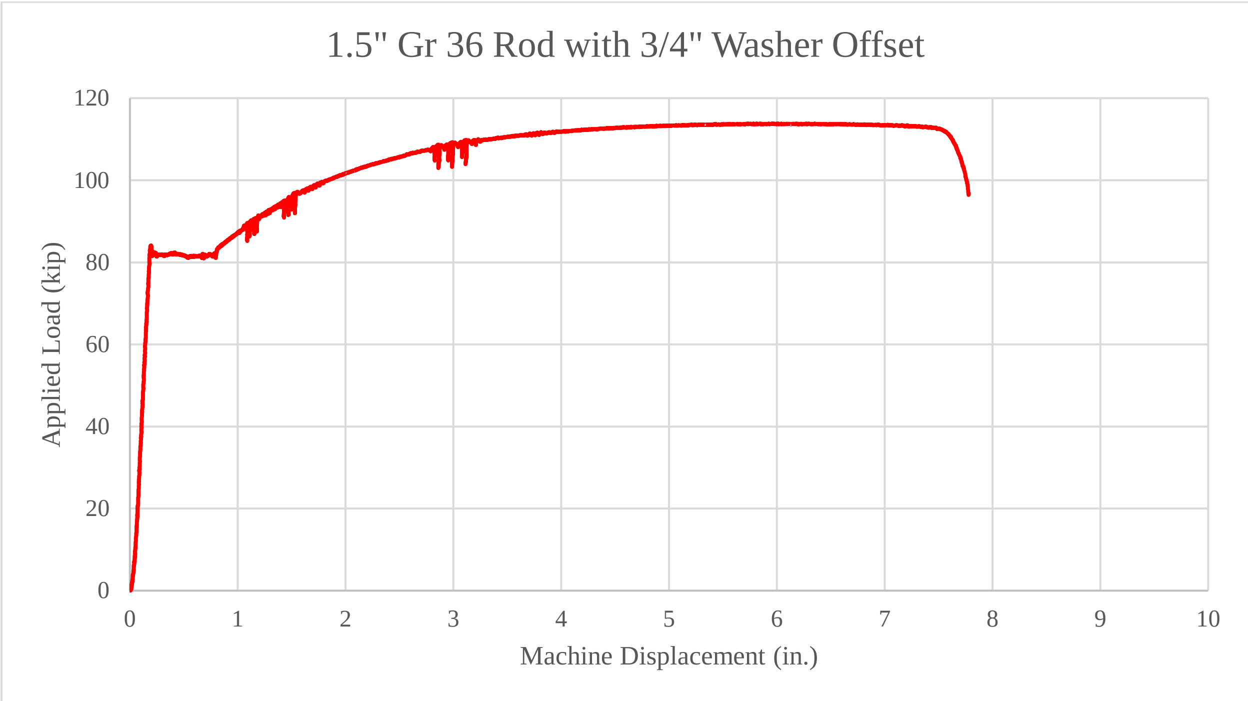

Figure A.38: 1.5" Gr 36 Rod with 3/4 " Washer Offset

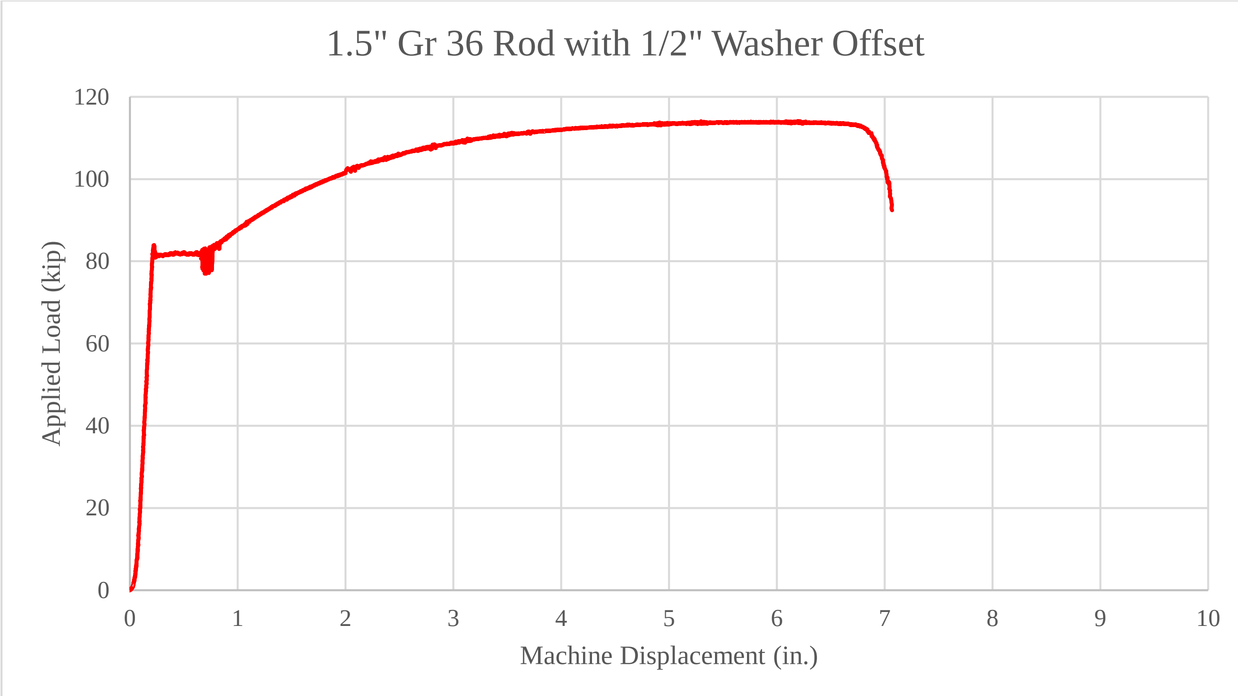

Figure A.39: 1.5" Gr 36 Rod with 1/2" Washer Offset

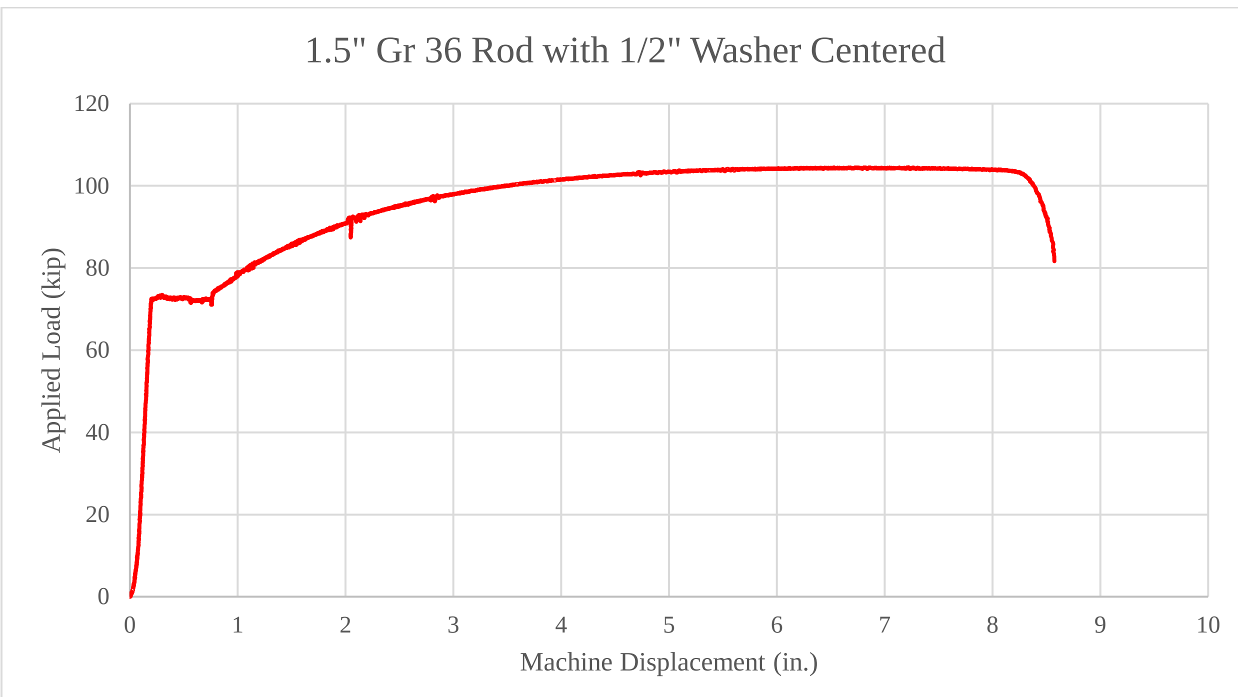

Figure A.40: 1.5" Gr 36 Rod with 1/2" Washer Centered

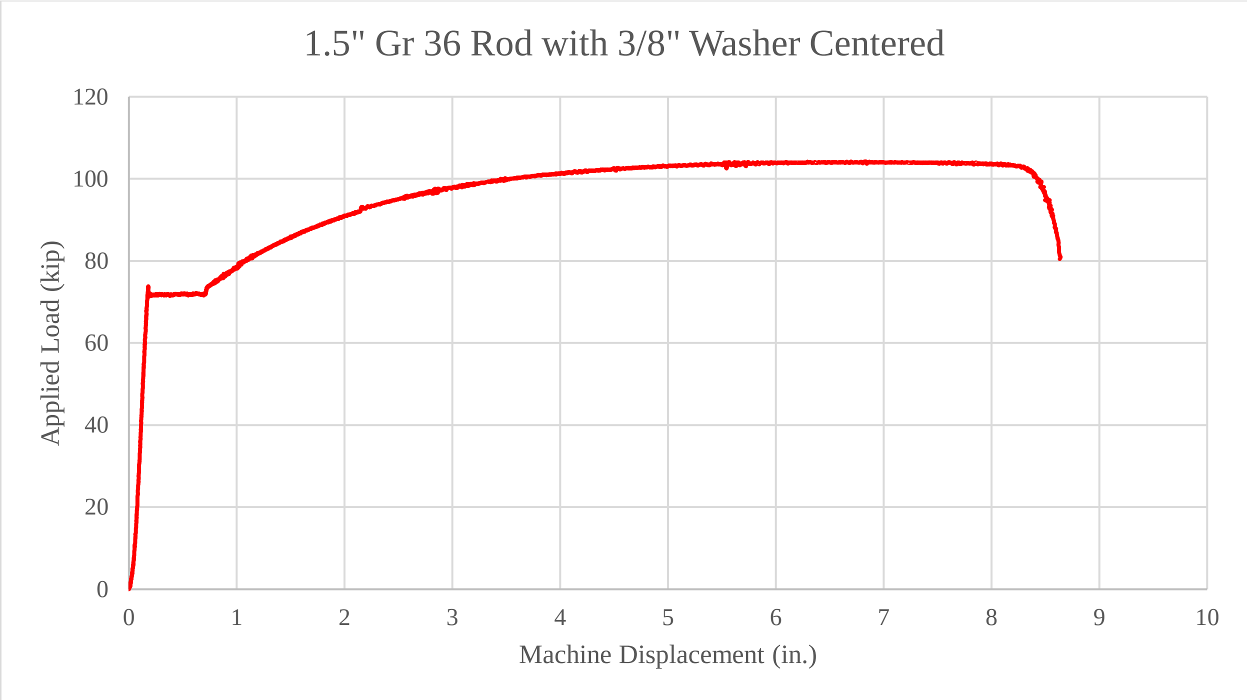

Figure A.41: 1.5" Gr 36 Rod with 3/8" Washer Centered

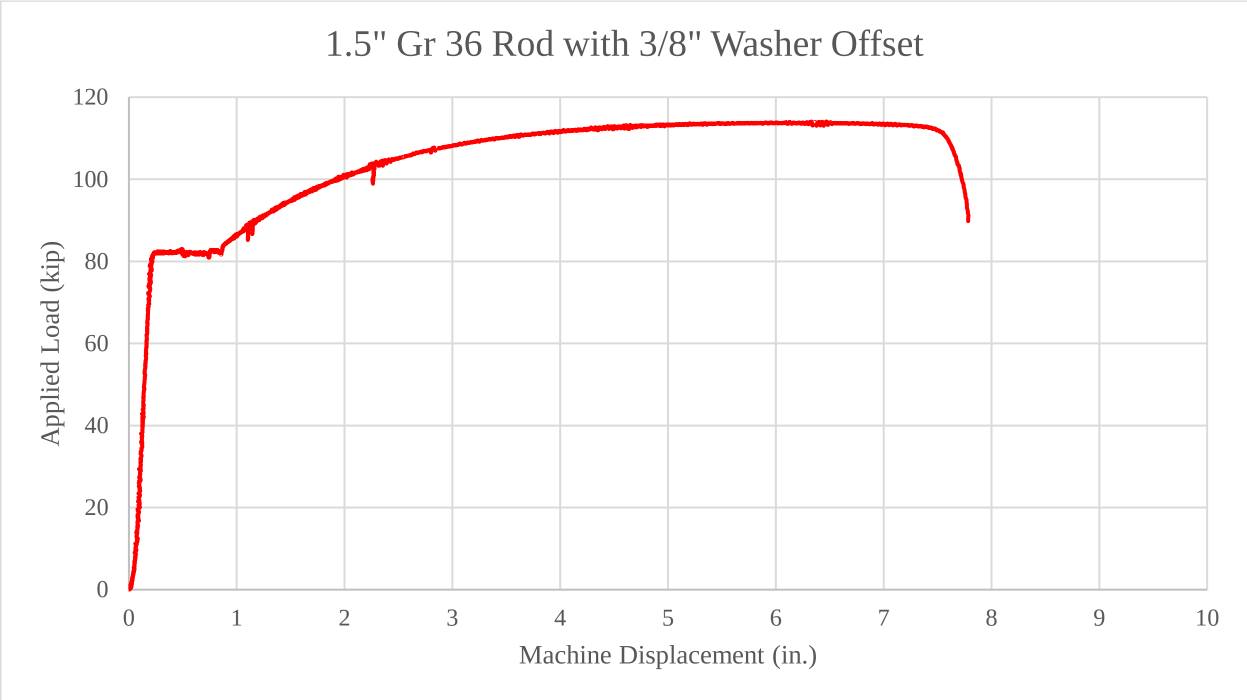

Figure A.42: 1.5" Gr 36 Rod with 3/8" Washer Offset

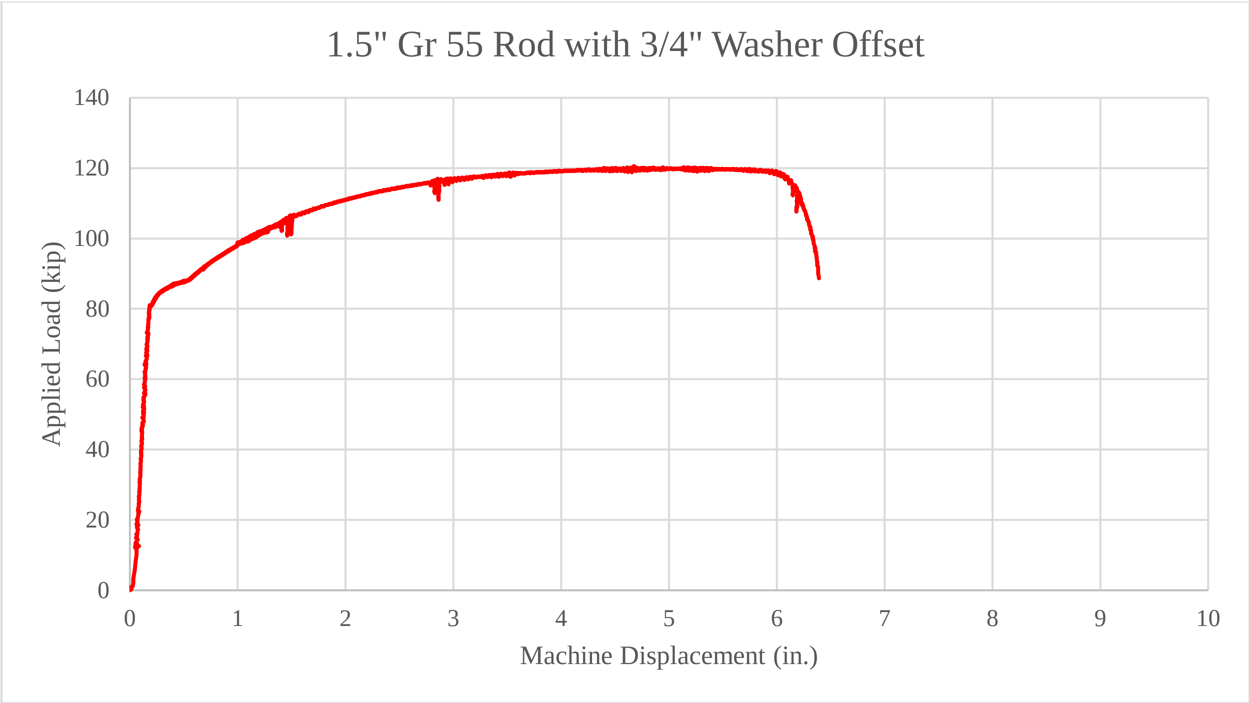

Figure A.43: 1.5" Gr 55 Rod with 3/4 " Washer Offset

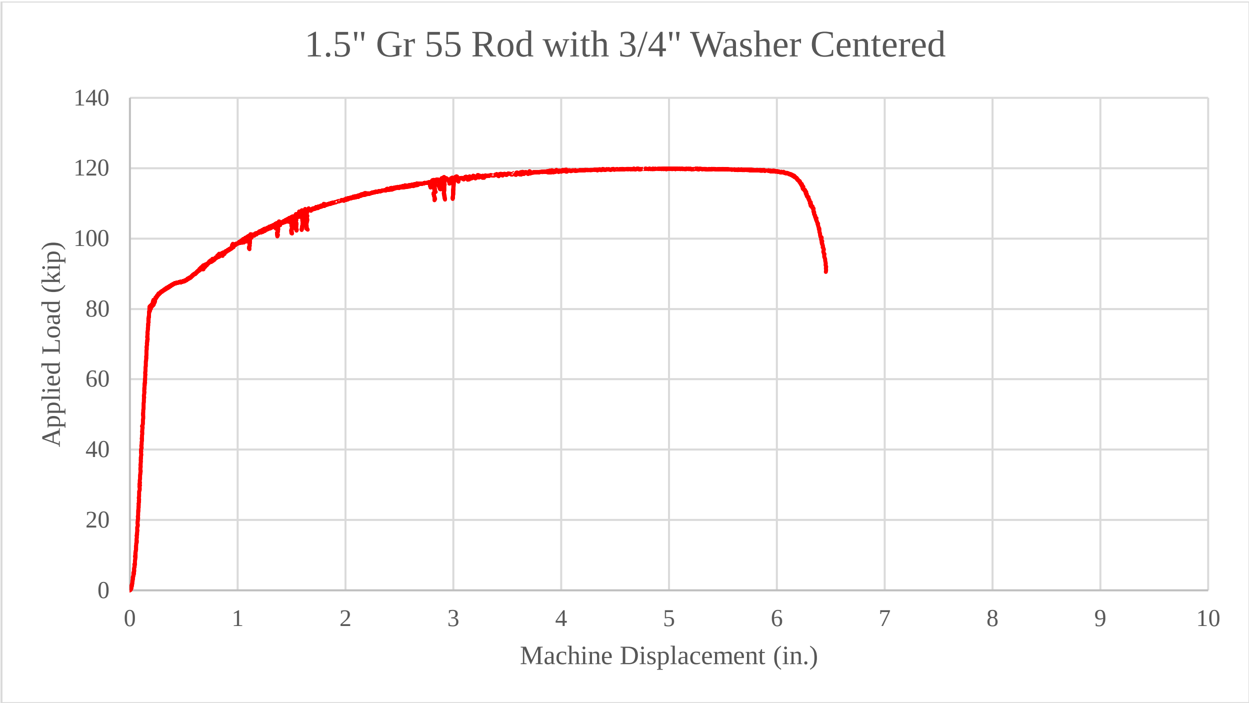

Figure A.44: 1.5" Gr 55 Rod with 3/4" Washer Centered

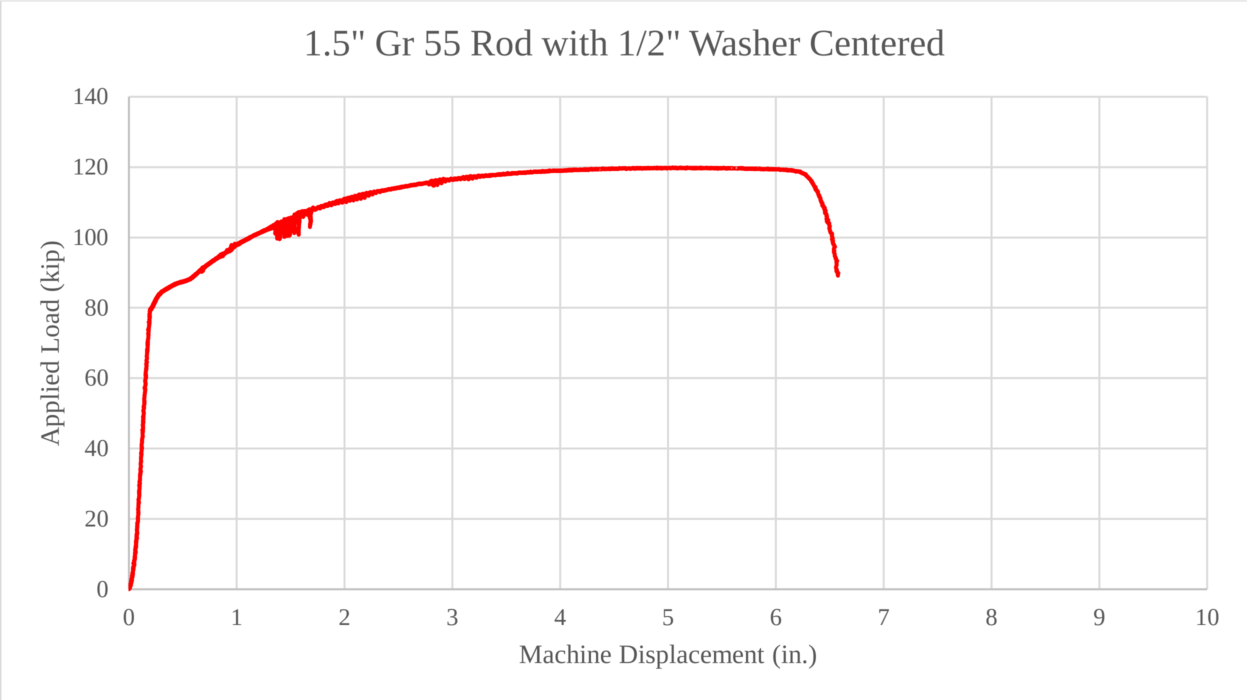

Figure A.45: 1.5" Gr 55 Rod with 1/2" Washer Centered

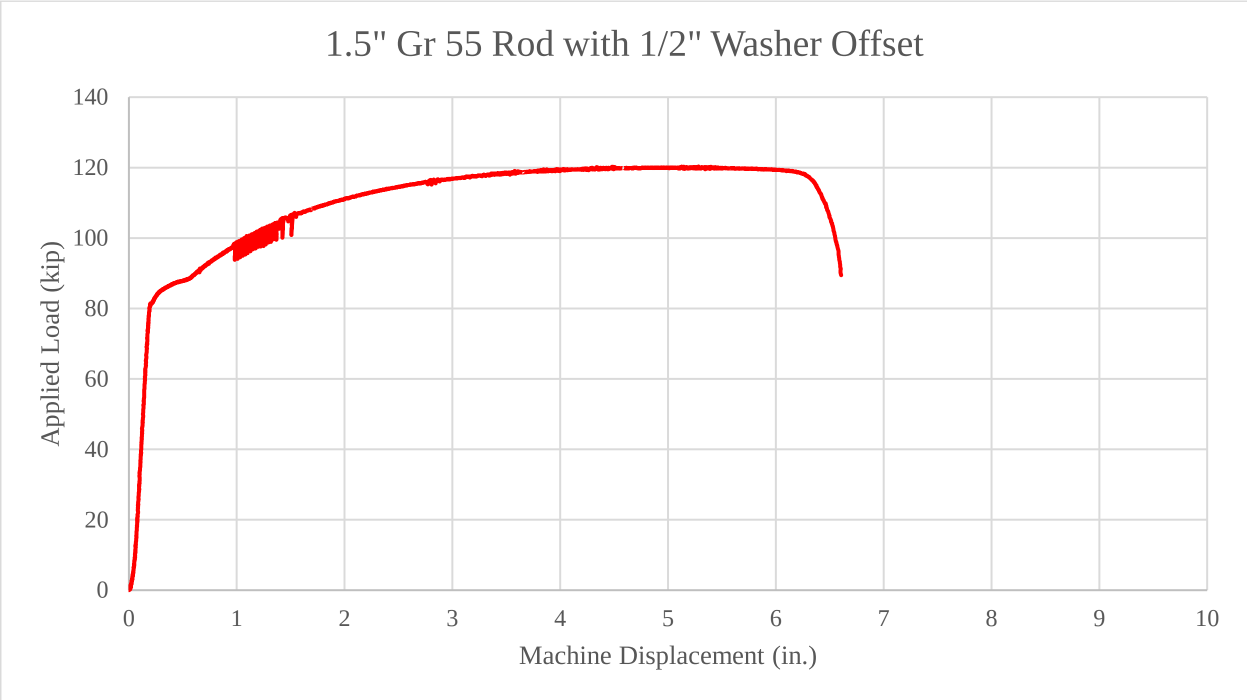

Figure A.46: 1.5" Gr 55 Rod with 1/2" Washer Offset

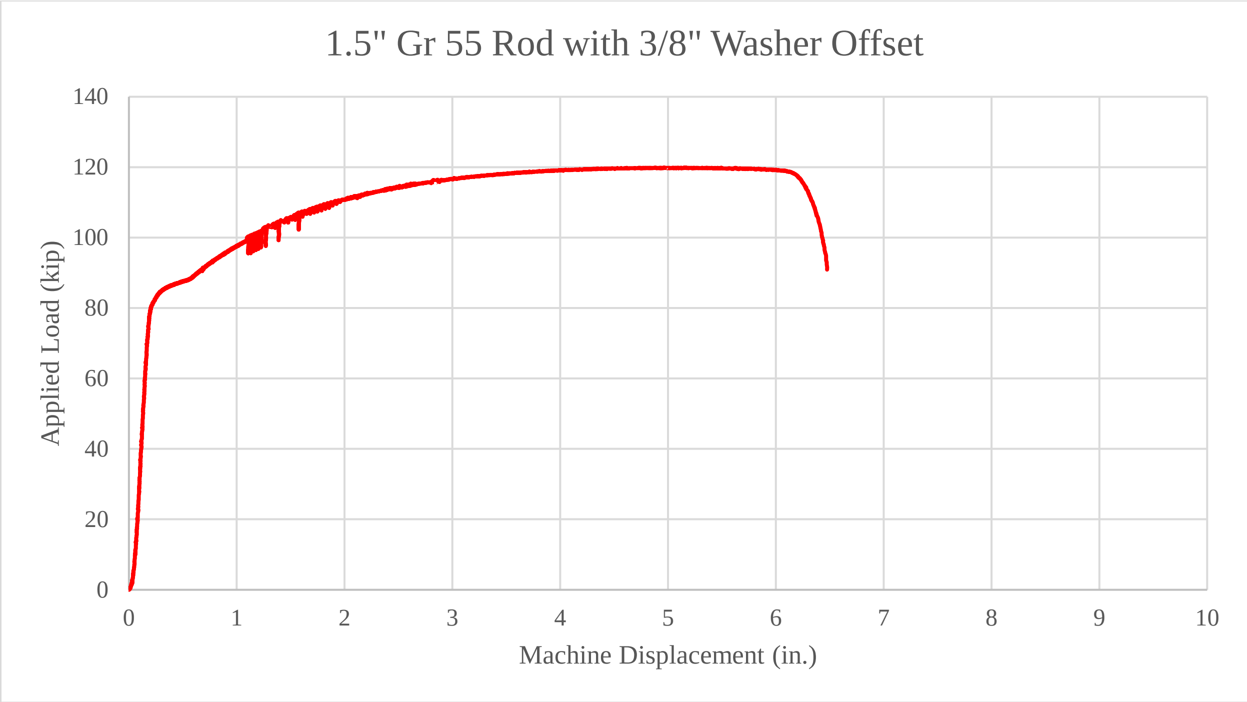

Figure A.47: 1.5" Gr 55 Rod with 3/8" Washer Offset

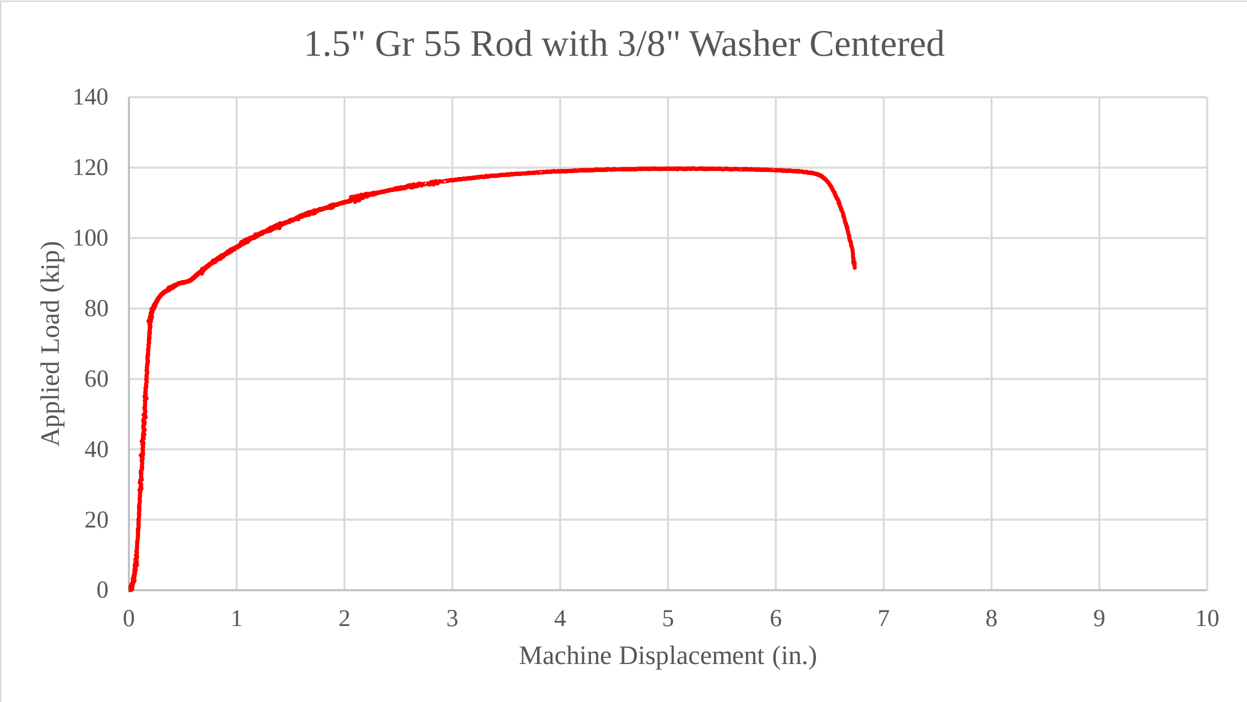

Figure A.48: 1.5" Gr 55 Rod with 3/8" Washer Centered

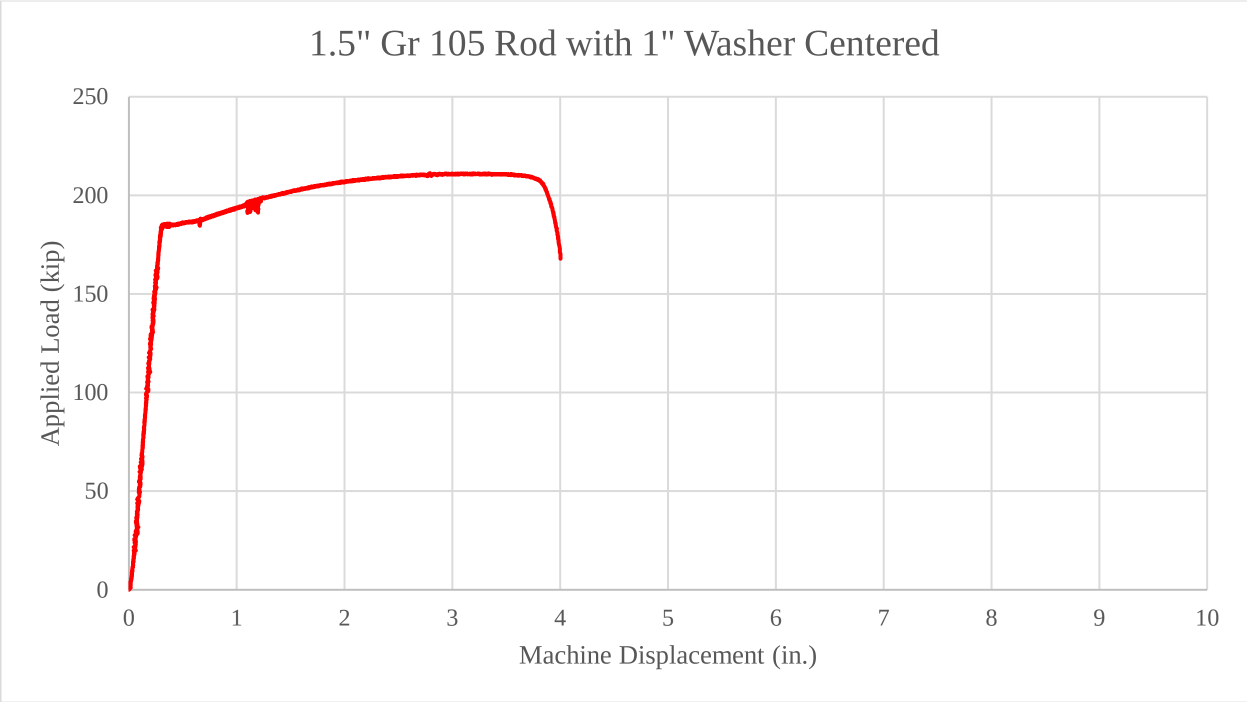

Figure A.49: 1.5" Gr 105 Rod with 1" Washer Centered

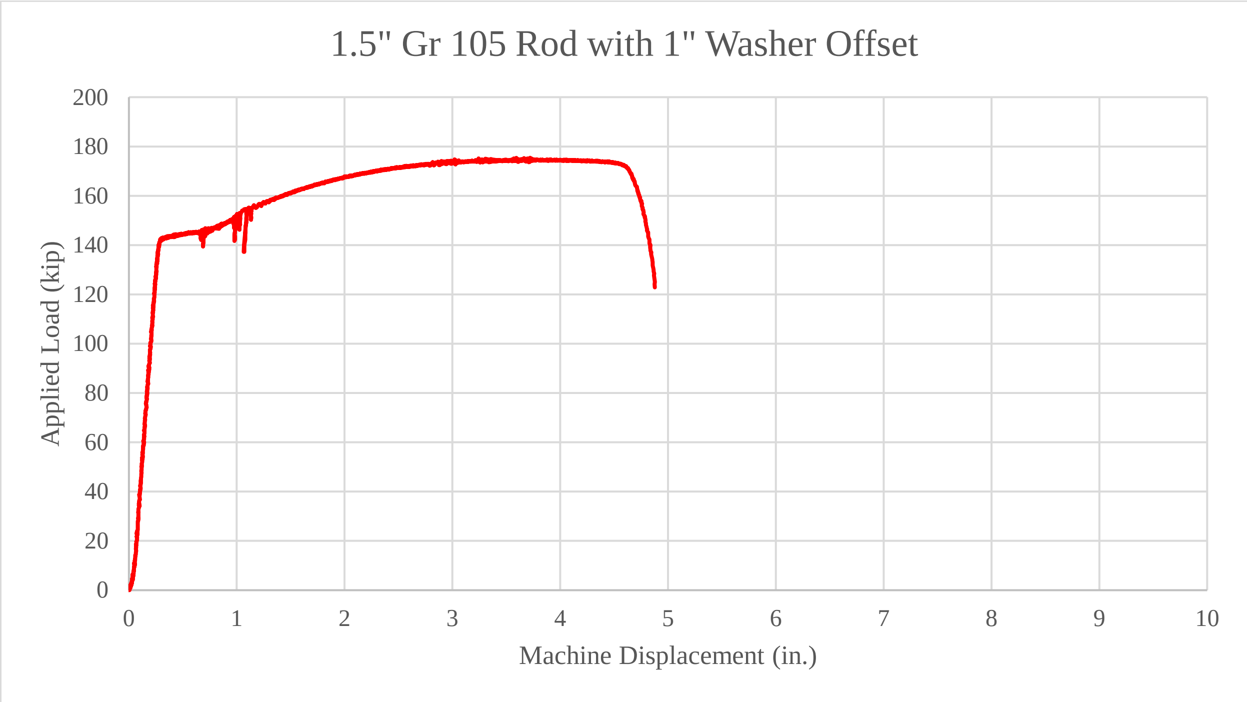

Figure A.50: 1.5" Gr 105 Rod with 1" Washer Offset

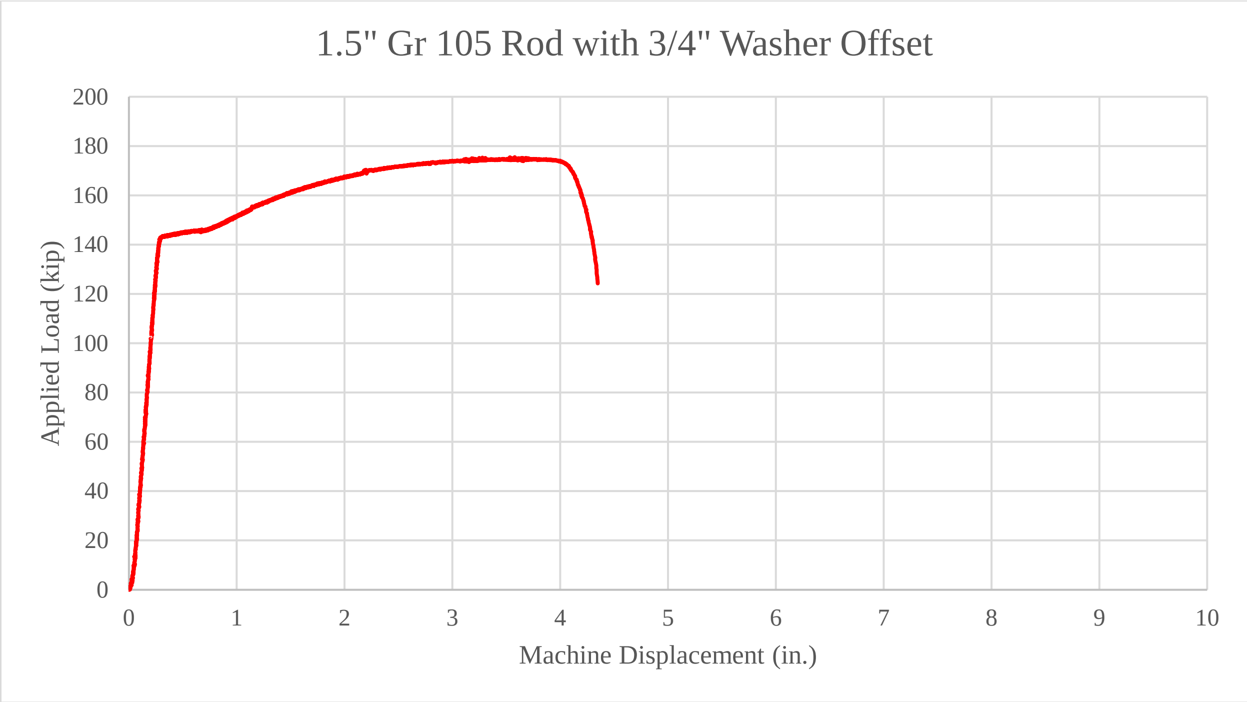

Figure A.51: 1.5" Gr 105 Rod with 3/4" Washer Offset

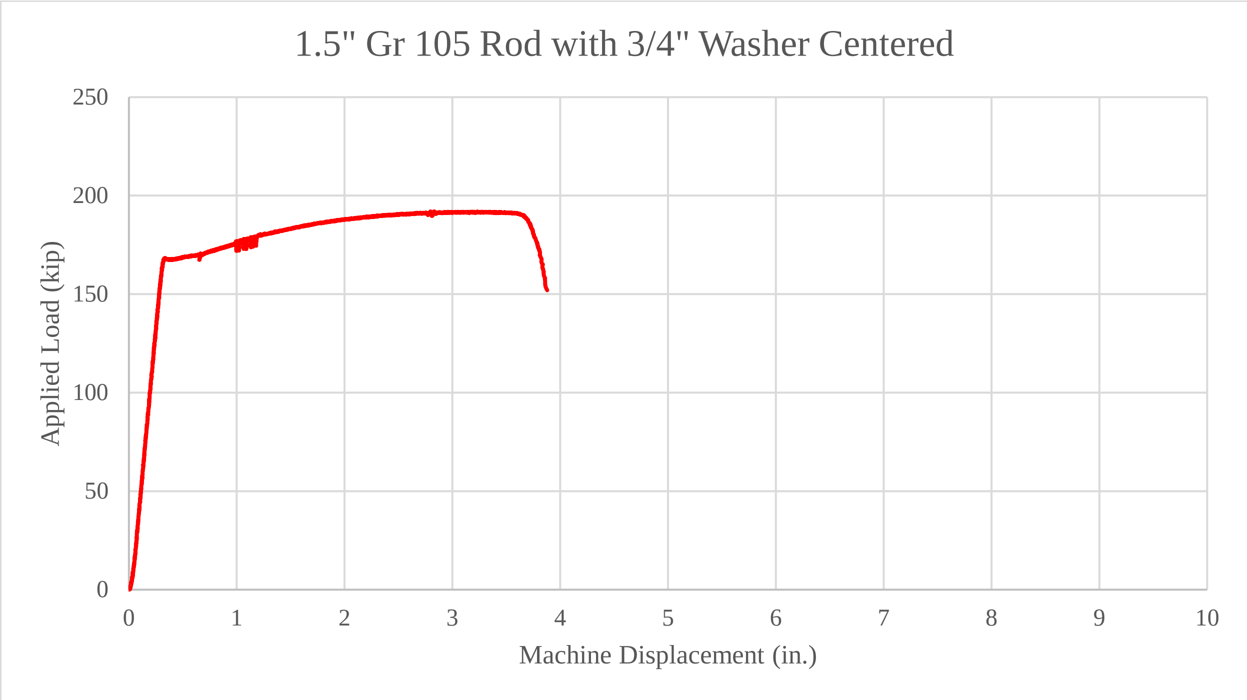

Figure A.52: 1.5" Gr 105 Rod with 3/4" Washer Centered

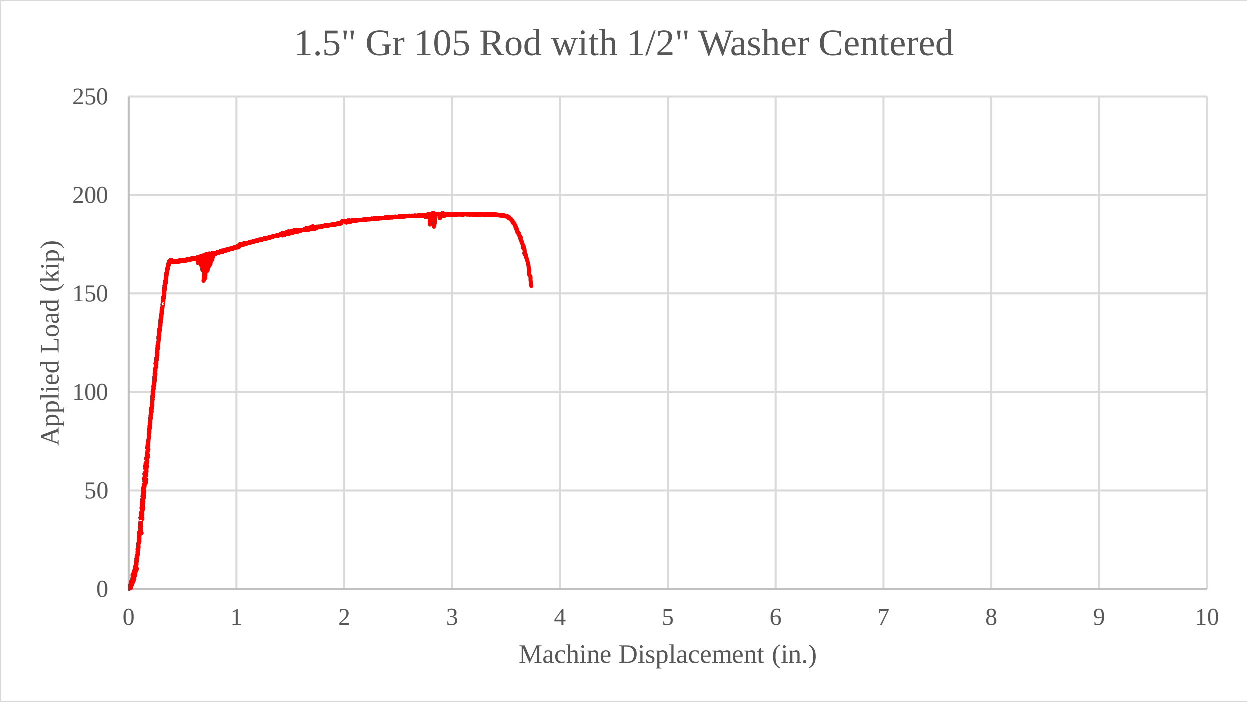

Figure A.53: 1.5" Gr 105 Rod with 1/2" Washer Centered

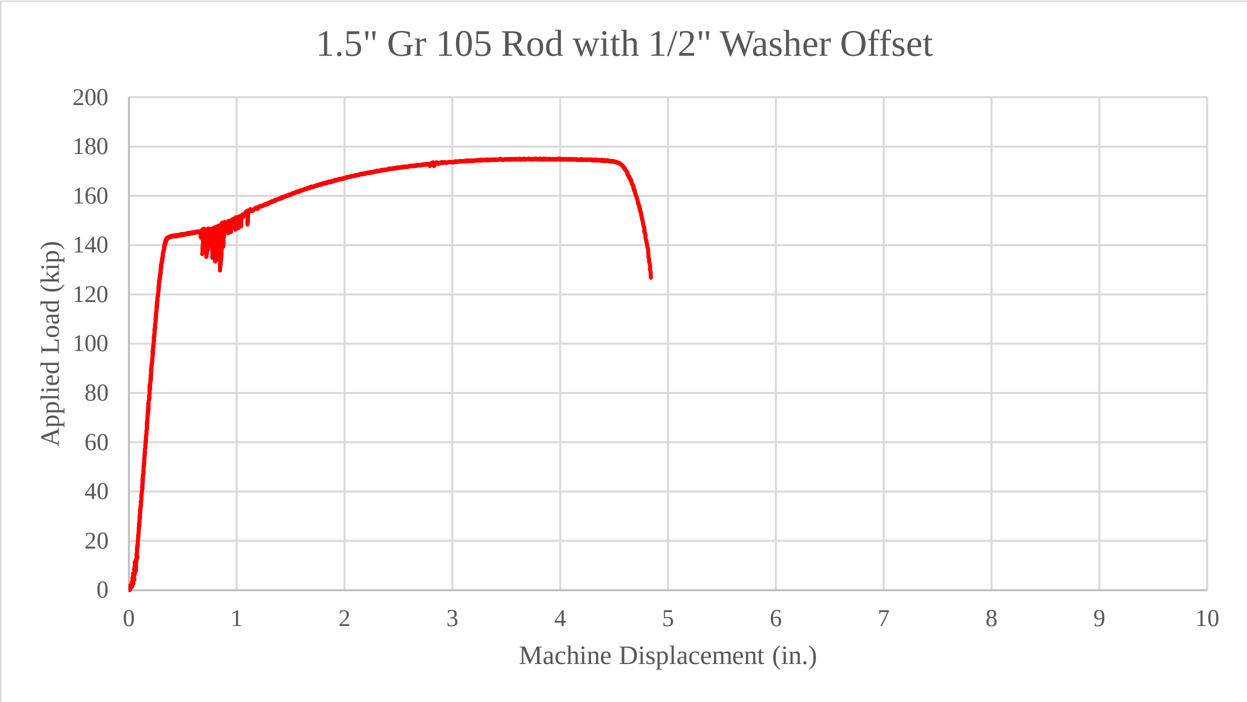

Figure A.54: 1.5" Gr 105 Rod with 1/2" Washer Offset

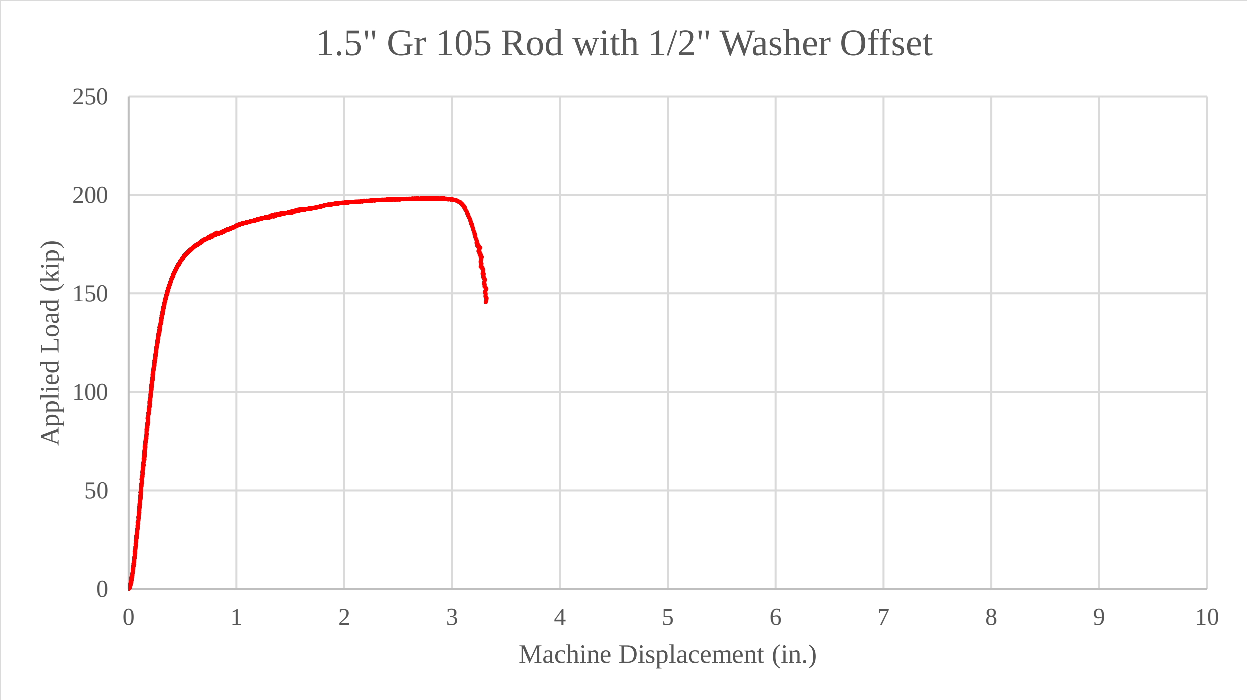

Figure A.55: 1.5" Gr 105 Rod with 1/2" Washer Offset

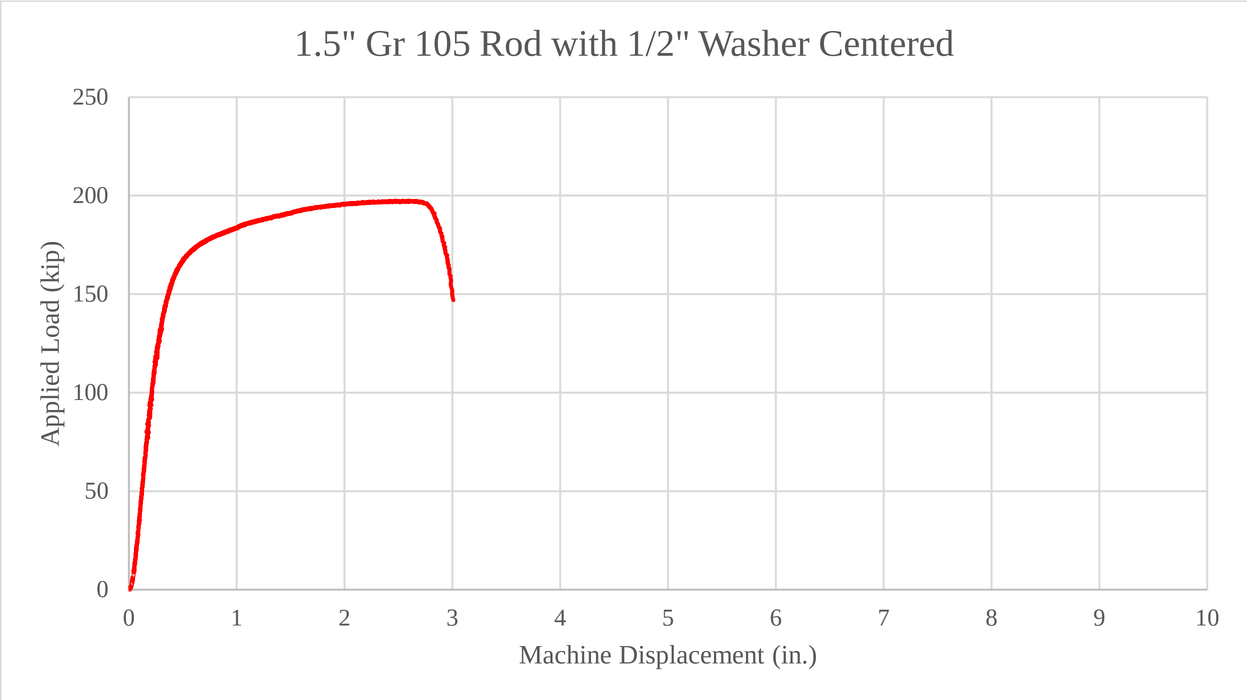

Figure A.56: 1.5" Gr 105 Rod with 1/2" Washer Centered

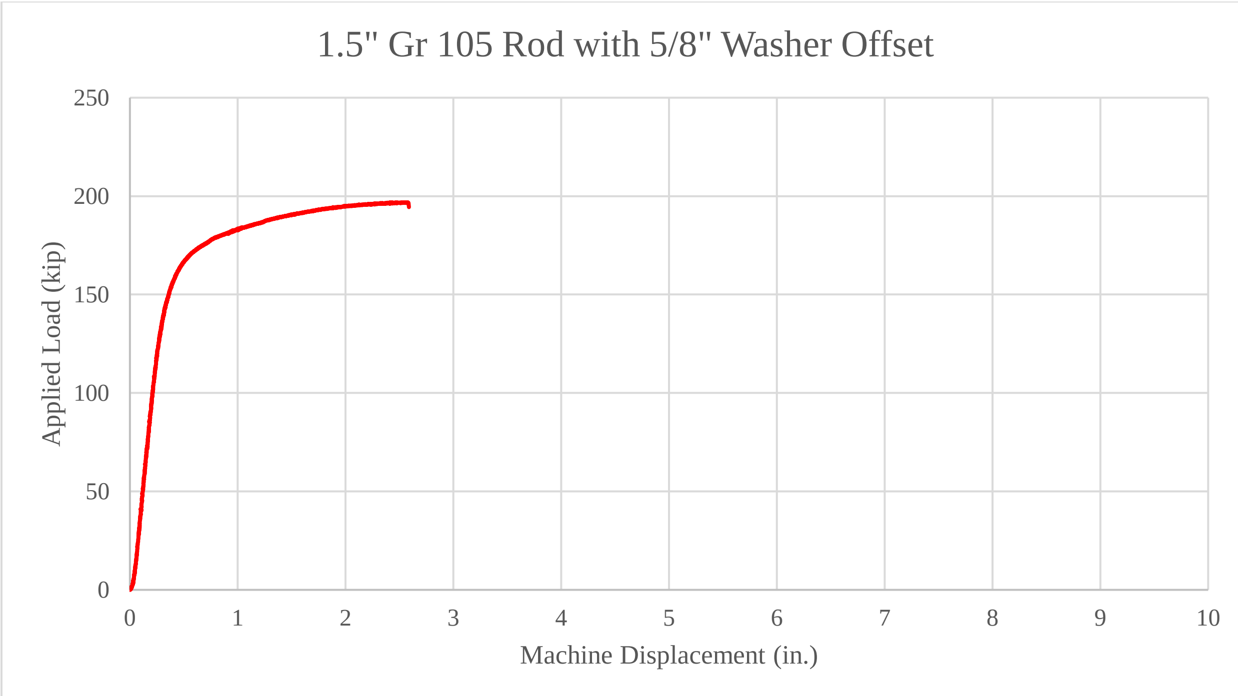

Figure A.57: 1.5" Gr 105 Rod with 5/8" Washer Offset

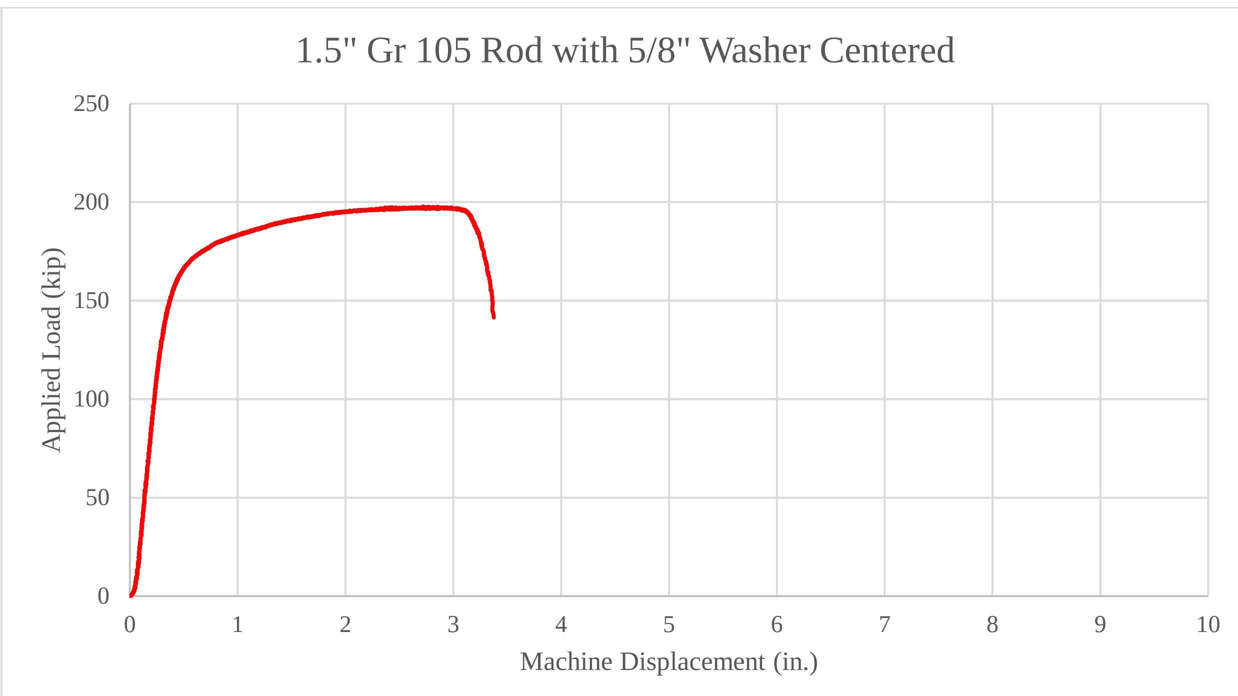

Figure A.58: 1.5" Gr 105 Rod with 5/8" Washer Centered

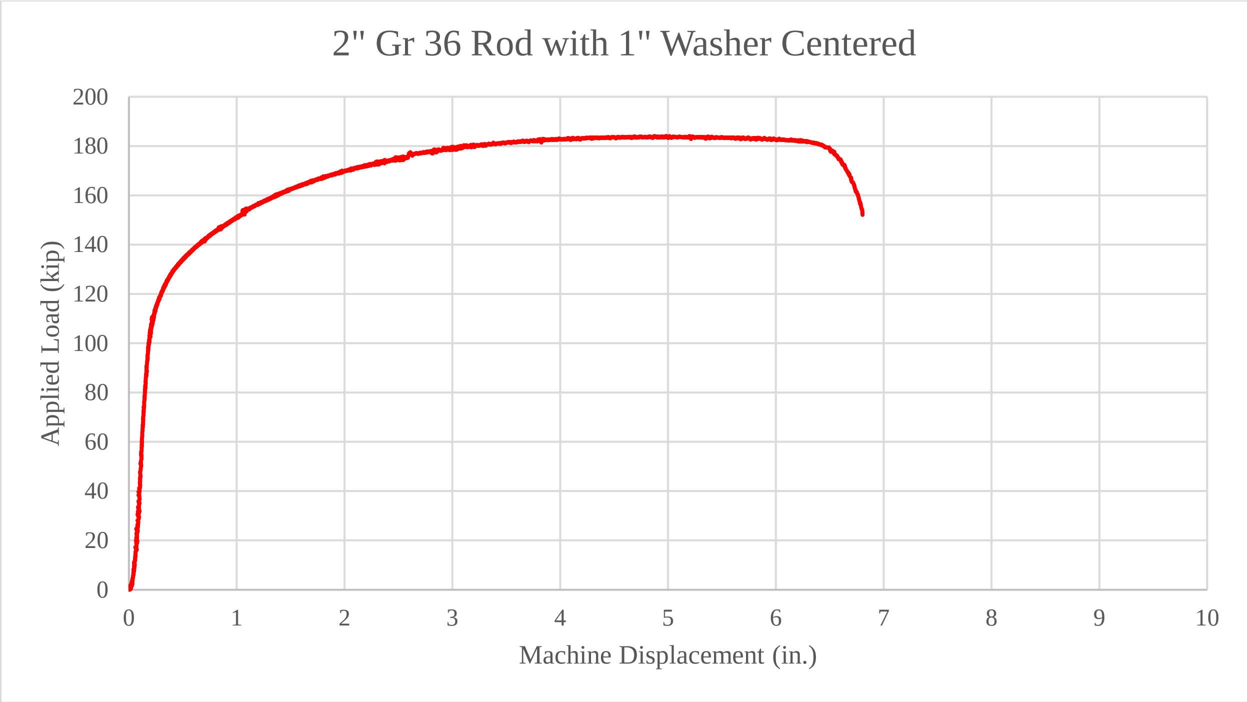

Figure A.59: 2" Gr 36 Rod with 1" Washer Centered

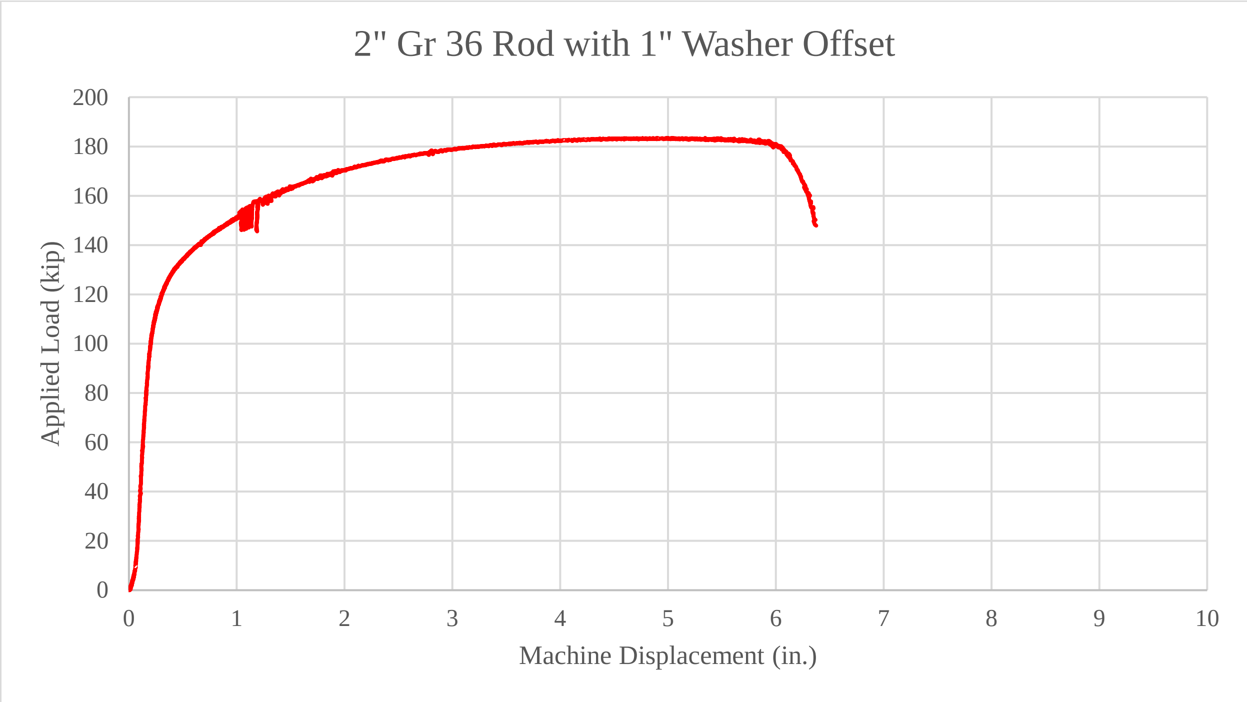

Figure A.60: 2" Gr 36 Rod with 1" Washer Offset

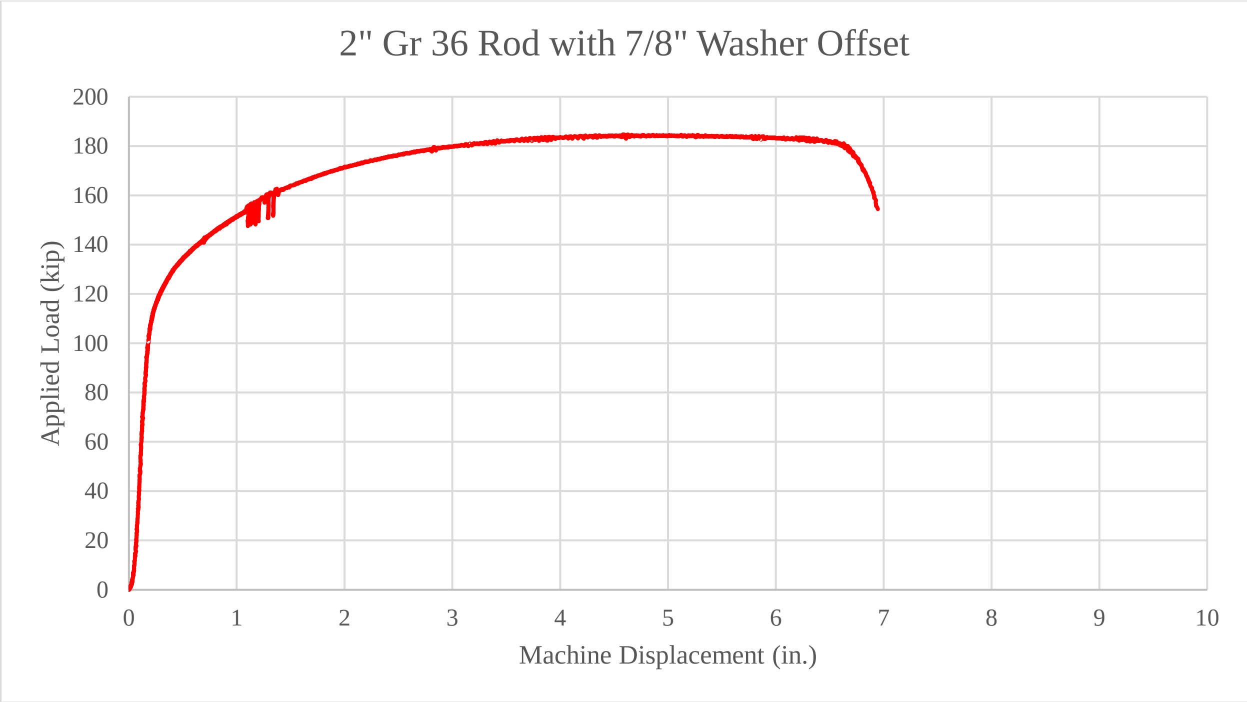

Figure A.61: 2" Gr 36 Rod with 7/8" Washer Offset

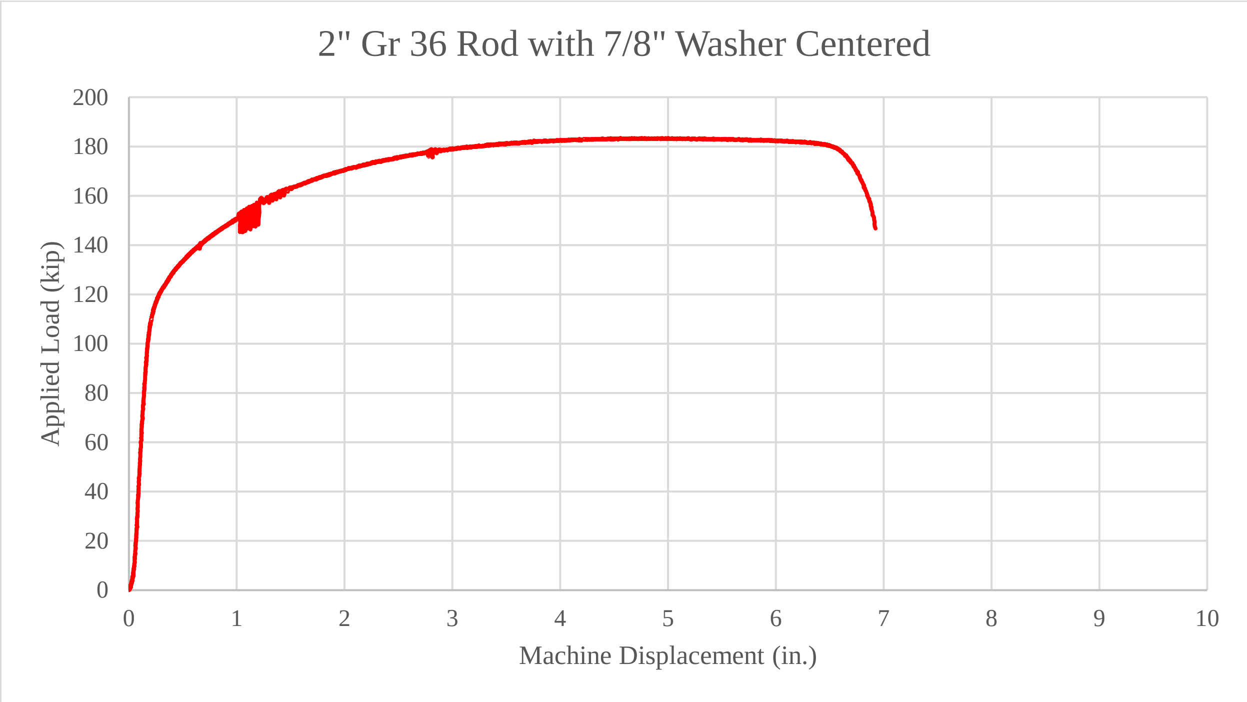

Figure A.62: 2" Gr 36 Rod with 7/8" Washer Centered

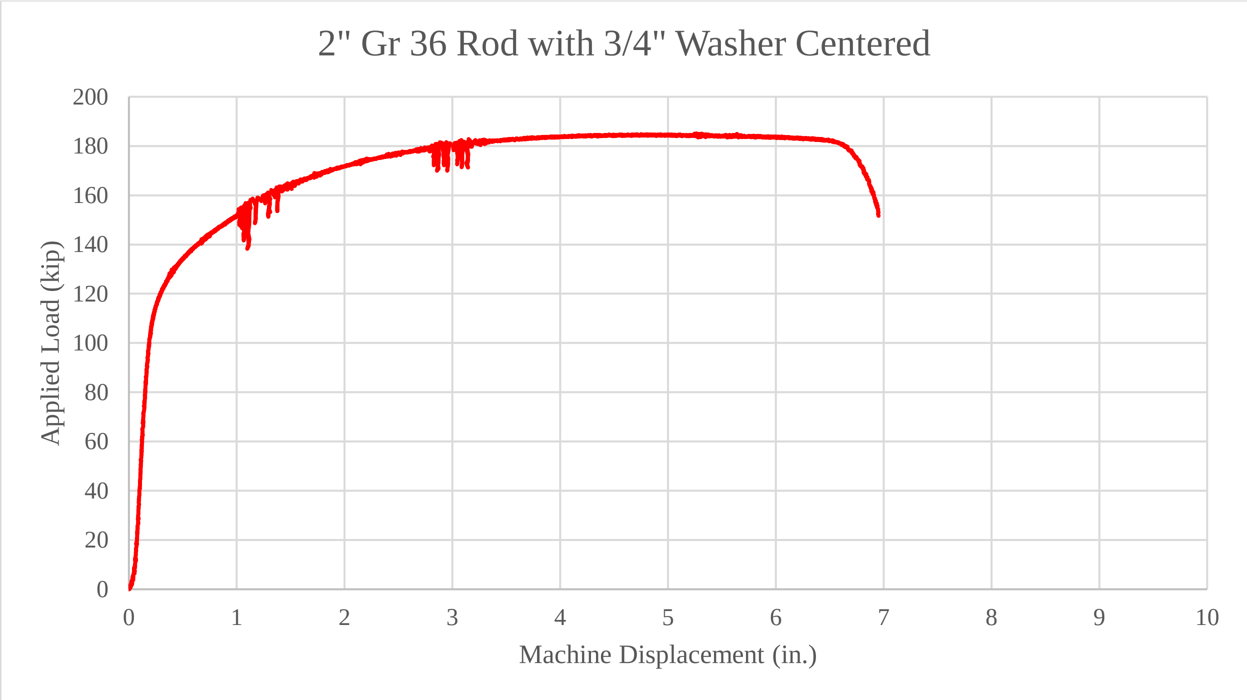

Figure A.63: 2" Gr 36 Rod with 3/4" Washer Centered

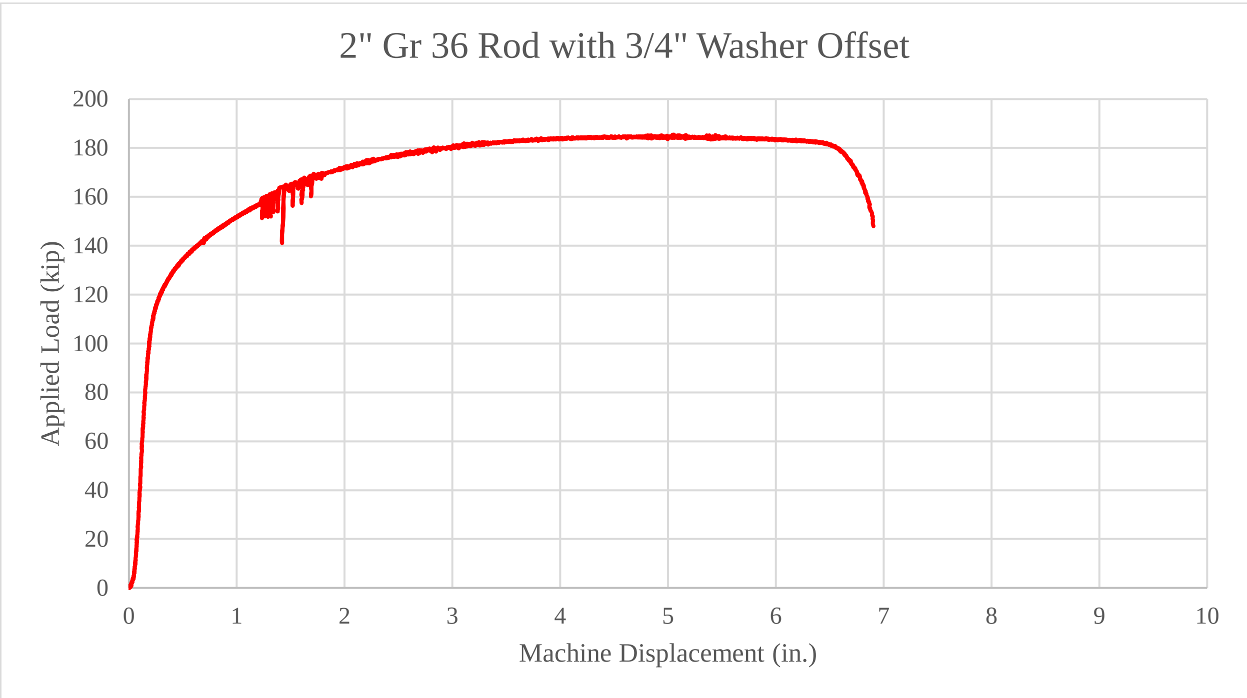

Figure A.64: 2" Gr 36 Rod with 3/4" Washer Offset

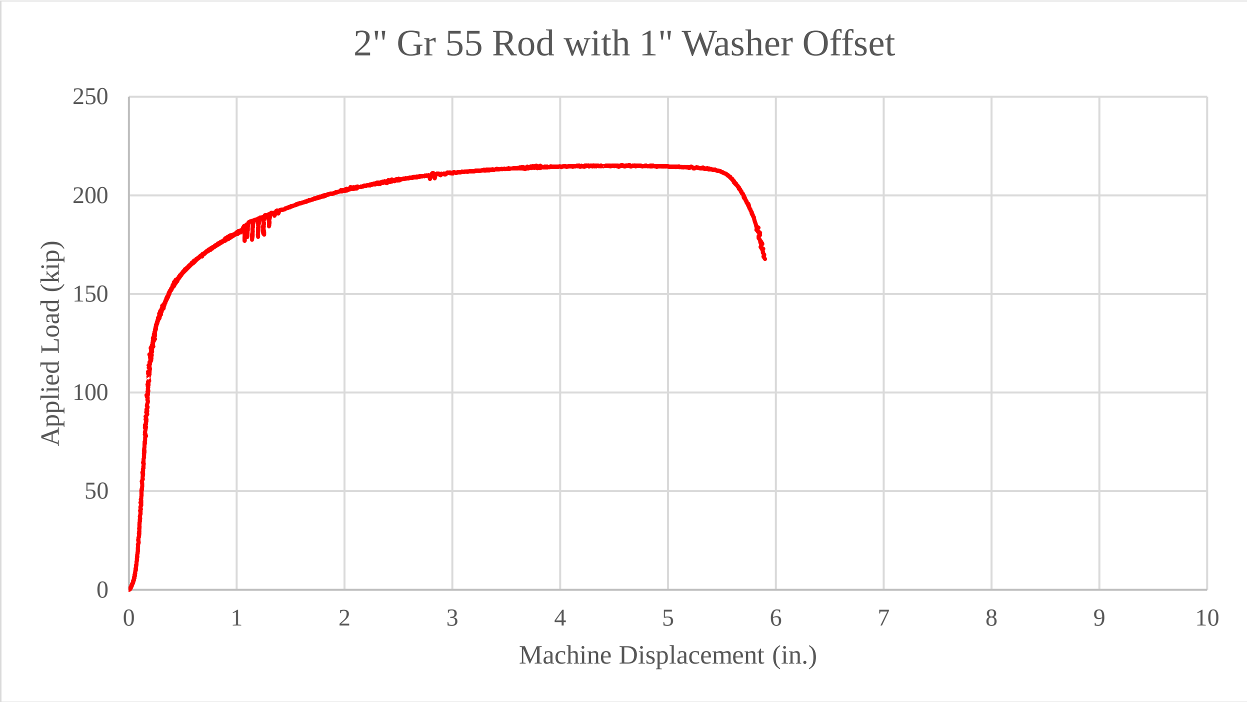

Figure A.65: 2" Gr 55 Rod with 1" Washer Offset

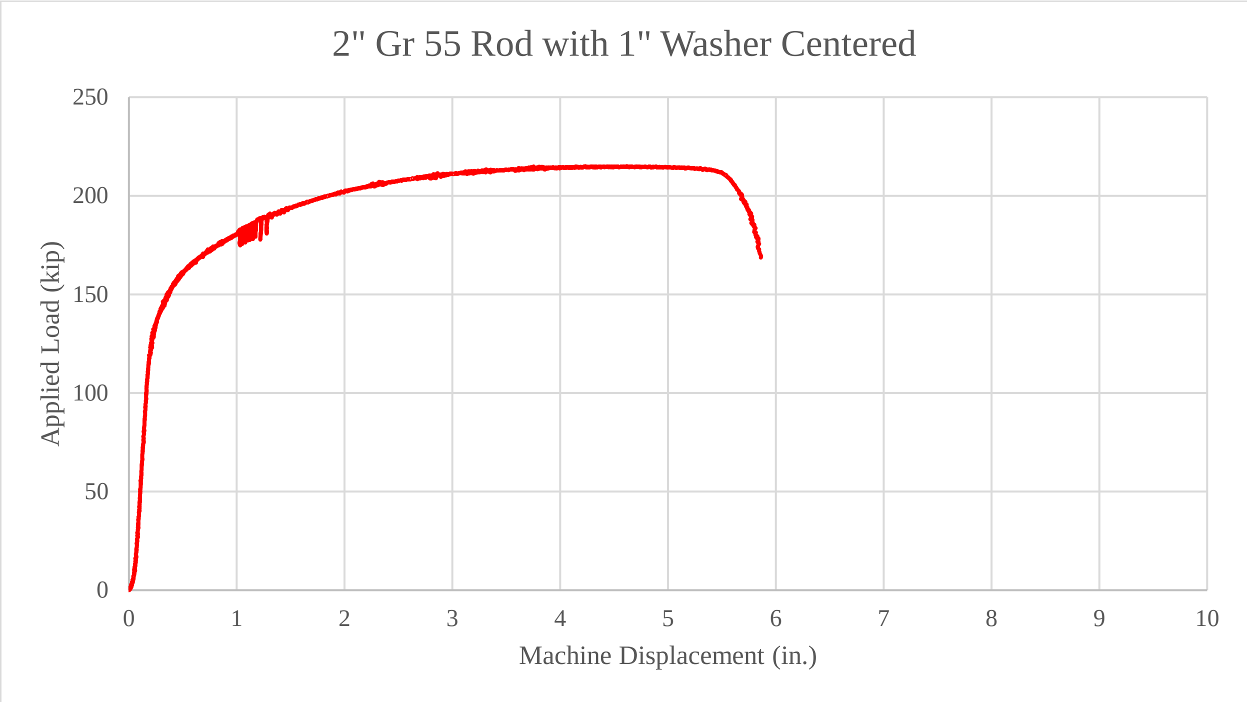

Figure A.66: 2" Gr 55 Rod with 1" Washer Centered

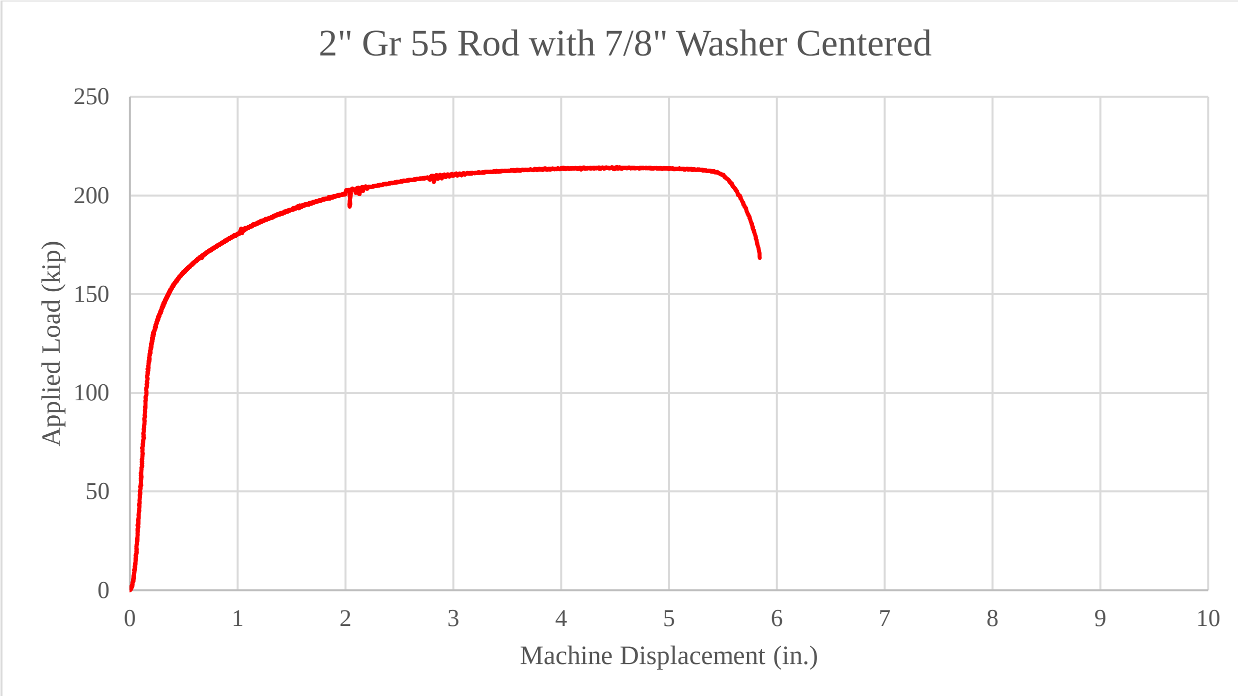

Figure A.67: 2" Gr 55 Rod with 7/8" Washer Centered

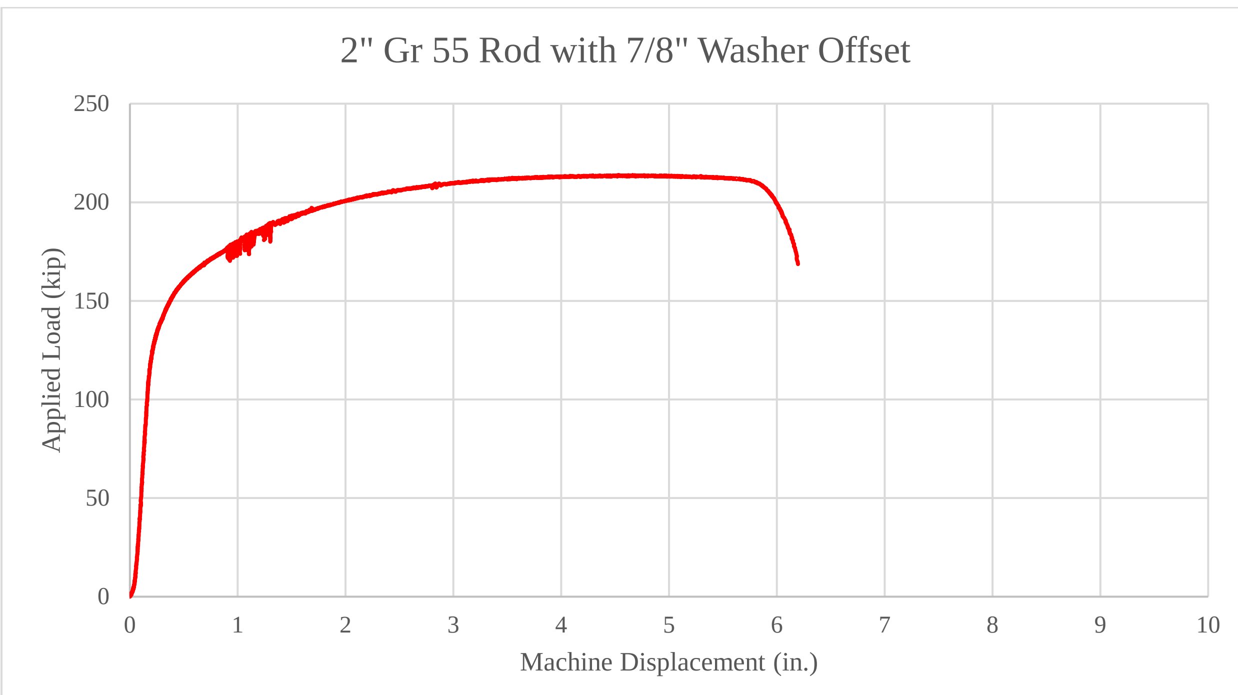

Figure A.68: 2" Gr 55 Rod with 7/8" Washer Offset

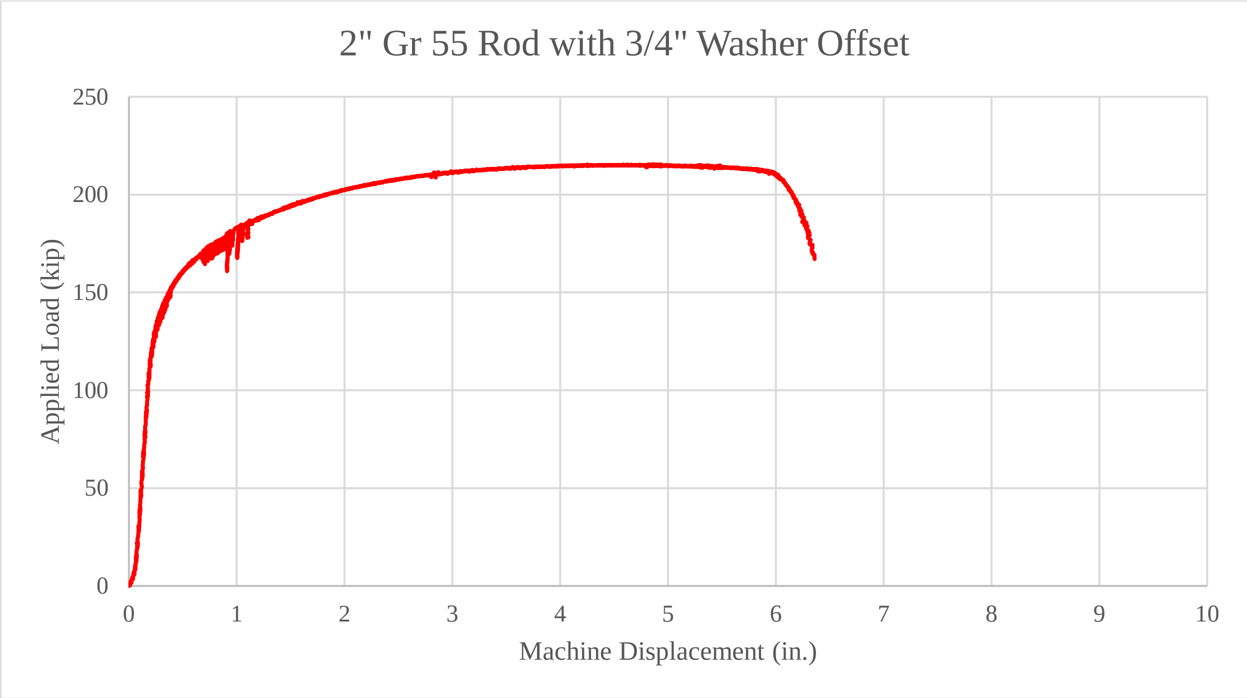

Figure A.69: 2" Gr 55 Rod with 3/4" Washer Offset

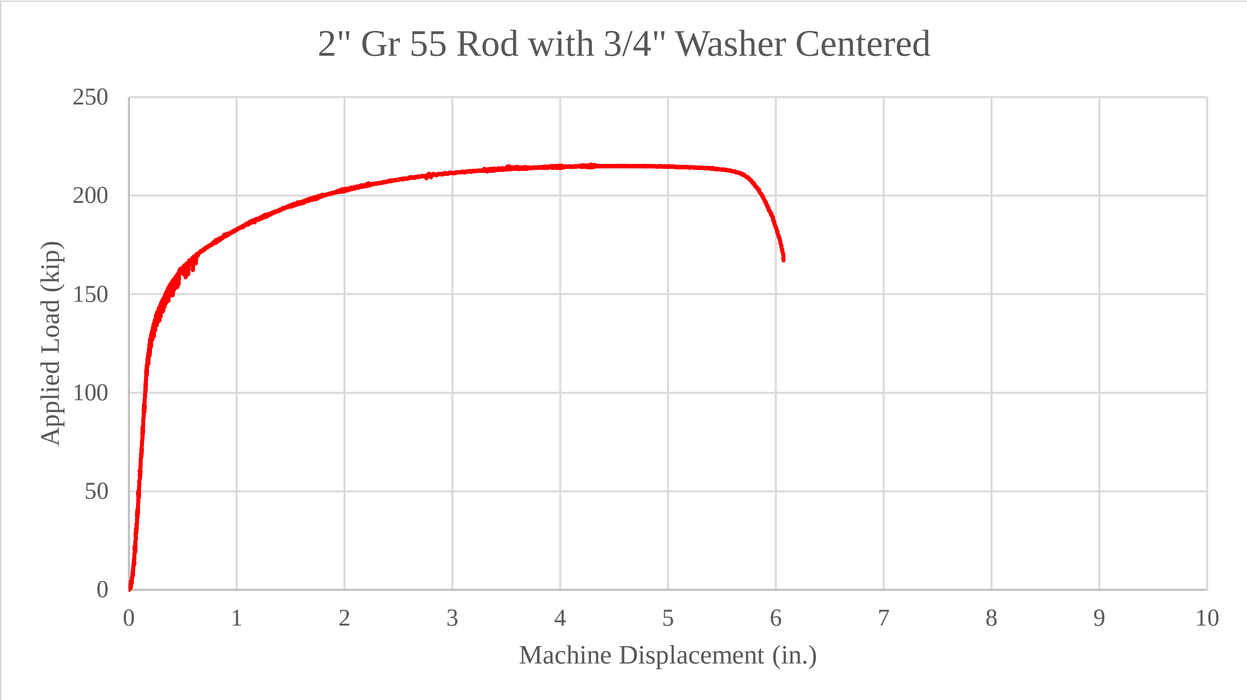

Figure A.70: 2" Gr 55 Rod with 3/4" Washer Centered

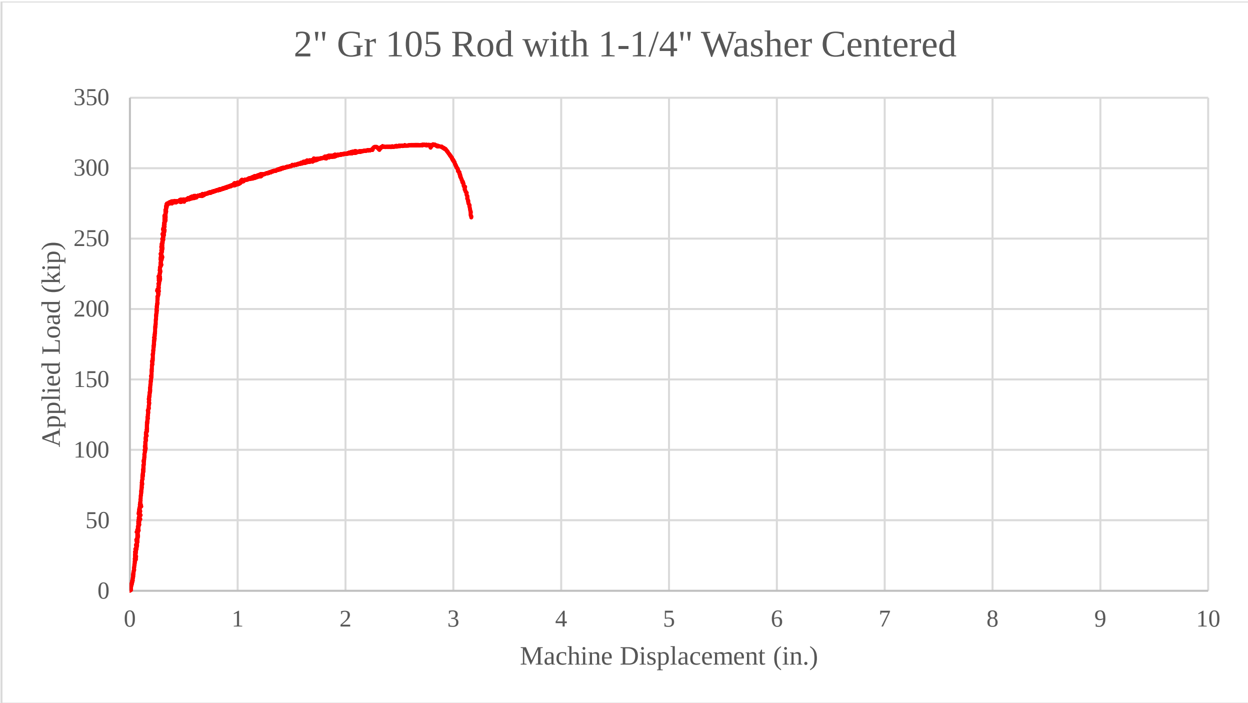

Figure A.71: 2" Gr 105 Rod with 1-1/4" Washer Centered

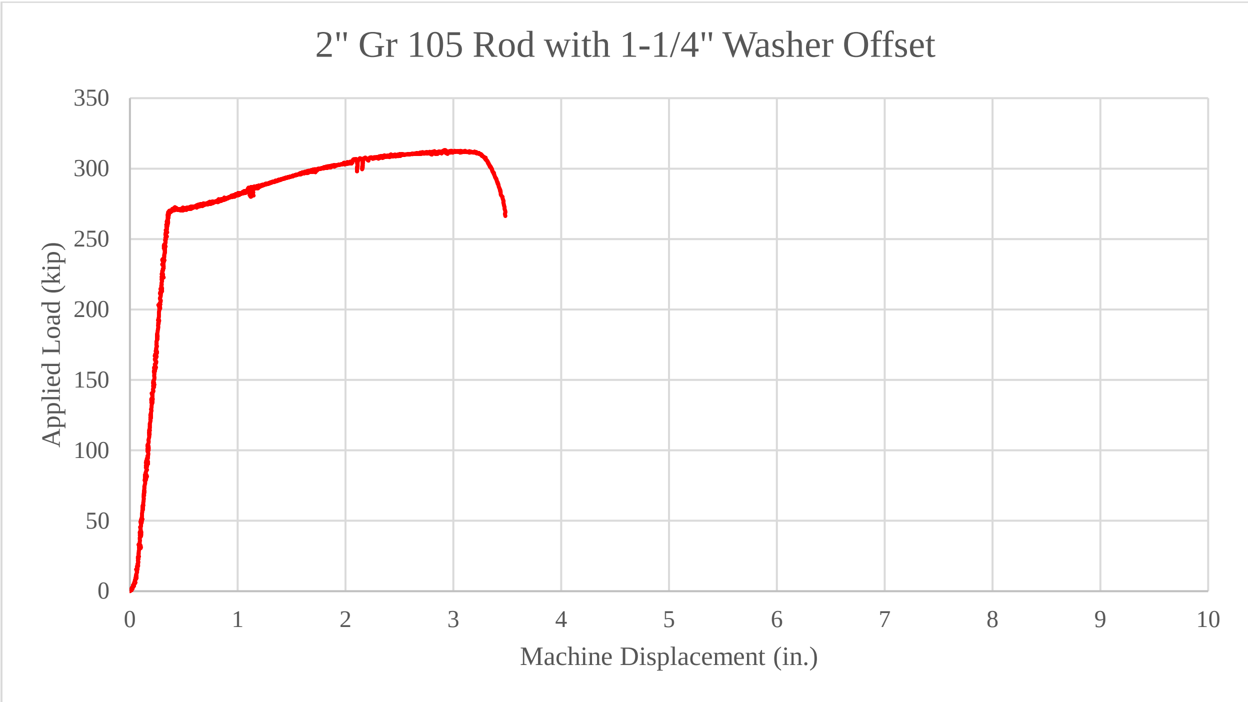

Figure A.72: 2" Gr 105 Rod with 1-1/4" Washer Offset

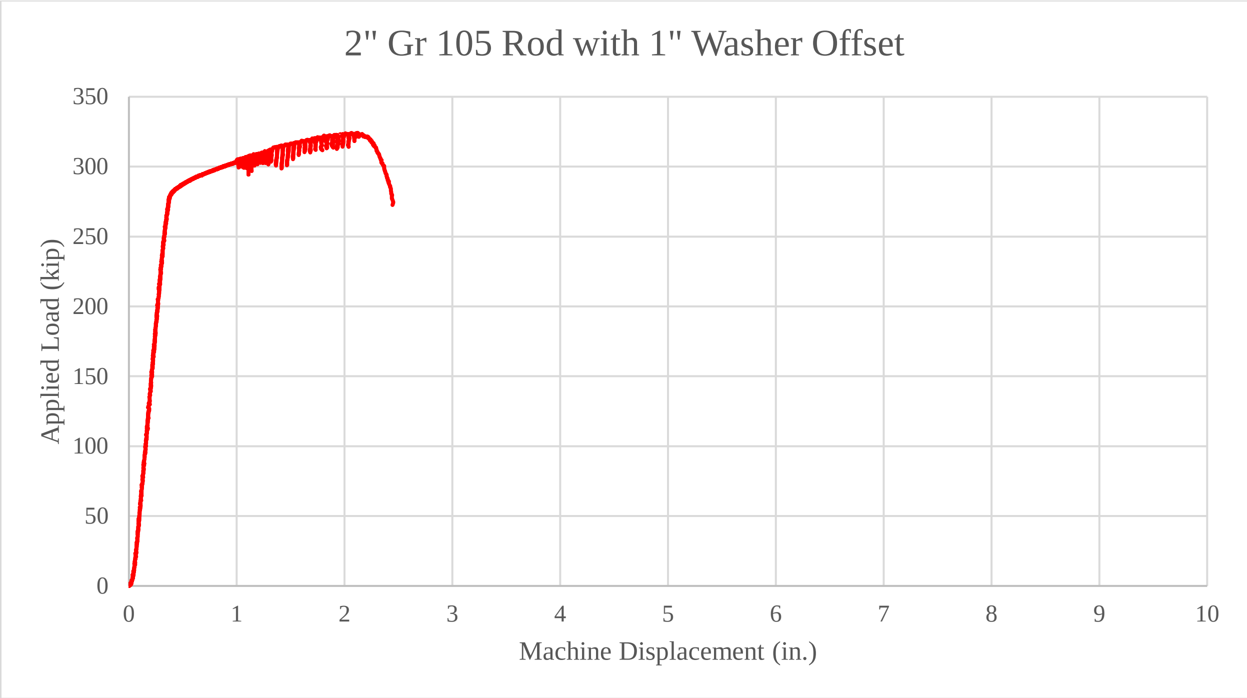

Figure A.73: 2" Gr 105 Rod with 1" Washer Offset

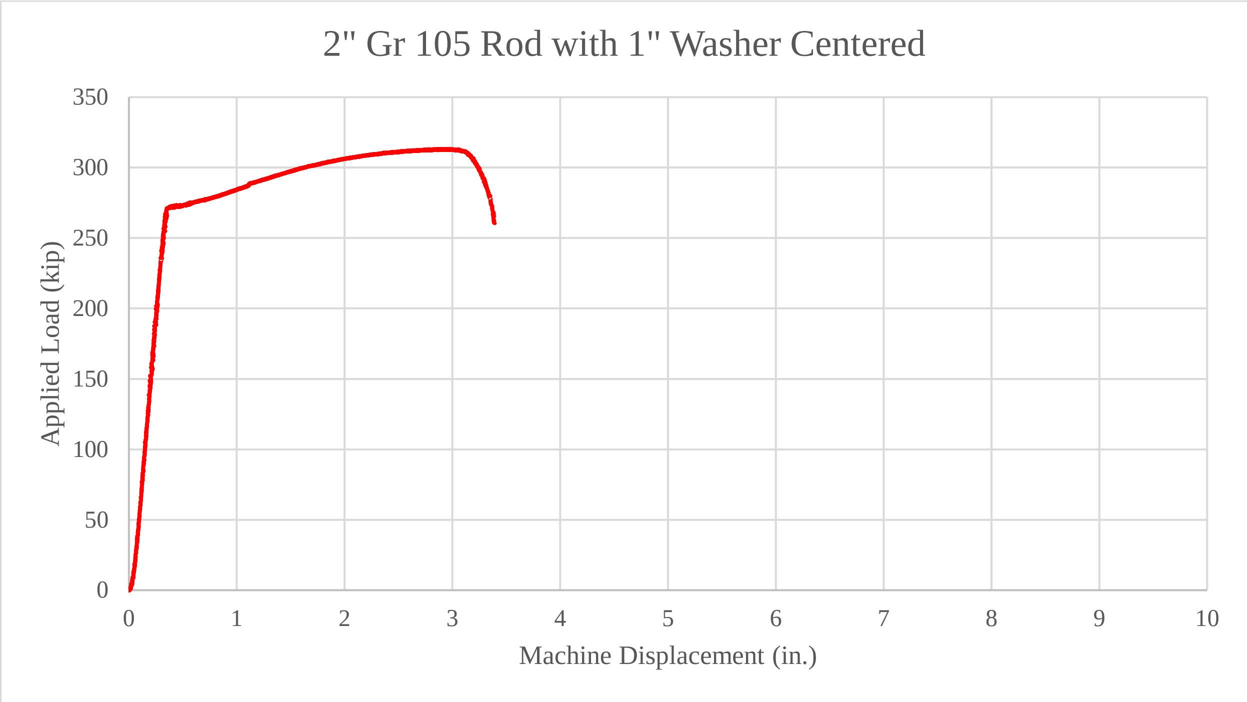

Figure A.74: 2" Gr 105 Rod with 1" Washer Centered

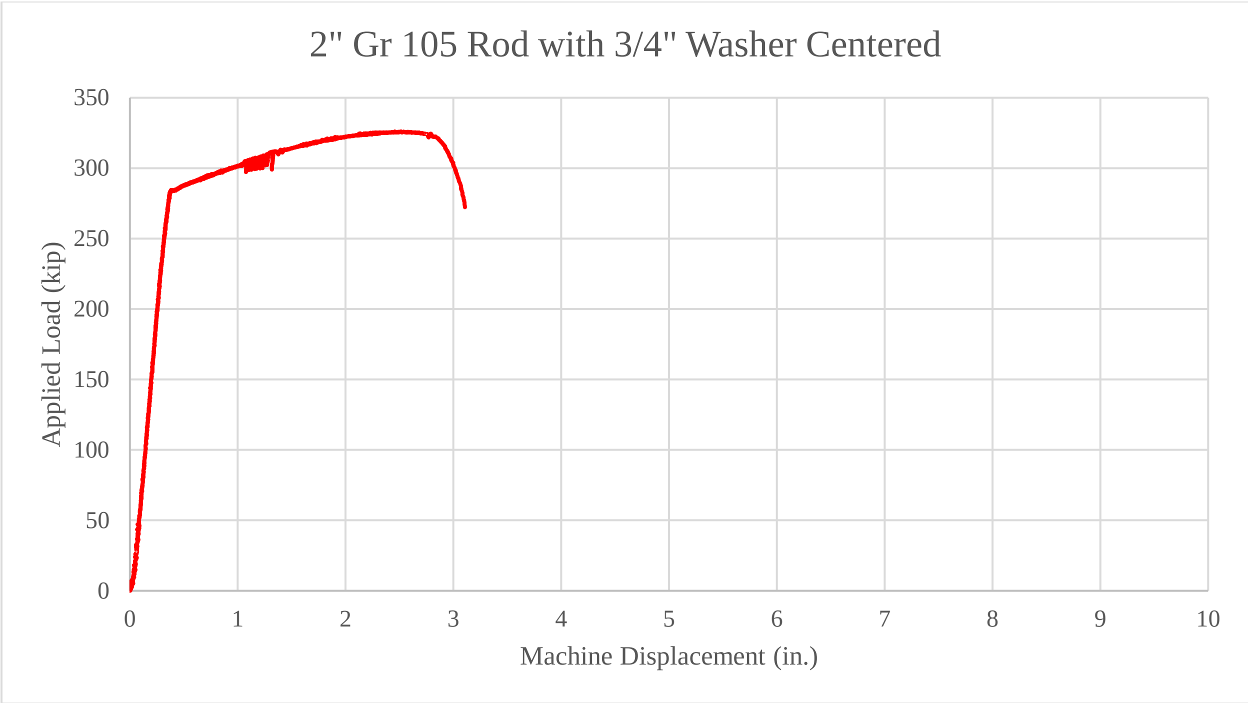

Figure A.75: 2" Gr 105 Rod with 3/4 " Washer Centered

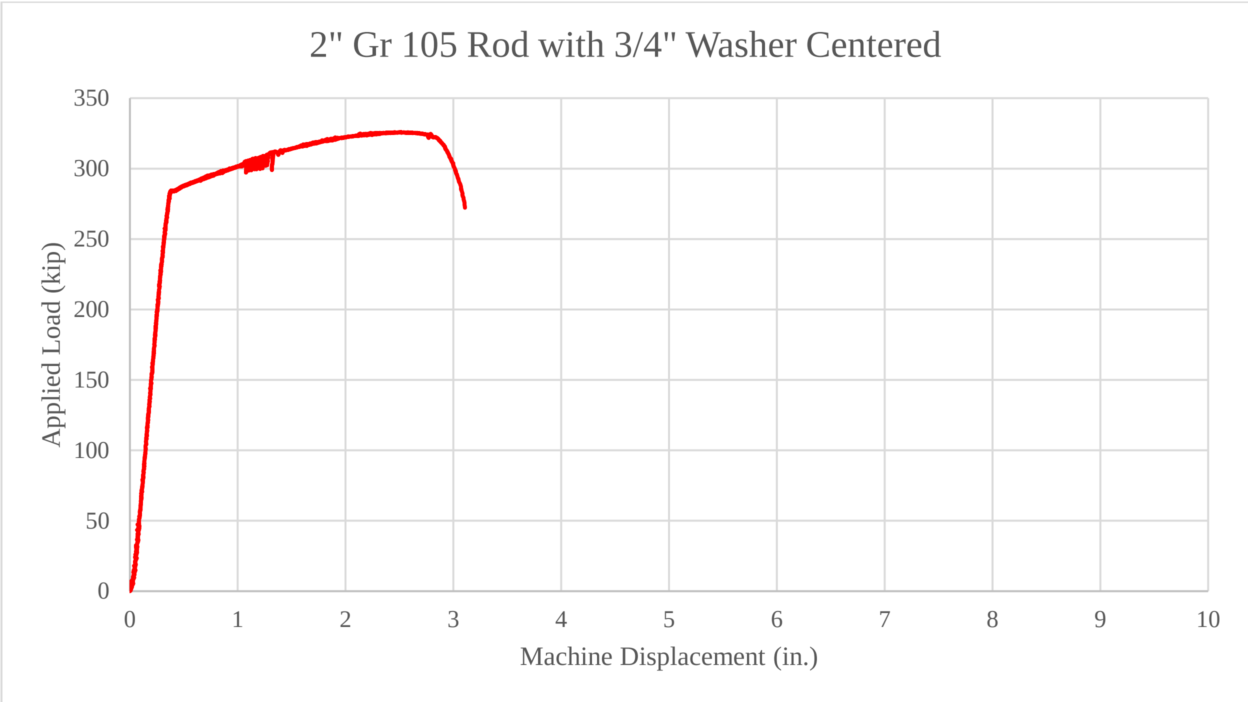

Figure A.76: 2" Gr 105 Rod with 3/4" Washer Centered

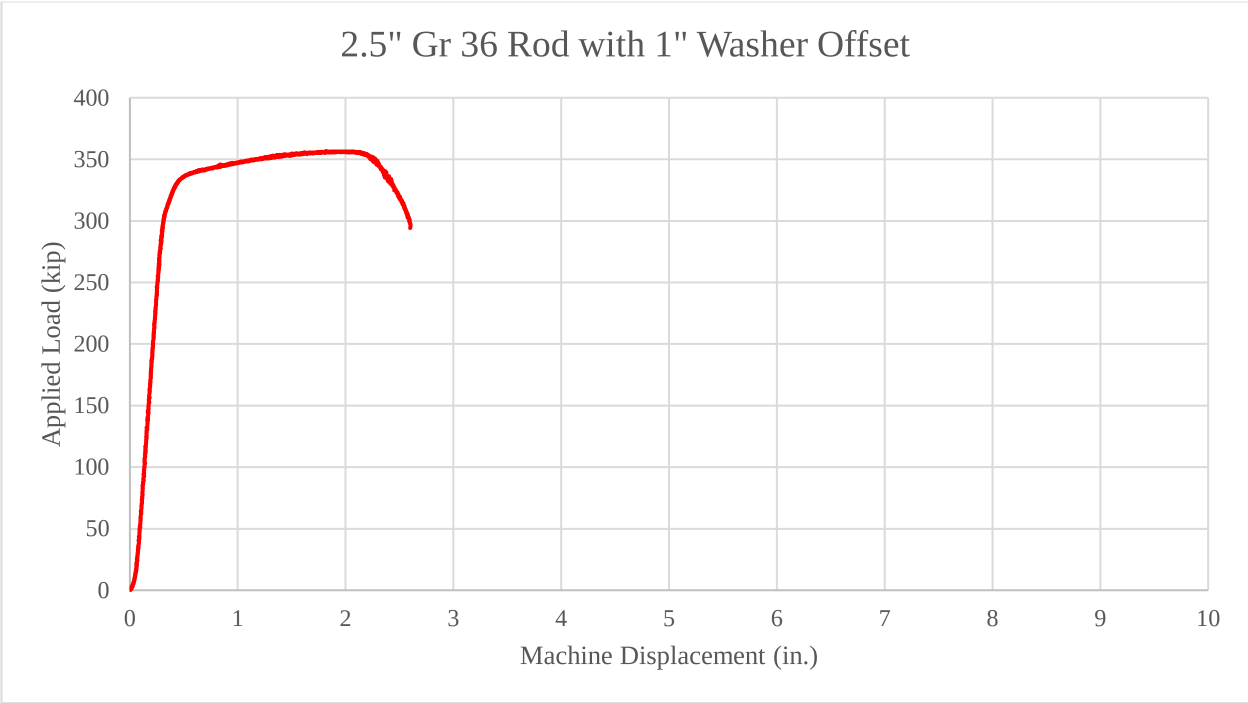

Figure A.77: 2.5" Gr 36 Rod with 1" Washer Offset

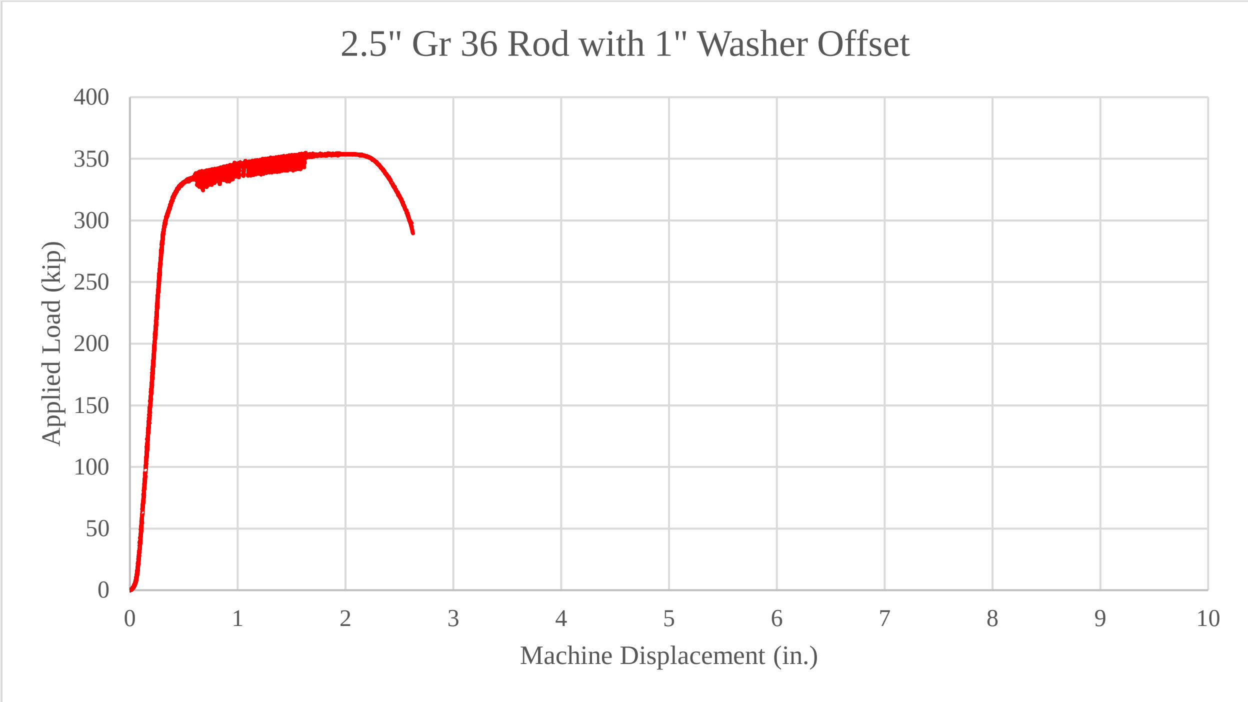

Figure A.78: 2.5" Gr 36 Rod with 1" Washer Offset

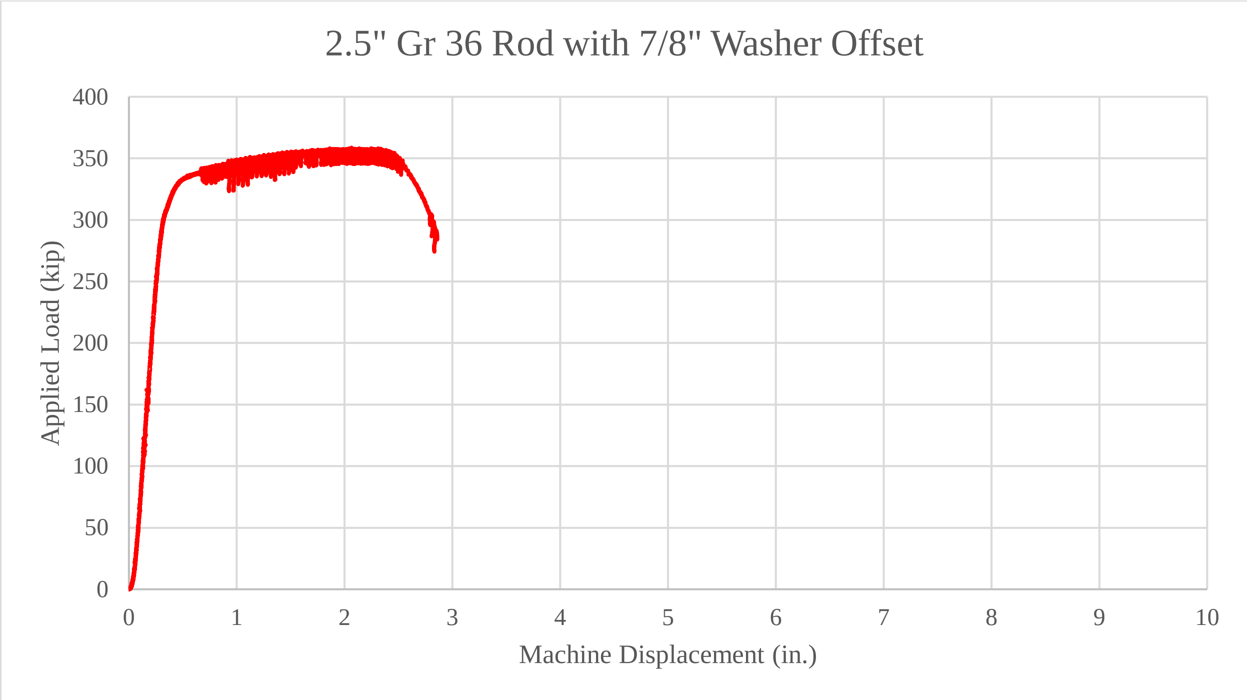

Figure A.79: 2.5" Gr 36 Rod with 7/8" Washer Offset

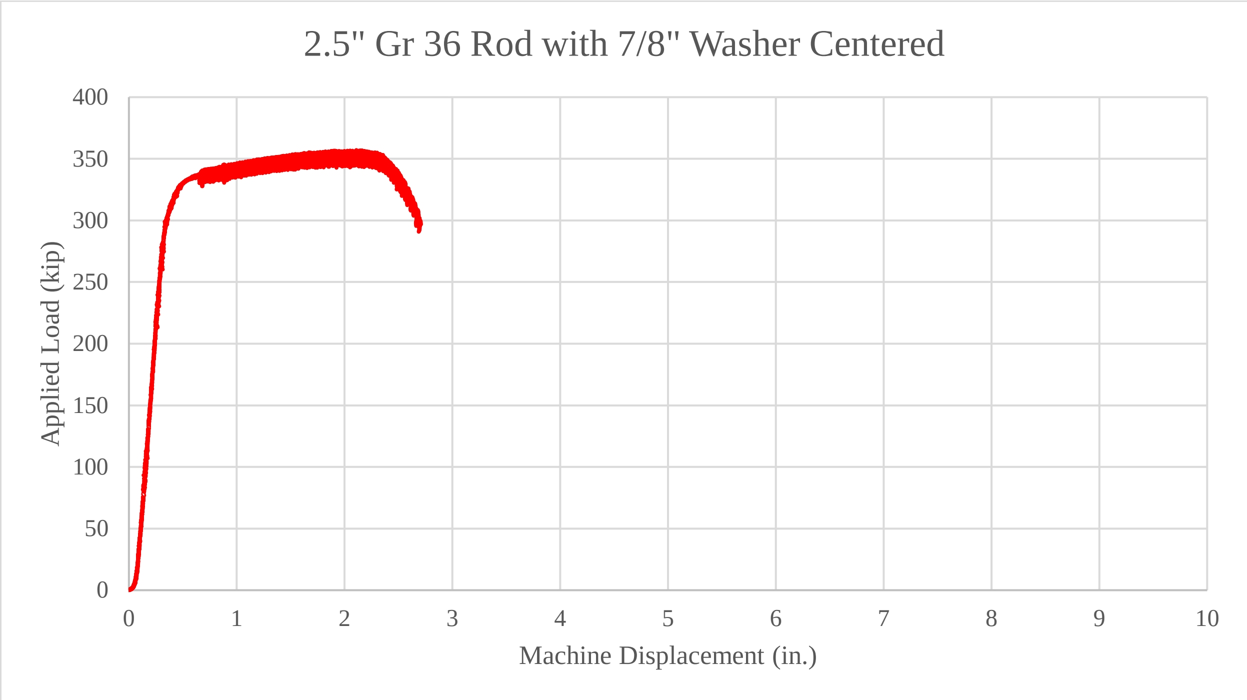

Figure A.80: 2.5" Gr 36 Rod with 7/8" Washer Centered

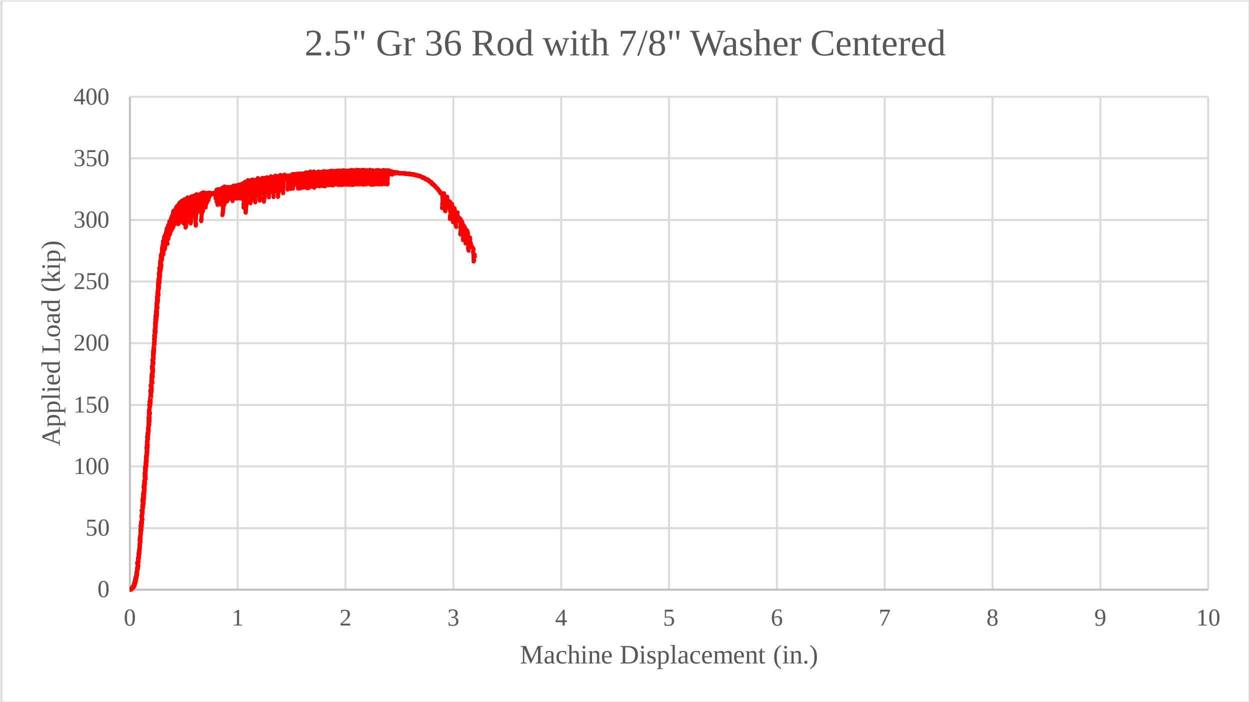

Figure A.81: 2.5" Gr 36 Rod with 7/8" Washer Centered

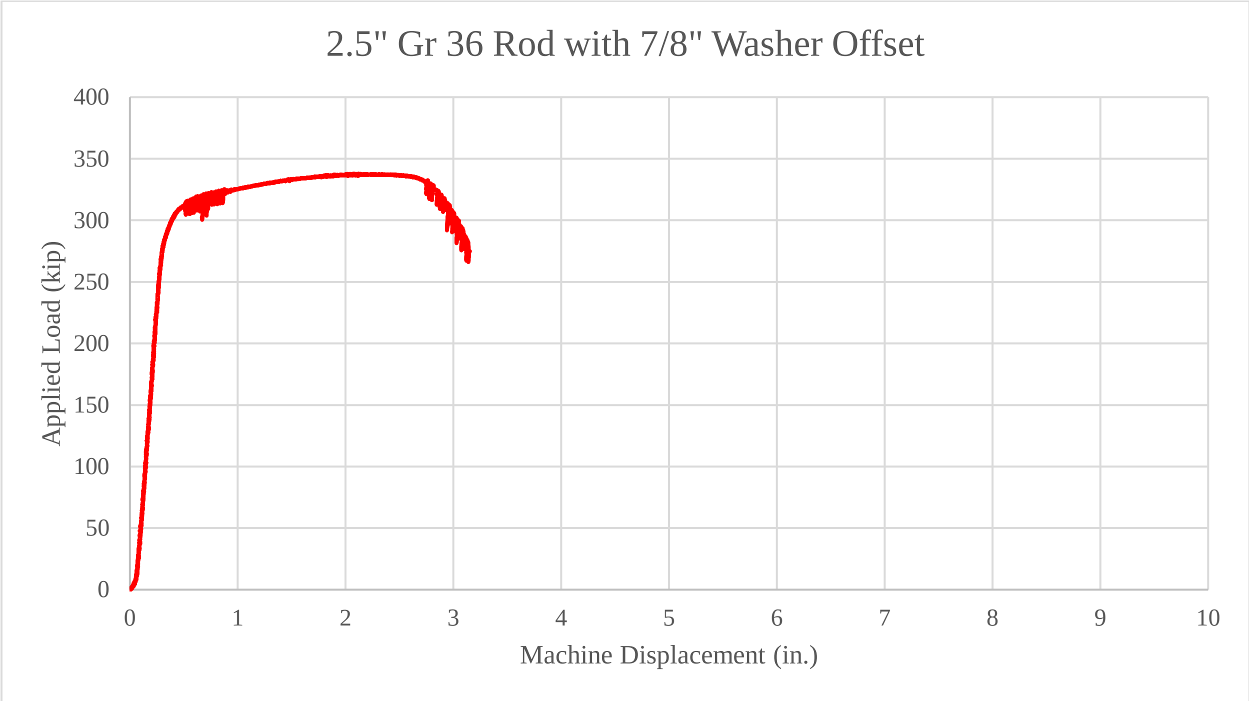

Figure A.82: 2.5" Gr 36 Rod with 7/8" Washer Offset

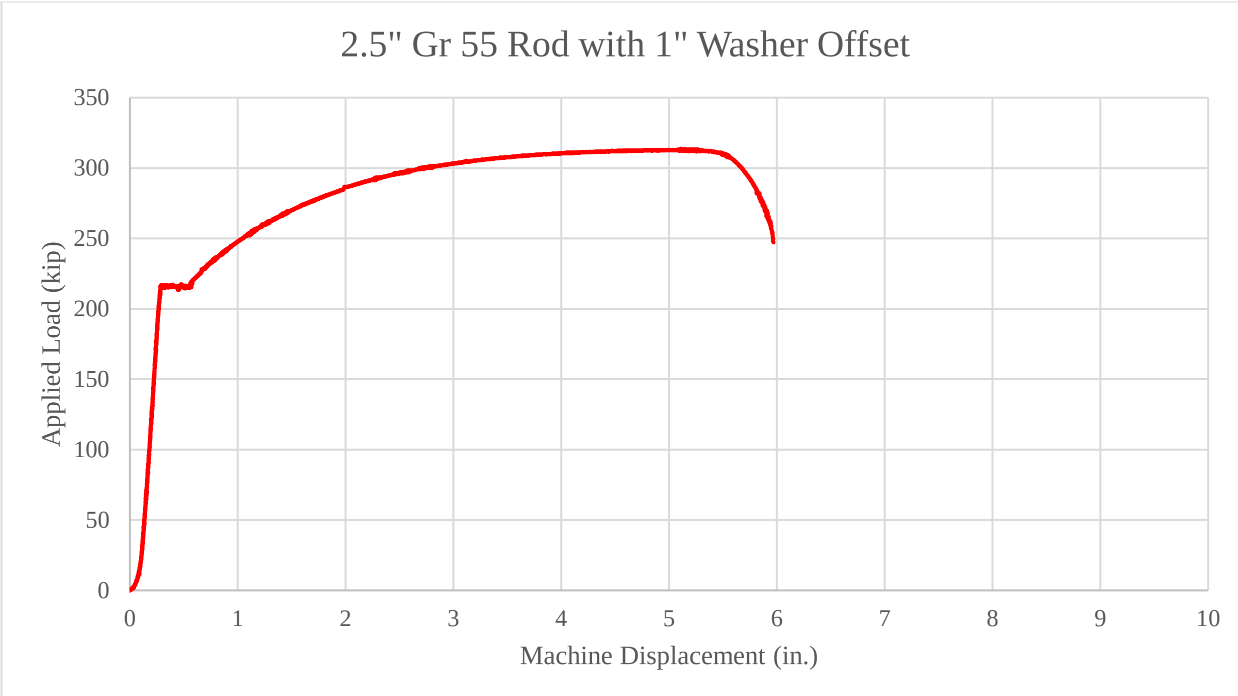

Figure A.83: 2.5" Gr 55 Rod with 1" Washer Offset

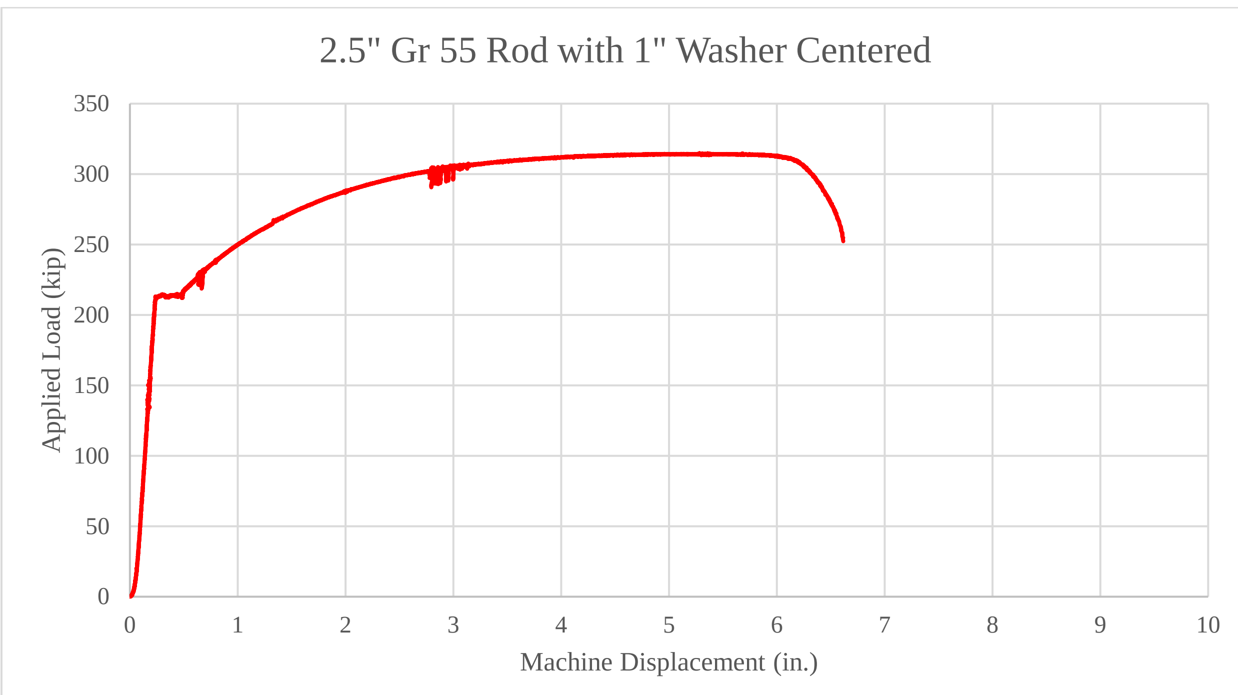

Figure A.84: 2.5" Gr 55 Rod with 1" Washer Centered

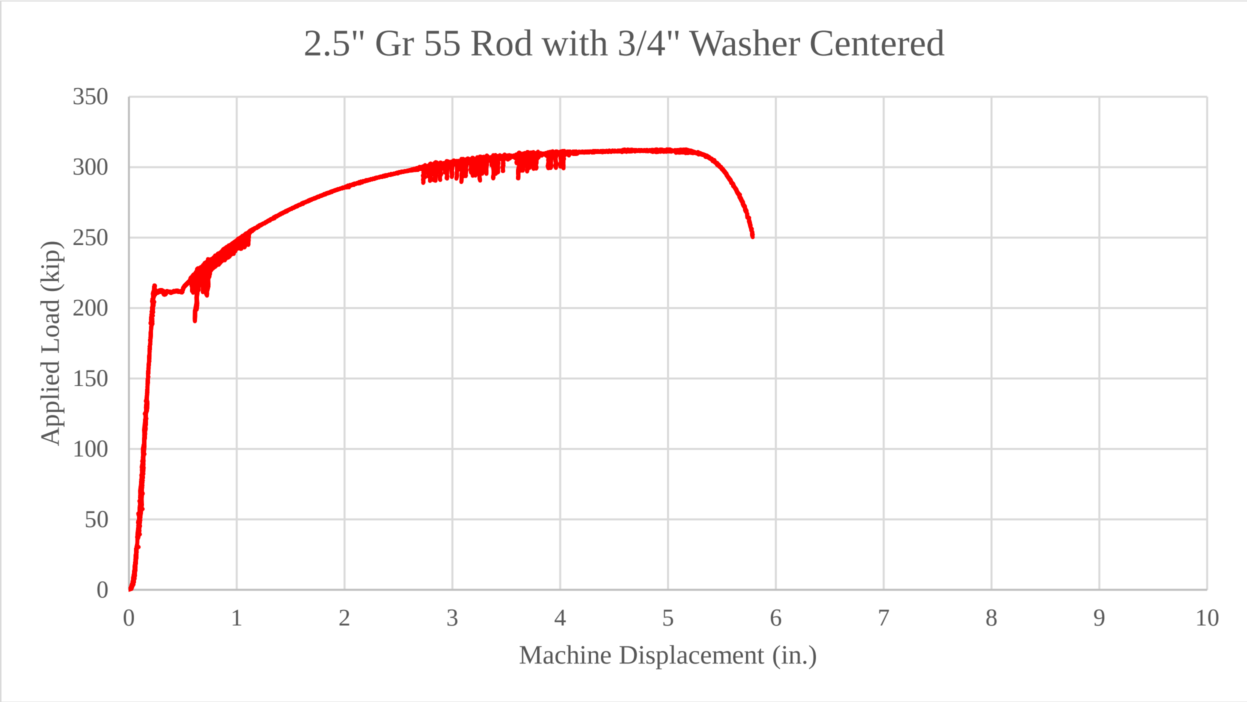

Figure A.85: 2.5" Gr 55 Rod with 3/4" Washer Centered

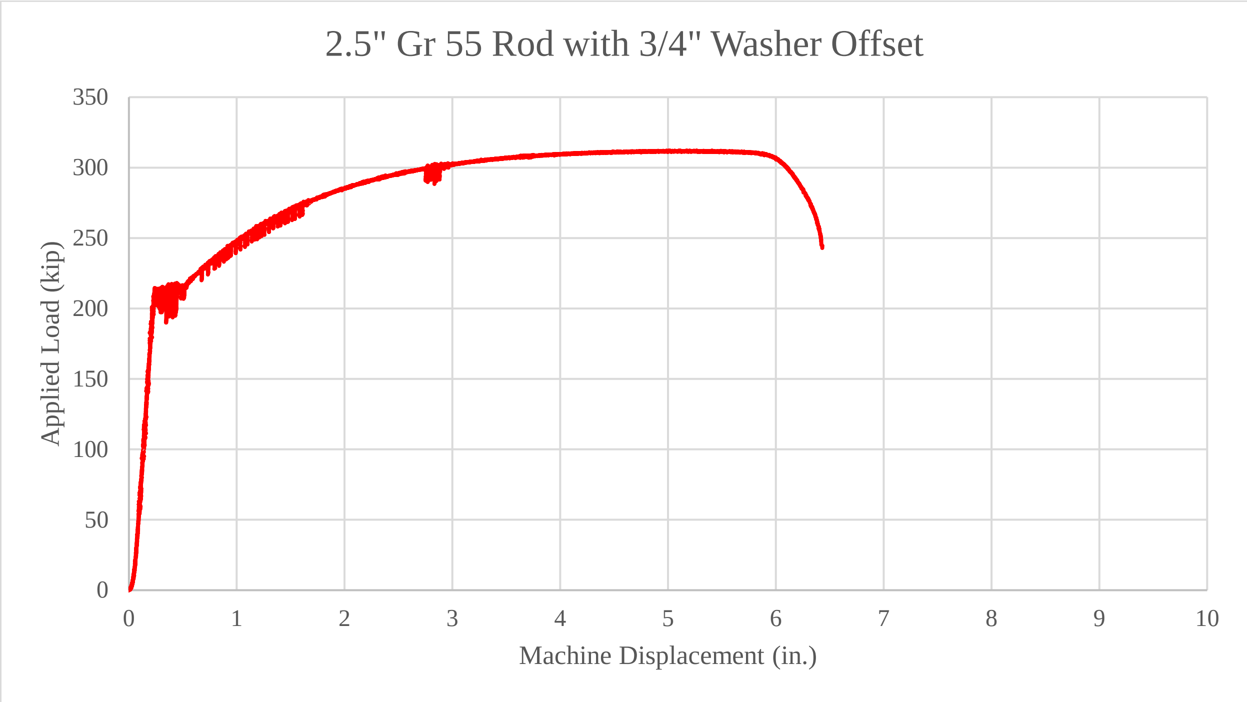

Figure A.86: 2.5" Gr 55 Rod with 3/4" Washer Offset

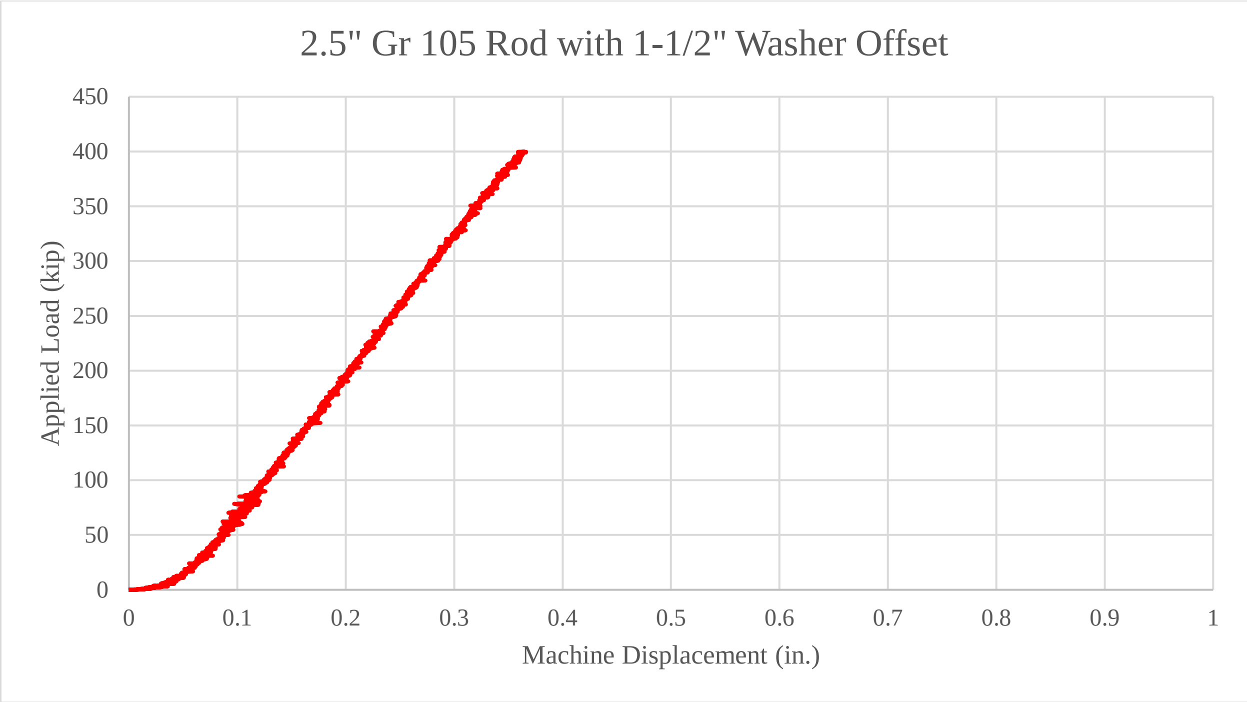

Figure A.87: 2.5" Gr 105 Rod with 1-1/2" Washer Offset

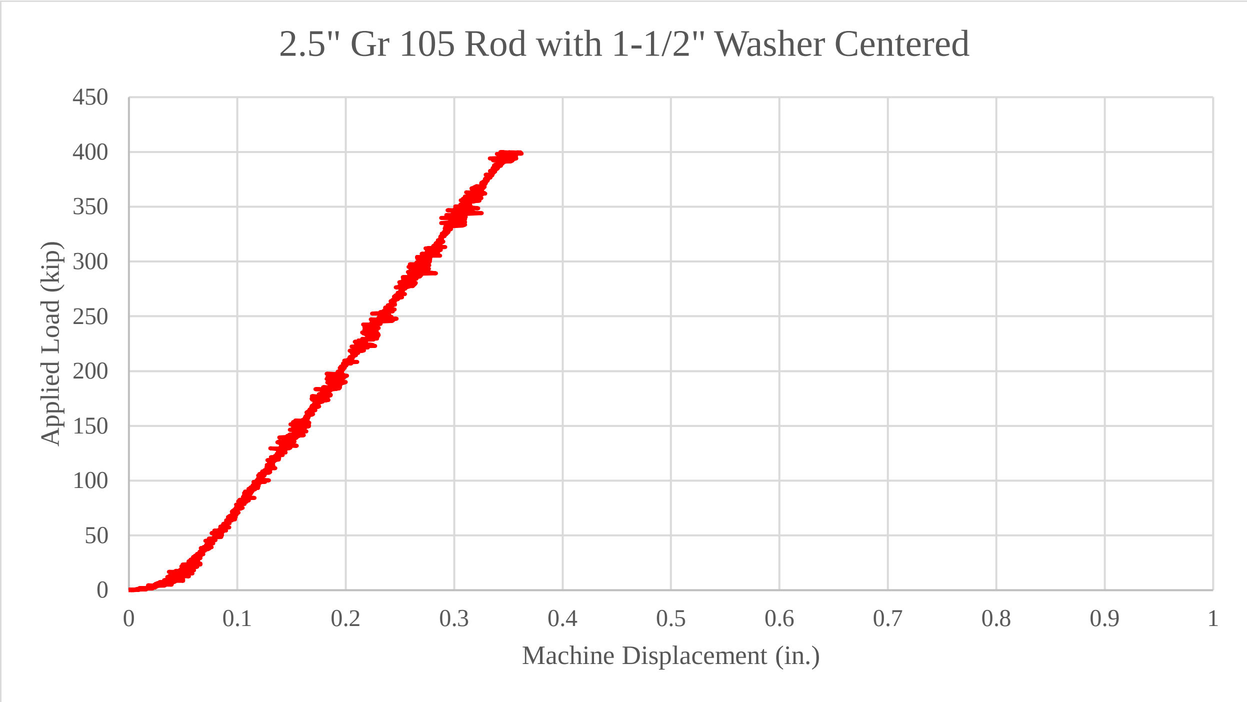

Figure A.88: 2.5" Gr 105 Rod with 1-1/2" Washer Centered

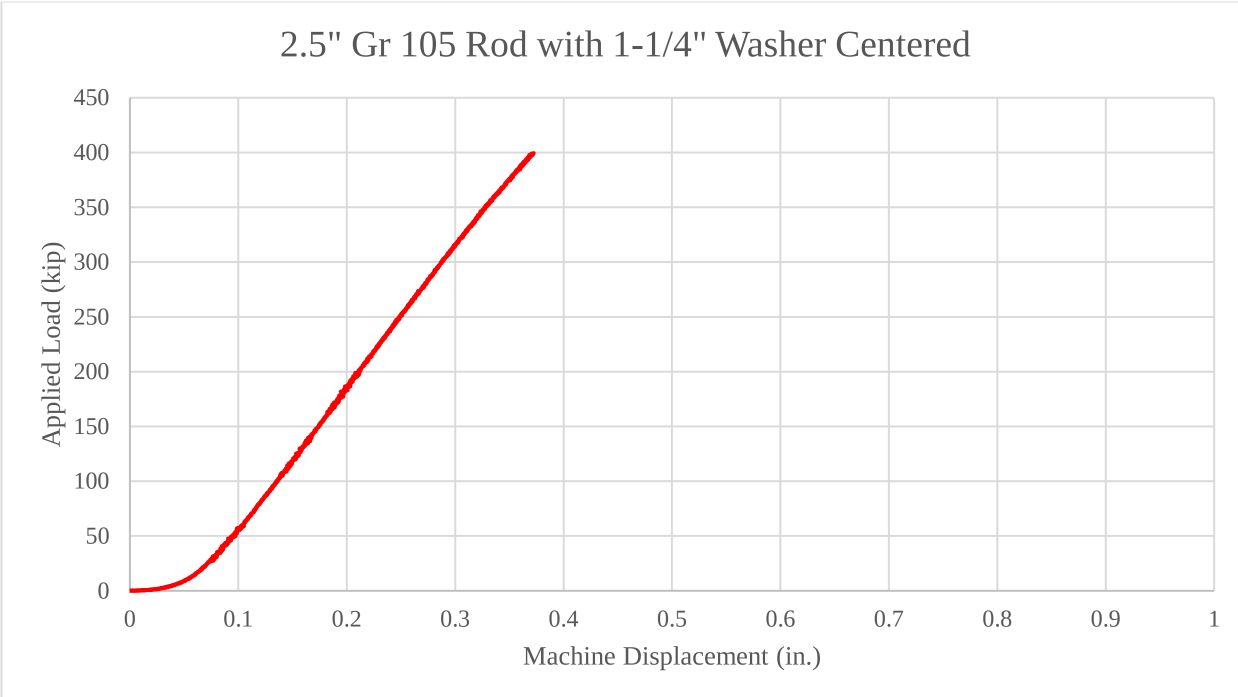

Figure A.89: 2.5" Gr 105 Rod with 1-1/4" Washer Centered

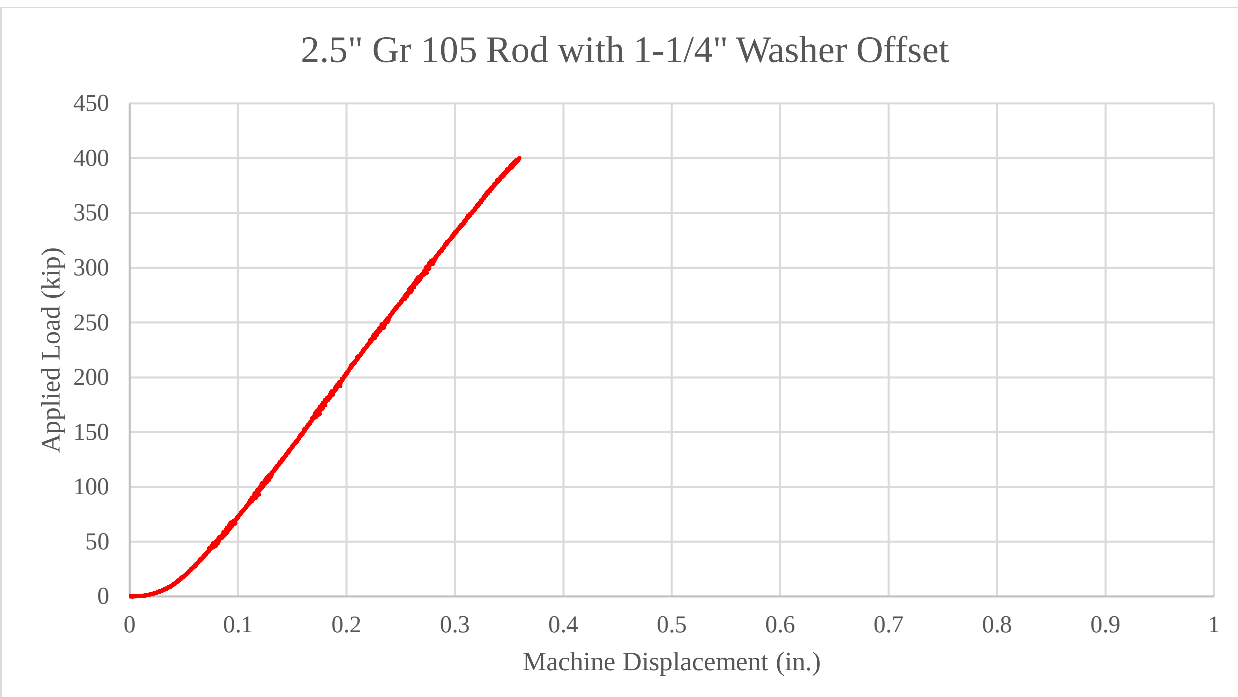

Figure A.90: 2.5" Gr 105 Rod with 1-1/4 " Washer Offset

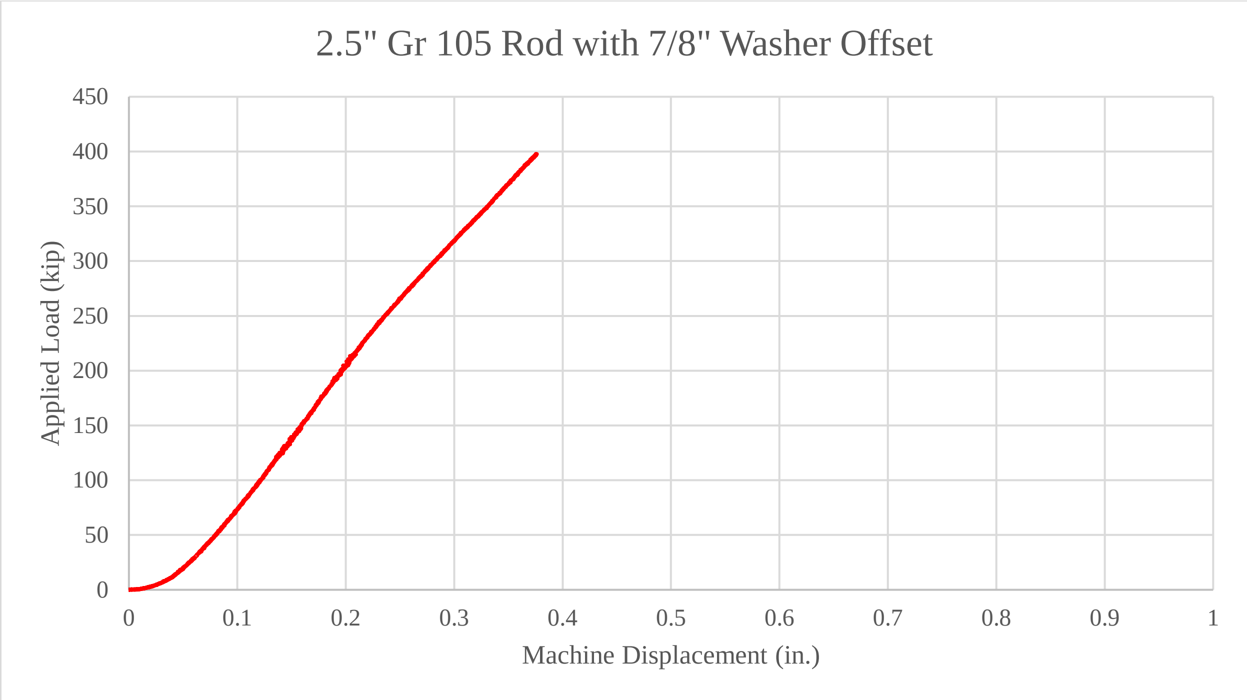

Figure A.91: 2.5" Gr 105 Rod with 7/8" Washer Offset

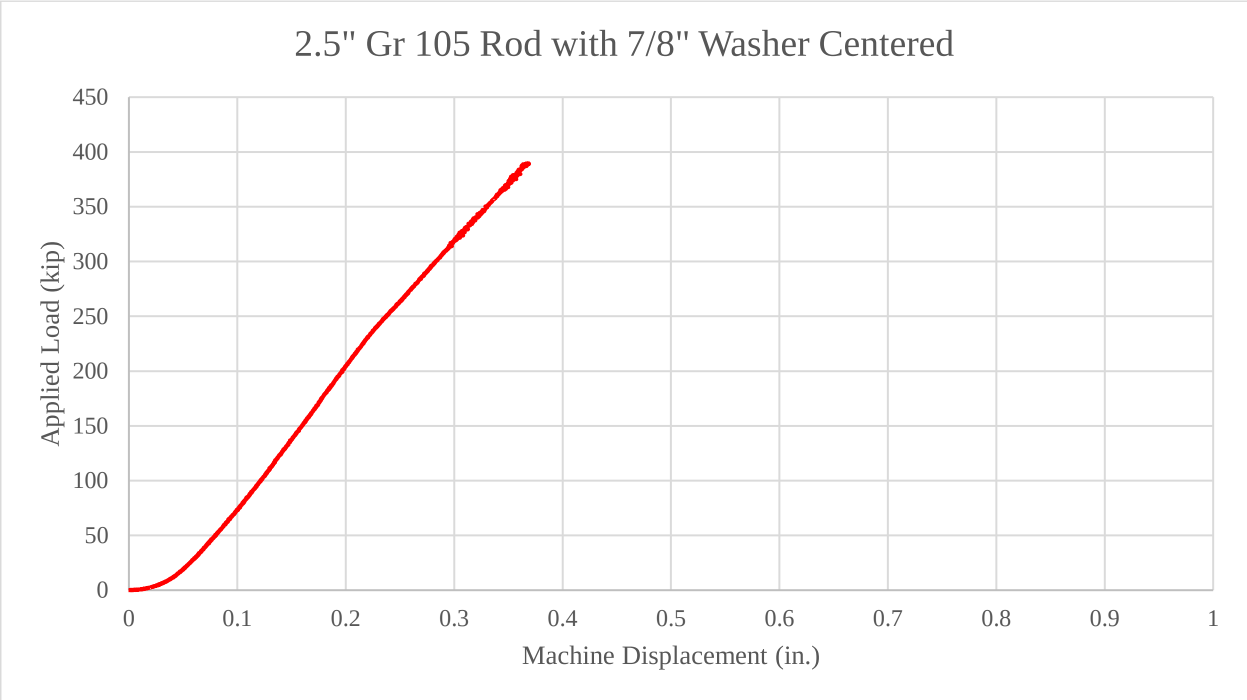

Figure A.92: 2.5" Gr 105 Rod with 7/8" Washer Centered

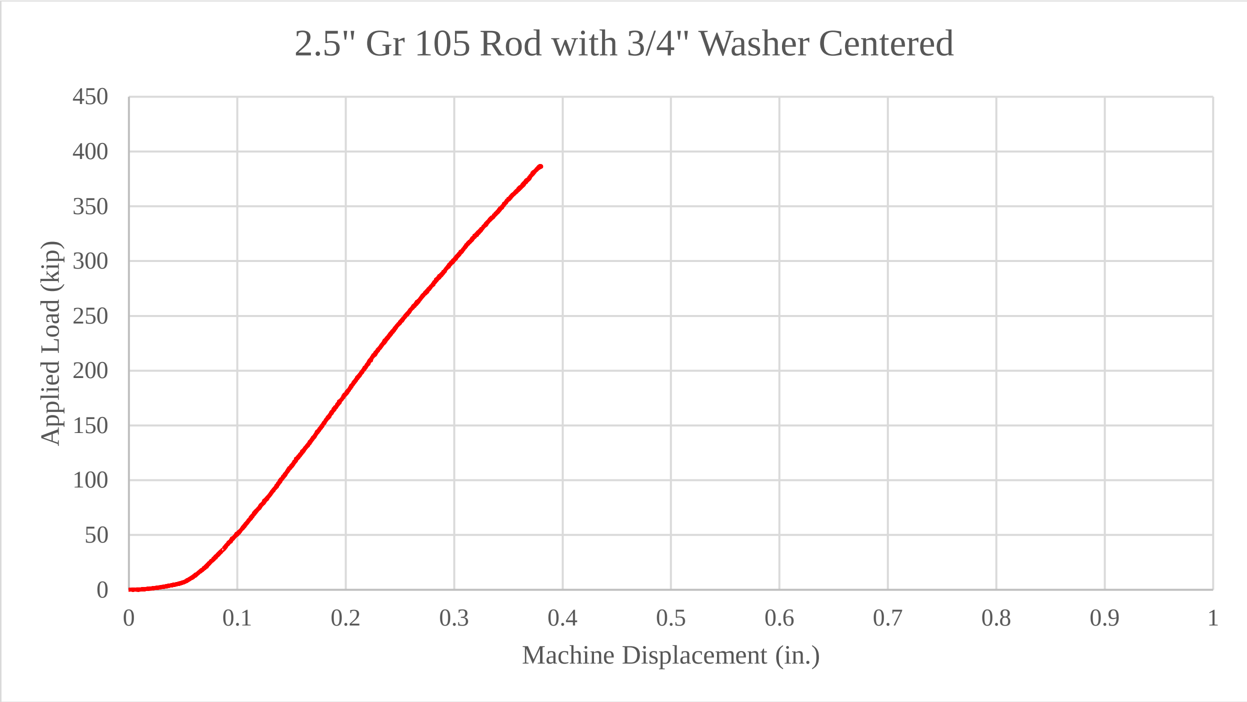

Figure A.93: 2.5" Gr 105 Rod with 3/4 " Washer Centered

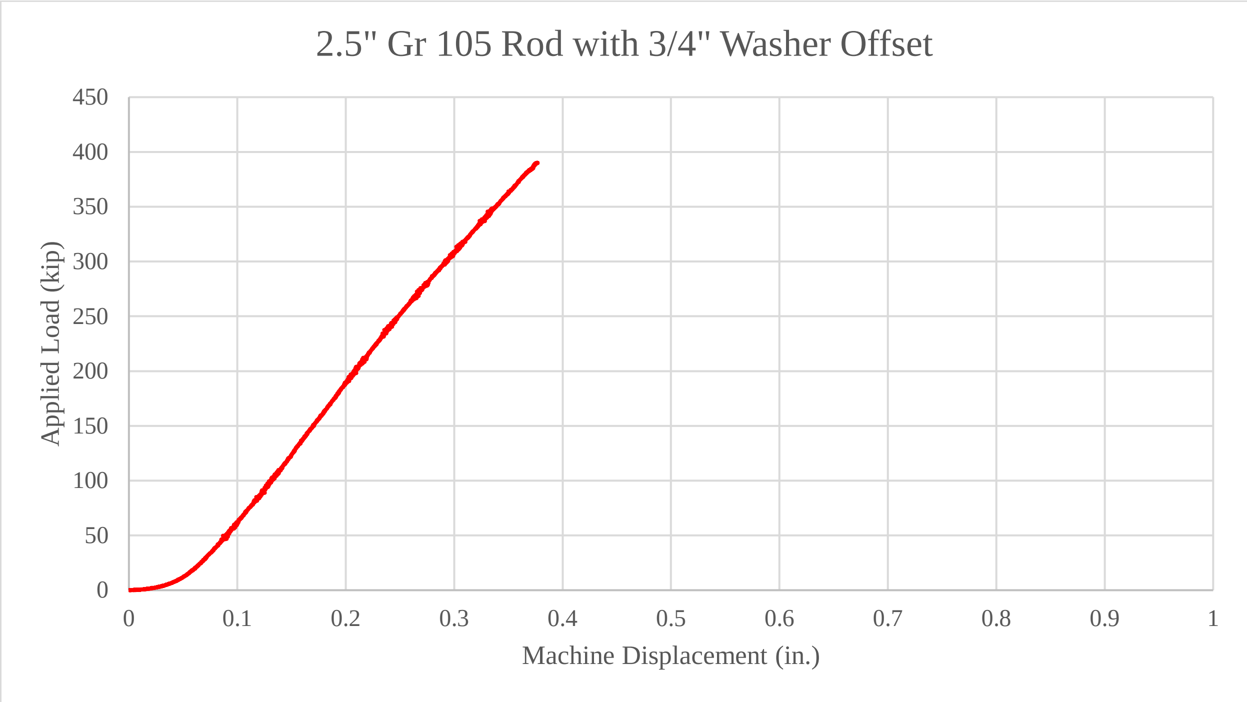

Figure A.94: 2.5" Gr 105 Rod with 3/4 " Washer Offset

Appendix B: Testing Photos and Results

Figure B.1: Test #1

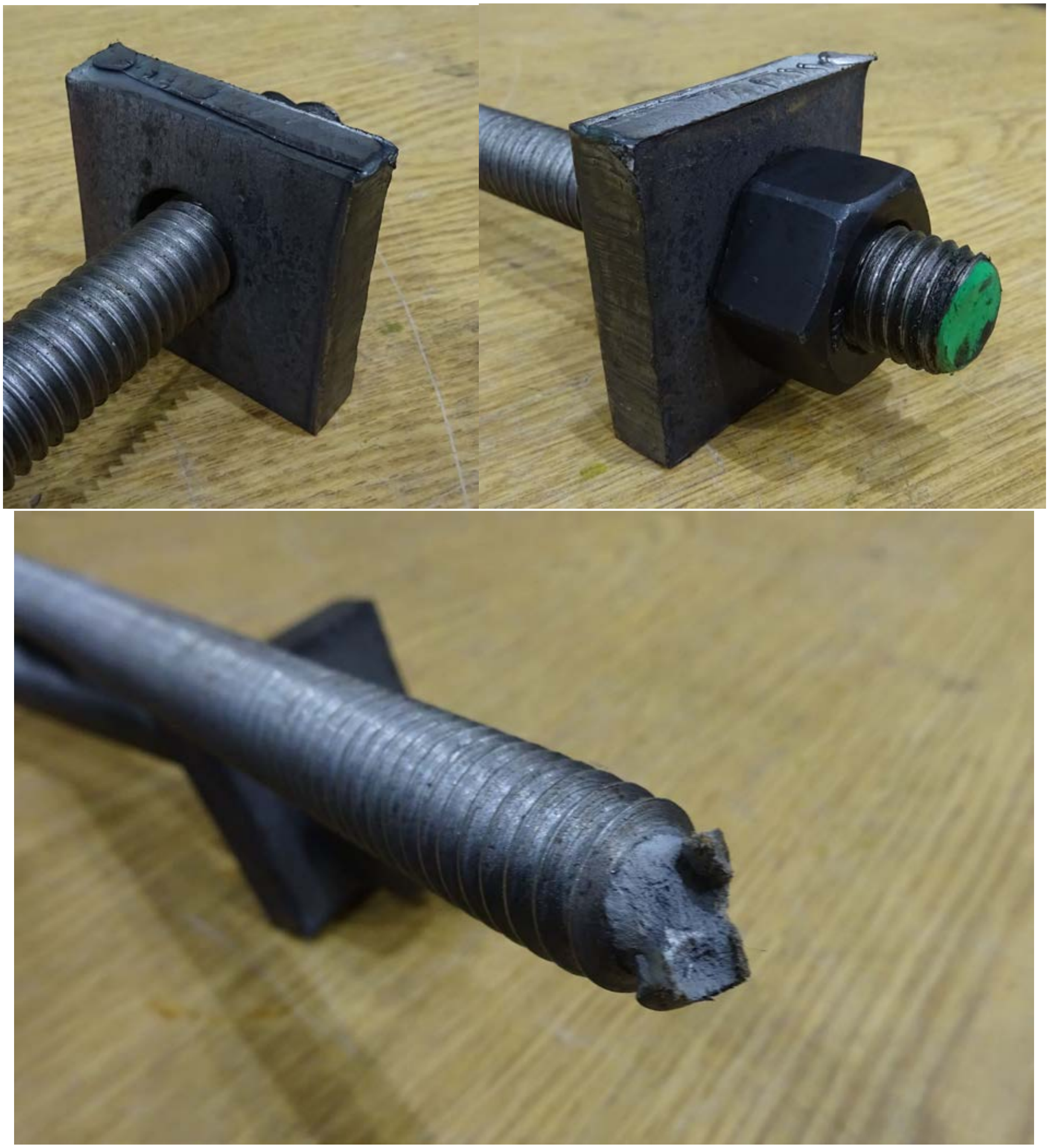

Figure B.2: Test #2

Figure B.3: Test #3 - 6% Relative Deformation

Figure B.4: Test #4 - 4% Relative Deformation

Figure B.5: Test #5 - 25% Relative Deformation

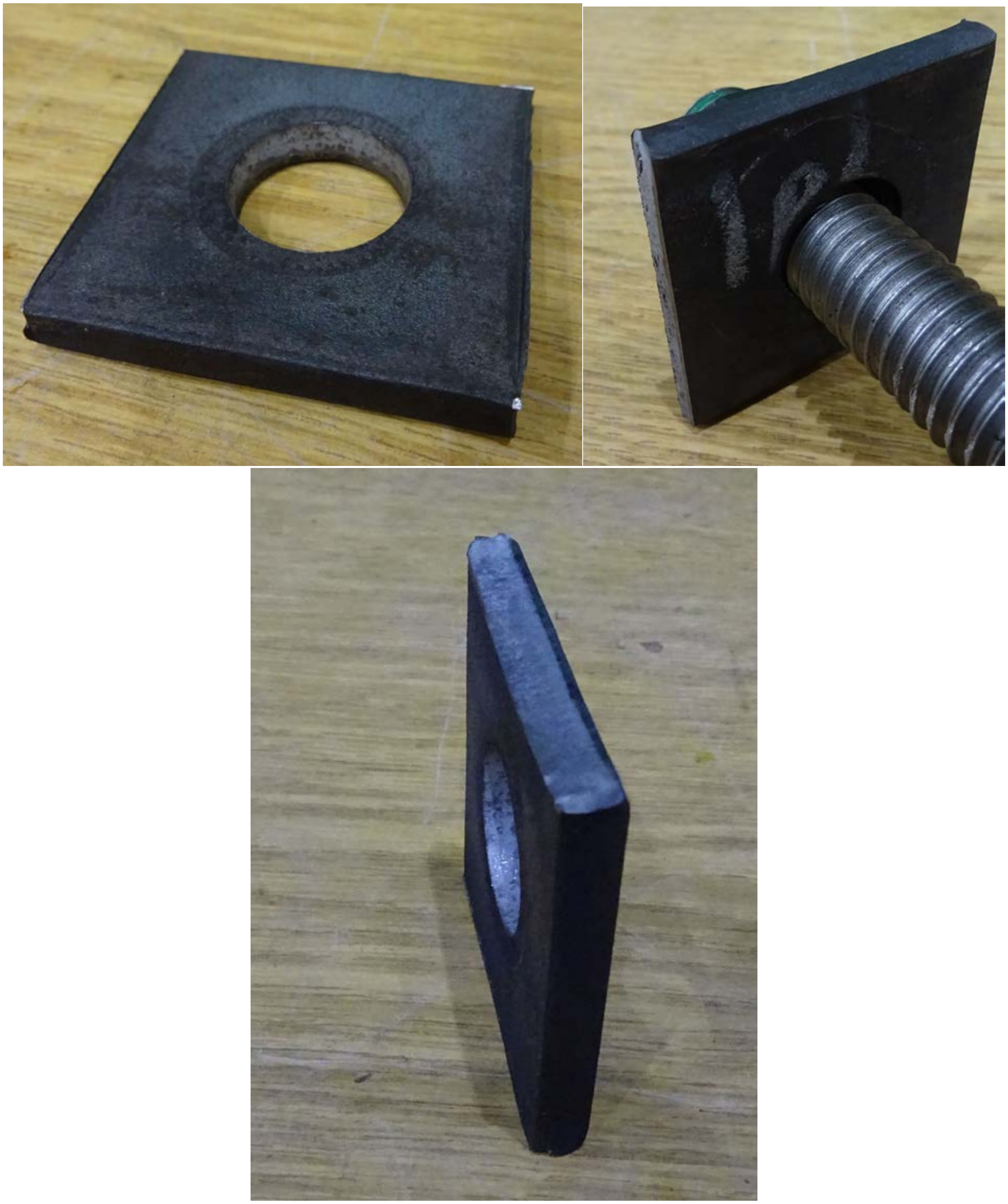

Figure B.6: Test #6 - 11% Relative Deformation

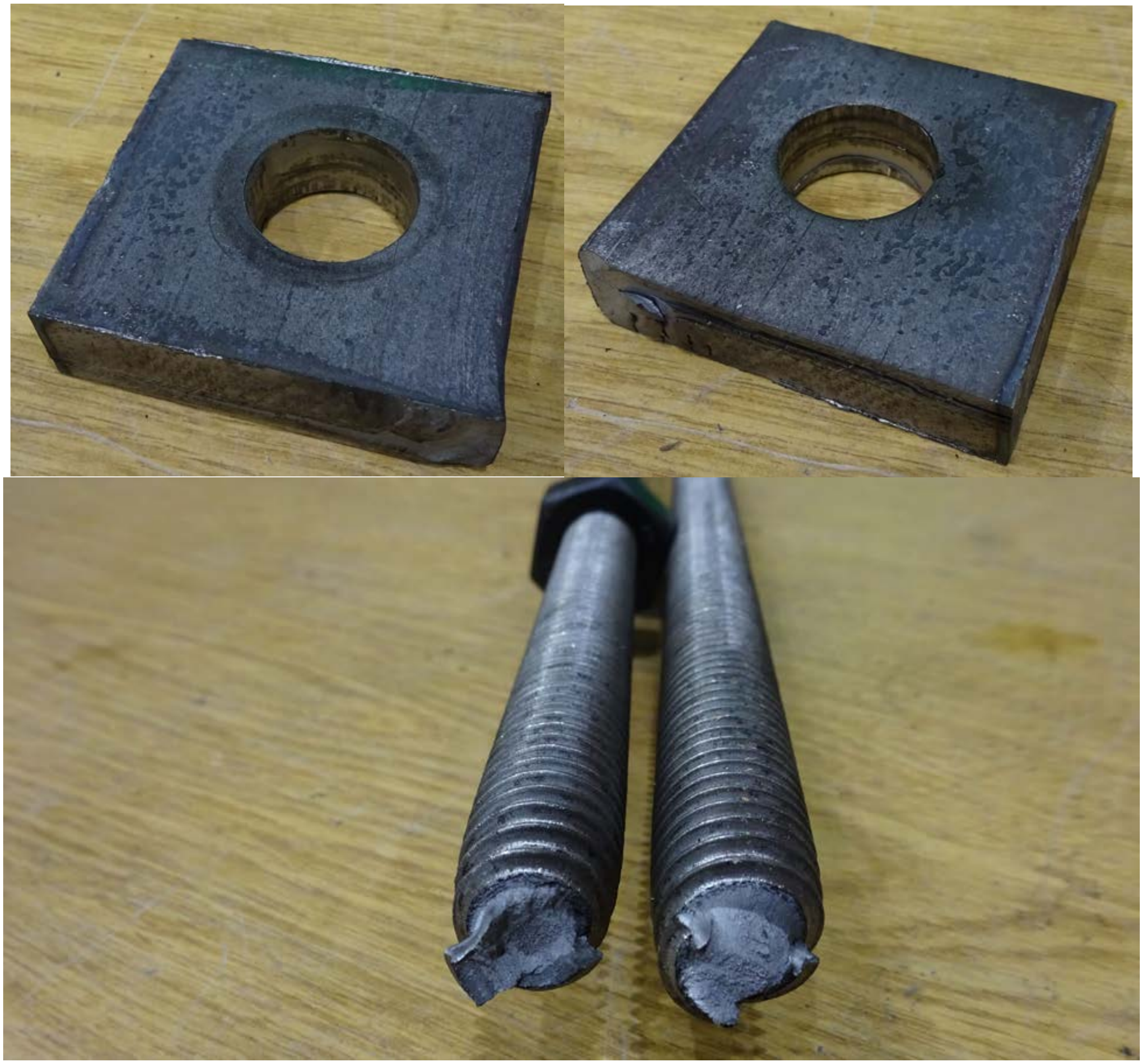

Figure B.7: Test #7 - 3% Relative Deformation

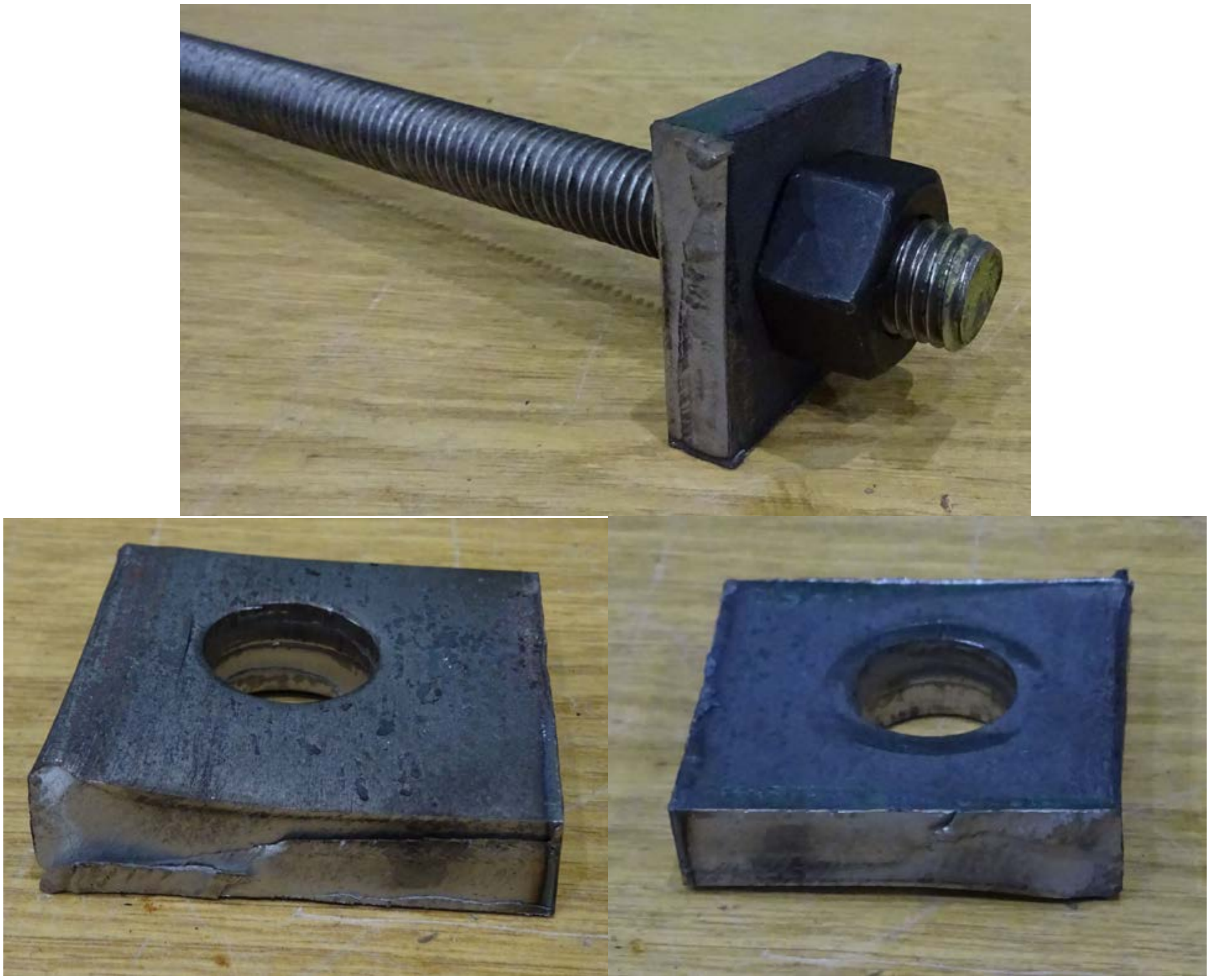

Figure B.8: Test #8 - 17% Relative Deformation

Figure B.9: Test #9 - 7% Relative Deformation

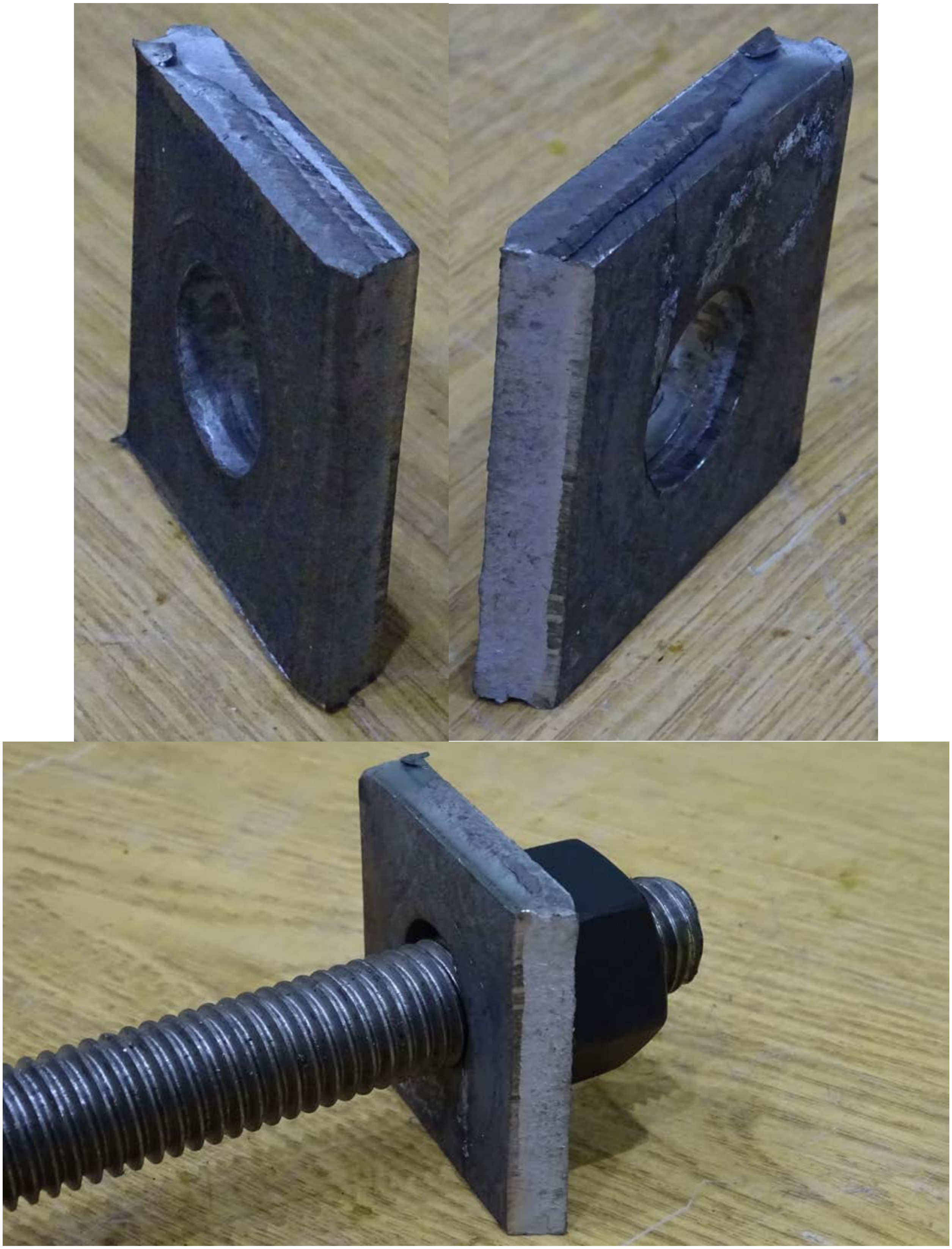

Figure B.10: Test #10 - 5% Relative Deformation

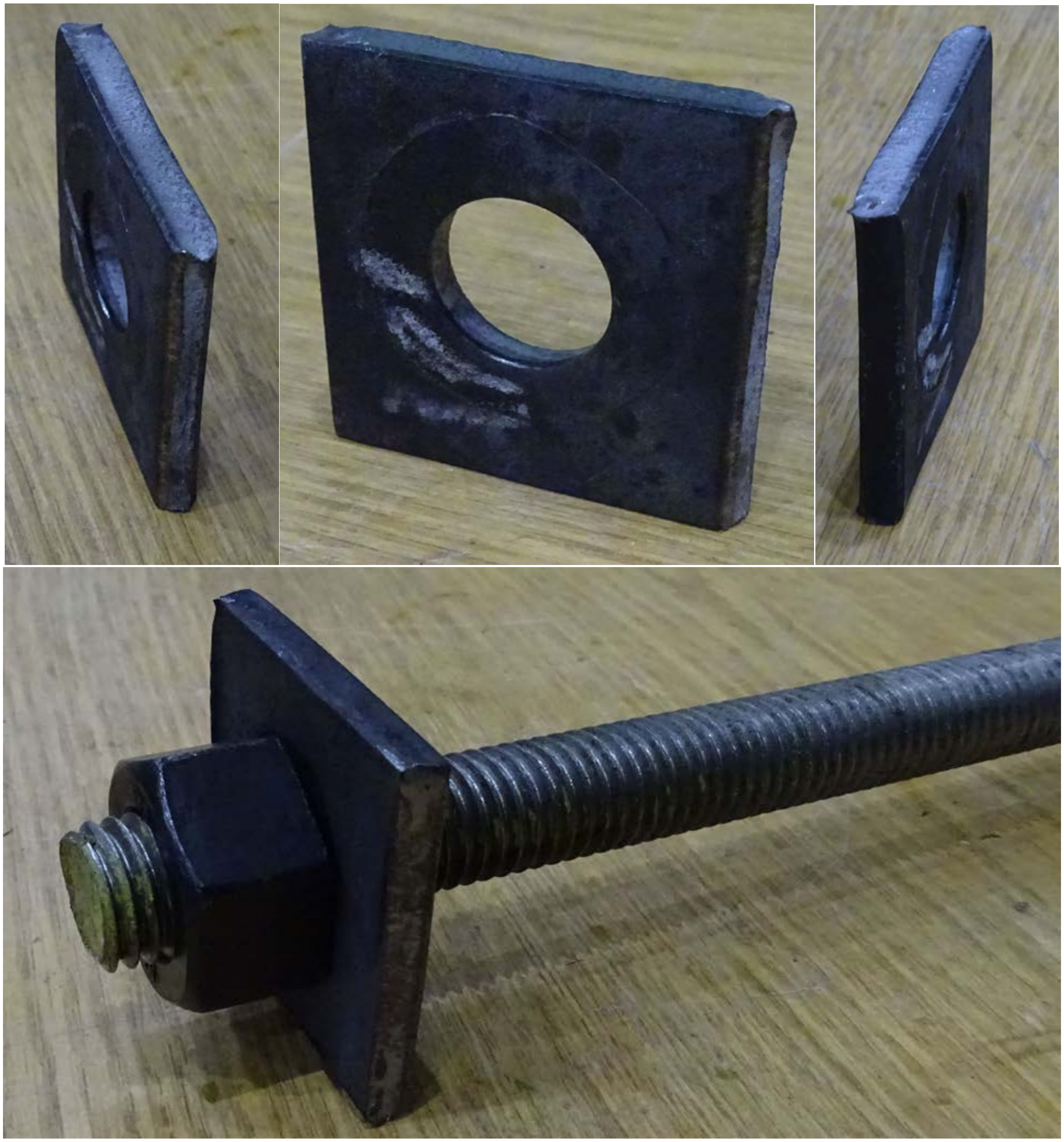

Figure B.11: Test #11 - 20% Relative Deformation

Figure B. 12: Test #12 - 28% Relative Deformation

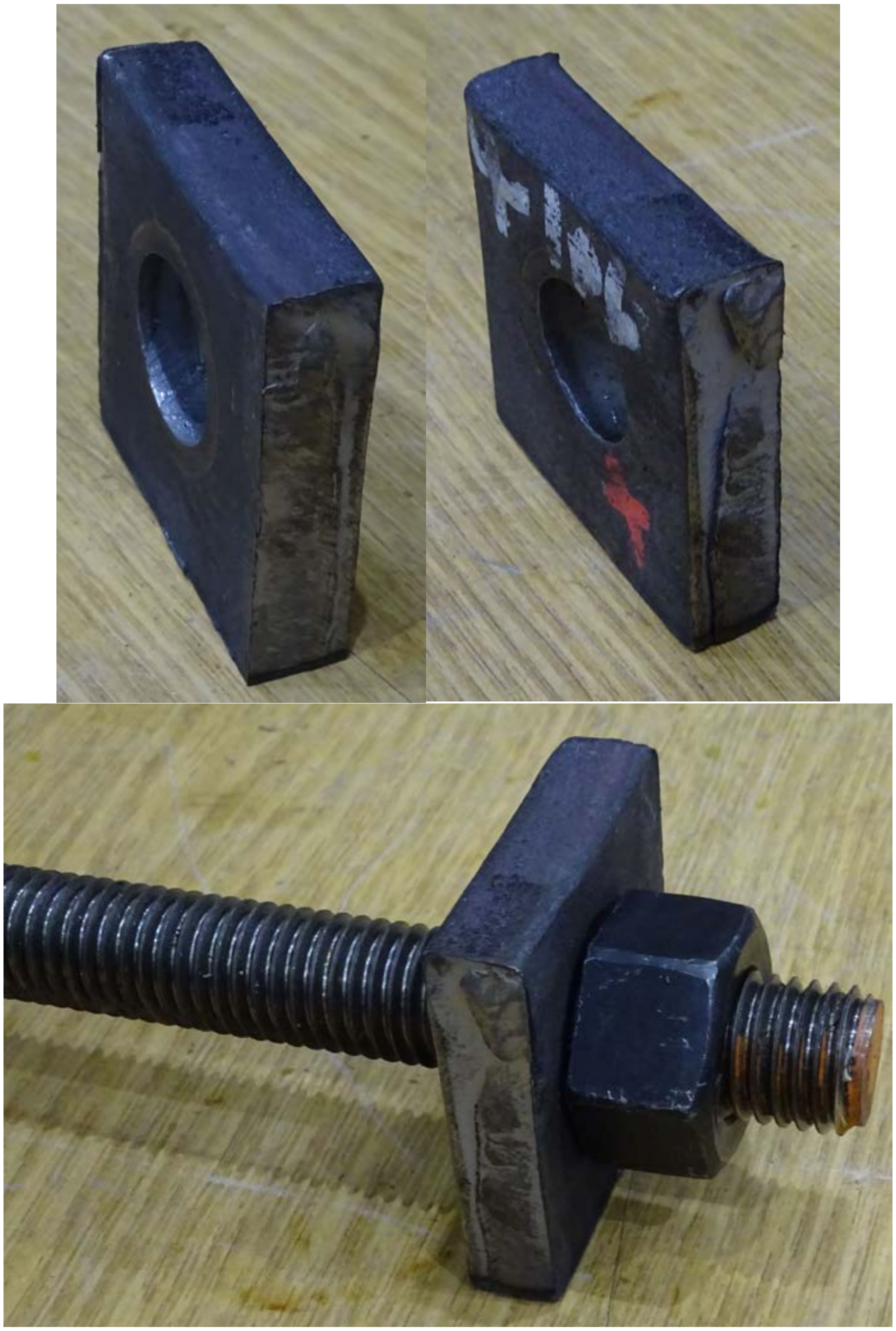

Figure B.13: Test #13 - 5% Relative Deformation

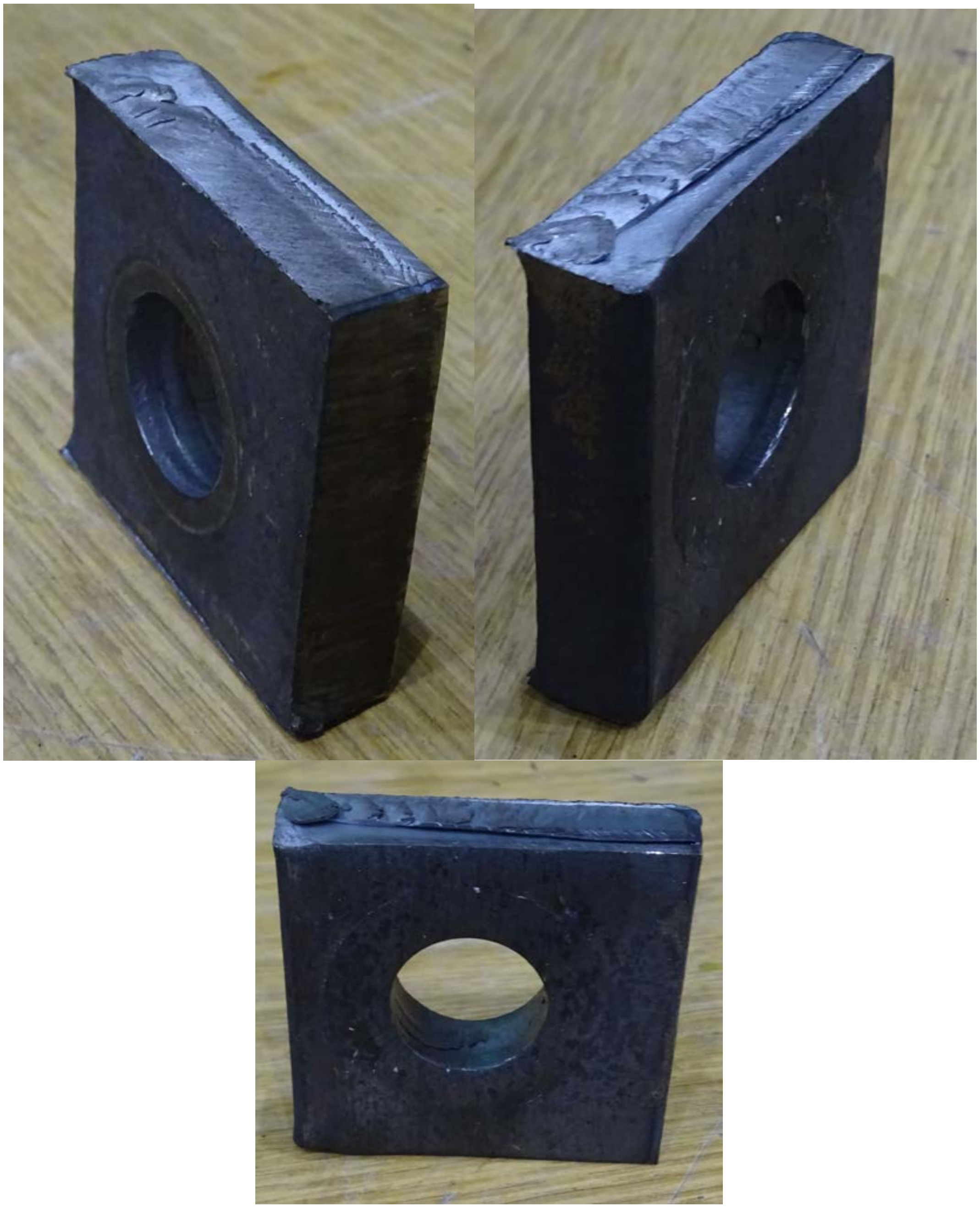

Figure B.14: Test #14 - 9% Relative Deformation

Figure B.15: Test #15 - 13% Relative Displacement

Figure B.16: Test #16 - 12% Relative Deformation

Figure B.17: Test #17 - 71% Relative Deformation

Figure B.18: Test #18 – 68% Relative Deformation

Figure B.19: Test #19 - 12% Relative Deformation

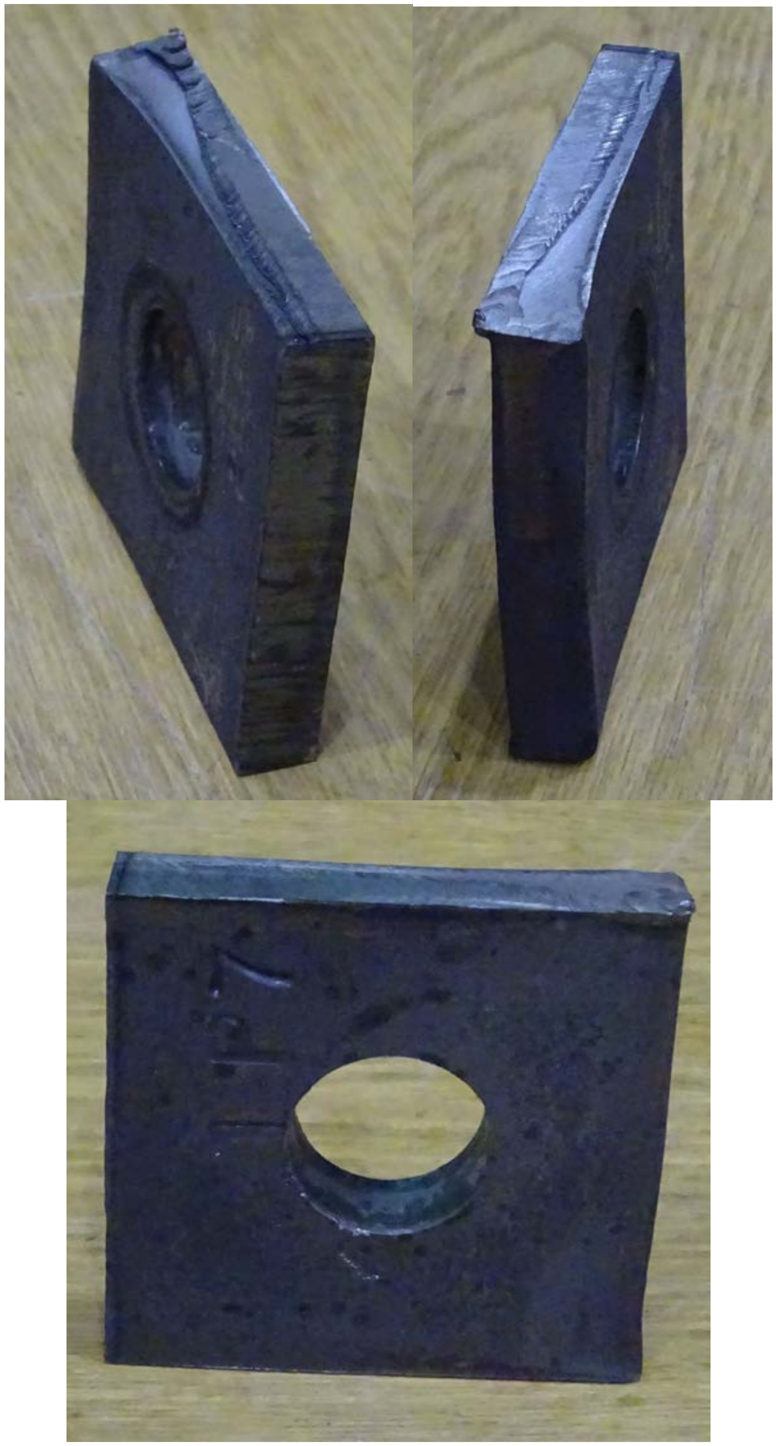

Figure B.20: Test #20 - 12% Relative Deformation

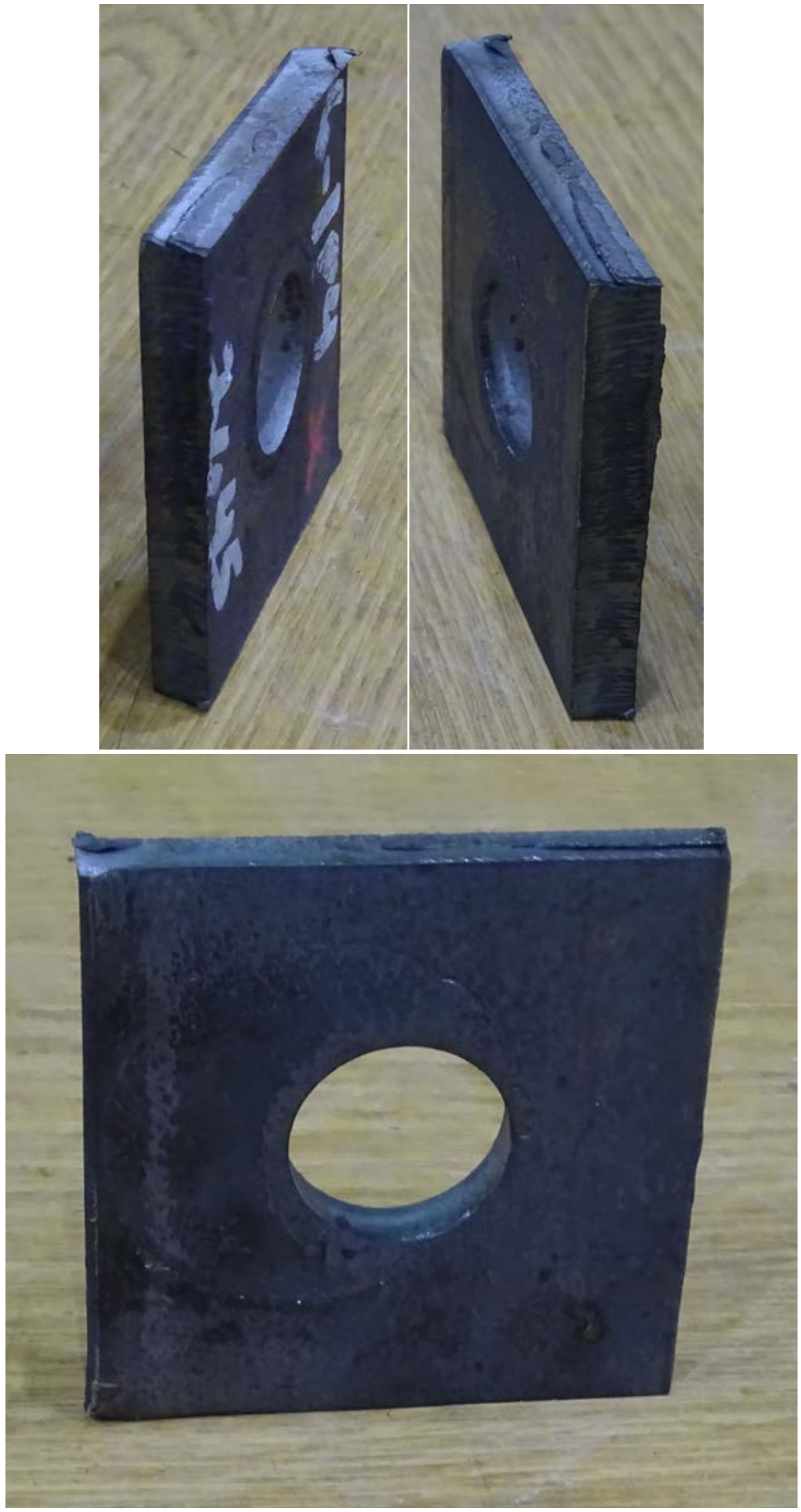

Figure B.21: Test #21 - 10% Relative Deformation

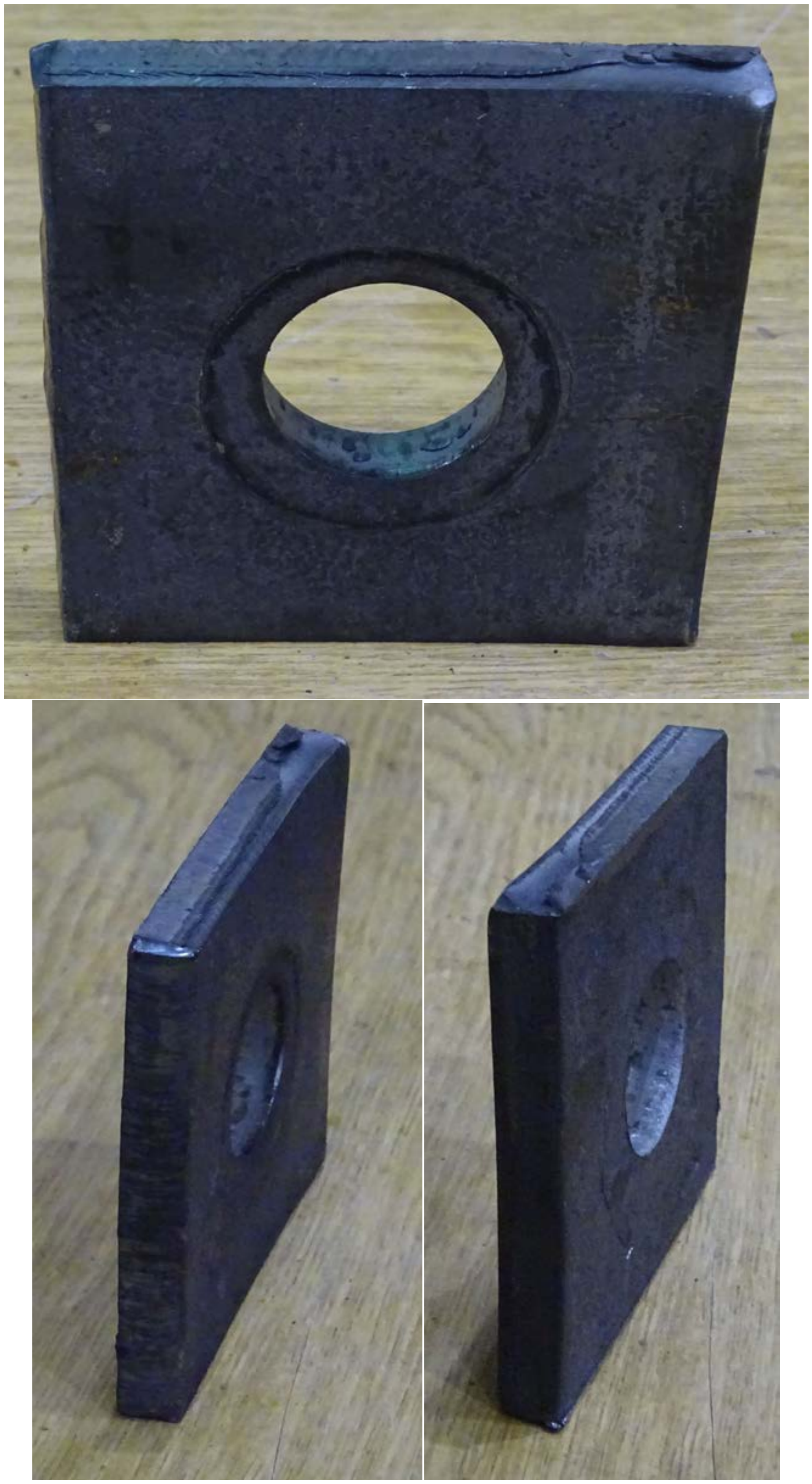

Figure B.22: Test #22 - 12% Relative Deformation

Figure B.23: Test #23 - 97% Relative Deformation

Figure B.24: Test #24 - 109% Relative Deformation and Rod Bending

Figure B.25: Test #25 - 9% Relative Deformation

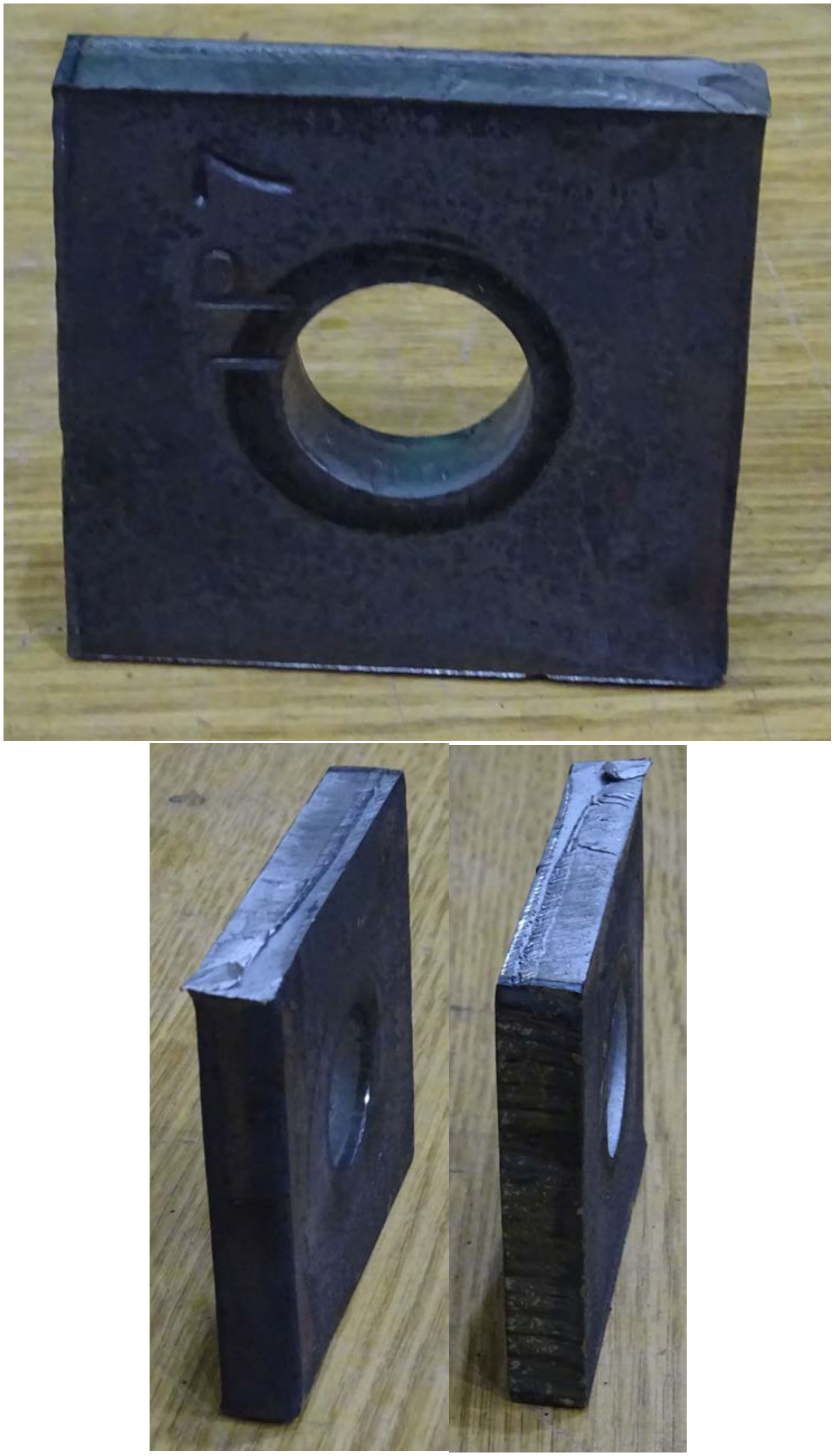

Figure B.26: Test #26 - 11% Relative Deformation

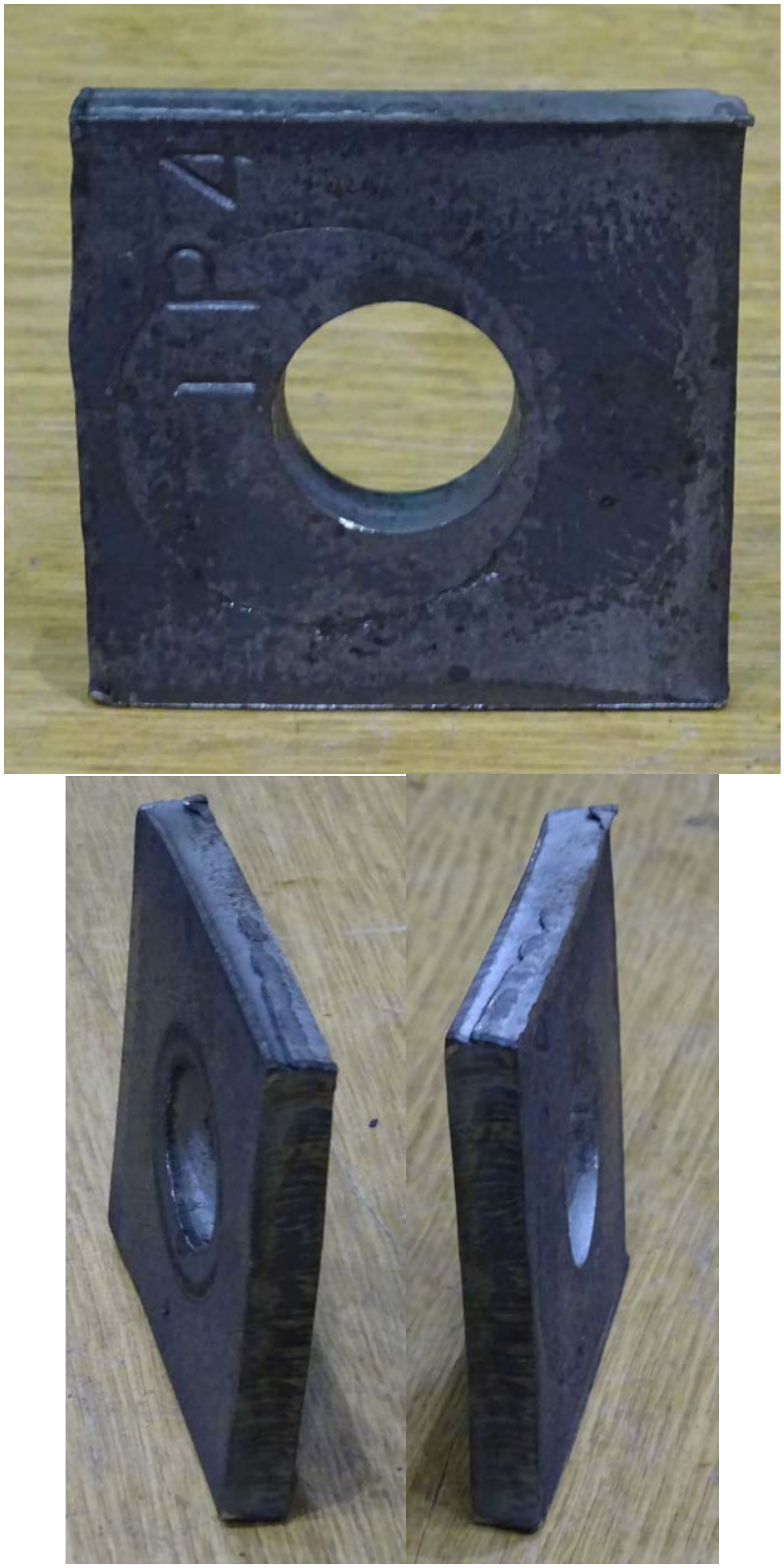

Figure B.27: Test #27 - 17% Relative Deformation

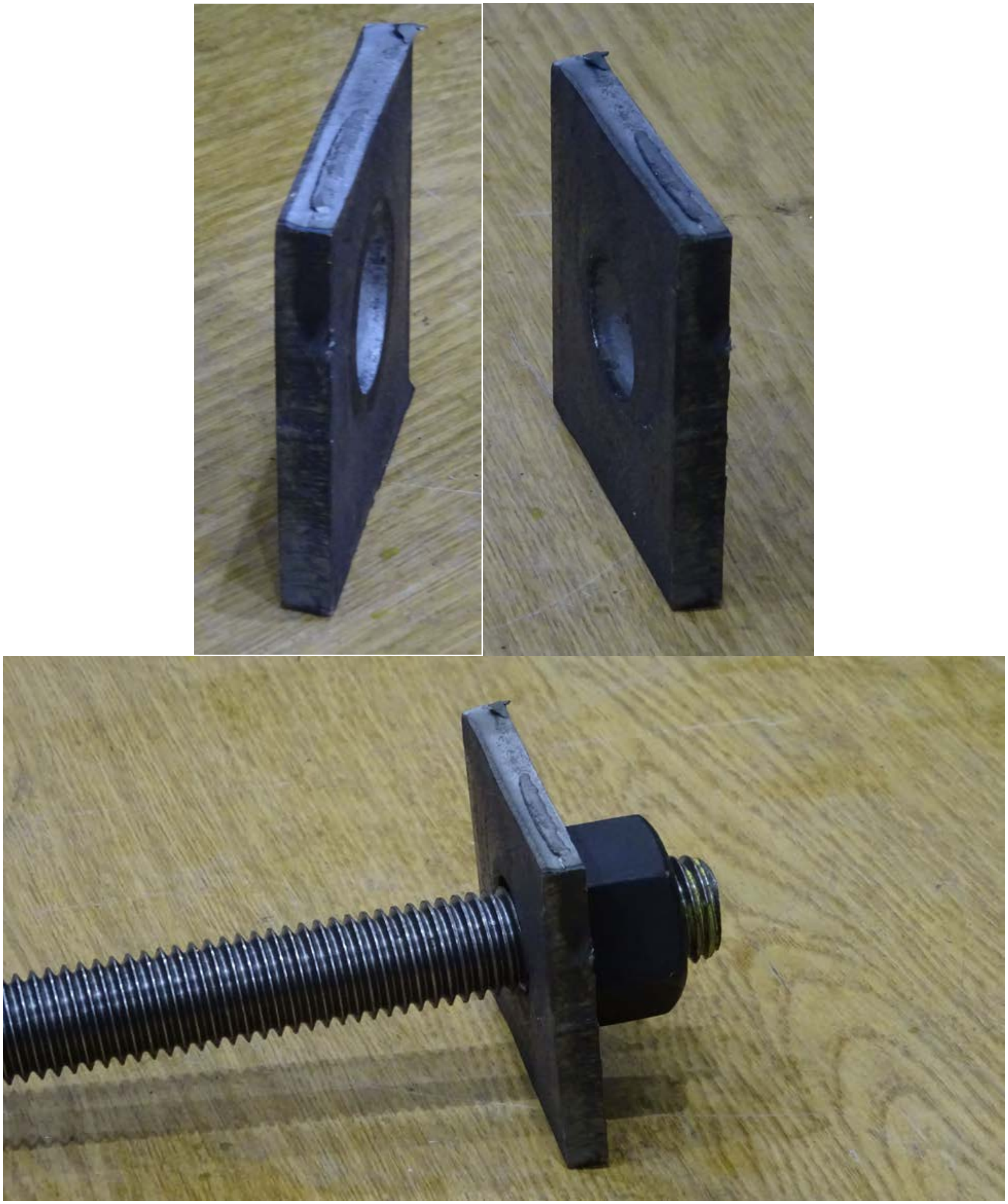

Figure B.28: Test #28 - 10% Relative Deformation

Figure B.29: Test #29 - 138% Relative Deformation and Rod Bending

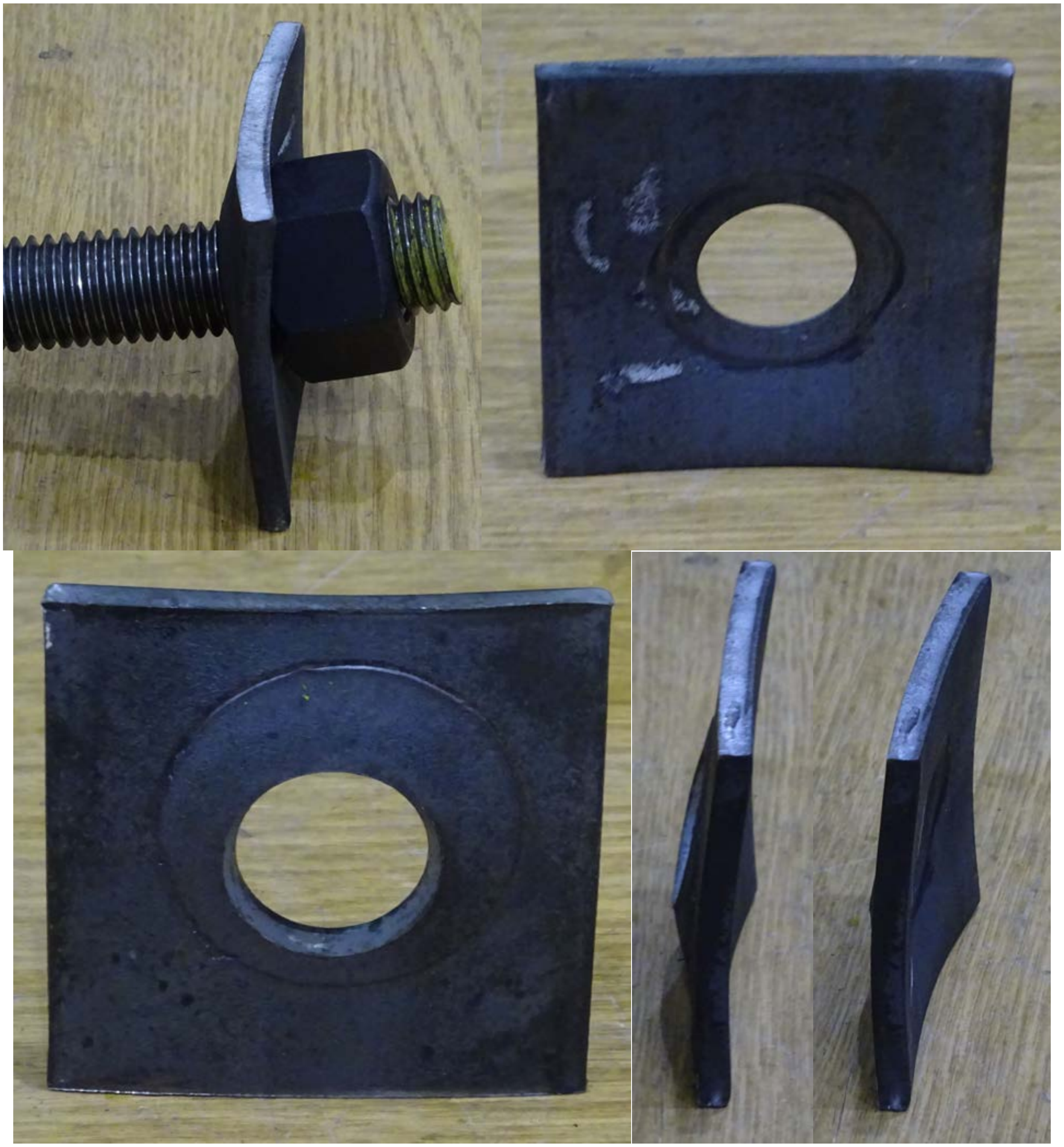

Figure B.30: Test #30 - 137% Relative Deformation

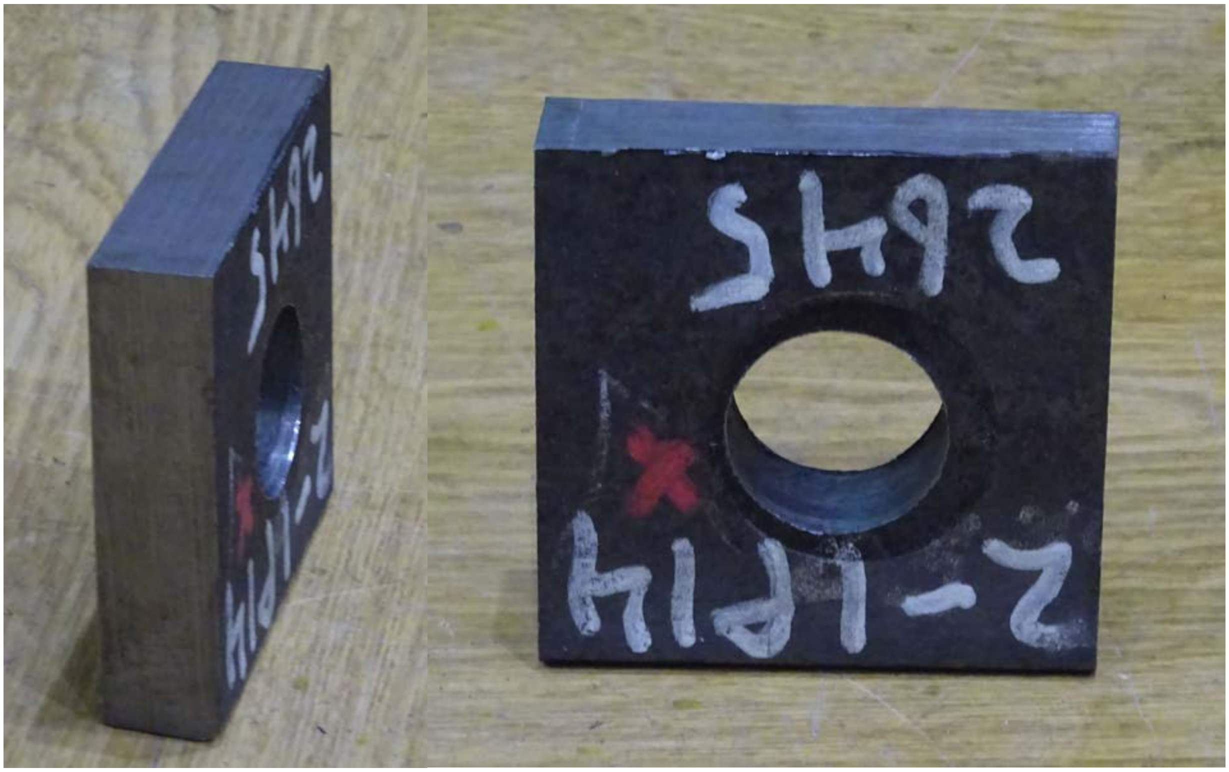

Figure B.31: Test #31 - 3% Relative Deformation

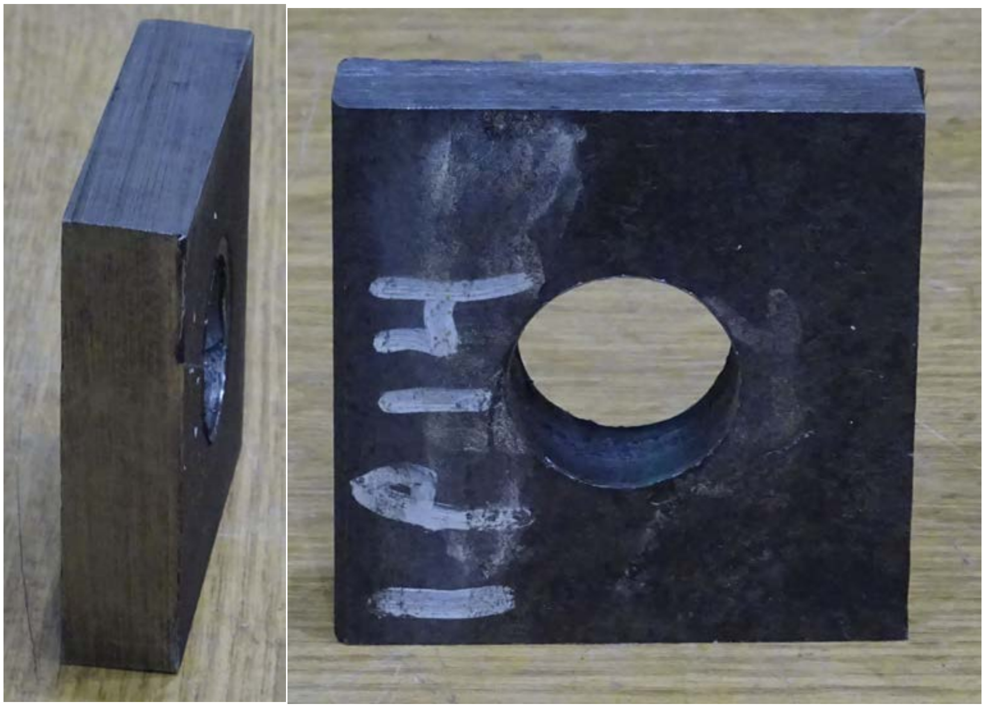

Figure B.32: Test #32 - 2% Relative Deformation

Figure B.33: Test #33 - 14% Relative Deformation

Figure B.34: Test #34 - 14% Relative Deformation

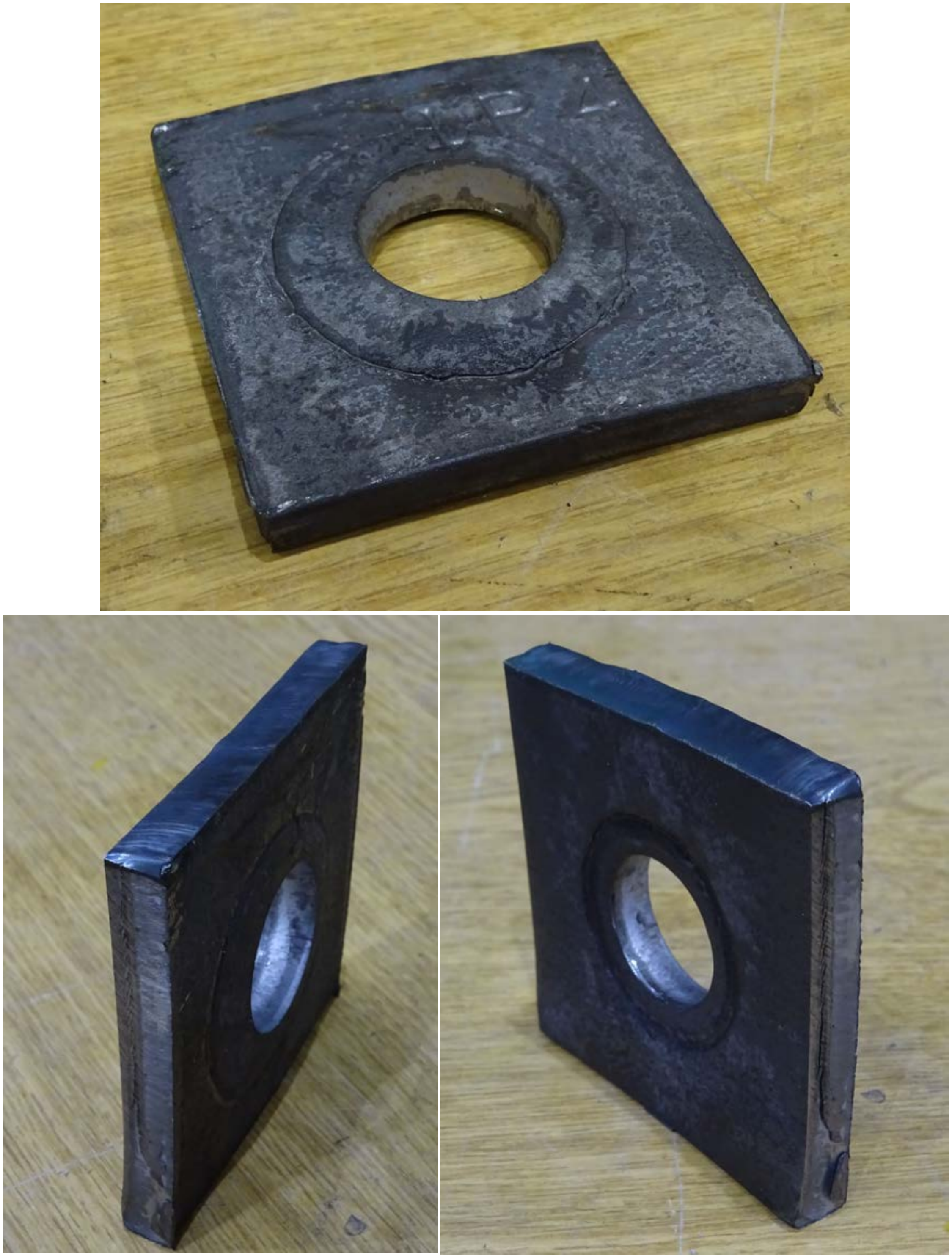

Figure B.35: Test #35 - 35% Relative Deformation

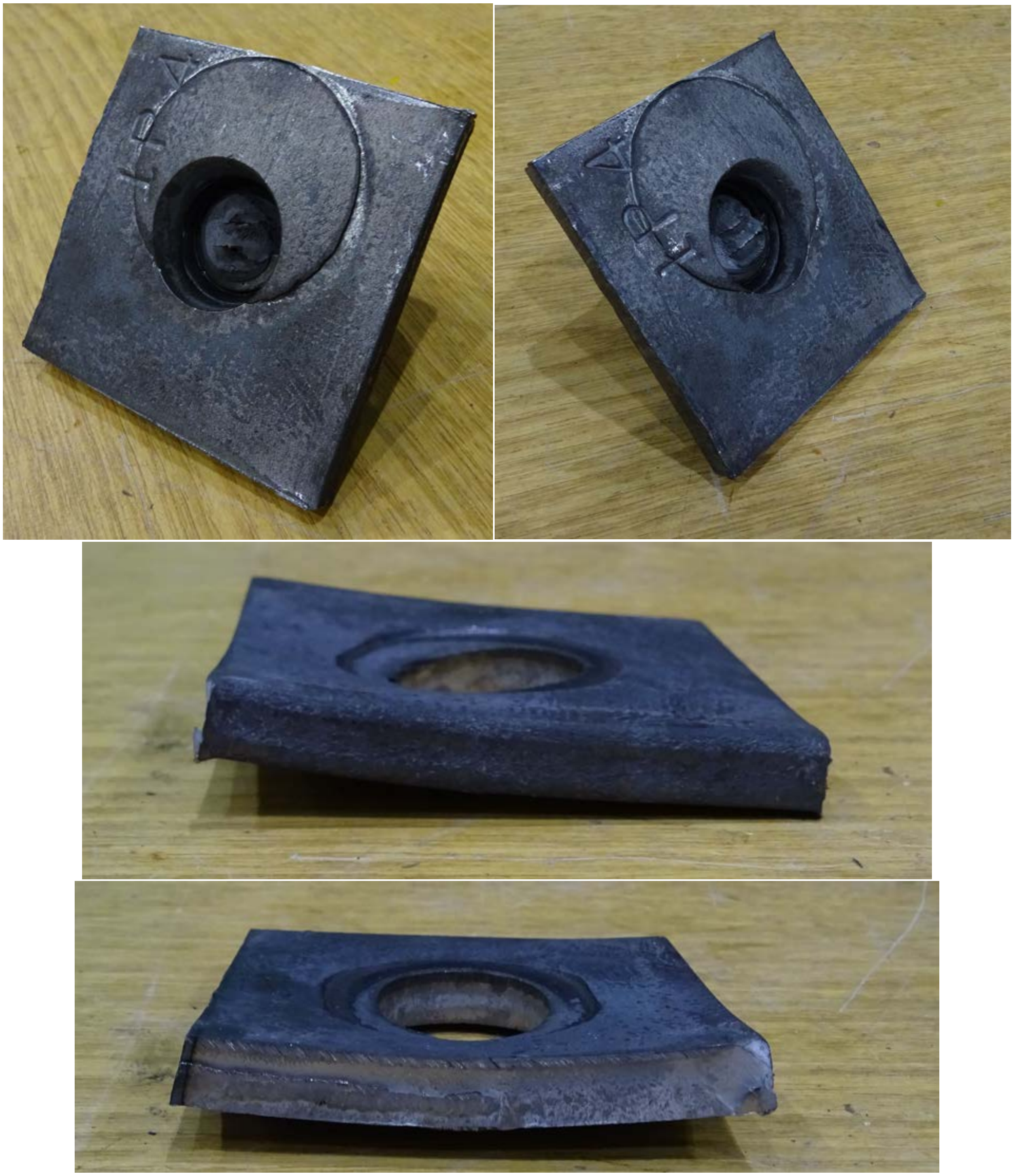

Figure B.36: Test #36 - 62% Relative Deformation

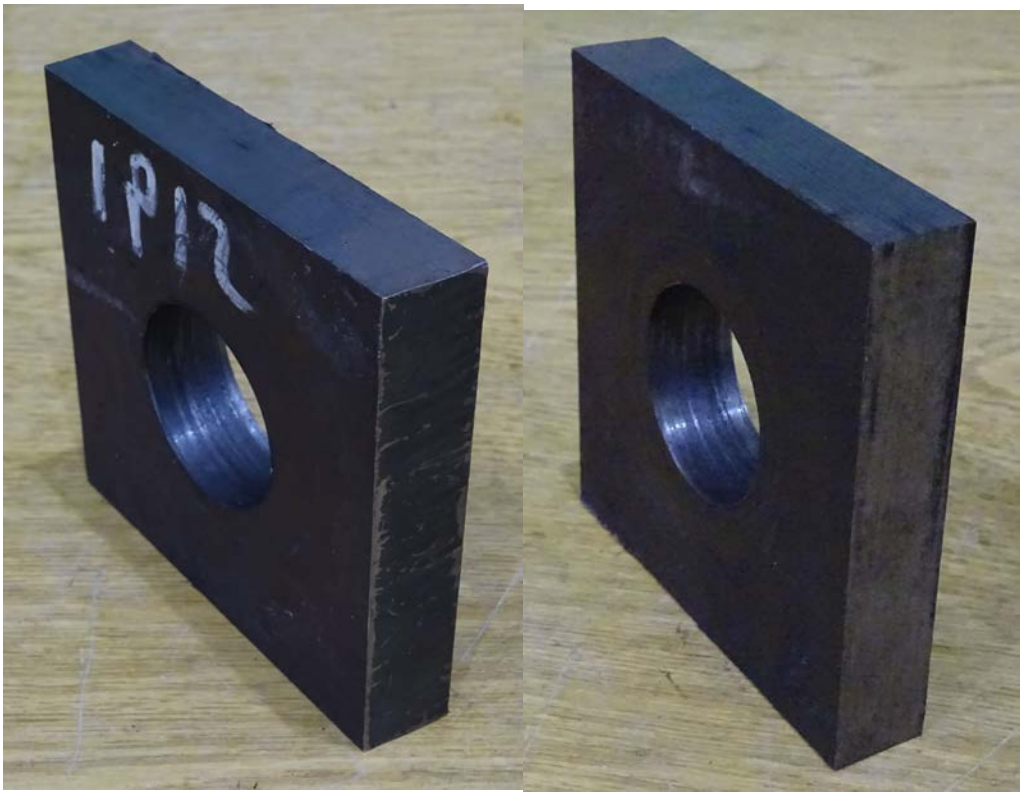

Figure B.37: Test #37 - 3% Relative Deformation

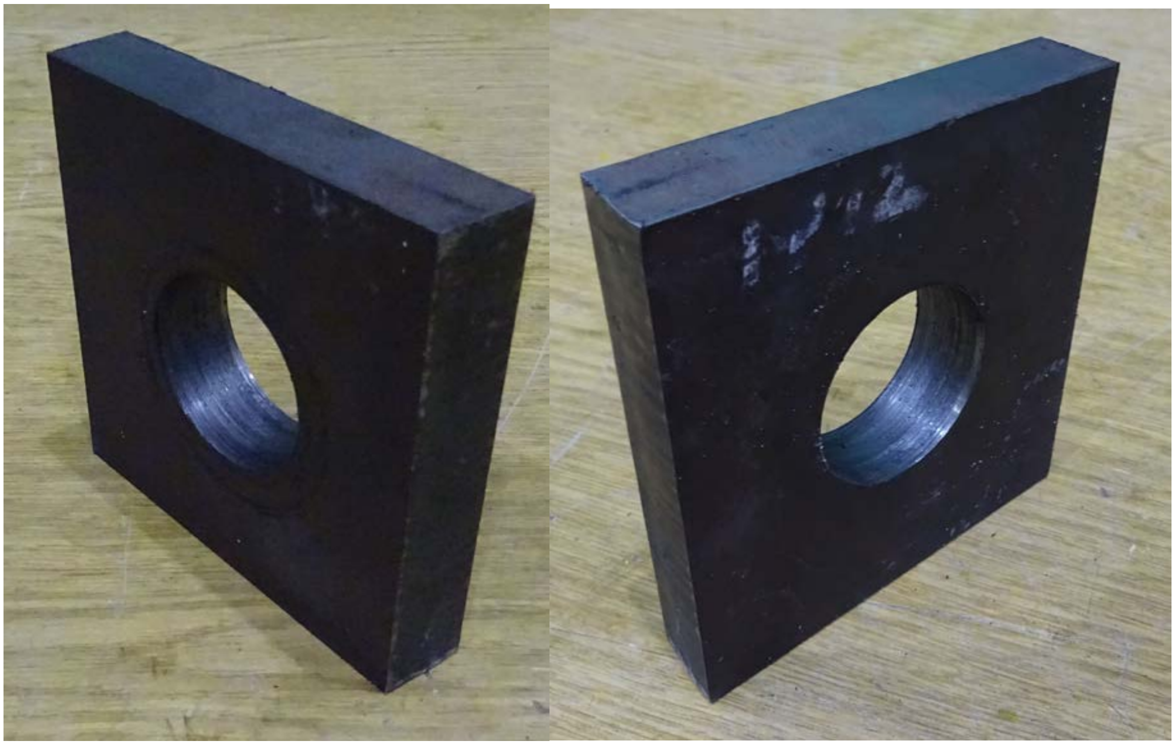

Figure B.38: Test #38 - 4% Relative Deformation

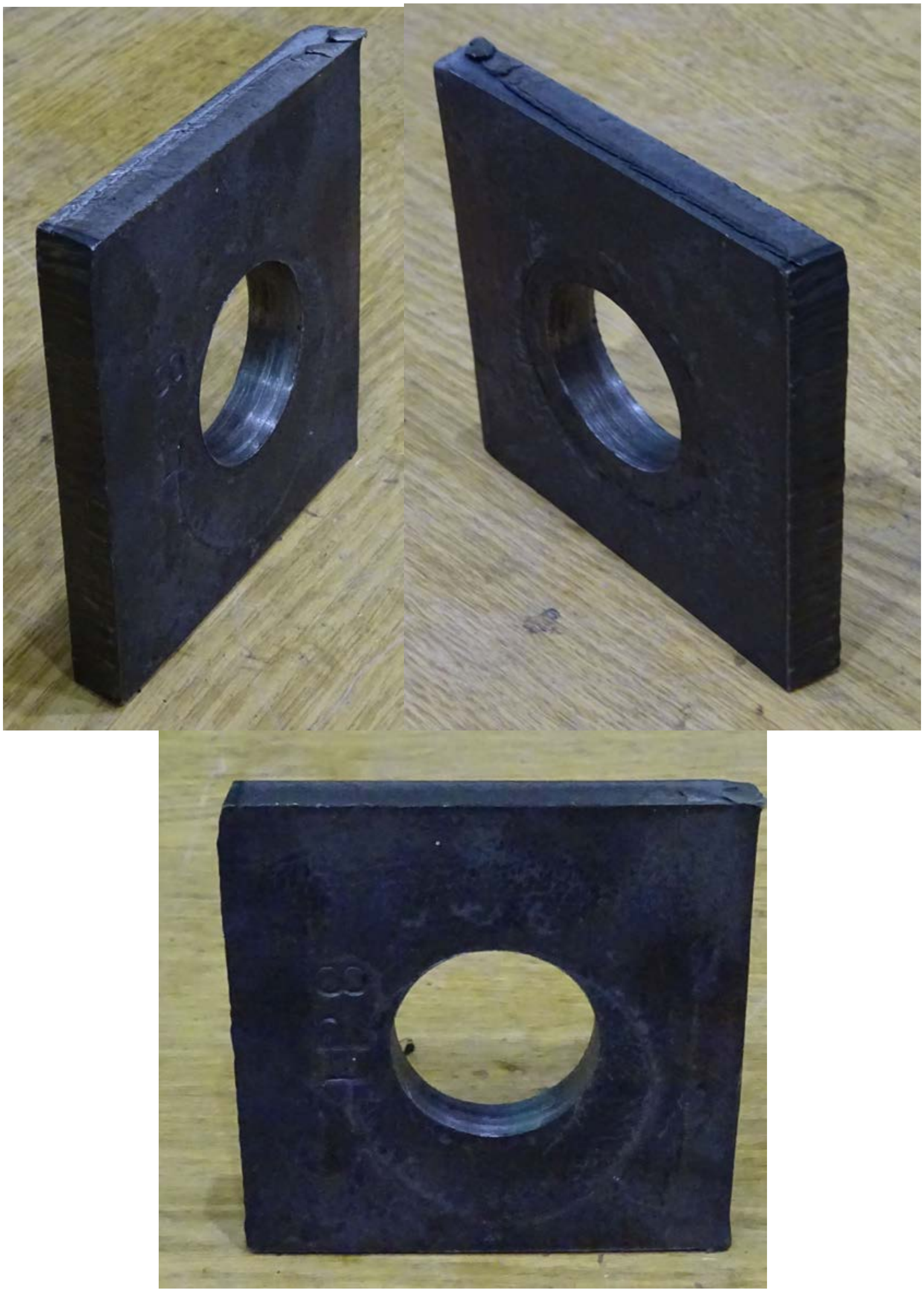

Figure B.39: Test #39 - 15% Relative Deformation

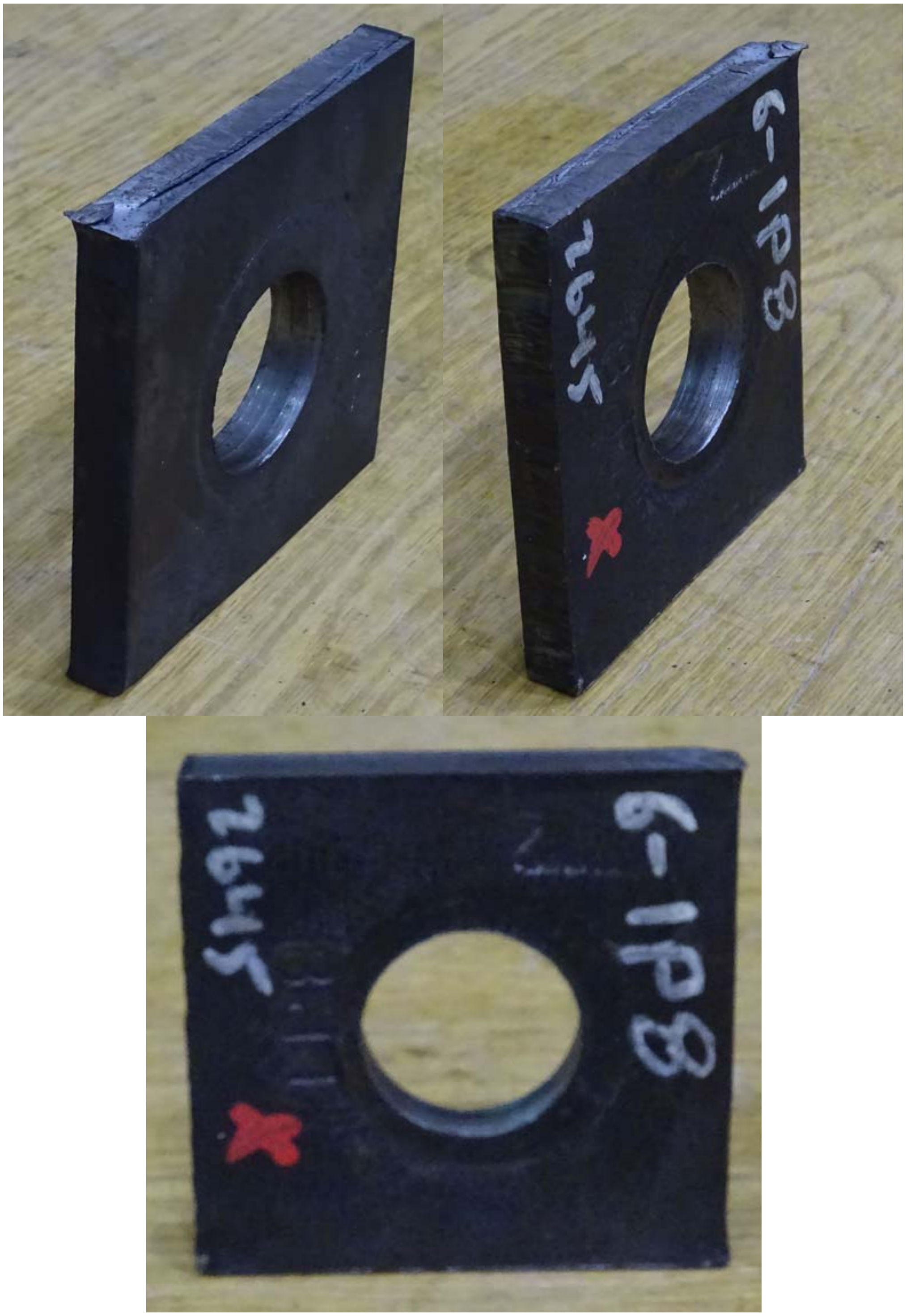

Figure B.40: Test #40 - 16% Relative Deformation

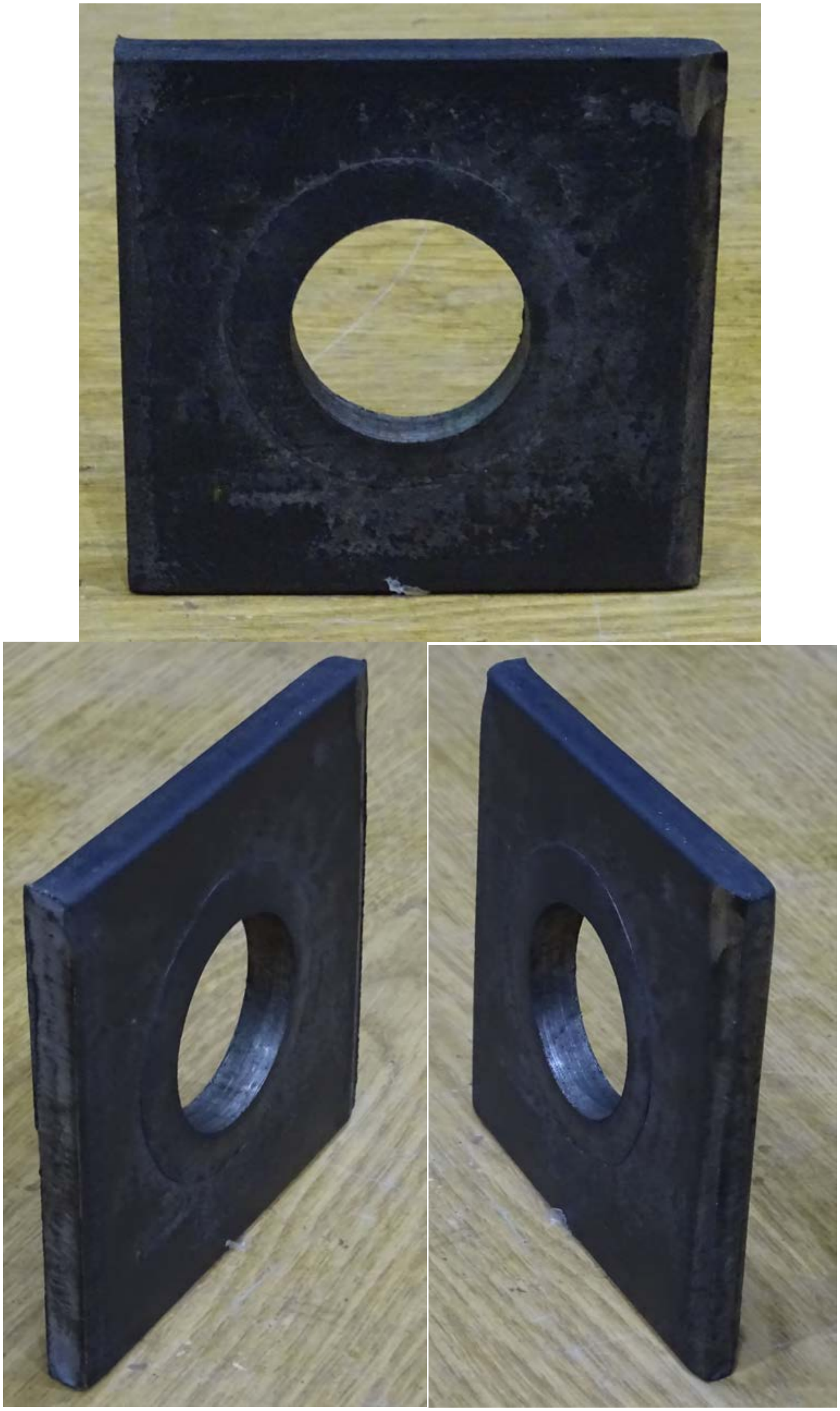

Figure B.41: Test #41 - 17% Relative Deformation

Figure B.42: Test #42 - 52% Relative Deformation

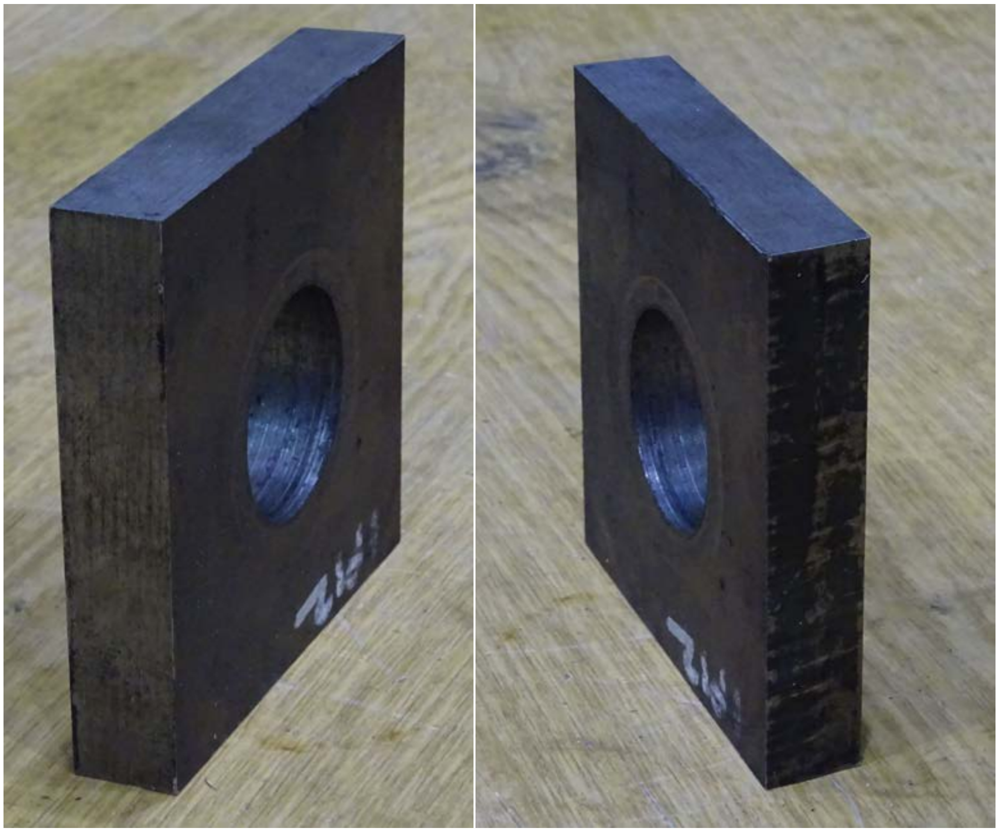

Figure B.43: Test #43 - 4% Relative Deformation

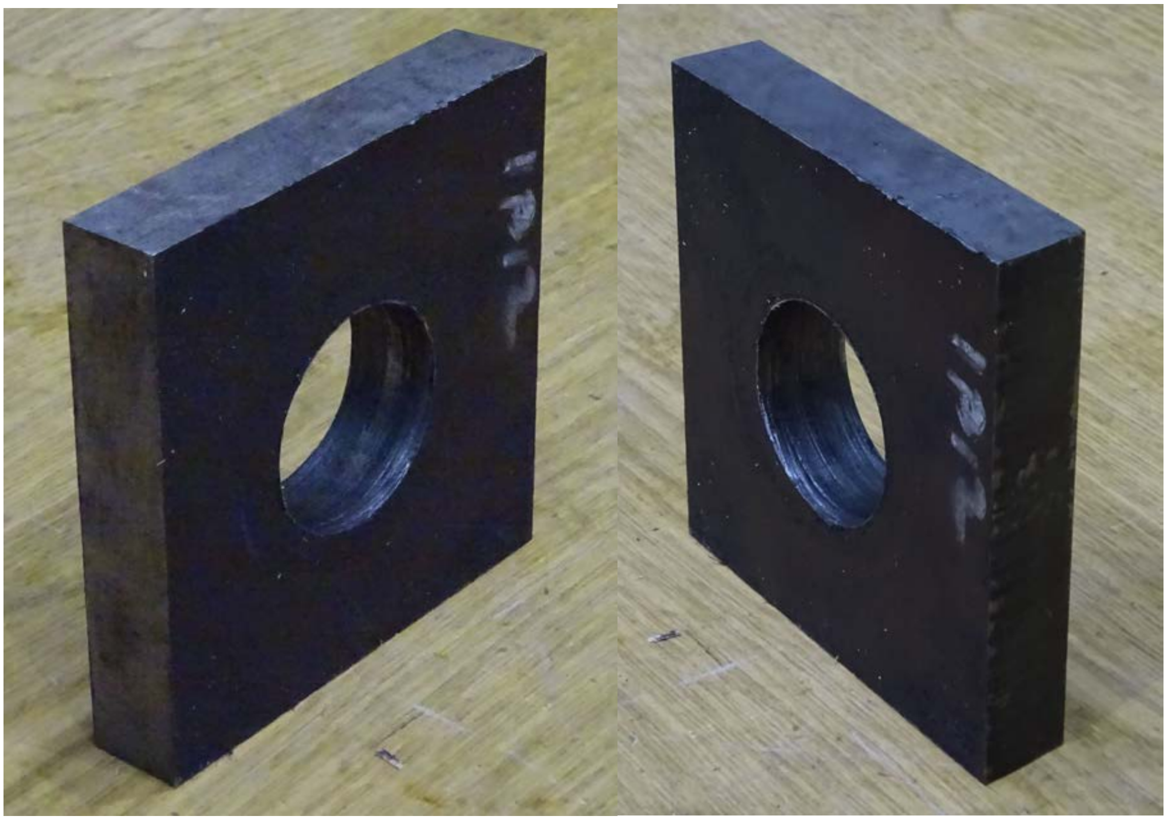

Figure B.44: Test #44 - 2% Relative Deformation

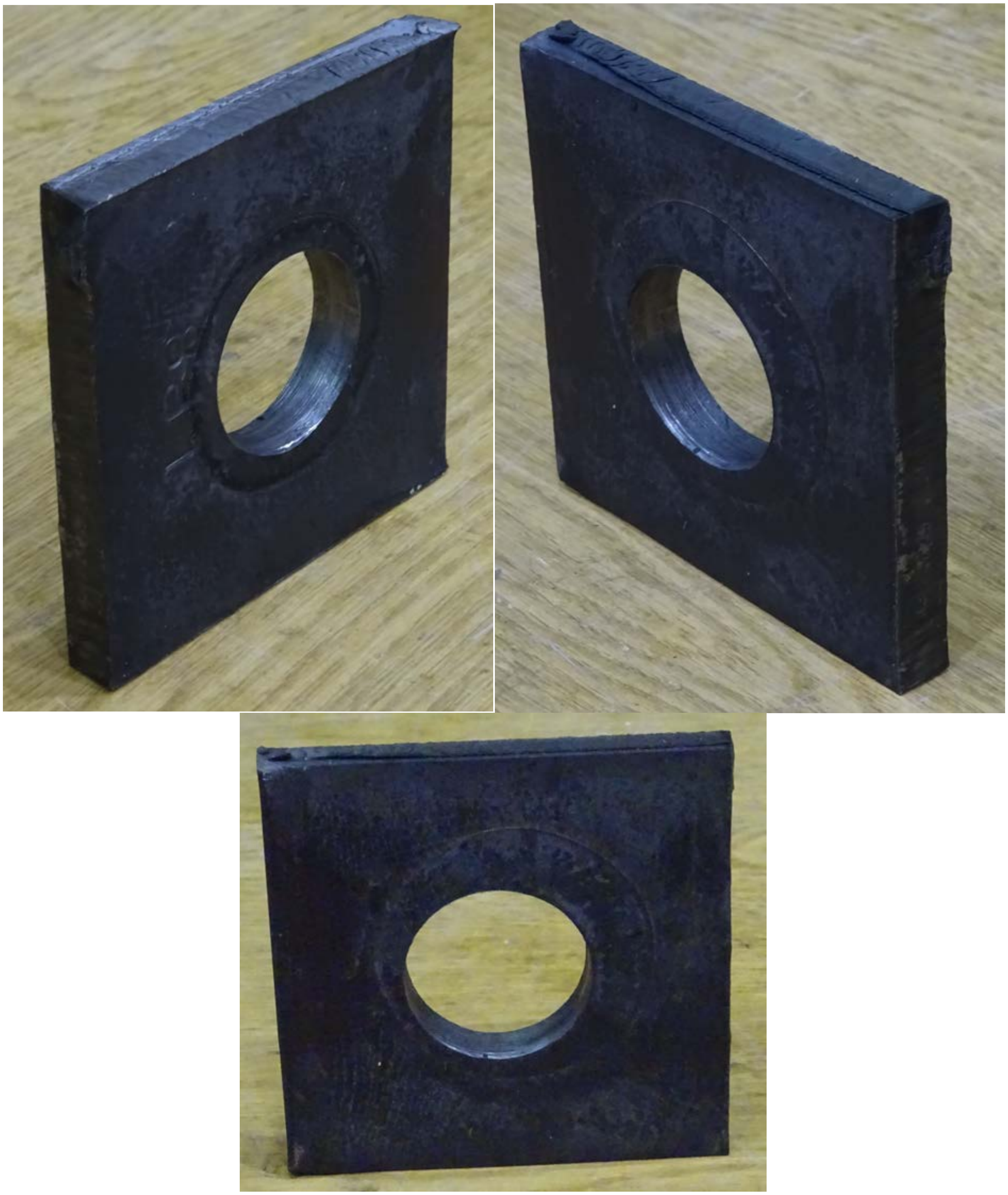

Figure B.45: Test #45 - 15% Relative Deformation

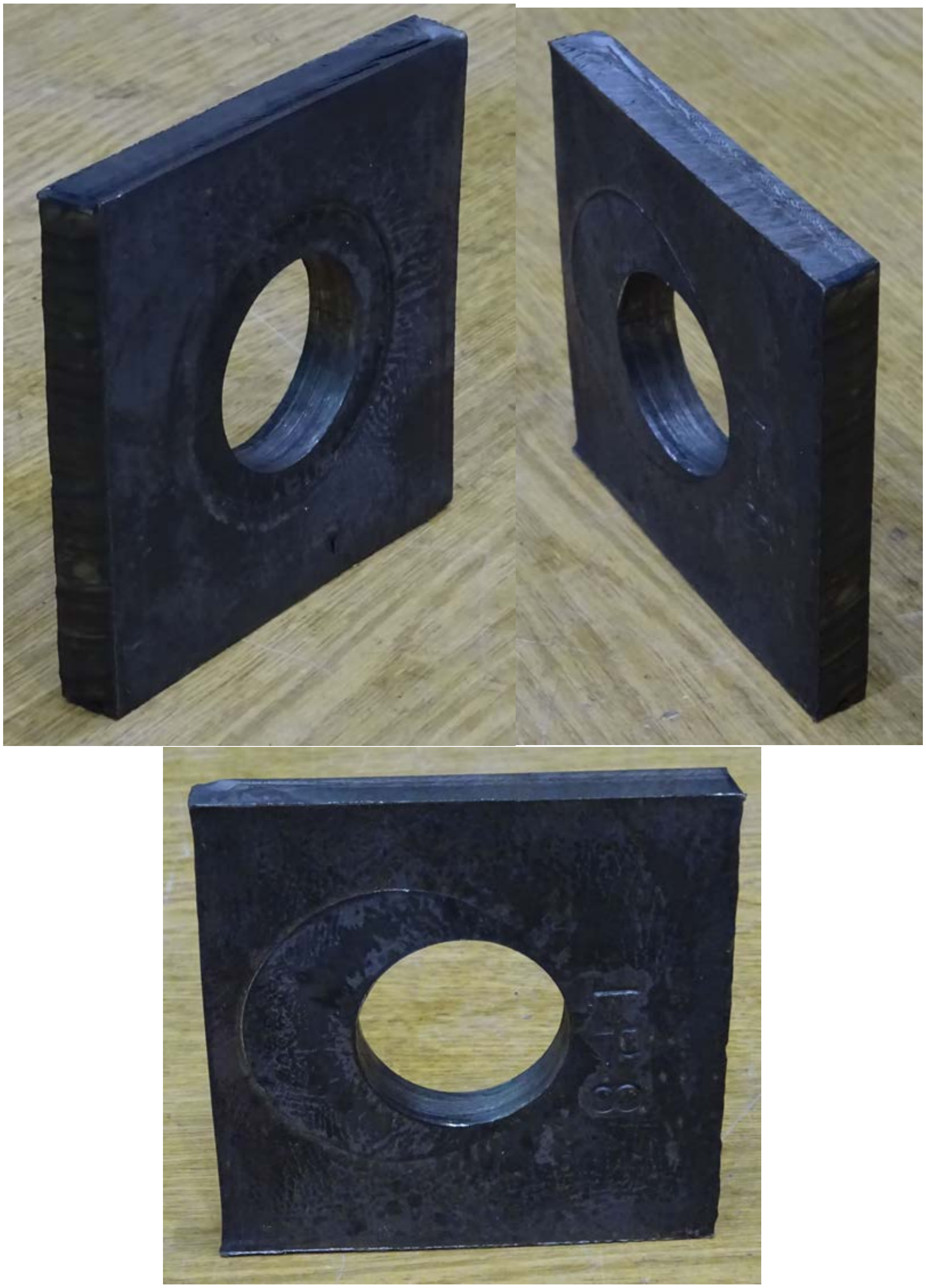

Figure B.46: Test #46 - 19% Relative Deformation

Figure B.47: Test #47 - 45% Relative Deformation

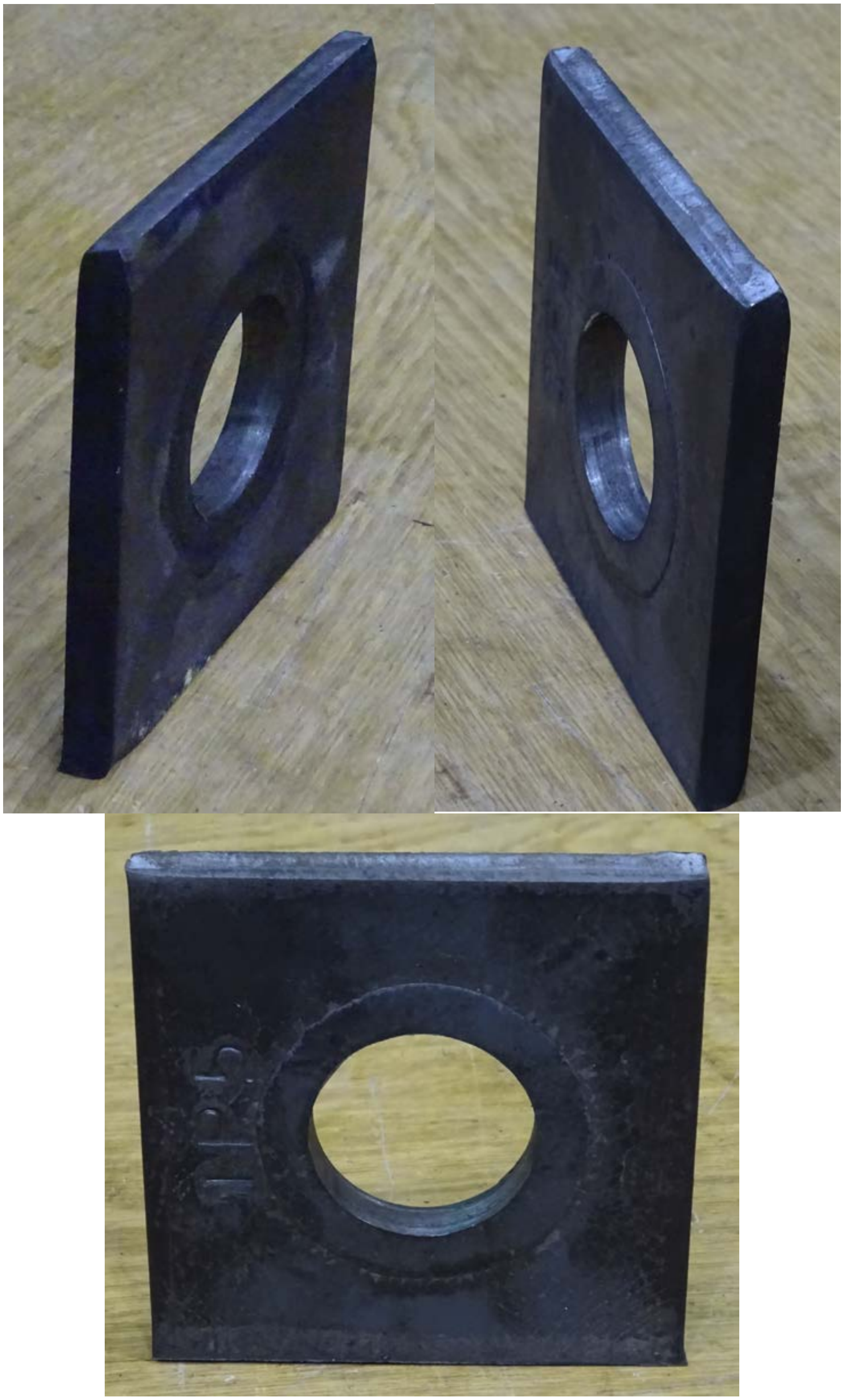

Figure B.48: Test #48 - 18% Relative Deformation

Figure B.49: Test #49 - 2% Relative Deformation

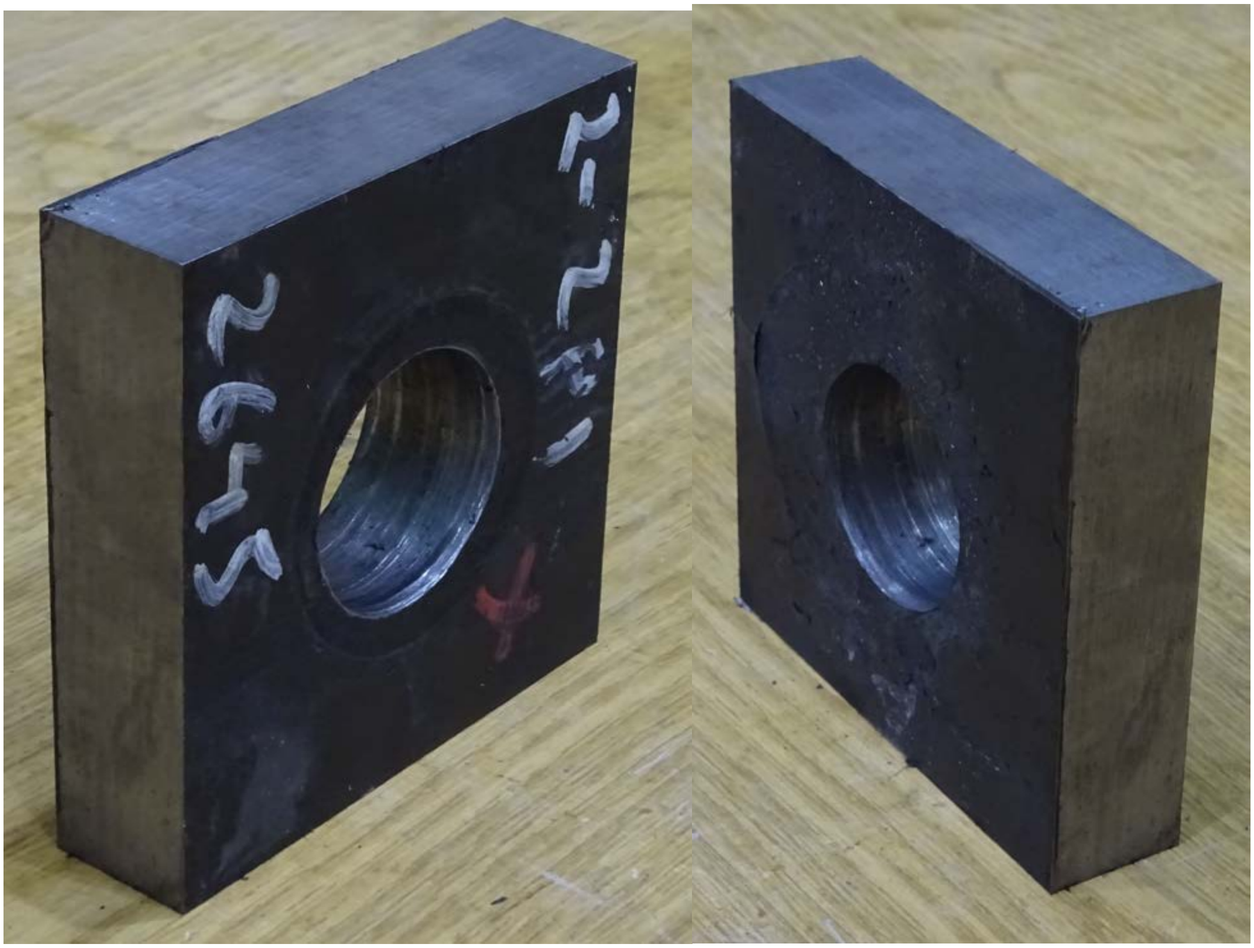

Figure B.50: Test #50 - 2% Relative Deformation

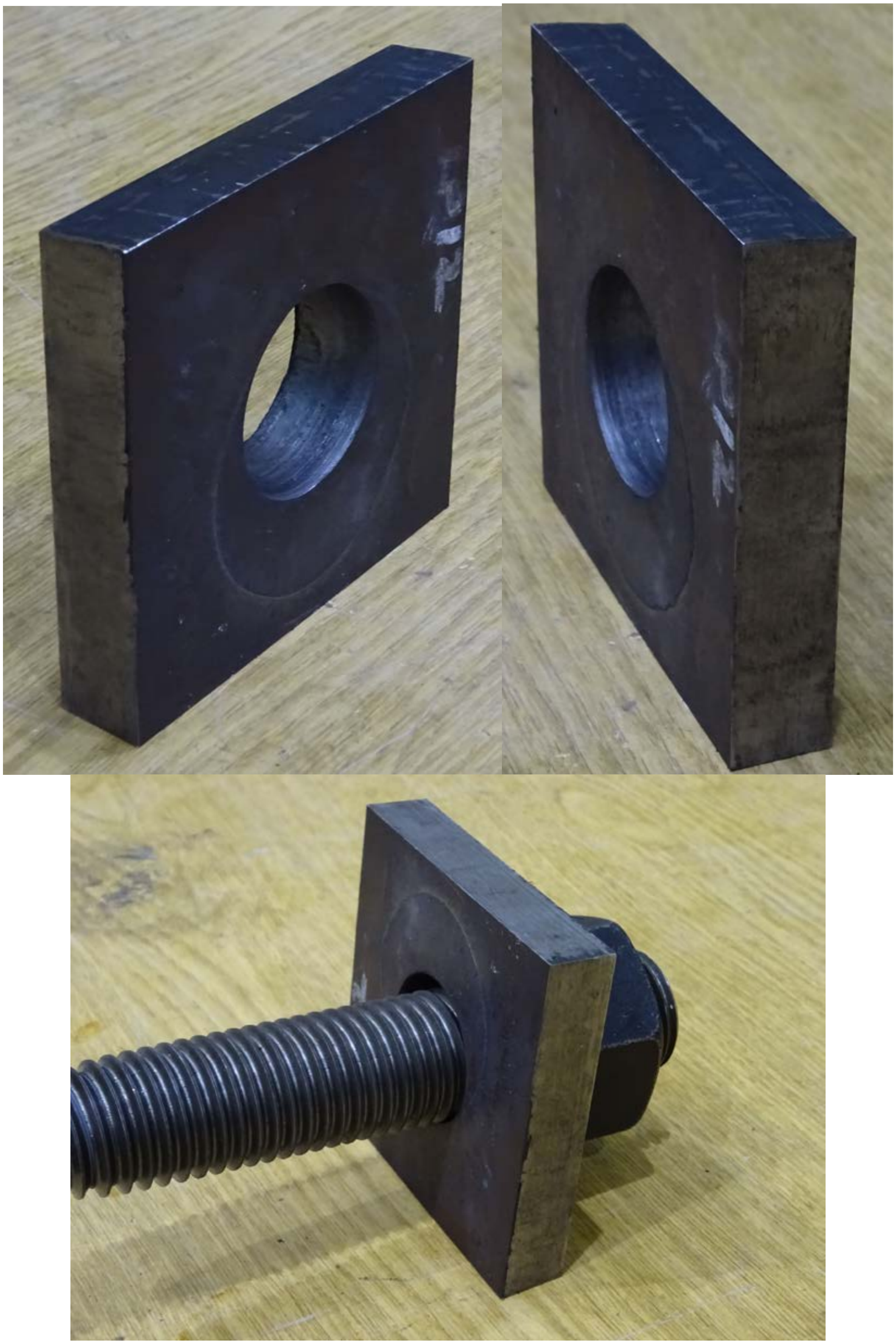

Figure B.51: Test #50 - 5% Relative Deformation

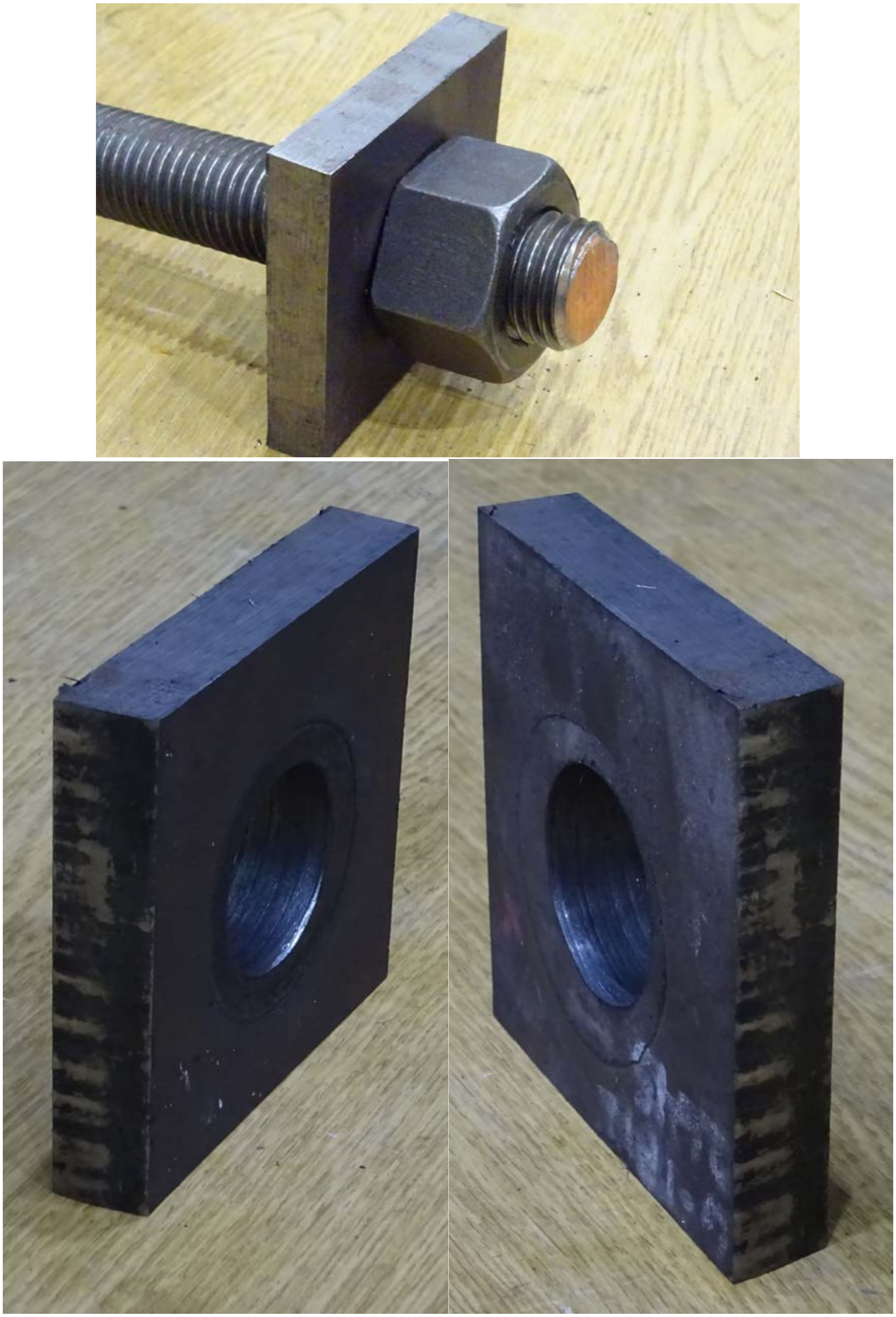

Figure B.52: Test #52 - 6% Relative Deformation

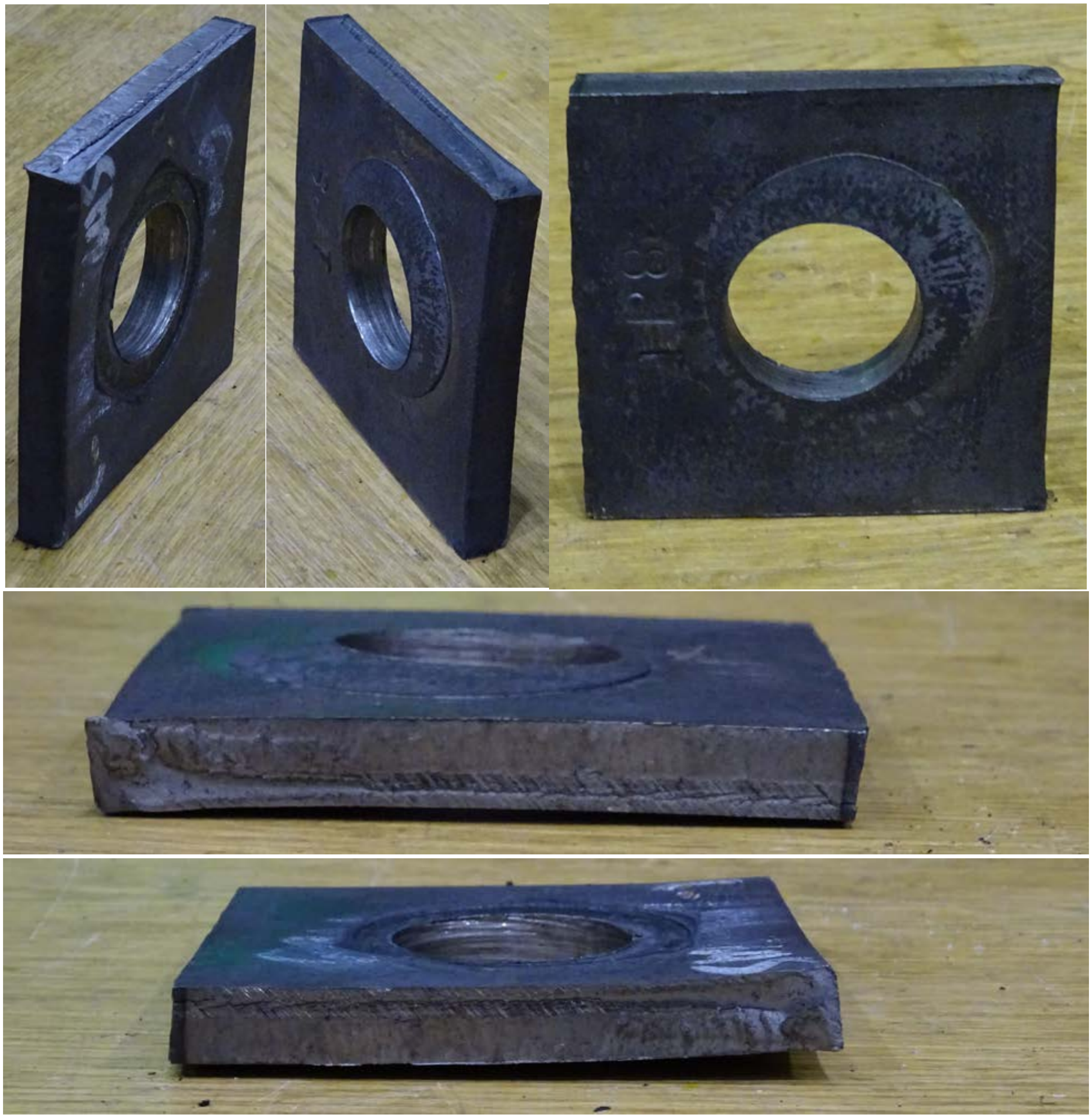

Figure B.53: Test #53 - 36% Relative Deformation

Figure B.54: Test #54 - 38% Relative Deformation and Rod Bending

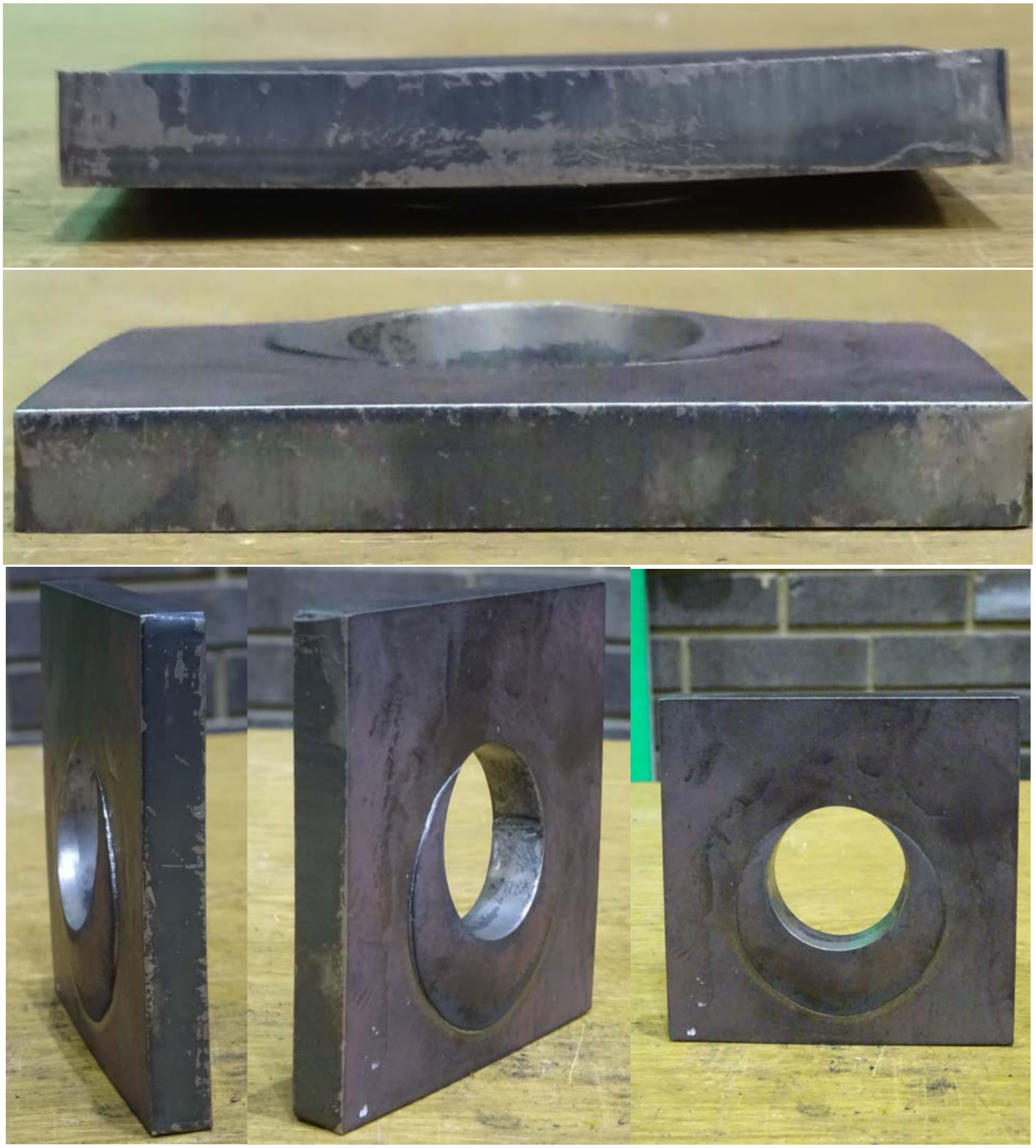

Figure B.55: Test #1A - 42% Relative Deformation

Figure B.56: Test #2A - 14% Relative Deformation

Figure B.57: Test #3A - 11% Relative Deformation

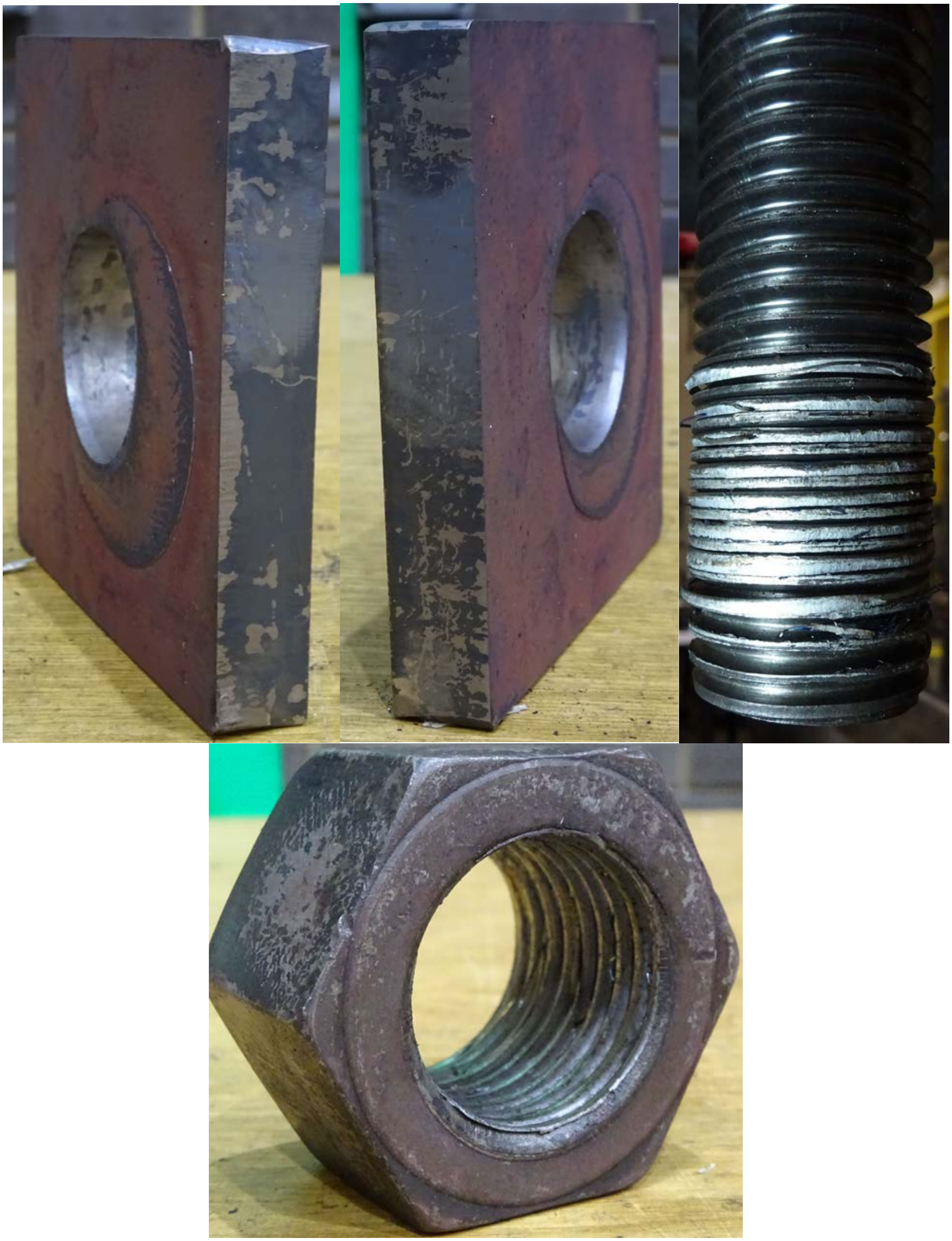

Figure B.58: Test #4A - 11% Relative Deformation and Sheared Nut

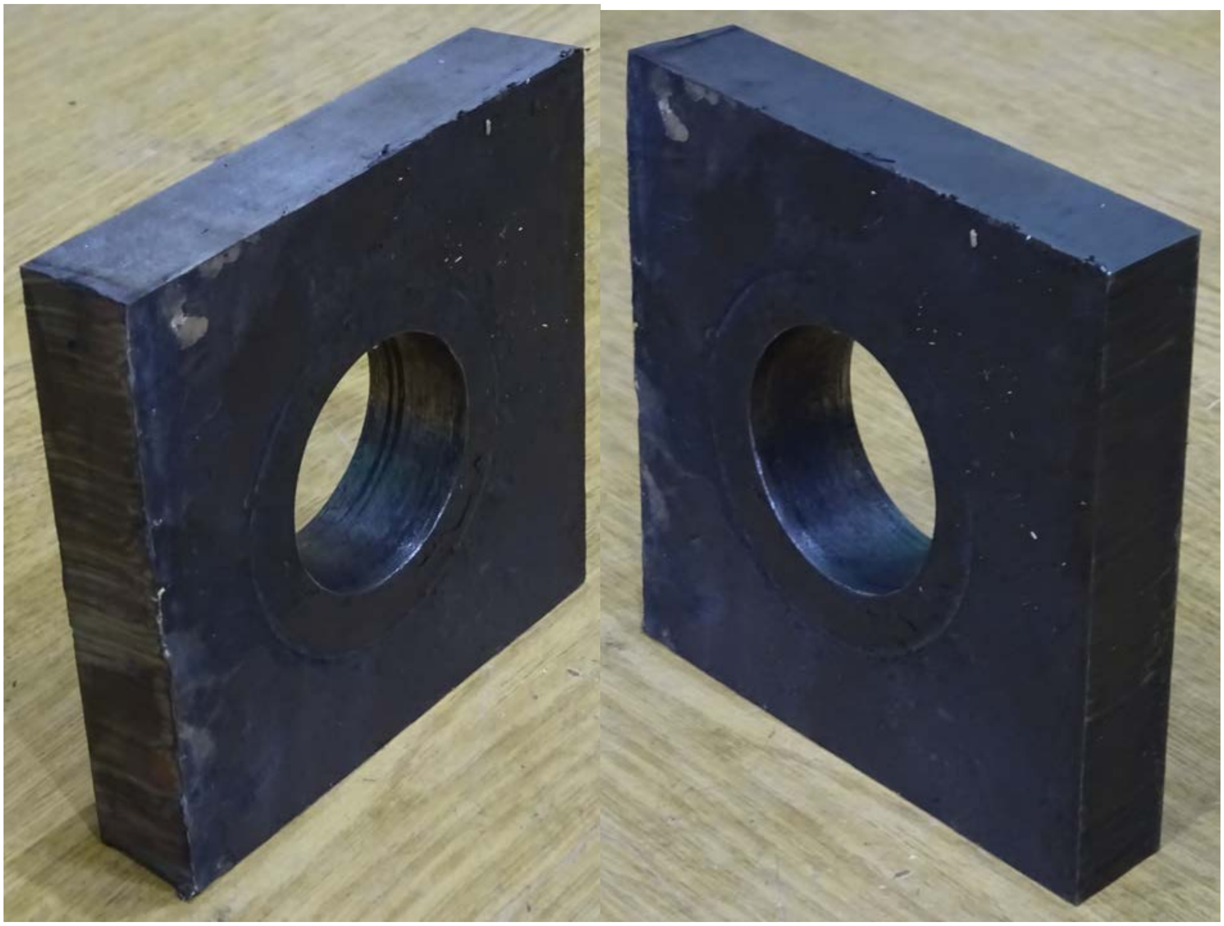

Figure B. 59: Test #55 - 1% Relative Deformation

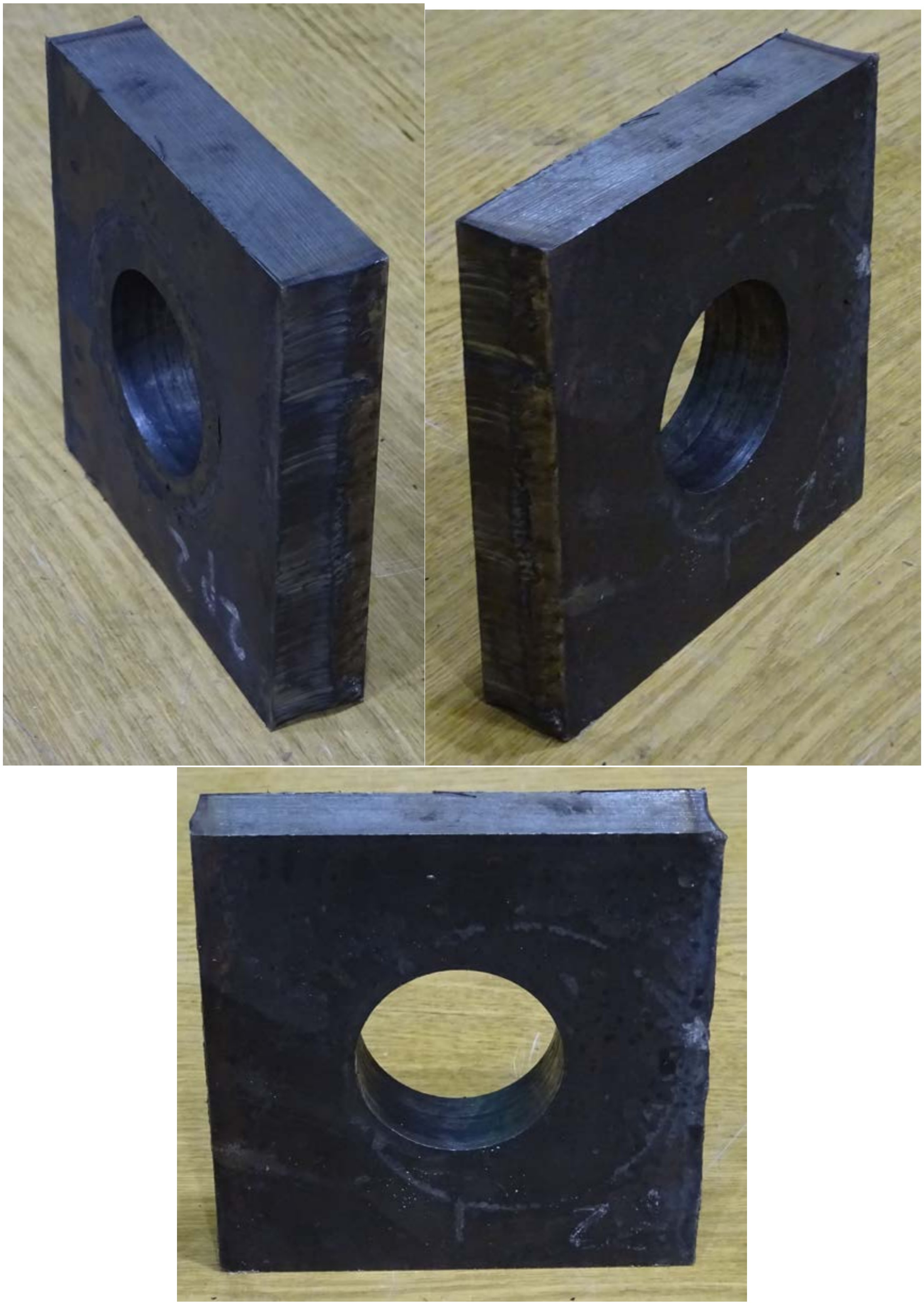

Figure B.60: Test #56 - 1% Relative Deformation

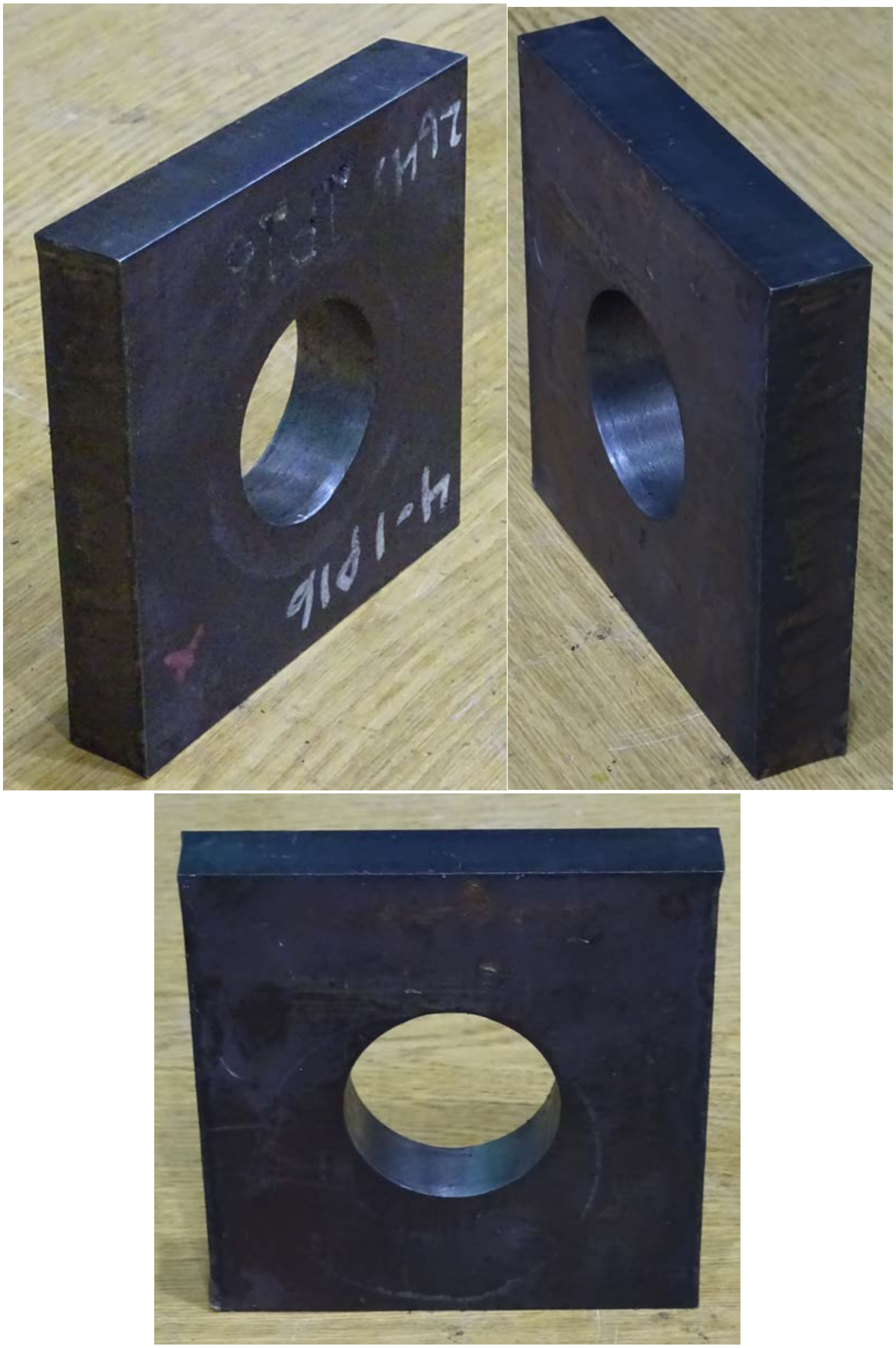

Figure B.61: Test #57 - 2% Relative Deformation

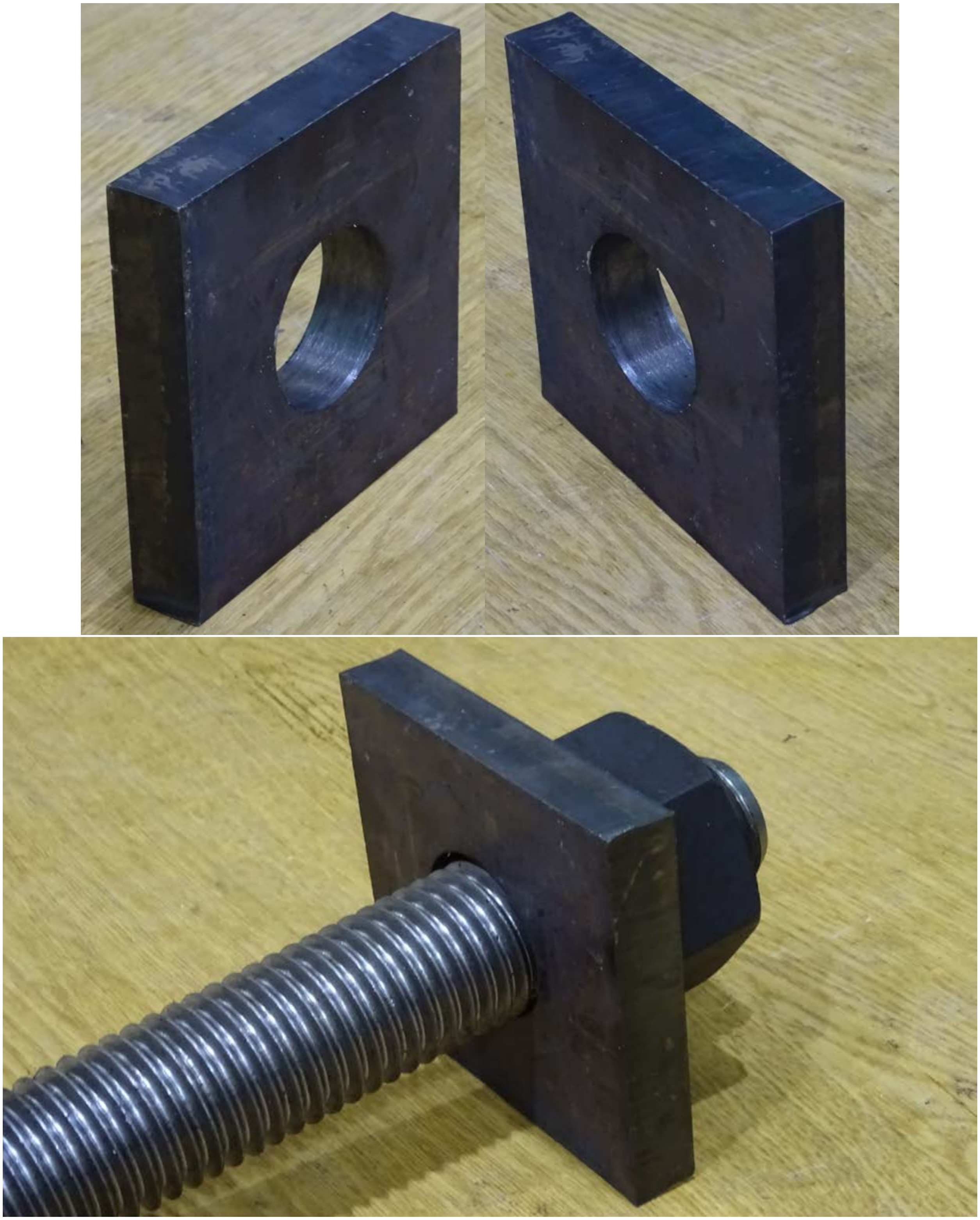

Figure B.62: Test #58 - 2% Relative Deformation

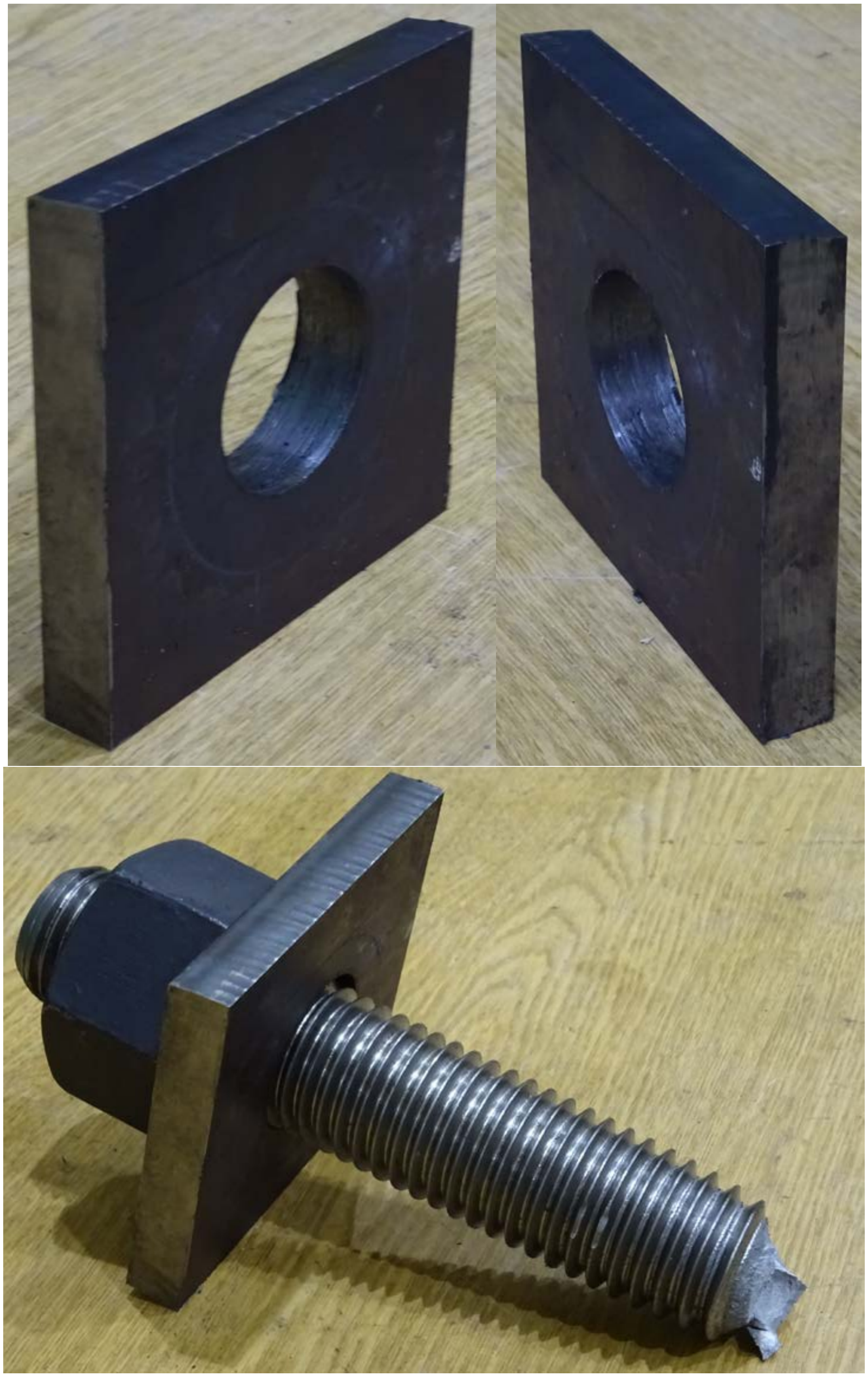

Figure B.63: Test #59 - 1% Relative Deformation

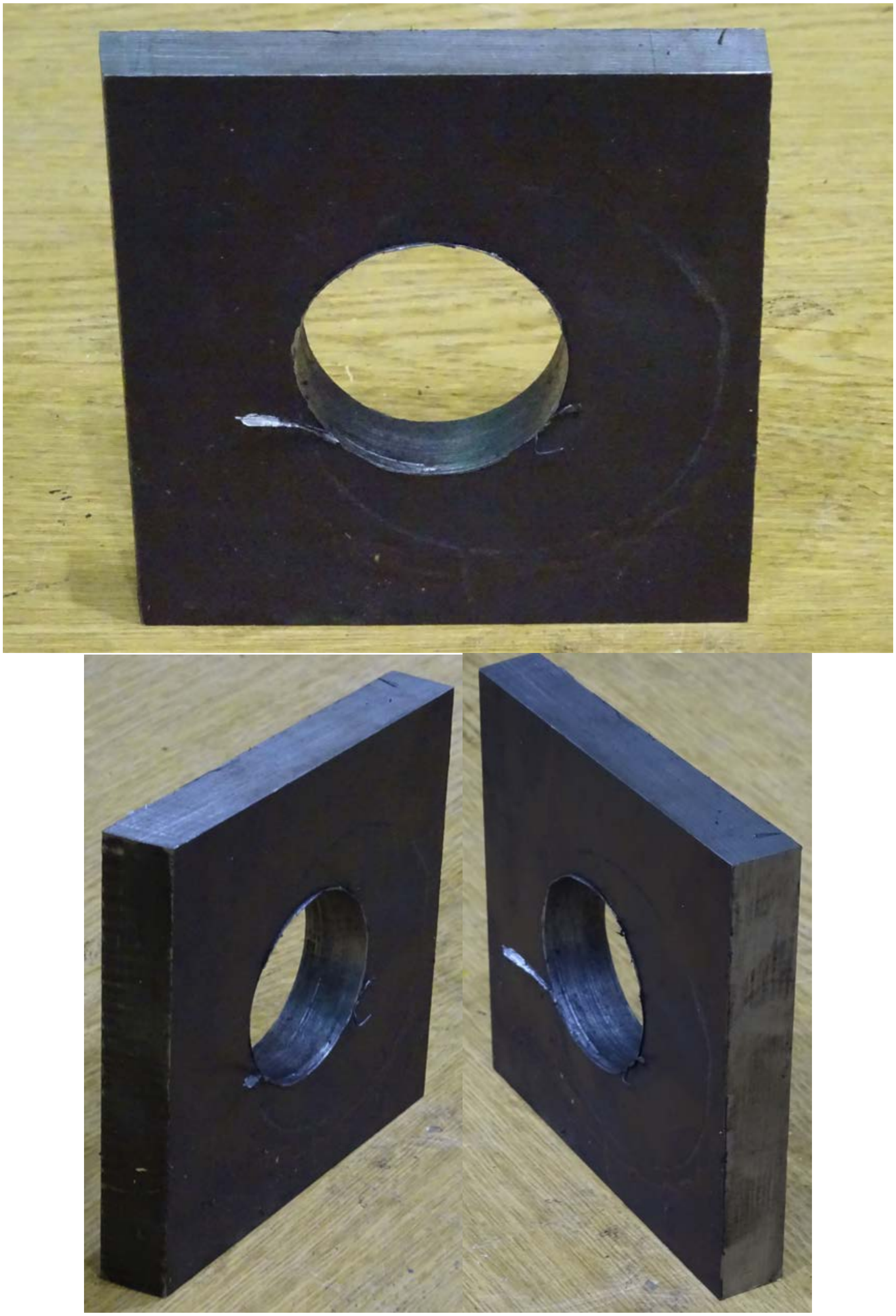

Figure B.64: Test #60 - 6% Relative Deformation

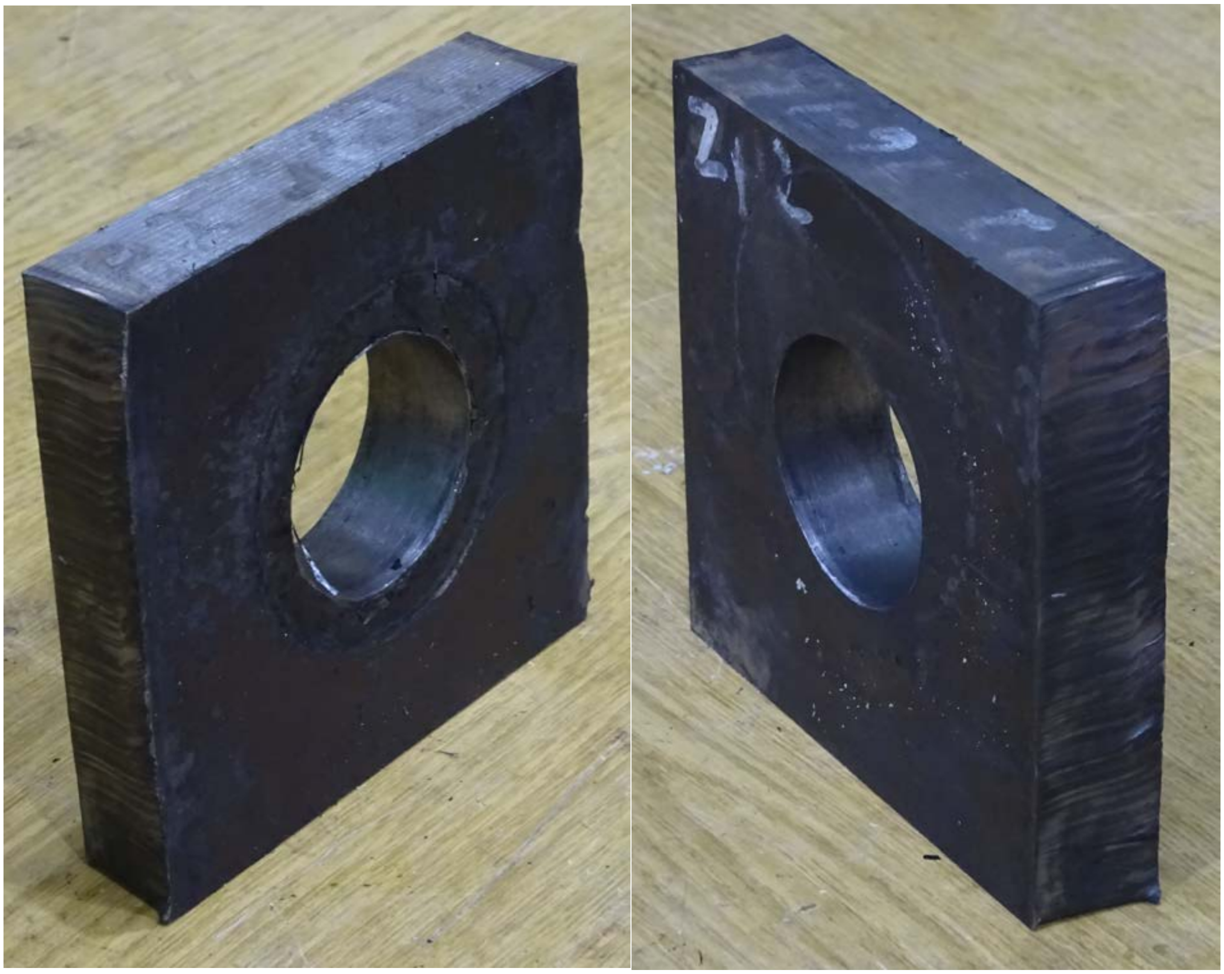

Figure B.65: Test #61 - 3% Relative Deformation

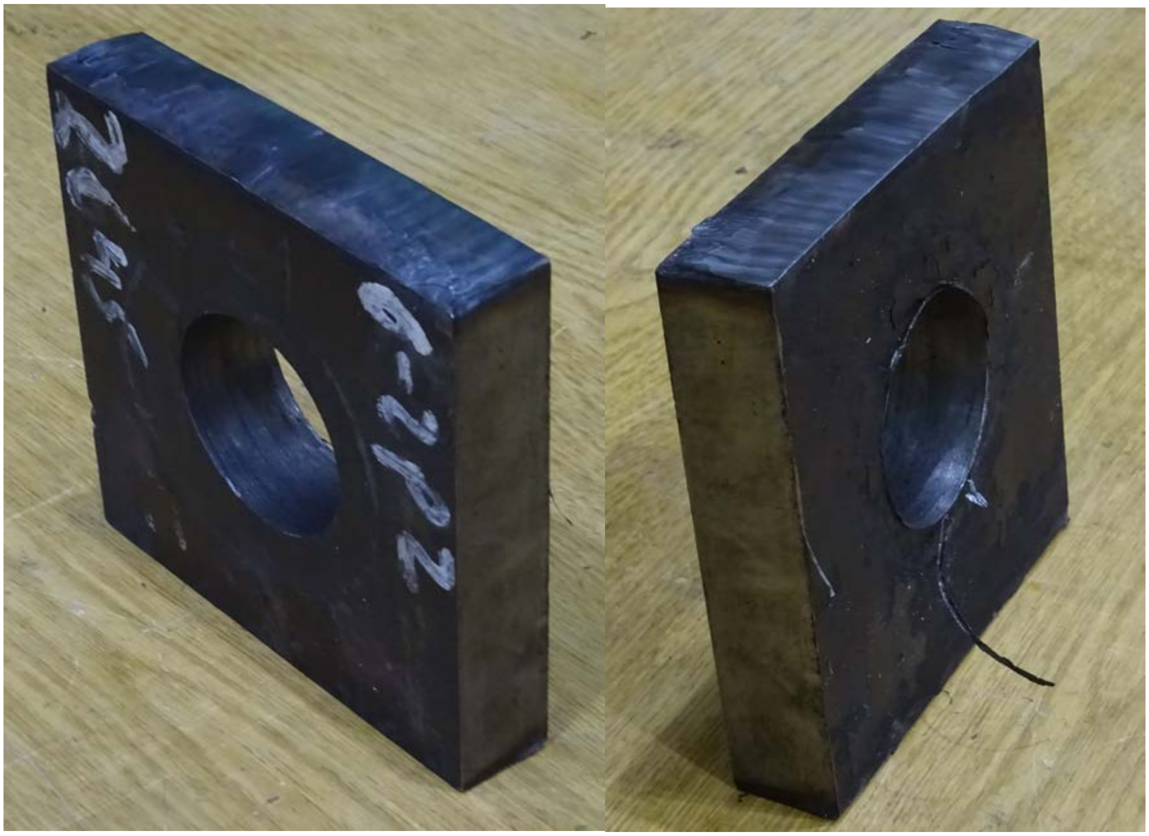

Figure B.66: Test #62 - 6% Relative Deformation

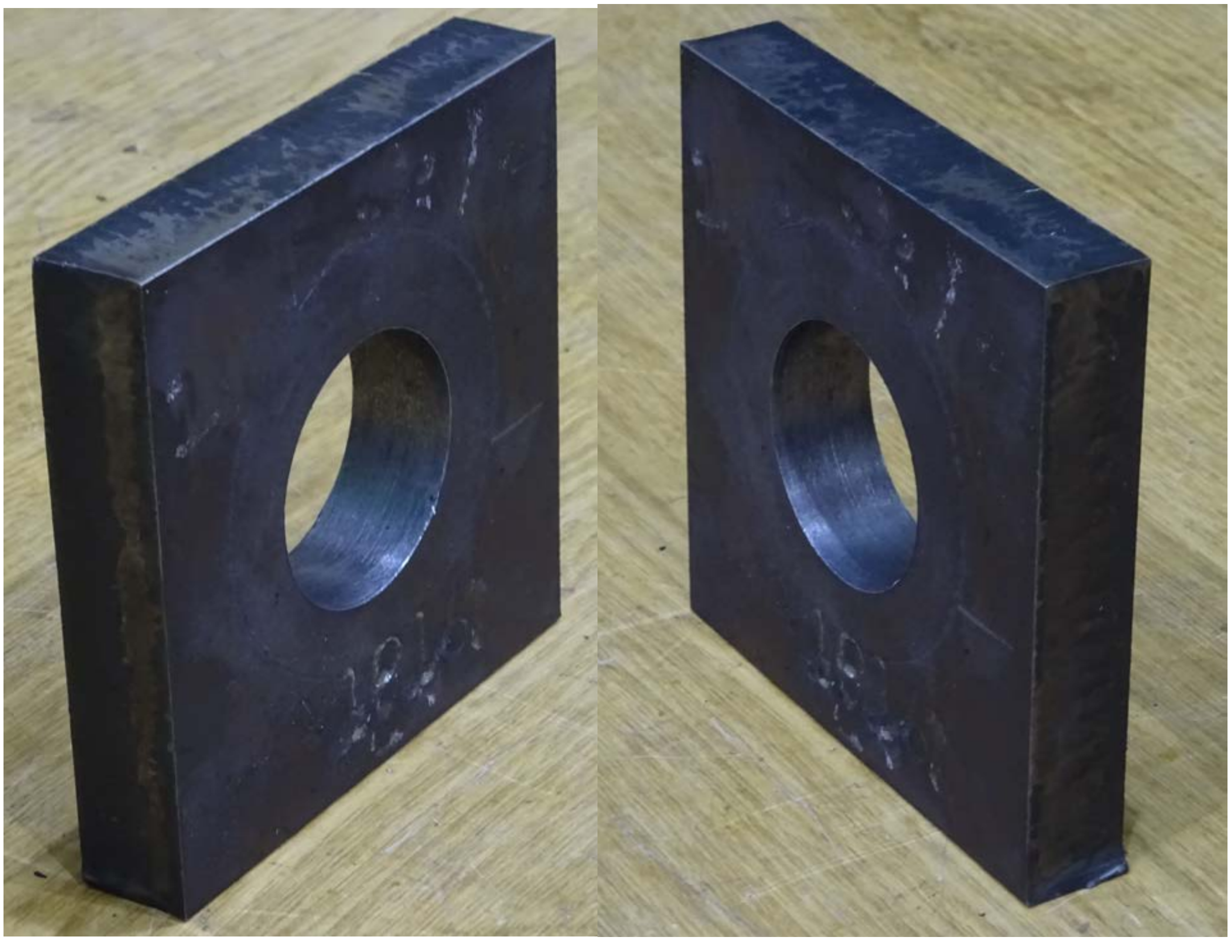

Figure B.67: Test #63 - 4% Relative Deformation

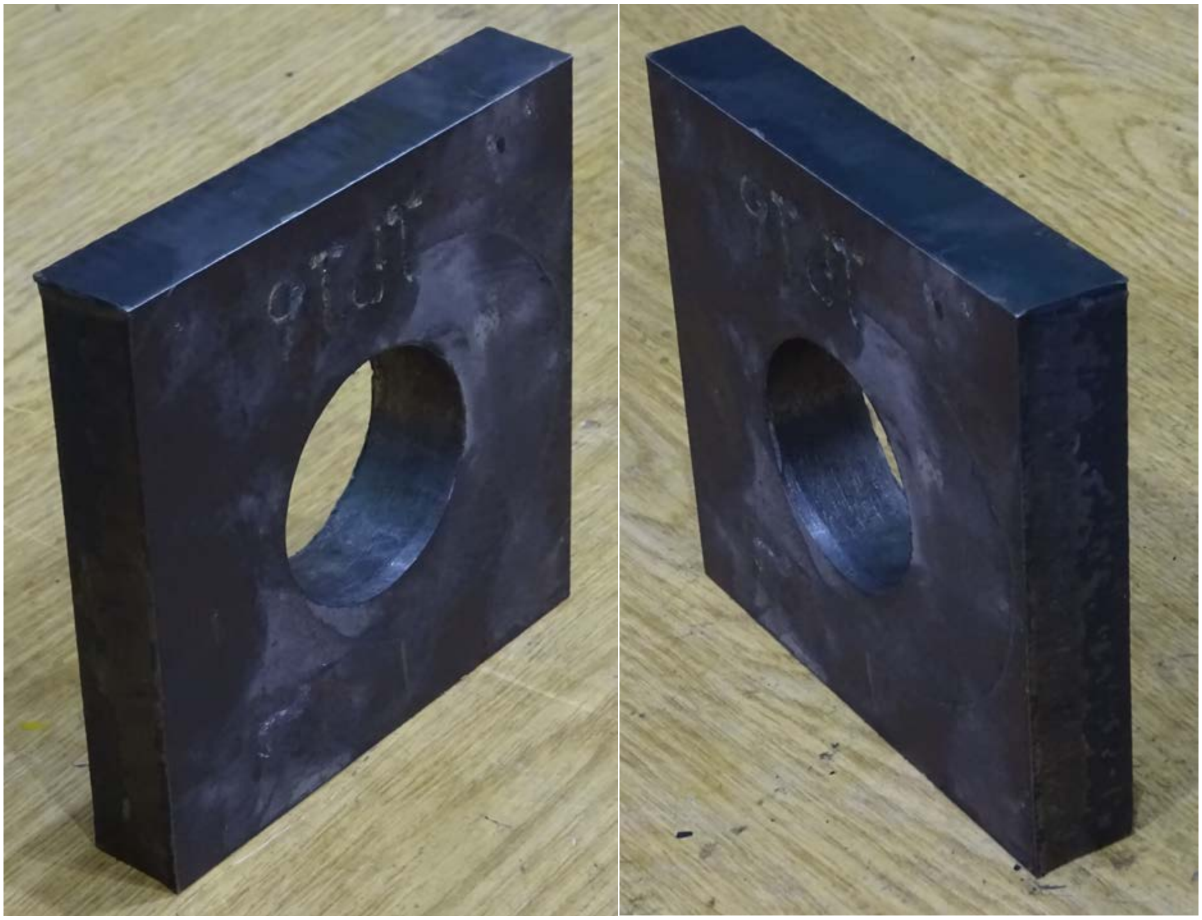

Figure B.68: Test #64 - 7% Relative Deformation

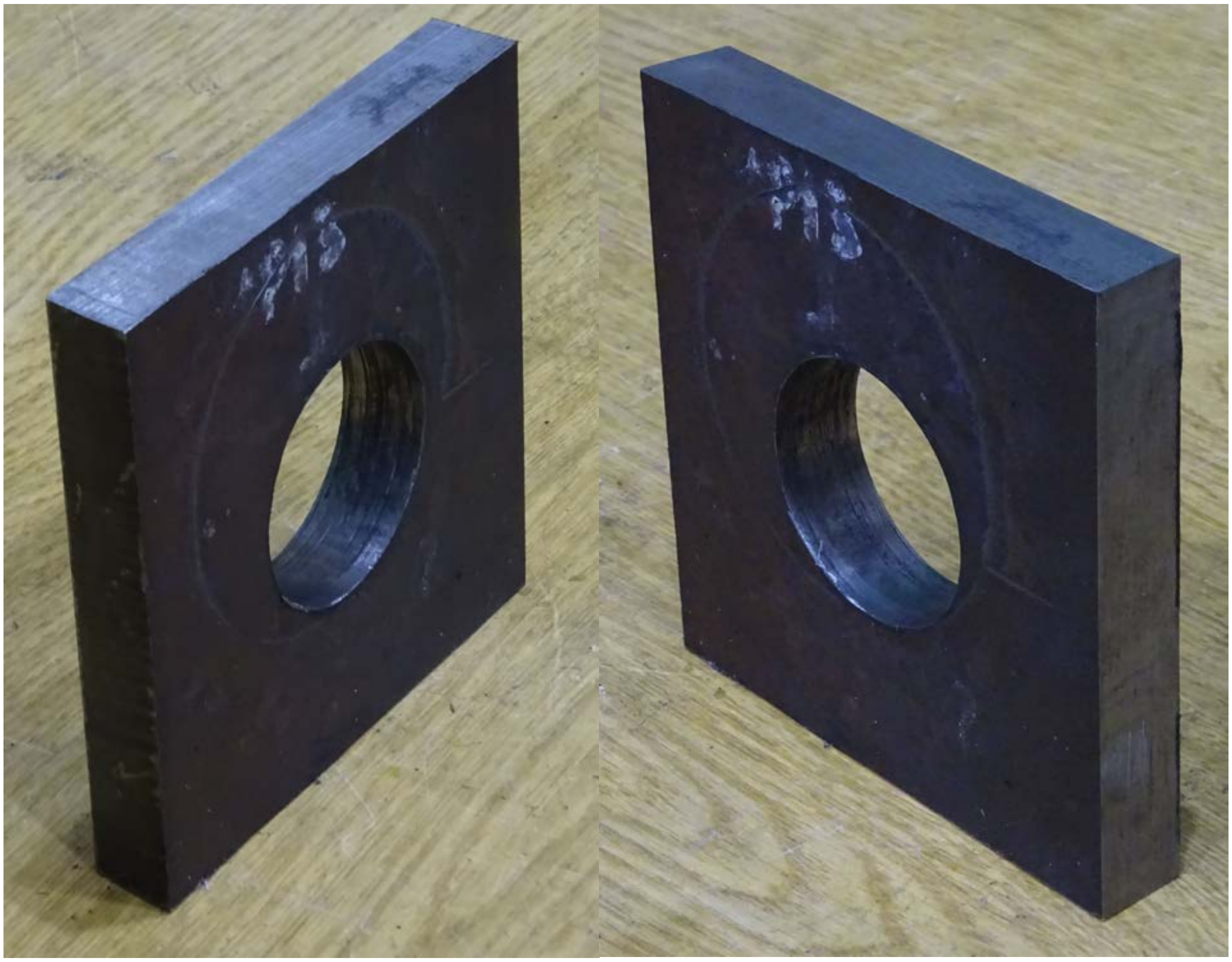

Figure B.69: Test # 65 - 7% Relative Deformation

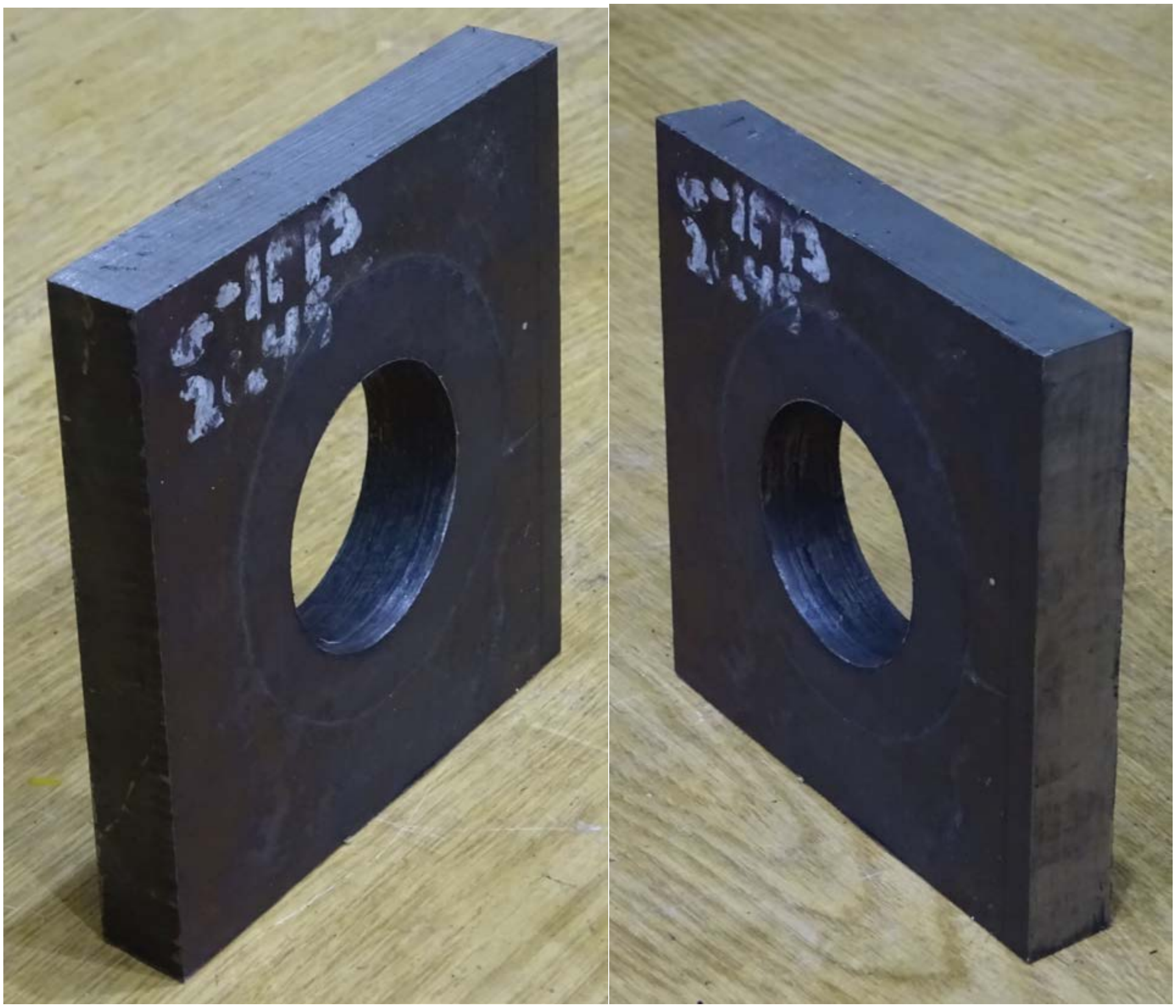

Figure B.70: Test #66 - 7% Relative Deformation

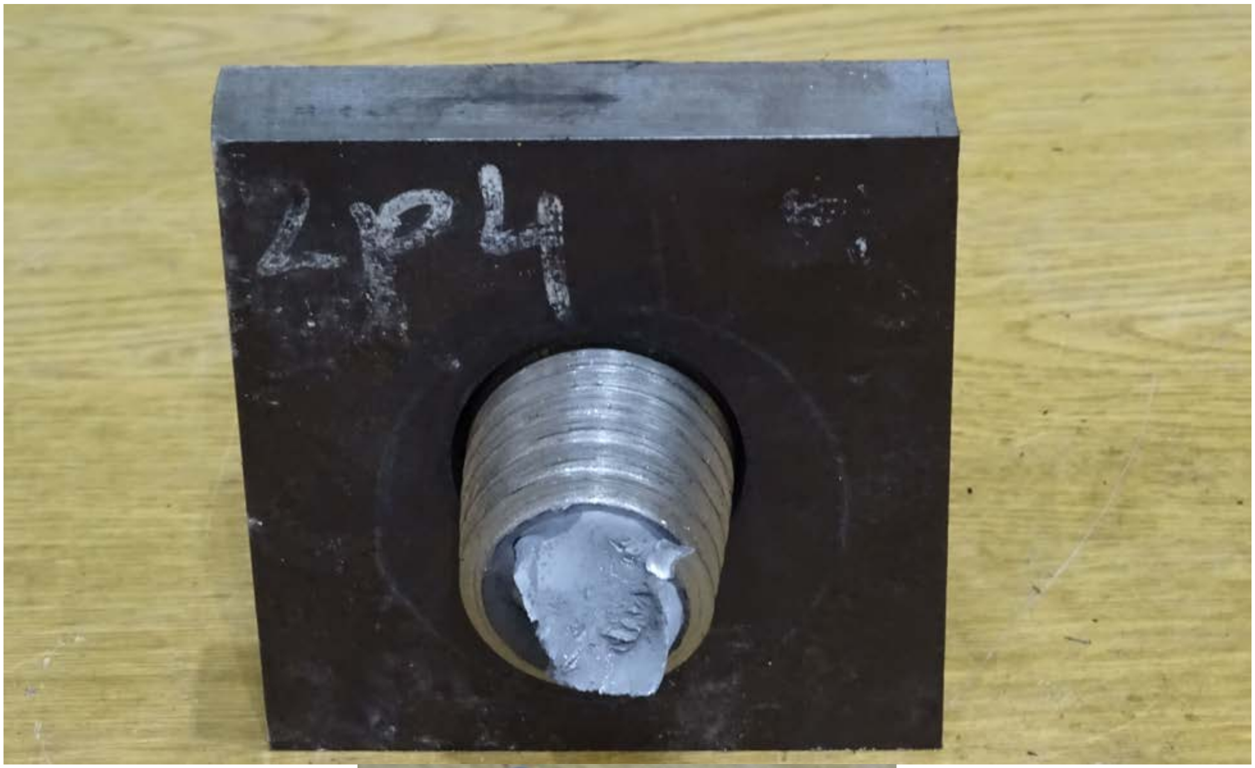

Figure B.71: Test #67 - 3% Relative Deformation

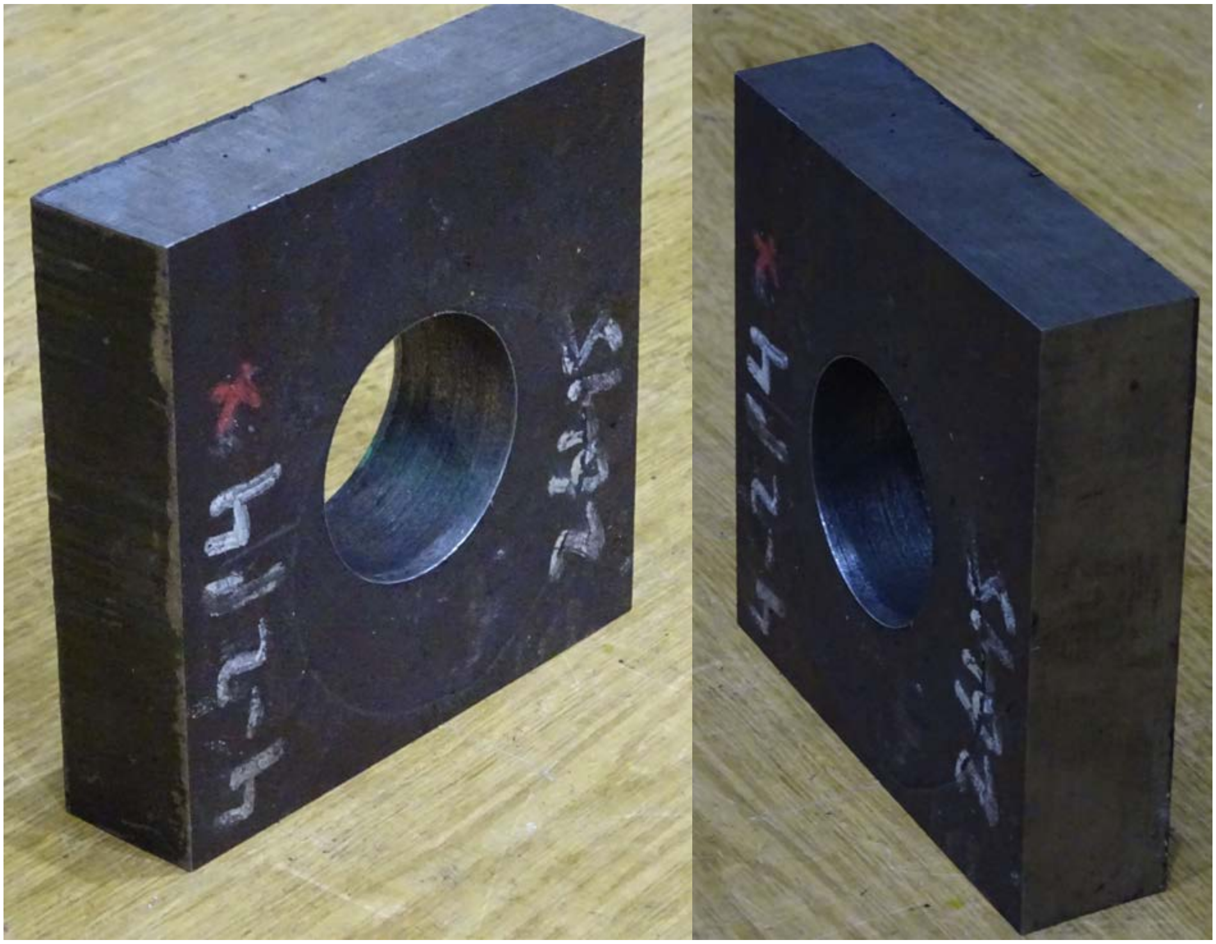

Figure B.72: Test #68 - 4% Relative Deformation

Figure B.73: Test #69 - 8% Relative Deformation

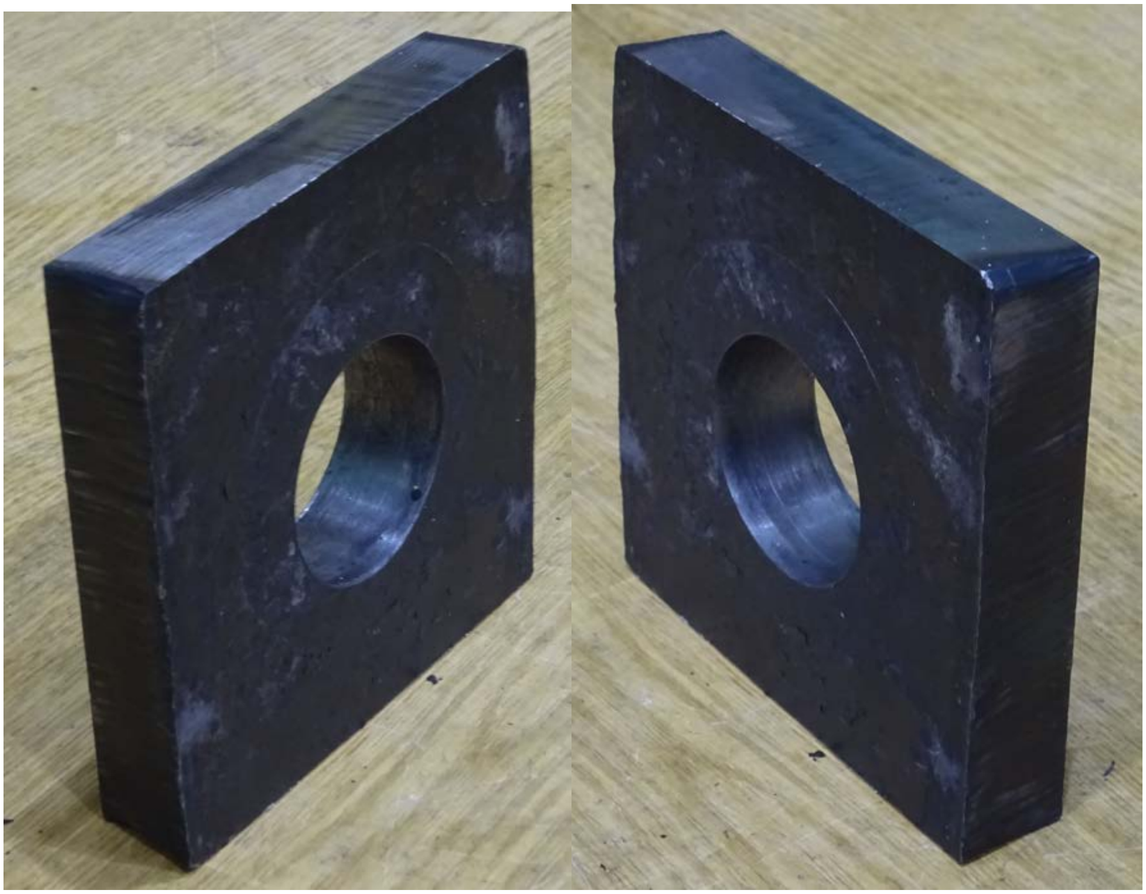

Figure B.74: Test #70 - 5% Relative Deformation

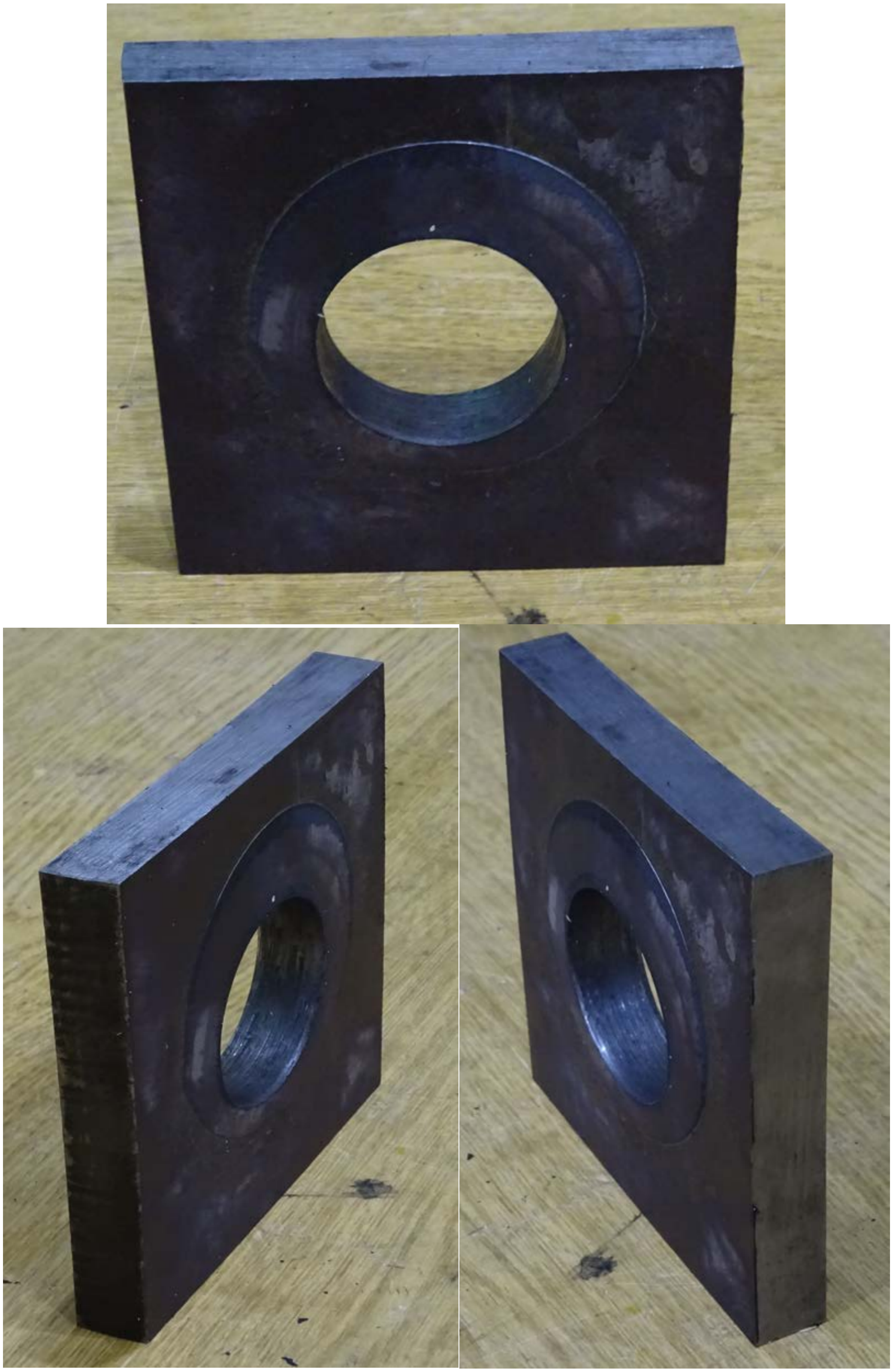

Figure B.75: Test #71 - 16% Relative Deformation

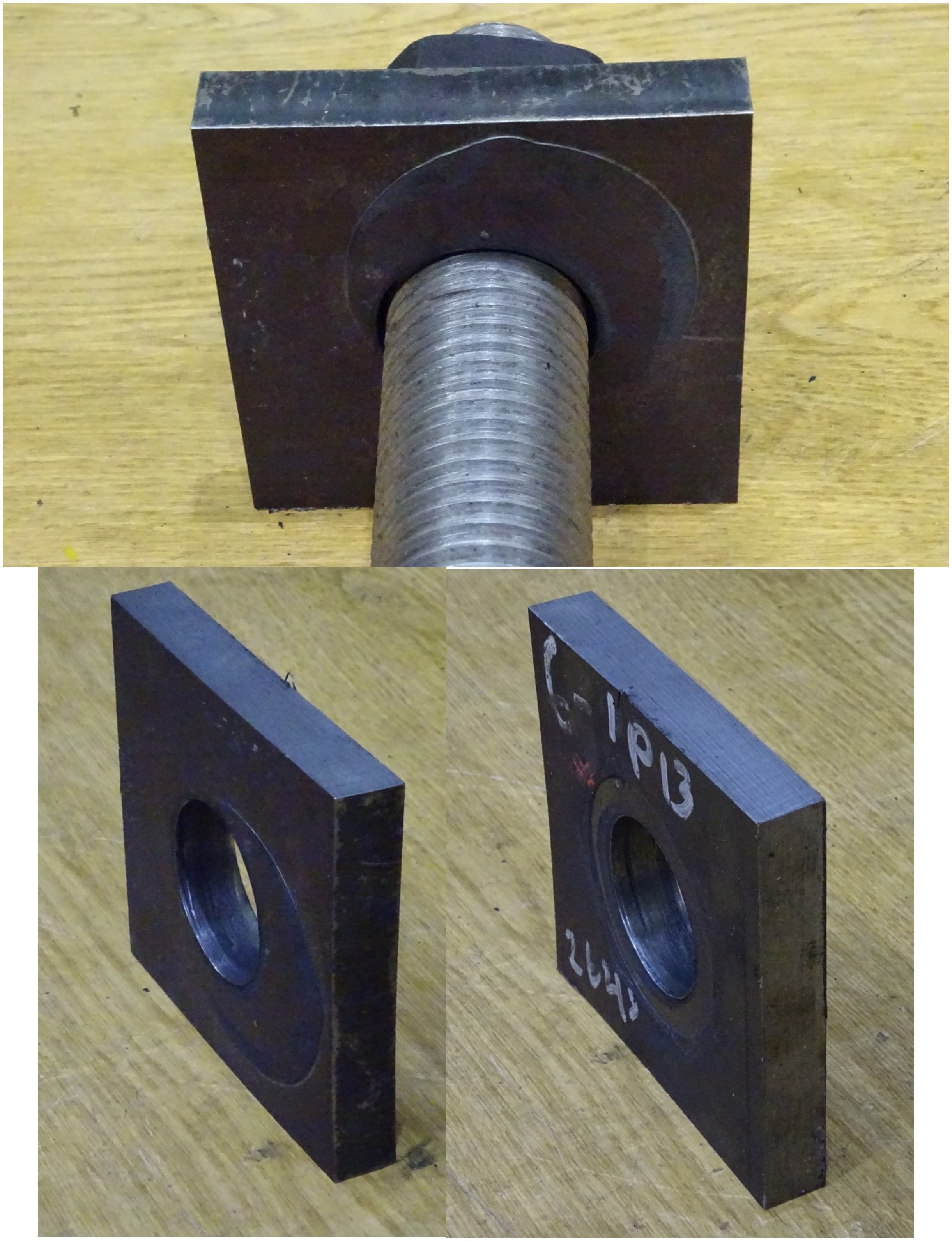

Figure B.76: Test #72 - 19% Relative Deformation

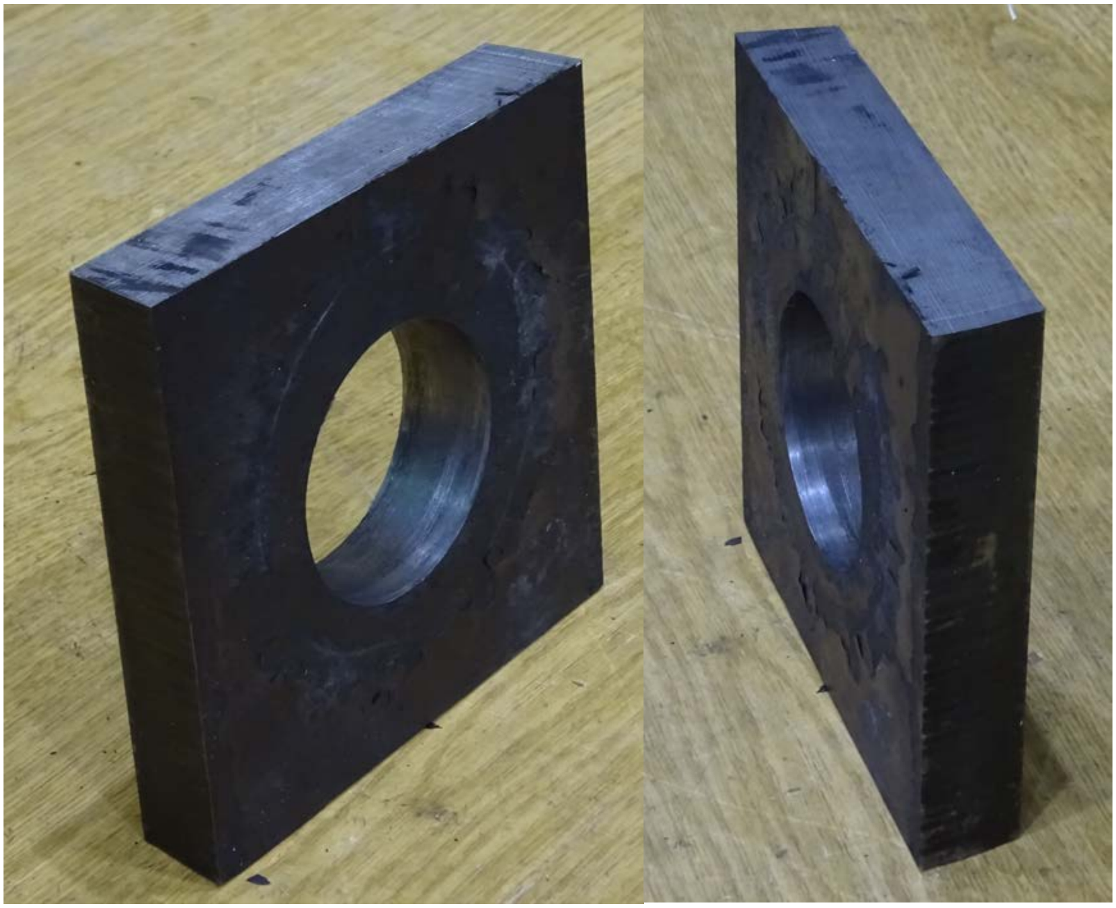

Figure B.77: Test #73 - 6% Relative Deformation

Figure B.78: Test #74 - 5% Relative Deformation

Figure B.79: Test #75 - 12% Relative Deformation

Figure B.80: Test #76 - 9% Relative Deformation

Figure B.81: Test #77 - 9% Relative Deformation

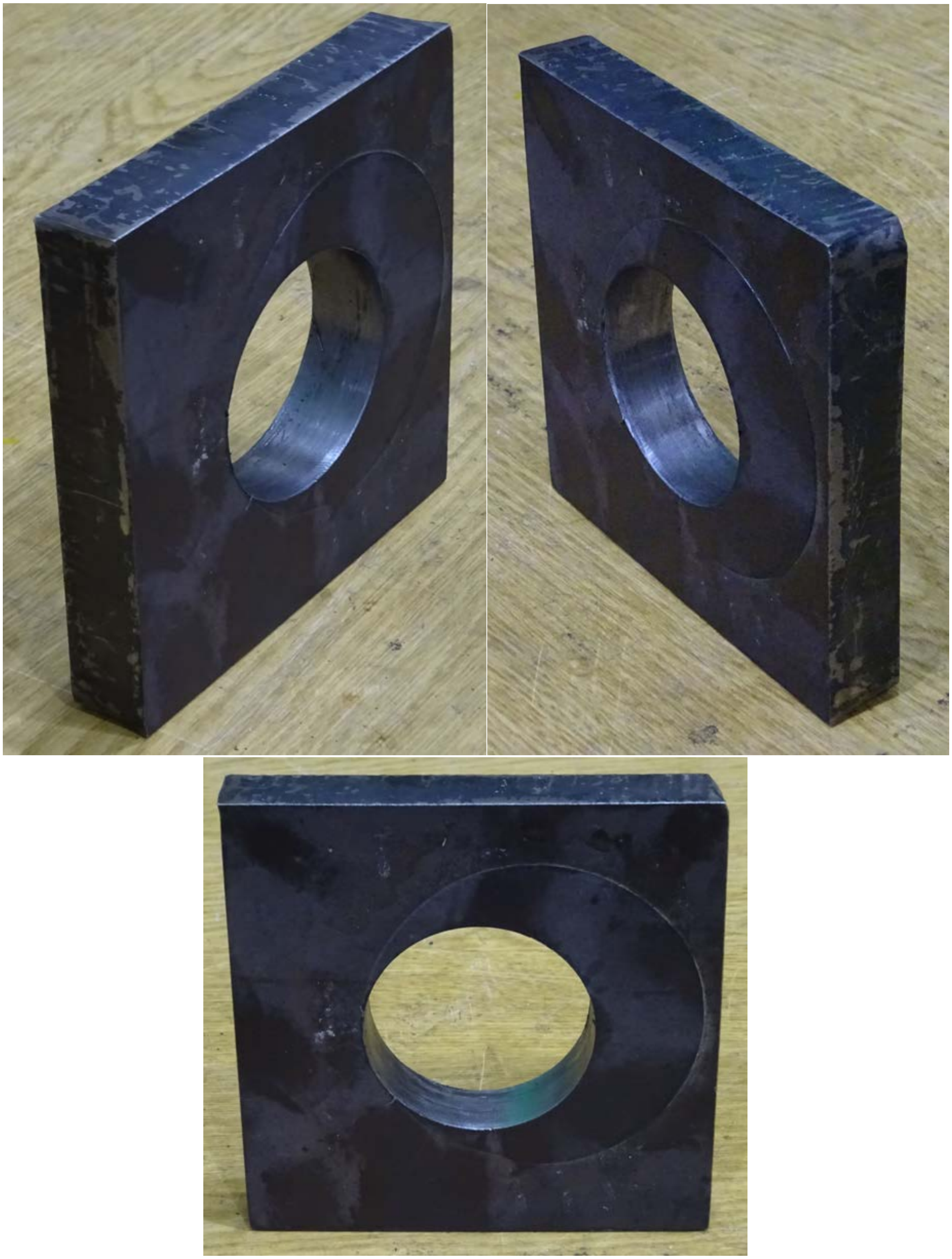

Figure B.82: Test #78 - 12% Relative Deformation

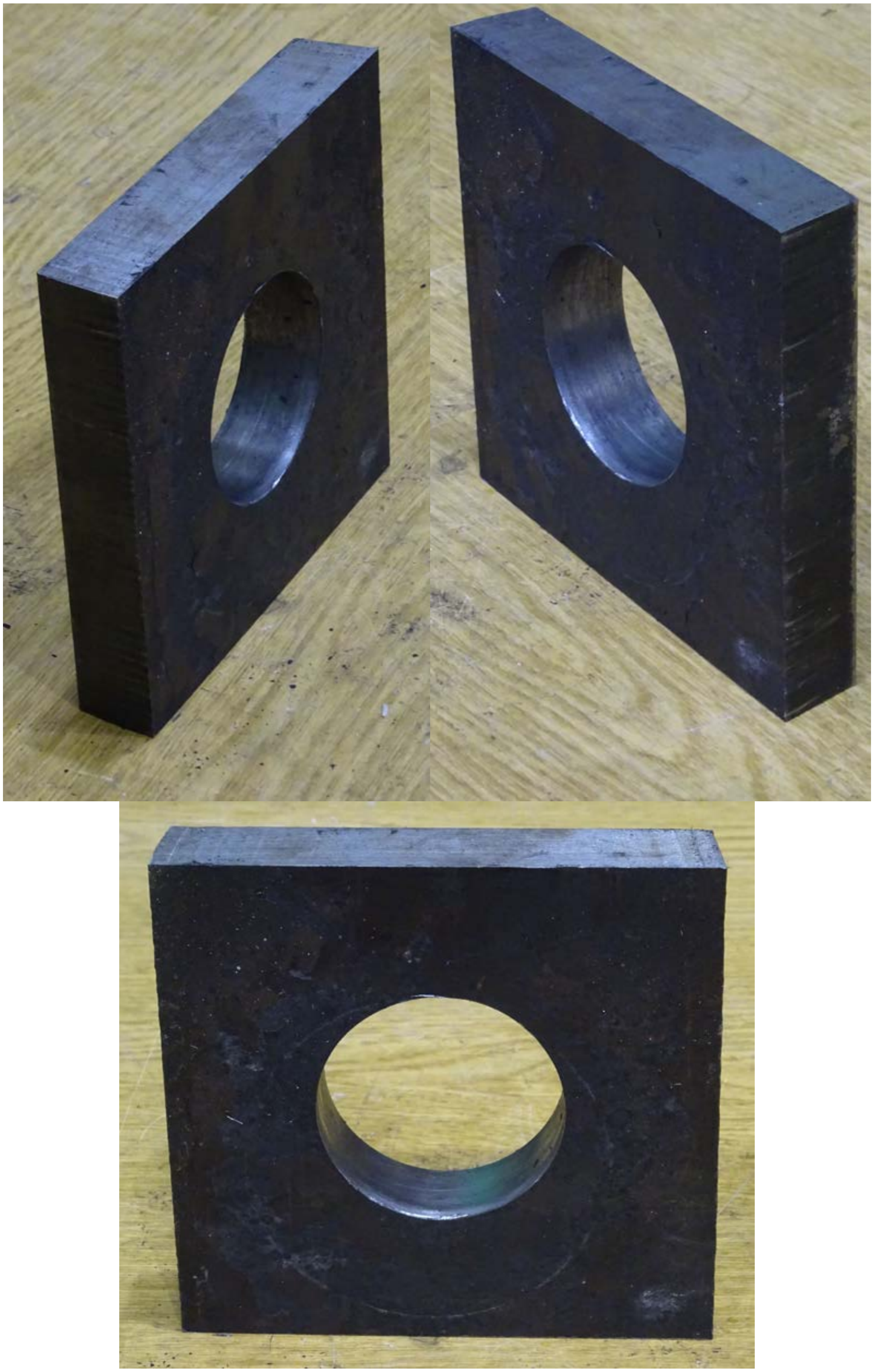

Figure B.83: Test #79 - 3% Relative Deformation

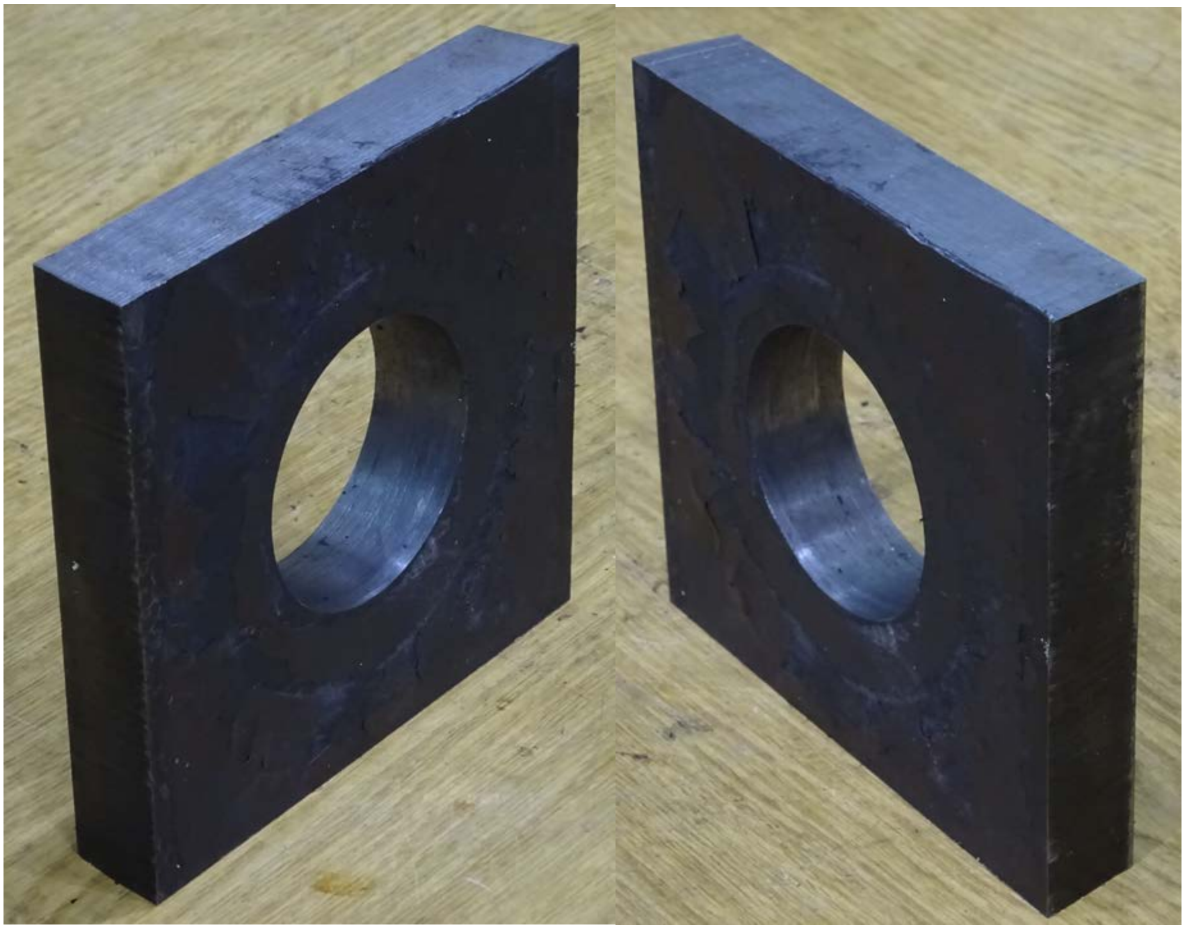

Figure B.84: Test #80 - 4% Relative Deformation

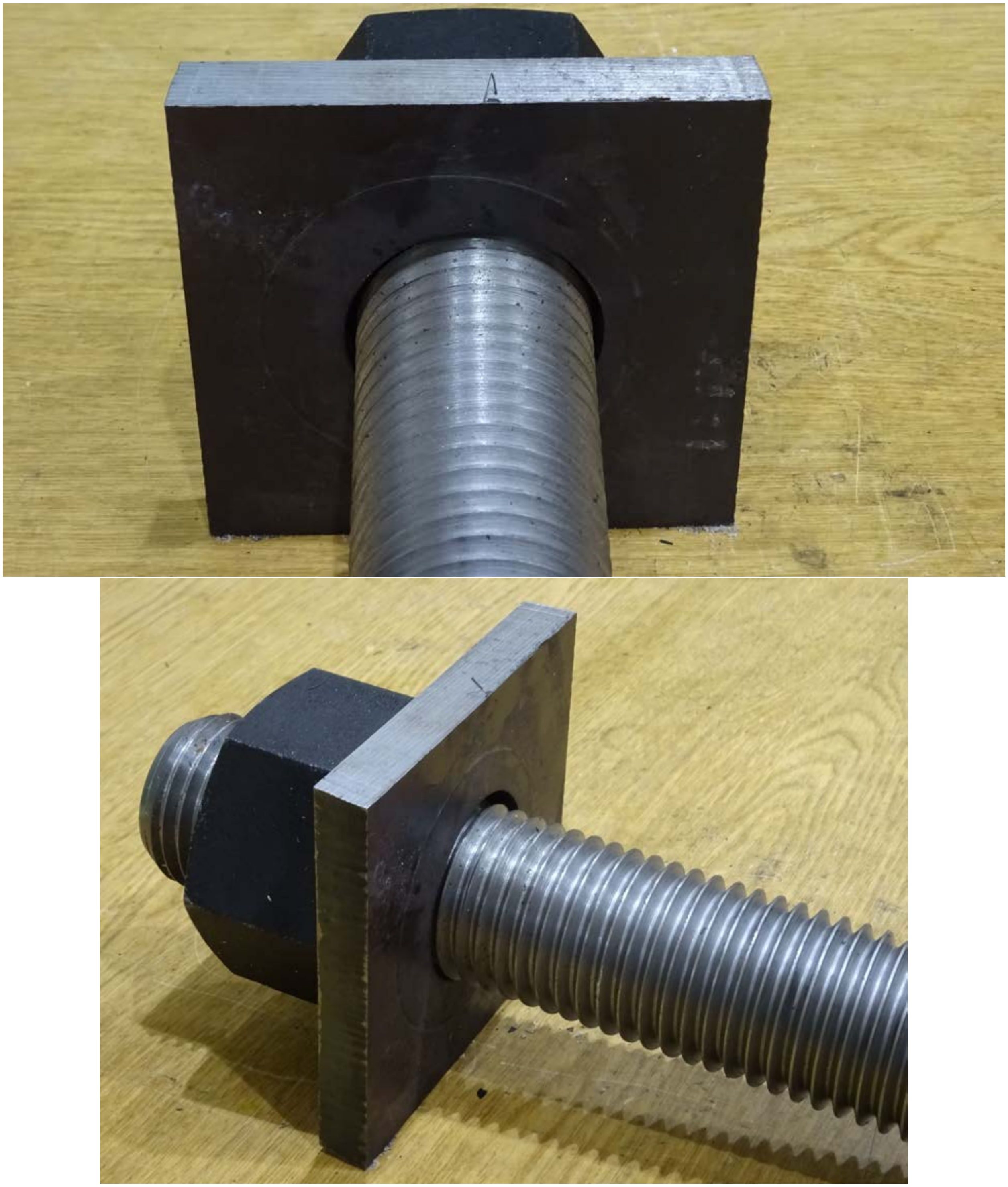

Figure B.85: Test #81 - 7% Relative Deformation

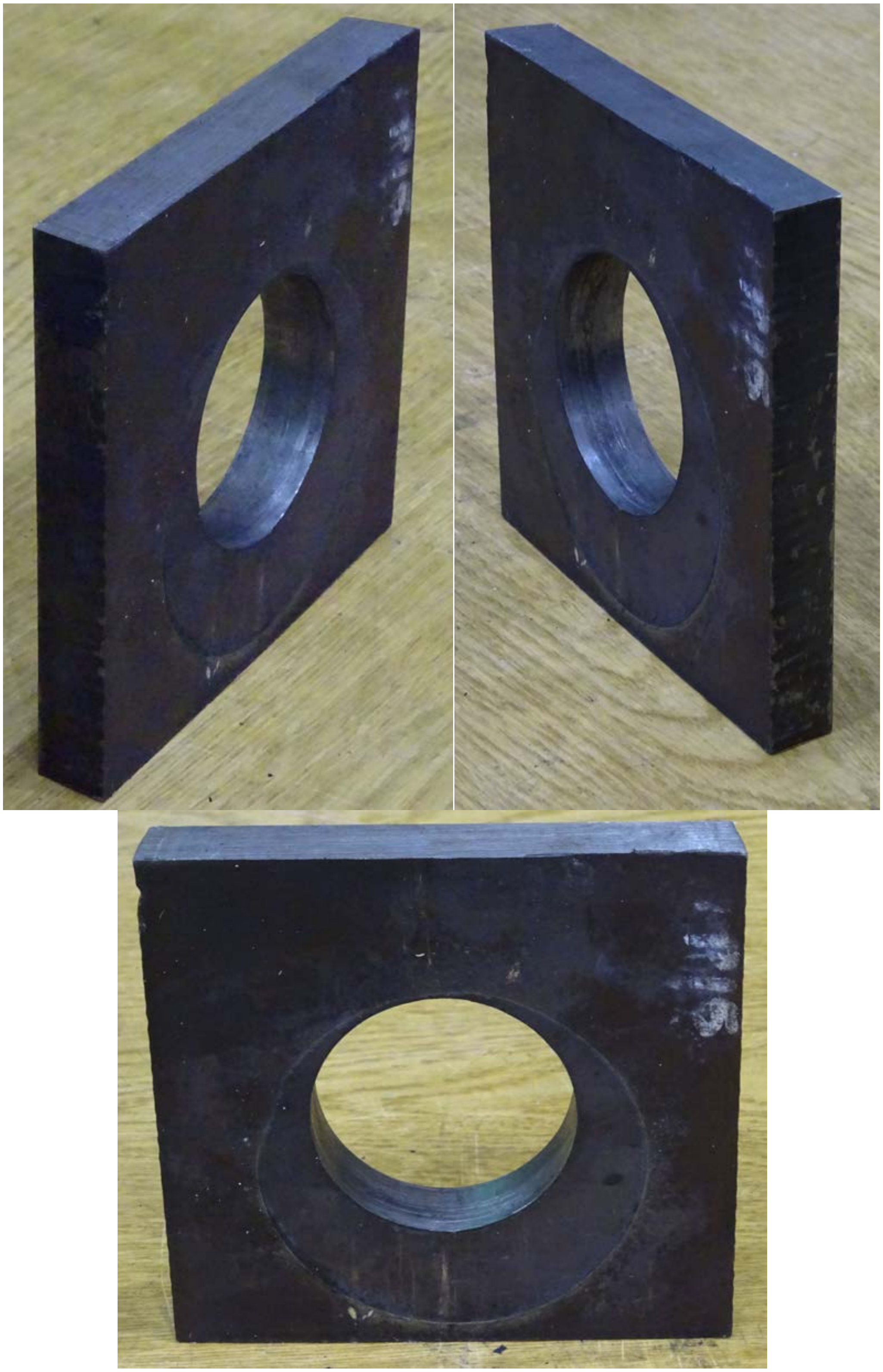

Figure B.86: Test #82 - 12% Relative Deformation

Figure B.87: Test #83 - 1% Relative Deformation

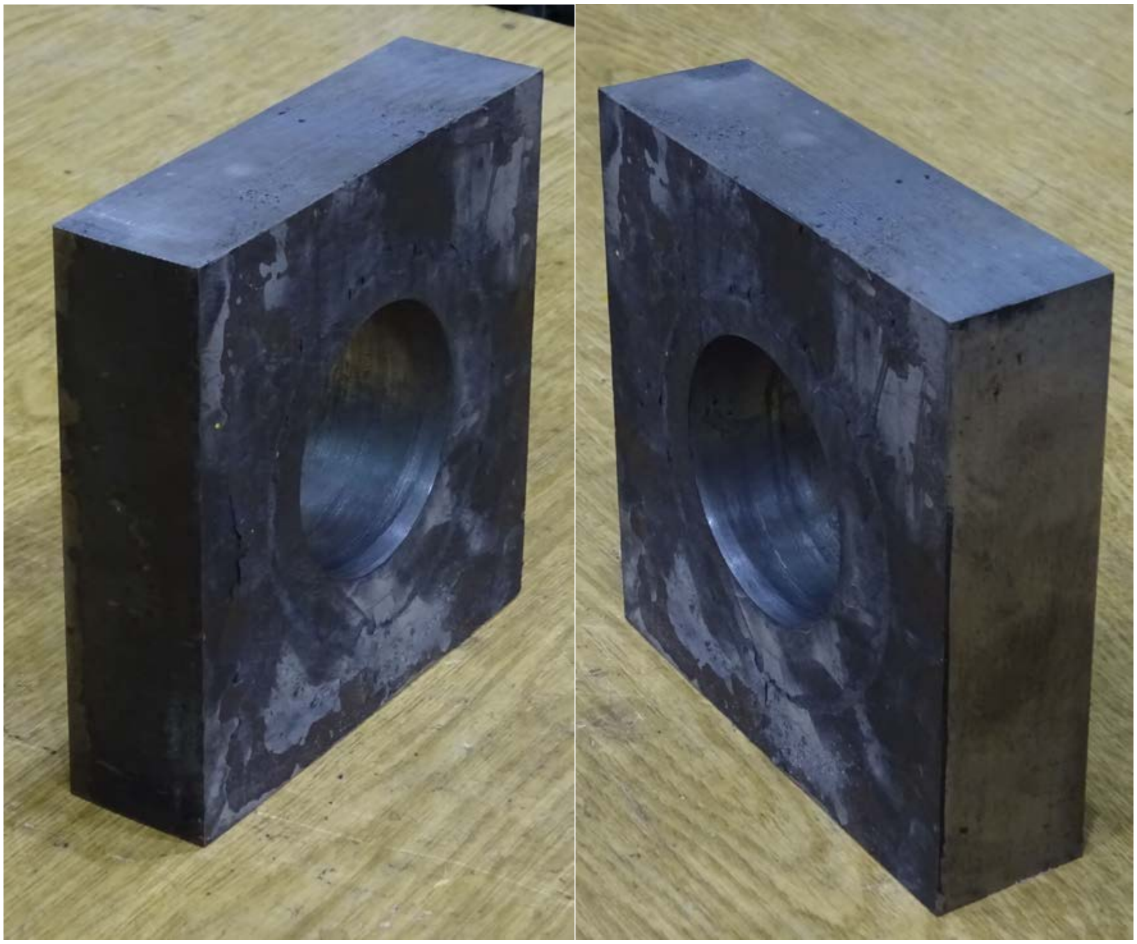

Figure B.88: Test #84 - 2% Relative Deformation

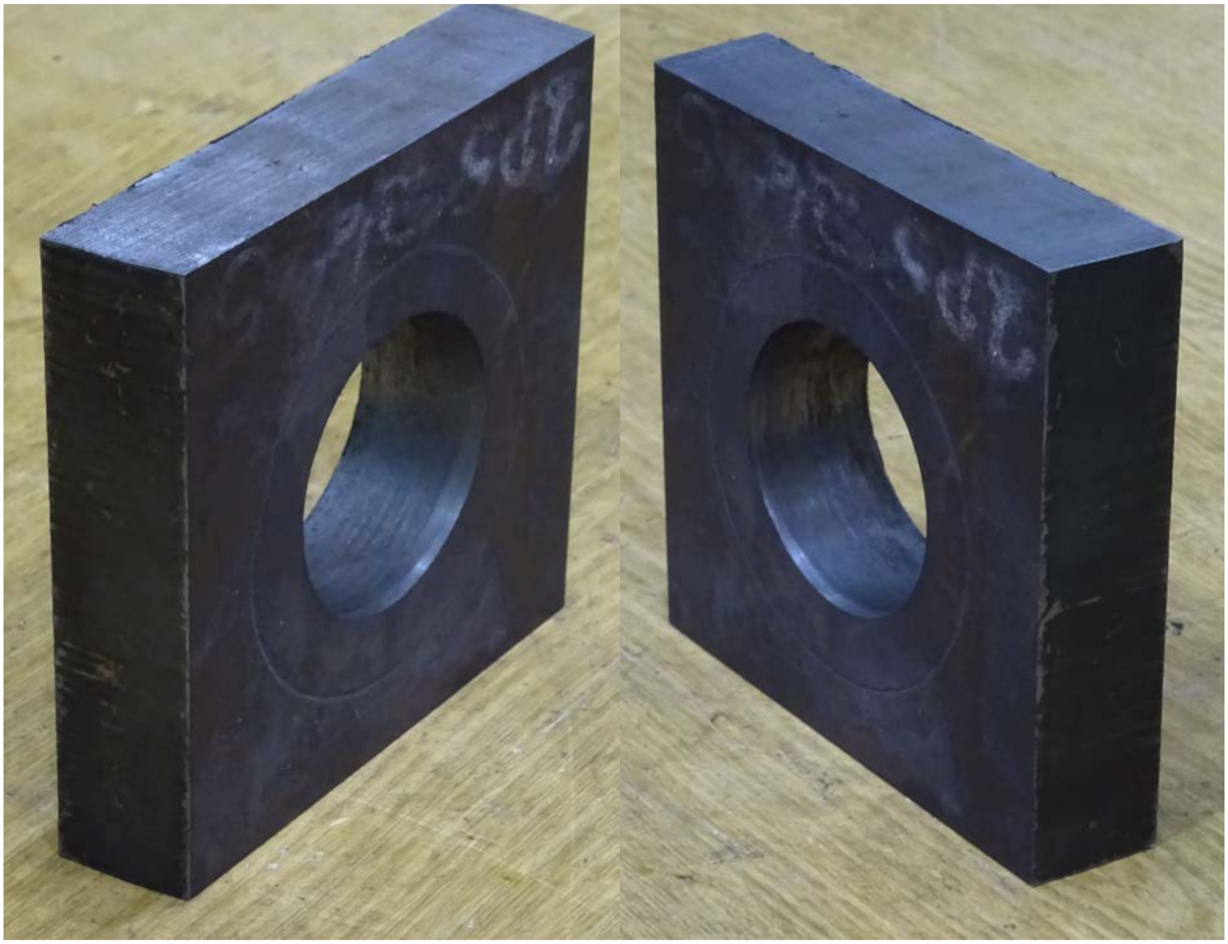

Figure B.89: Test #85 - 4% Relative Deformation

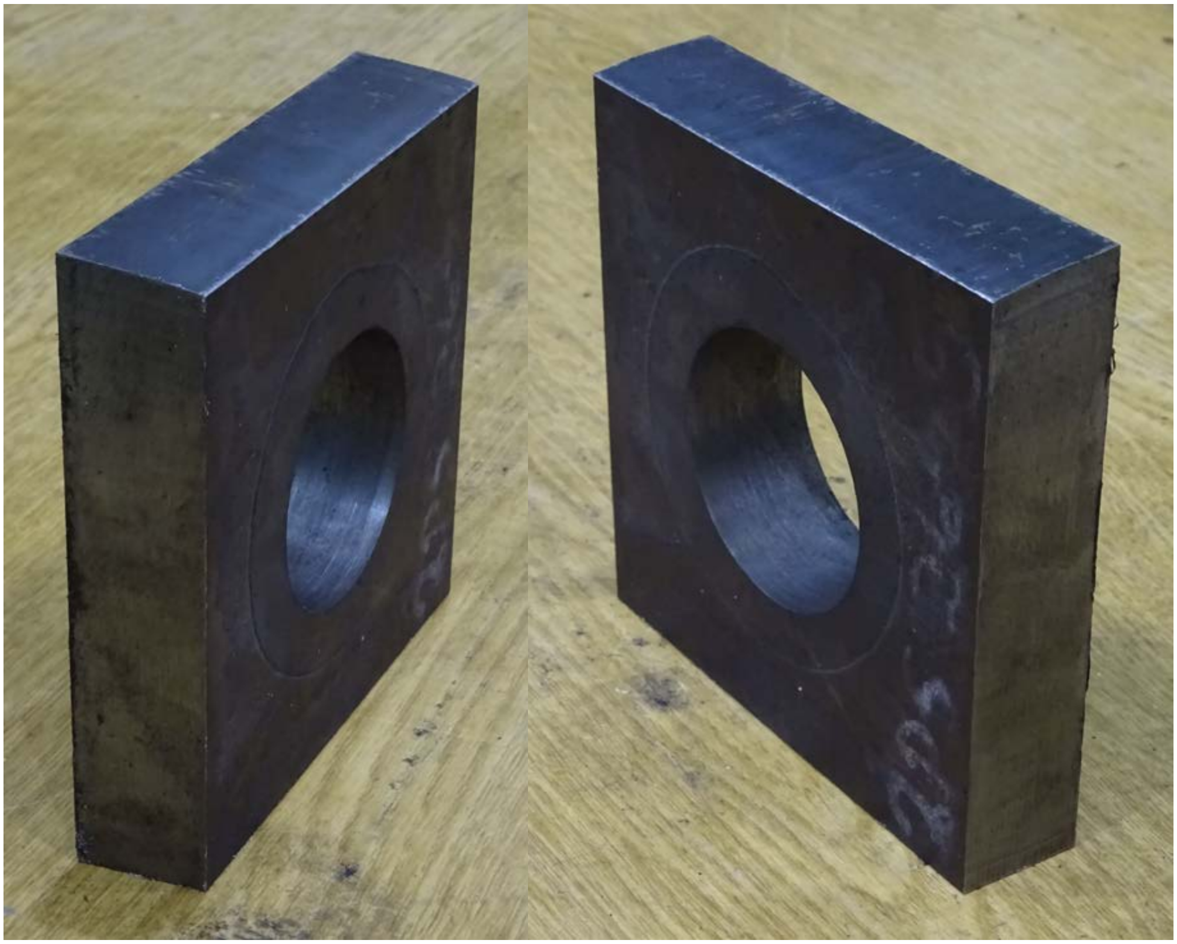

Figure B.90: Test # 86 - 3% Relative Deformation

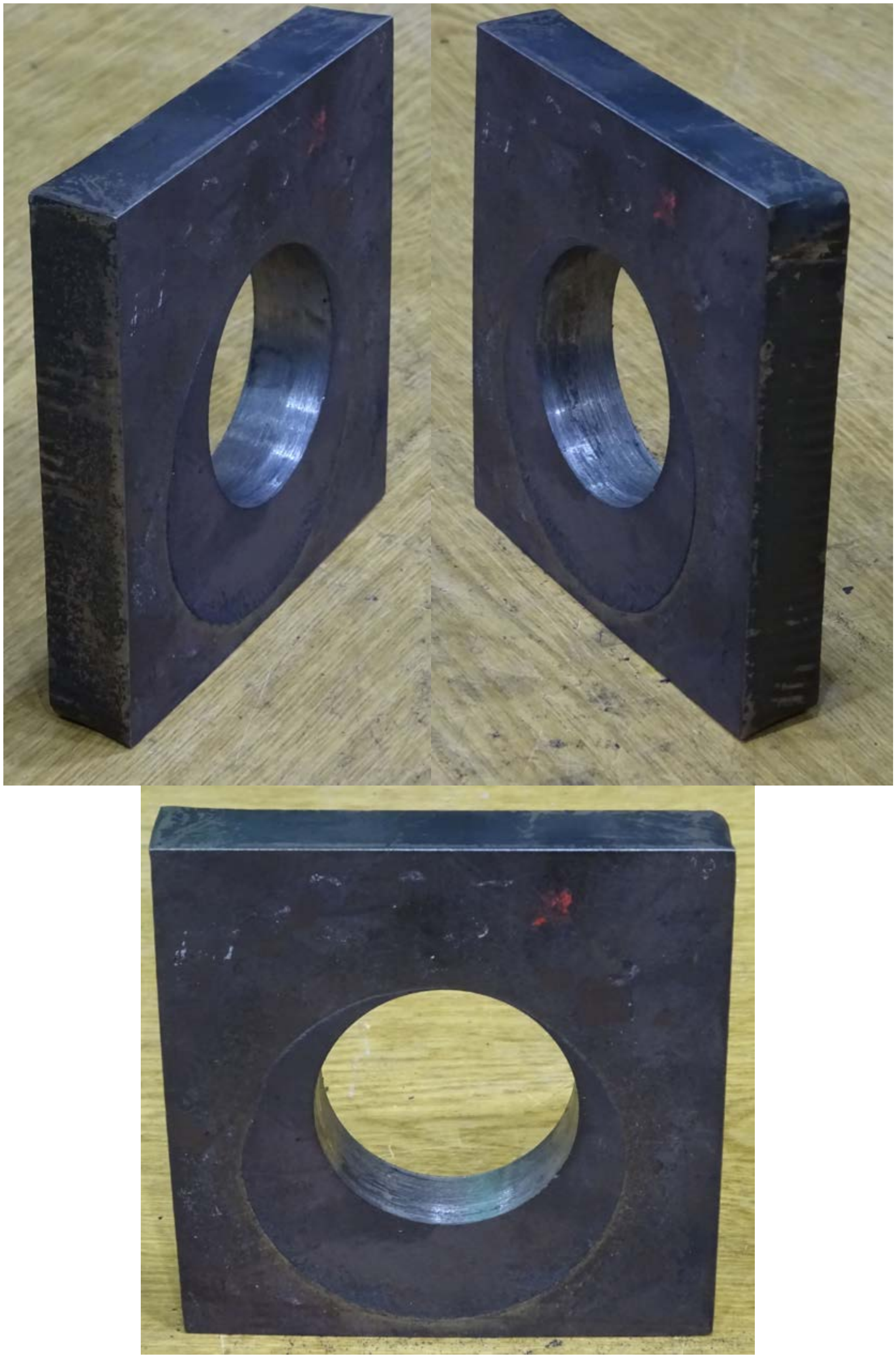

Figure B.91: Test #87 - 13% Relative Deformation

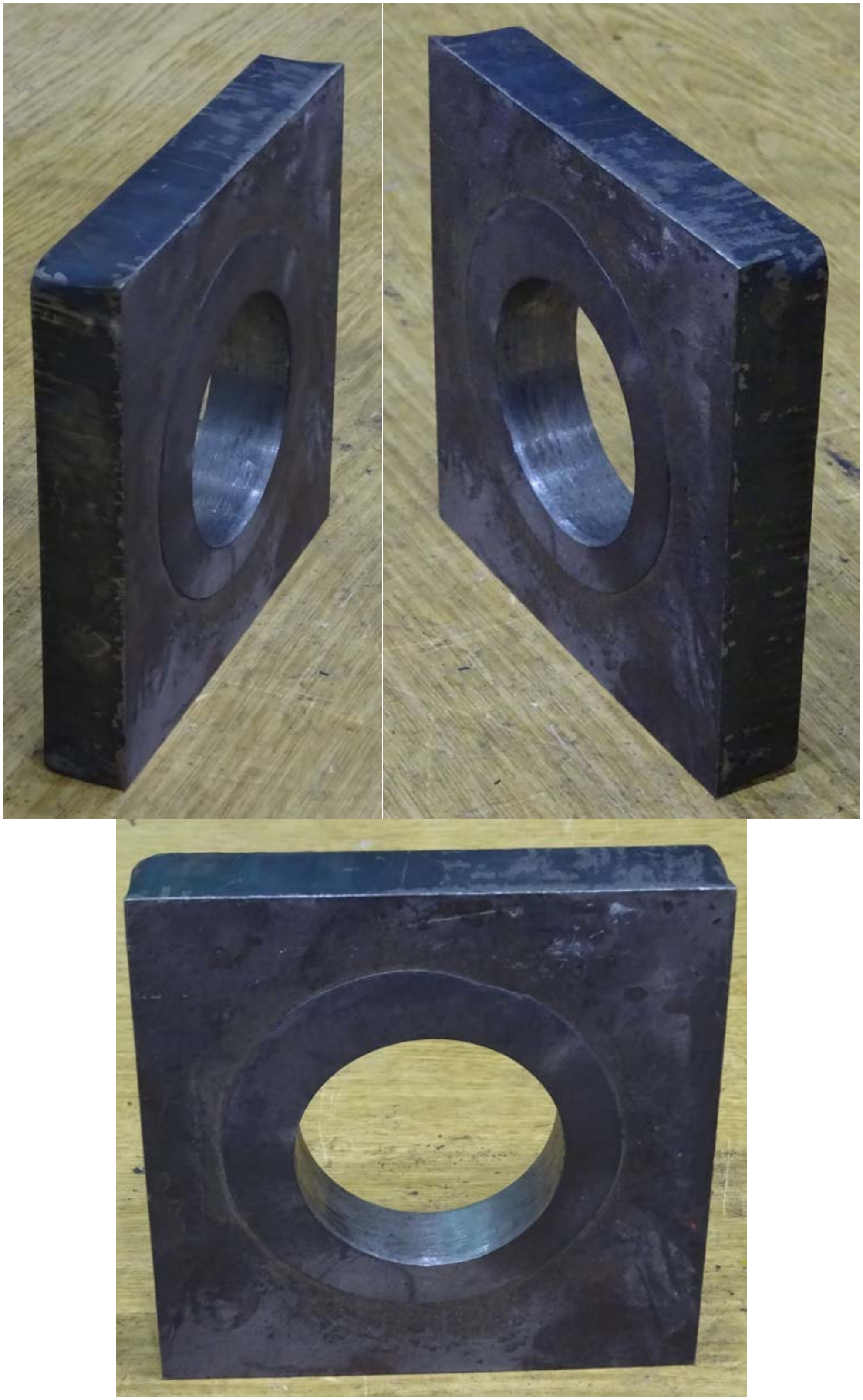

Figure B.92: Test #88 - 9% Relative Deformation

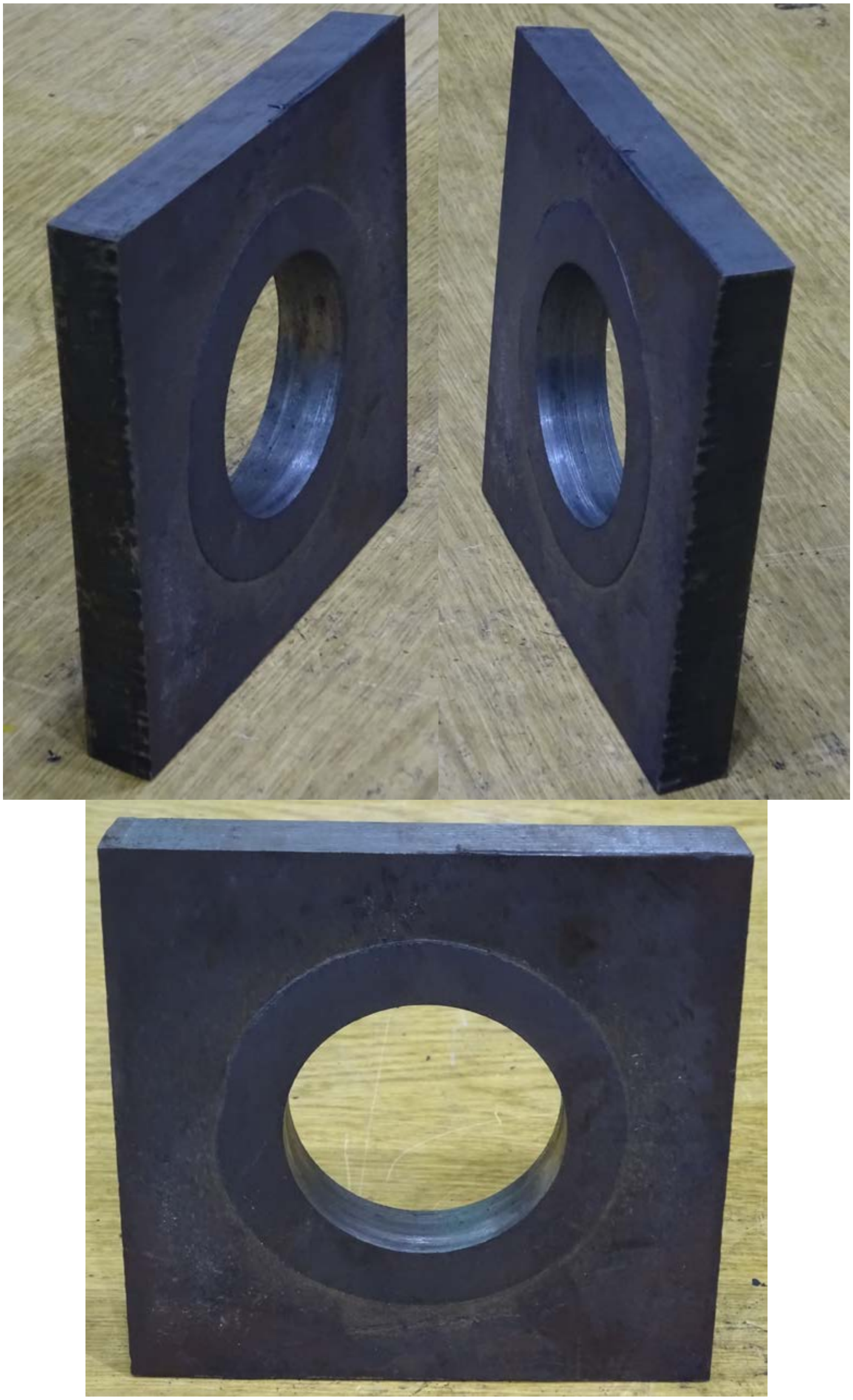

Figure B.93: Test #89 - 10% Relative Deformation

Figure B.94: Test #90 - 17% Relative Deformation