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Optimum Slot Weld Width for Cold-Formed Steel

Emilee A. Martin[1] and Fredrick R. Rutz[2]

Abstract

Slot welds can be used for connections in cold-formed steel (CFS) structures. However, structural engineers will find AISI S100, "North American Specification for the Design of Cold-Formed Steel Structural Members" (AISI 2016) - which can be used for guidance in calculating structural capacity of many welds types - silent on this specific application.

Research at the University of Colorado Denver has been directed toward determination of the strength of slot welds in sheet steel. A comprehensive series of tests were performed to determine structural capacity and ductility of various slot weld widths using a metal inert gas (MIG) welding process. A slot weld connection between two pieces of sheet steel was designed, one with punched slots of various widths, and the other a blank piece to receive the weld. Weldability problems associated with slot welds of various widths on galvanized sheet steel were encountered. The testing program to investigate slot widths to address these concerns is reported upon.

A program of monotonic tension tests was conducted. This testing program built on 1979 research by Pekoz and McGuire at Cornell University for fillet welds on lap joint specimens. While AISI is silent on slot weld design criteria, the authors found certain slot widths were more advantageous than others.

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Introduction

Slot welds can be used for connections in cold-formed steel structures. Slots can be punched in a piece of sheet steel, referred to as a “gusset plate”, which can overlap studs or tracks. AISI S100, “North American Specification for the Design of Cold-Formed Steel Structural Members,” (AISI 2016) which is used by structural engineers internationally, can be used for guidance in calculating structural capacity of many welds types but it is silent on the specific application of slot welds. The aim of this research is to determine the optimum width of slot for such slot welds.

In an August 2017 article from *Structure* magazine, Dr. Roger LaBoube discussed how “in cold-formed steel construction, welding is a viable connection method” (LaBoube, 2017). In cold-formed steel construction, prefabrication of trusses and wall panels is very common. When shop manufacturing is used, welding is a desirable connection joining method because it is faster and more economical than using mechanical fasteners. The governing design standards for welded connections in cold-formed steel (CFS) are AISI S100-16 (AISI 2016) and the Structural Welding Code – Sheet Steel AWS D1.3 (AWS 2008). These standards provide provisions for groove welds, arc spot welds, arc seam welds, fillet welds, flare groove welds, and plug welds.

There are many different welding processes used today, but for the scope of this research Gas Metal Arc Welding (GMAW), also known as metal inert gas (MIG), was the sole process used in this study. The MIG process uses a fed wire at an adjustable speed and an argon-based shielding gas that protects the weld puddle against elements in the atmosphere, including oxygen, hydrogen, and nitrogen. The MIG welds for this testing program were made both manually and robotically.

It is the purpose of this paper to provide test data and design guidance for slot welded connections in CFS with the goal of the determination of an optimum width for slot welds in cold formed sheet steel. Through executing a comprehensive variable width slot weld study an optimum slot width was determined.

Description

Tests of welded connections were conducted by J.R. Harris & Company in 2017. A connection using 14 gage metal, welded at punched slots to 16 gage metal, was designed. The test configuration was designed to be on a simple rectangular sheet.

All weld tests were conducted at the University of Colorado Denver (UCD) Structures Laboratory in Denver, CO using a 20-kip MTS testing machine. A total of 40 weld specimens were tested. All tests were run in monotonic tension under displacement control at a rate of 0.006"/sec (0.152mm/sec).

Recognizing that narrow slots present weldability concerns related to welder tip access into the slot and wide slots present weldability concerns related to burn-through of the lower sheet, a study of multiple slot widths was conducted. The purpose of this research was to determine an optimum slot width in an attempt to balance weldability, fusion, and strength, all with the goal of achieving an optimum width.

Both the 14 and 16 gage plates were 4" (102mm) wide by 10" (254mm) long, as shown in Figure 1. Each connection consisted of one slot of variable width by 2" long (51mm). The testing program included the following four variable slot widths: 1/8" (3.18mm), 3/16" (4.76mm), 1/4" (6.35mm), and 3/8" (9.53mm). The design of the test is shown in Figure 1 and a photo of a typical slot width test specimen is shown in Figure 2. Variable manual welding parameters for the widths under consideration are summarized in Table 1.

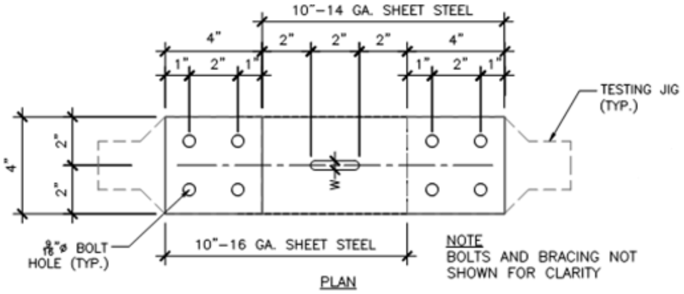

Figure 1. Variable slot width test specimen arrangement design.

Figure 2. Typical slot weld test specimen, consisting of a 14 gage sheet slot welded to a 16 gage sheet, mounted in the bracing jig and installed in a 20 kip (89 kN) MTS testing machine.

Table 1. Welding parameters used for the variable slot weld widths (manual).

Slot width x length in. (mm)	Voltage V	Wire feed speed in. / min (mm/min)	Weld pattern
1/8 x 2 (3.175 x 50.8)	18.3	320 (8128)	Straight push
3/16 x 2 (4.76 x 50.8)	18.0	305 (7747)	Small loops
1/4 x 2 (6.35 x 50.8)	17.6	300 (7620)	Weave
3/8 x 2 (9.525 x 50.8)	17.0	290 (7366)	Weave
3/8 x 2 (9.525 x 50.8)	16.5	290 (7366)	3 Fillet Weld Passes

Results

A typical graph of the displacement vs. time is shown in Figure 3. A typical load developed vs. time graph and typical load developed vs. displacement graph are shown in Figure 4 and Figure 5. Graphs summarizing the data shown in Figure 6, Figure 7, Figure 8, and Figure 9, followed by a brief discussion of the results. The average maximum strength achieved for each monotonic test group is shown in Table 2.

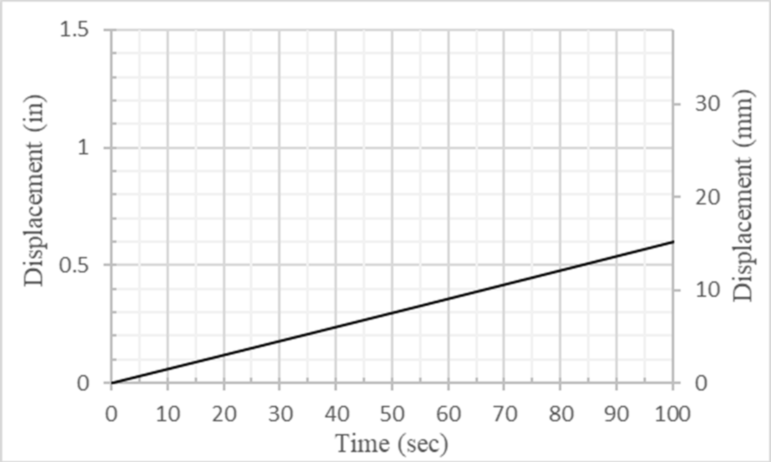

Figure 3. Graph of displacement vs. time. The testing protocol was monotonic tension using displacement control at the rate of 0.006 inches (0.152mm) per second.

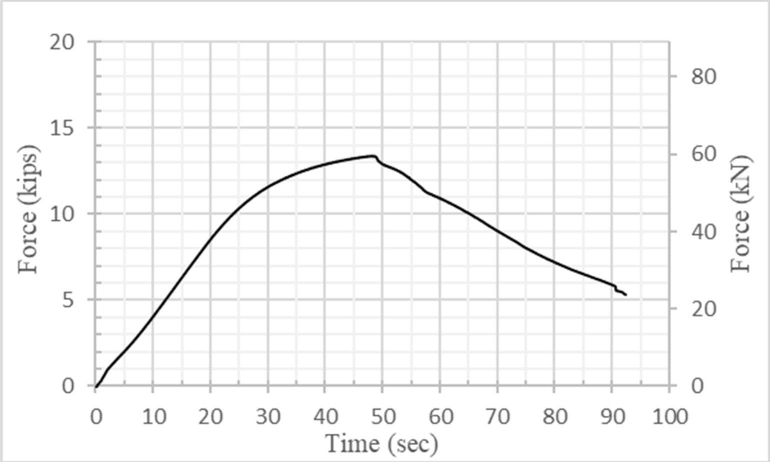

Figure 4. Typical graph of load developed vs. time

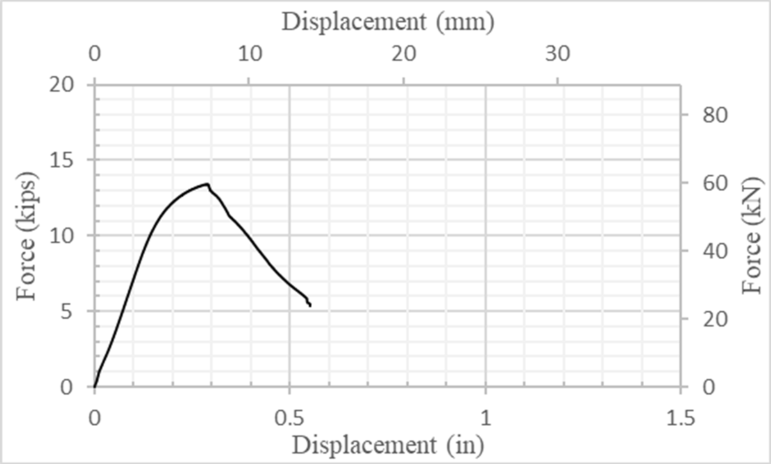

Figure 5. Typical graph of load developed vs. displacement

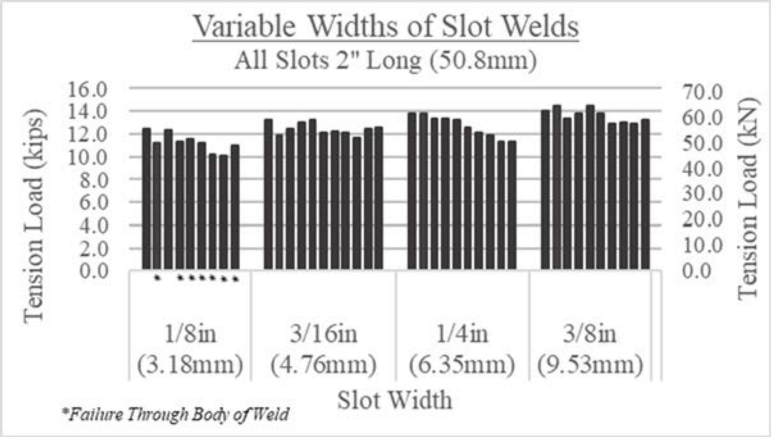

Figure 6. Tension load results for variable slot widths. The specimens are grouped by like slot widths. The bars represent the maximum tension load achieved. Welds that failed in direct shear are indicated by an asterisk (*).

As the test results in Table 2 show, as the width of slot increased, the average of the ultimate tension load for that group increased slightly. Table 2 shows that a slot width of 3/16-inch (4.76mm) had the lowest coefficient of variation and the 1/8-inch (3.18mm) and 1/4-inch (6.35mm) had the highest; the 1/8-inch (3.18mm) slot width tends to have less predictable strengths. 78% of the 1/8-inch (3.18mm) slot width group had the specimen's failure mode as direct shear through the body of the weld. No other groups experienced a weld failure through the body of the weld.

Table 2. Summary of results.

Variable Slot Width Testing Summary				
	1/8in (3.18mm)	**3/16in (4.76mm)**	**1/4in (6.35mm)**	**3/8in (9.53mm)**
Mean, kips (kN)	11.3 (50.3)	12.4 (55.2)	12.7 (56.5)	13.6 (60.5)
COV	0.073	0.041	0.076	0.044

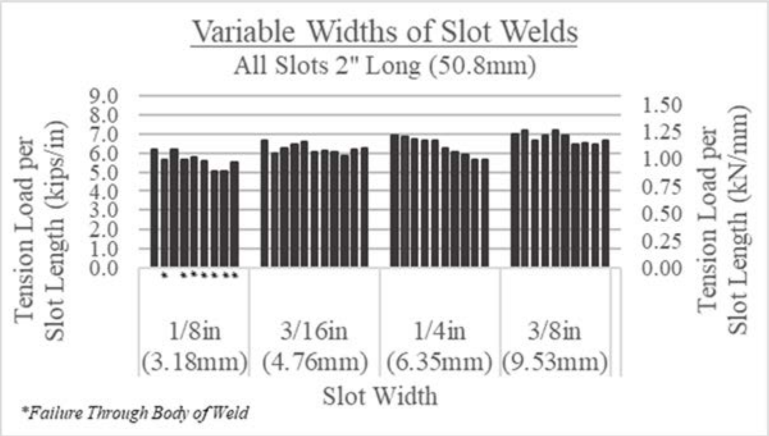

Figure 7. Tension load per unit length for variable slot widths

Figure 8 shows the ultimate tension load per perimeter inch of slot for each slot width. The graph shows that the strength of a slot weld is slightly less than 3 kips per inch (0.525 kN/mm) of slot perimeter regardless of the slot width. This suggests the slot weld strength more closely relates to perimeter length of slot than simply the overall length of slot.

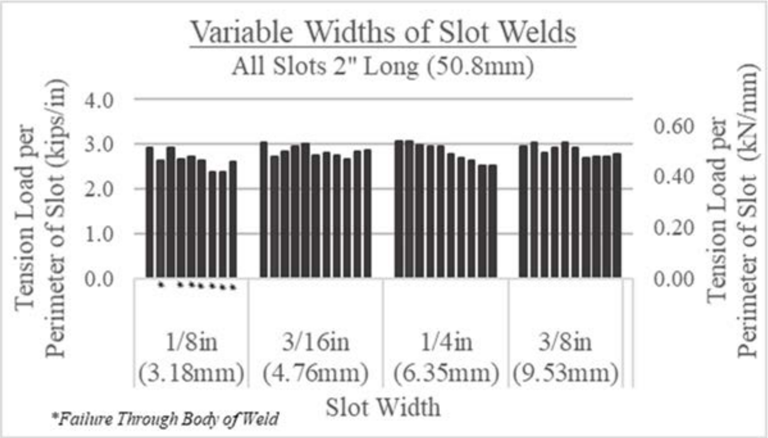

Figure 8. Tension load per unit perimeter length for variable slot widths

Strain energy is derived from the area under the force vs. displacement plots (linearly extrapolated to zero force when plot does not end at zero force). Strain energy is stored within a material when work has been done on the material. For the applied load, the work done is the straining or yielding the material. A high strain energy per unit length means more energy is being absorbed through permanent deformation in the specimen prior to failure. In other words, the connection deformed and slowly tore the sheet steel material prior to complete loss of capacity. A low strain energy per unit length indicates that there was little inelastic deformation occurring prior to failure; those specimens exhibited brittle behavior. Figure 9 shows strain energy for the various slot widths.

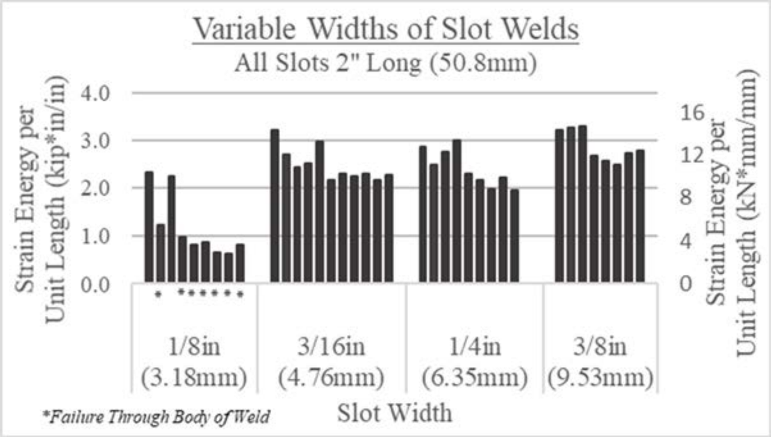

Figure 9. Strain energy per unit length for variable slot widths

Figure 10 and Figure 11 show a force versus displacement plot for a 3/16-inch (4.76mm) slot weld. The force rises until its ultimate load is reached then decreases as the specimen continues to deform until failure occurs. Inelastic deformation of the test specimen was seen as stretching (also seen for elastic) and tearing in the 16 gage plate surrounding the slot weld. Figure 12 shows a force versus displacement plot for a 1/8″ (3.18mm) slot weld that failed in shear through the body of the weld. The force rose until its ultimate load is reached and then suddenly failed with virtually no further deformation. The test specimen during loading showed little signs of yielding prior to a quick and sudden failure.

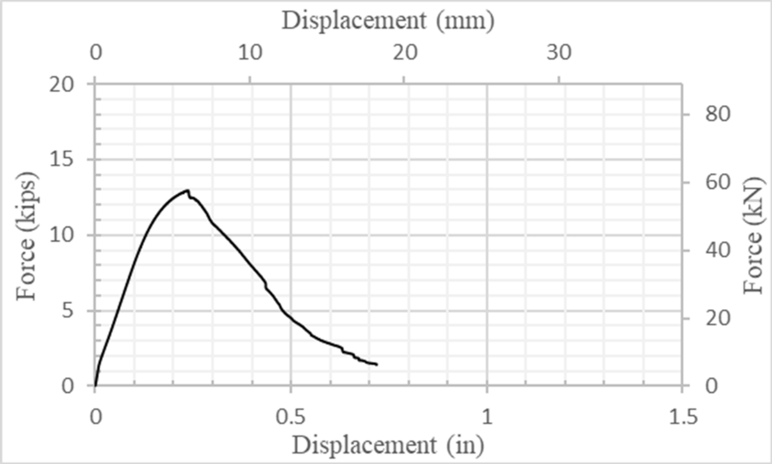

Figure 10. Example of a ductile failure in a 3/16" (4.76mm) wide manual weld sample result with ultimate fracture in the 16 gage sheet metal

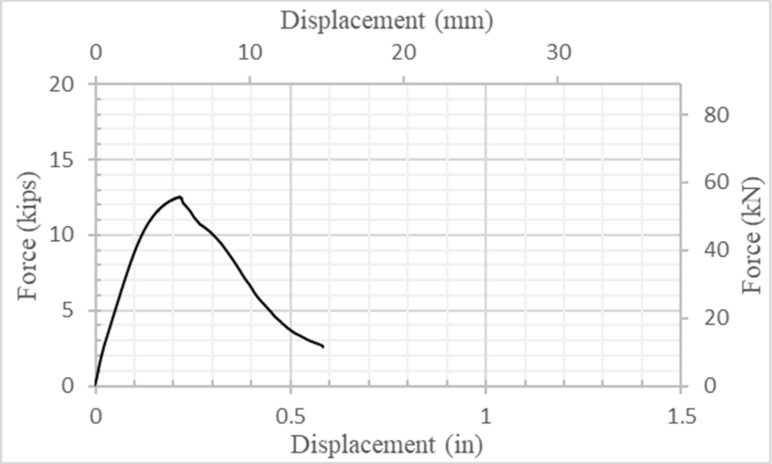

Figure 11. Example of a ductile failure in a 3/16" (4.76mm) wide robotic weld sample result

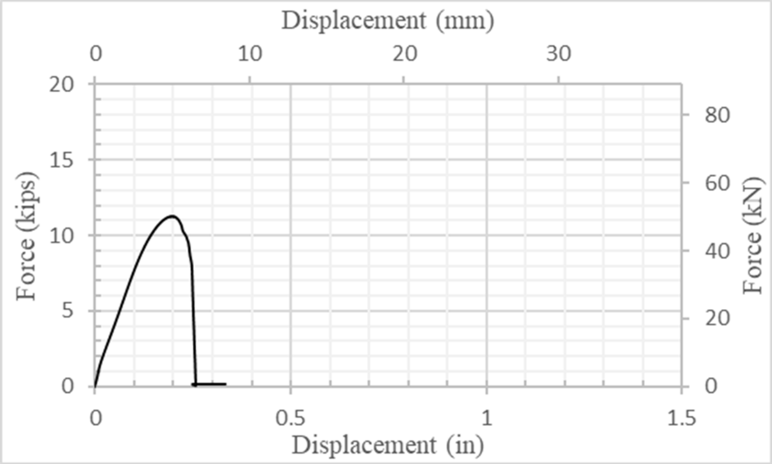

Figure 12. Example of weld shear failure upon completion of test. The area under this curve is significantly less at 1/8” wide slot than the area under the curves shown in Figure 10 and Figure 11, indicating significantly less strain energy in a the 1/8” (3.18mm) slot width compared to a 3/16” (4.76mm) wide slot width. Further, the sudden drop-off in strength is indicative of a sudden, brittle failure.

Discussion

The goal of the variable slot width test was to determine an optimal slot width that yields consistent results, ductile failures, good weldability, and good strength.

The 1/8-inch (3.18mm) by 2-inch (50.8mm) slot is a standard slot weld size for a current building system. Nine slot welds of this width were tested, three manual and six robotic. The welders (manual) were comfortable and familiar with welding this slot. The results are as follows:

- Mean strength = 11.3 kip (50.1 kN)
- High variability (COV=0.073)
- 7 of 9 (78%) direct shear failure through body of weld

A direct shear failure through body of weld is a sudden failure where ultimate strength drops to zero virtually instantaneously (see Figure 12). The controlling failure was observed to occur as a shear through the body of the weld metal, a shear failure parallel to the plane of the sheet metal pieces. This failure is sudden (i.e. brittle). The brittle failure mode in direct shear is distinctly different from the ductile failure mode of tearing in the 16 gage metal around the perimeter of the slot. Comparison of Figure 12 with Figure 10 and Figure 11 illustrate why direct shear failure through the body of the weld is an undesirable failure. This type of failure is brittle and loses all strength once it′s ultimate load is reached.

Ductility is the extent to which the weld connection can undergo increased deformation without failure, a property particularly important during seismic events. A ductile failure in terms of this study refers to the tearing of the sheet metal adjacent to the slot weld, a failure that happens slowly and allows for large deformations. This is indicative of the weld′s high energy dissipation capability prior to failure during a seismic event. The direct shear failure through the body of the weld is an undesired, brittle failure. Little deformation occurs before sudden failure. Seven of nine of the 1/8-inch (3.18mm) slot welds underperformed because of brittle behavior.

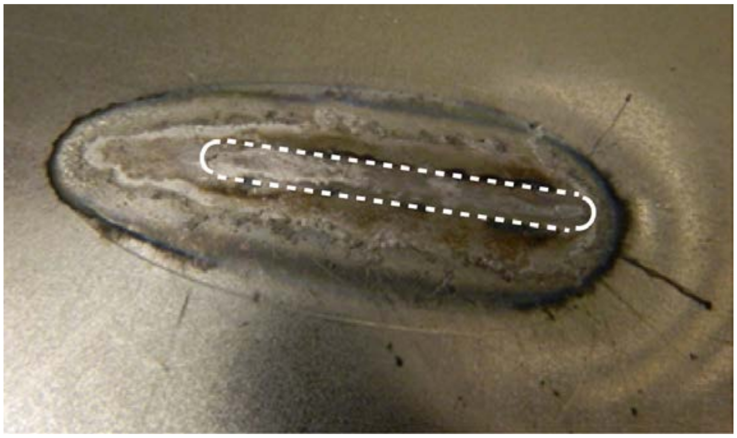

Figure 13. Photograph of 16 gage sheet with failed weld subject to "direct shear through the body of weld." The failure occurred on a shear plane parallel to and between the two sheets of metal, instead of tearing the 16 gage metal around the perimeter of the weld. The dashed outline encloses the direct shear failure plane.

Eleven 3/16-inch (4.76mm) by 2-inch (50.8mm) slot welds were tested to ultimate tension failure, five manual and six robotic. Some of the welders (manual) reported that the extra width compared to the 1/8″ (3.18mm) width made it easier to see the wire position in the slot. The results are as follows:

- Mean strength = 12.4 kip (55.3kN)
- Lowest variability (COV = 0.041)
- No direct shear failure through body of weld

Ten 1/4-inch (6.35mm) by 2-inch (50.8mm) slot welds were tested to ultimate tension failure, five manual and five robotic. (The increase in size led to burn-through weldability issues. Travel speed was increased in attempt to mitigate burn-through.) The results are as follows:

- Mean strength = 12.7 kip (56.4 kN)
- High variability (COV = 0.076)
- No direct shear failure through body of weld

Ten 3/8-inch (9.53mm) by 2-inch (50.8mm) slot welds were tested to ultimate tension failure, five manual and five robotic. Burn-through often occurred, and many specimens had to be remade. One of the five manual welds was made with a slightly different technique in that the welder made two fillet welds, one on each side of the slot and a third pass to close the gap between those two fillet welds. The results are as follows:

- Mean strength = 13.6 kip (60.5kN)
- COV = 0.044
- Welders had difficulty with burn-through
- One of five manual welds was made with (2) fillet welds instead of slot weld. This technique was more constructible than other slot welds made using weaves for the 3/8″ width (9.53mm).

In Figure 14, the average tension load for each variable slot width is shown. There is not a significant increase in strength from the 3/16″ wide slot to the ¼″ or 3/8″ wide slots. This further supports the 3/16″ wide slot as the recommended optimum slot width.

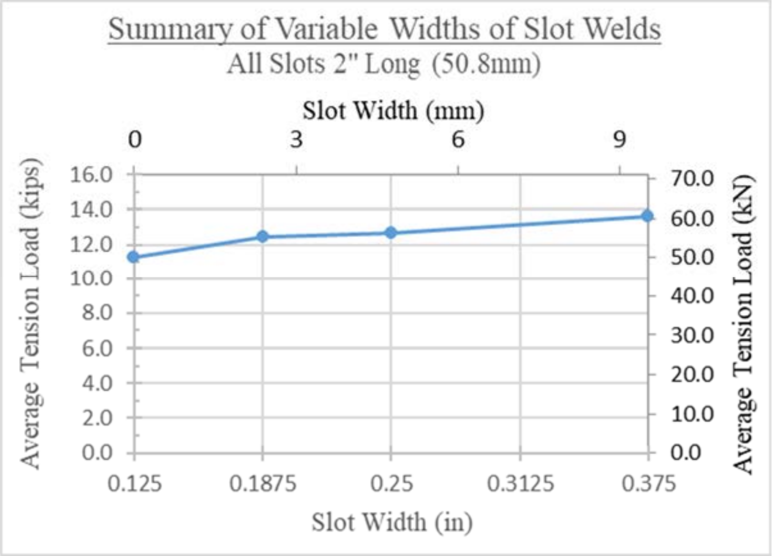

Figure 14. The average tension load for each variable slot width

Conclusions and Recomendations

The goal of the variable slot width test was to determine an optimal slot width that yielded consistent results, ductile failures, good weldability, and good strength. From the results discussed, the 3/16-inch (4.76mm) slot width best fits these criteria. There were no brittle shear failures through body of weld in this test group. Failure modes were ductile and strength was good. The welders (manual) preferred the 3/16″ (4.76mm) width. The 3/16-inch (4.76mm) slot width yielded consistent results, ductile failures, and good strength. Therefore, the authors recommend utilizing 3/16″ (4.76mm) widths for slots in 14 gage metal welded to 16 gage metal.

Limitations

The limitations of this study include the following: test specimens were comprised of 14 gage plates welded to 16 gage plates. All welds were made with a metal inert gas (MIG) process. This paper does not address a comparison between manually and robotically welded specimens.

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