

Resistance of Arc Spot Welds – Update to Provisions

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PREFACE

The American Iron and Steel Institute (AISI) Standards Council selected this project as one of four winning research proposals for its 2015 Small Project Fellowship Program. Project selections were based on several factors, including the potential for long-term impact on the industry; steel industry engagement and co-funding; and results for the AISI standards development committee, the student, and the academic institution.

The objective of this project was to evaluate the provisions for determining the strength of arc spot welds in light of recent research studies. It is anticipated that the results of this study will impact the provisions in future editions of AISI S100 and guide future research and development efforts.

RESISTANCE OF ARC SPOT WELDS – UPDATE TO PROVISIONS

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ABSTRACT

The provisions of the AISI S100-12 standard for strength of arc spot welds loaded in shear and tension have not been revised since the 1999 standard. Since then, four new research studies have created and tested arc spot welded connections, expanding the database of available tests. Therefore, a reconsideration of both the resistance equations and the resistance and safety factors using the enlarged data base was undertaken. This study performed a comprehensive analysis of the entire arc spot weld data base, where 450 specimens were categorized by their respective failure modes to assess current AISI S100-12 resistance equations. Performance of the existing equations was re-evaluated and compared with the performance of equations used in previous AISI S100 editions.

This study found that current equations and resistance and safety factors for sheet tearing failure modes are conservative and could be relaxed for shear as well as tension loading. New distinctions are proposed to improve the performance of side-lap connection resistance calculations. Also, removing the upper limit and adding a lower limit to the effective weld diameter calculation sharpened accuracy for calculated weld resistance of arc spot welds made through thicker sheet connections. Most AISI S100-12 equations were found to be adequate and can be made less conservative, however current provisions for weld failure under tensile load were found to substantially over predict weld strength. Adjustments to the tension weld resistance equation are recommended by this study to improve performance, however future research on tension weld failure of combined sheet connections would be beneficial.

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LIST OF VARIABLES

β = Target reliability index, taken as 3.0, 3.5 or 4.0 based on AISI S100-12 specs

C_p = Correction factor (AISI S100-12 F1.1)

C_ϕ = Calibration coefficient (AISI S100-12 F1.1)

COV = Coefficient of variation

d' = Weld overlap onto top sheet on a side-lap connection, as used by LaBoube (1991)

d = Visual diameter of arc spot weld

d_a = Average diameter

d_e = Effective weld diameter at the plane of failure

E = Modulus of elasticity of sheet steel, taken as 29,500 ksi

F_m = Mean value of fabrication factor (AISI S100-12 F1.1)

F_u = Ultimate tensile strength of sheet steel

F_y = Yield tensile strength of sheet steel

F_{xx} = Ultimate tensile strength of weld metal

L = Length of top flange on a side-lap connection, as used by LaBoube (1991)

M_m = Mean value of material factor (AISI S100-12 F1.1)

n = Total number of samples included in the specific analysis

Ω = Omega, safety factor calculated for use in ASD

P_m = Mean value of professional factor (AISI S100-12 F1.1)

P_n = Calculated predicted resistance of arc spot weld connection

P_t = Ultimate load at failure during specimen testing

ϕ = Phi, resistance factor calculated separately for use in either LRFD or LSD

r = proposed reduction coefficient applied in resistance calculations

t = total combined thickness of sheets

V_F = Coefficient of variation of fabrication factor (AISI S100-12 F1.1)

V_M = Coefficient of variation of material factor (AISI S100-12 F1.1)

V_P = Coefficient of variation of test results (AISI S100-12 F1.1)

V_Q = Coefficient of variation of load effect (AISI S100-12 F1.1)

CHAPTER 1 INTRODUCTION

Corrugated sheet steel diaphragms are often used within lateral load resisting systems and as well as roof applications. These corrugated diaphragms are composed of thin rectangular cold formed steel sheets typically ranging from 22 to 16 gauge thickness, covering a range of 0.028 inches to 0.060 inches (0.72 mm to 1.52 mm) thick. Sheet diaphragms transfer load to the underlying steel frame through either arc spot welds or mechanical fasteners. Arc spot welds are popular as they can be created rapidly and cost effectively.

To transfer shear and tensile forces arc spot welds are placed around diaphragm edges and through its main section as pictured in Figure 1.1. Connecting adjacent diaphragms together results in one, two, and four sheet overlaps whose combined thicknesses must be penetrated by the arc spot weld. The current equations in AISI S100-12 for arc spot welds are predominately based on Pekoz and McGuire's 1979 report for shear strength equations and on LaBoube's 1991 report for tension strength equations. Since these reports were published additional authors explored thicker sheet welding and various multi sheet configurations typically found in practice to bolster the existing arc spot weld data base. This study takes a comprehensive look at the entire data base of new and old data to re-evaluate the existing arc spot weld strength equations in AISI S100-12.

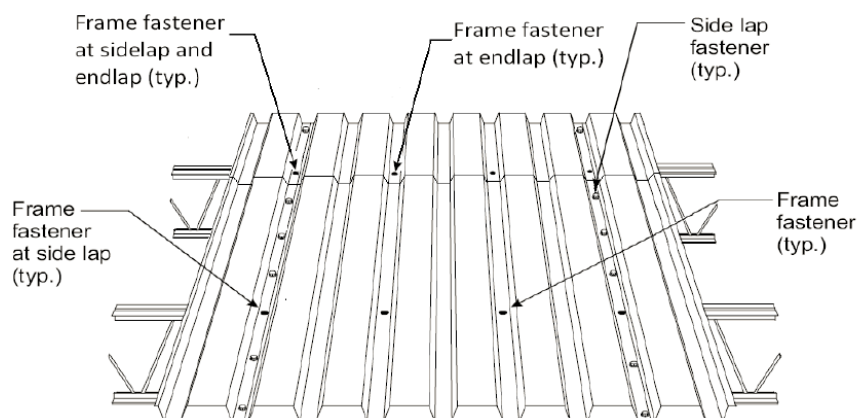


Figure 1.1: Typical arc spot locations (Guenfoud, 2010).

Creating an Arc Spot Weld

Arc spot welds are created by producing an electrode arc on the top sheet surface, forming a hole, heating up the base member (typically a hot rolled open-web steel joist) to ensure proper fusion and slowly moving the electrode in a circular motion filling the hole with weld metal until the hole is filled and proper fusion is achieved. Weld diameter is one major factor in the connection strength. Different weld diameter nomenclature includes: the visual diameter, d , measured at the surface of the top sheet; average diameter, d_a , defined as the average weld diameter from the bottom of the weld to the top sheet surface; and finally the effective weld diameter, d_e , the diameter of the weld at the plane of failure (see Figure 1.2). Calculation of effective and average weld diameters, d_e and d_a , is based on the visible diameter and total combined sheet thickness, t .

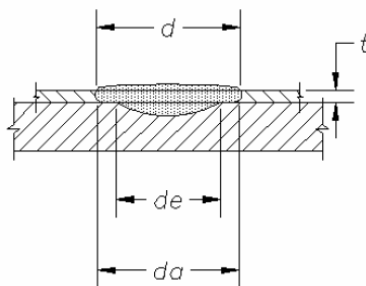


Figure 1.2: Arc spot weld diameters defined by AISI S100-12.

Failure modes

Arc spot welds fail in one of two general ways; either via sheet failure or via weld failure. This is true of both shear and tension loaded specimens. Shear failure through the weld, pictured in Figure 1.3, is typical when the ratio of weld diameter to total sheet thickness (d/t) is low. The result is a brittle failure mode where the weld metal reaches its ultimate load-carrying capacity before the sheet steel begins to deform and strain. In this case, the thicker combined sheets provide more shear resistance than a small weld can support.



Figure 1.3: Shear weld failure (Guenfoud, 2010).

Under shear loading, sheet failure occurs in either tearing or bearing behavior, both of which are associated with a larger diameter to thickness ratio (d/t). Sheet tearing, illustrated in Figure 1.4, begins on the tension side of the connection and propagates perpendicular to the direction of loading along the perimeter of the weld circumference as load is increased. As the tearing propagates, the compression side of the connection distorts out of plane. The tearing and deformation results in a ductile failure mode compared to the weld shear failure mode. A sheet bearing failure is also ductile, but instead of tearing, the weld plows through the sheet material parallel to the shear load and sheet metal deforms and piles up in front of the weld path as pictured in Figure 1.5. In both sheet tearing and bearing failure modes, the weld strength is stronger than the shear resistance provided by the sheet(s).



Figure 1.4: Sheet tearing failure mode (Guenfoud, 2010).



Figure 1.5: Sheet bearing failure mode (Guenfoud, 2010).

Tension failure also occurs via the sheet or through the weld. Tension weld failure develops when the diameter to sheet thickness ratio (d/t) is very low, and proves to be a rarer occurrence compared to other failure modes within the data base. Weld failure takes place through the effective weld diameter and in a violent, brittle manner. Figure 1.6 illustrates tension weld failure on a multi sheet connection where almost no sheet deformation can be noted. Tension sheet failure on the other hand exhibits significant sheet deformation as presented in Figure 1.7. As the sheet deforms under the tensile load, it creates concentrated stresses at the weld perimeter resulting in sheet tearing. Once sheet tearing initiates, the tear propagates about the weld perimeter in a circular fashion. Tension sheet failure is ductile in nature due to the substantial sheet deformation. This study reviews the AISI S100-12 equations associated with each of these failure modes.



Figure 1.6: Tension weld failure (Guenfoud, 2010).



Figure 1.7: Tension sheet failure (Guenfoud, 2010).

Objective

The arc spot weld strength equations in AISI S100-12 have not been examined with new data since 1999. This study re-evaluates the AISI arc spot weld strength equations with the entire existing data base including hundreds of new specimens tested within the last seventeen years. Resistance and safety factors for LRFD, ASD, and LSD were re-calculated for monostatic shear and tension loading design equations. The equations themselves were also evaluated for accuracy and applicability to various sheet configurations. A total of 1,193 arc spot weld specimens were uncovered, making up the entire data base, while 450 of those were determined applicable to this study.

Design Standards

AISI S100-12 design equations for sheet to base metal arc spot welds were reviewed. The equations below are presented in the order that exists in the AISI specification and will be referenced throughout this report. AISI S100-12 shear strength equations E2.2.2.1-1 through E2.2.2.1-4 are presented below as Equations 1-1 through 1-4. Existing and recalibrated resistance and safety factors for LRFD, ASD, and LSD for these equations are presented and compared in the results section.

$$P_n = \frac{\pi d_e^2}{4} 0.75 F_{xx} \quad (\text{Eq. 1-1})$$

$$\text{For } d_a/t \leq 0.815 \sqrt{(E/F_u)} : P_n = 2.20 t d_a F_u \quad (\text{Eq. 1-2})$$

$$\text{For } 0.815 \sqrt{(E/F_u)} < d_a/t < 1.397 \sqrt{(E/F_u)} : P_n = 0.280 \left[1 + 5.59 \frac{\sqrt{E/F_u}}{d_a/t} \right] t d_a F_u \quad (\text{Eq. 1-3})$$

$$\text{For } d_a/t \geq 1.397 \sqrt{(E/F_u)} : P_n = 1.40 t d_a F_u \quad (\text{Eq. 1-4})$$

$$\text{Where: } d_e = 0.7d - 1.5t \leq 0.55d \quad (\text{Eq. 1-5})$$

$$\text{Where: } d_a = d - t \quad (\text{Eq. 1-6})$$

Equation 1-1 calculates the shear strength of the weld area, predicting the load at which the weld metal itself fractures. Equations 1-2, 1-3 and 1-4 all represent sheet resistance and are bounded by the ratio size of average weld diameter, d_a , to total design sheet thickness, t . AISI S100-12 tension strength equations E2.2.3-1 and E2.2.3-2 are presented respectively in Equations 1-7 and 1-8. Similar to the shear equations, Equation 1-7 calculates the tension capacity of the weld metal and Equation 1-8 predicts the tensile strength of the sheets.

$$P_n = \frac{\pi d_e^2}{4} F_{xx} \quad (\text{Eq. 1-7})$$

$$P_n = 0.8 (F_u/F_y)^2 t d_a F_u \quad (\text{Eq. 1-8})$$

CHAPTER 2 LITERATURE REVIEW

Shear Tests

Pekoz and McGuire's 1979 report "Welding of Sheet Steel" summarized five reports co-authored by Pekoz between 1971 and 1978. A total of 342 shear loaded welded samples were created and tested at Cornell University over this time period, 126 of them being arc spot welded. All samples were tested with monotonically increasing shear load. Six sheet thicknesses were tested: 10 gauge (0.138 inches, 3.24 mm), 12 gauge (0.108 inches, 2.66 mm), 14 gauge (0.079 inches, 1.90 mm), 18 gauge (0.052 inches, 1.21 mm), 24 gauge (0.028 inches, 0.61 mm) and 28 gauge (0.019 inches, 0.38 mm). All sheets tested were created from ASTM A446 either Grade A ($F_y = 33$ ksi and $F_u = 45$ ksi) or Grade E ($F_y = 80$ ksi and $F_u = 82$ ksi) steel. Each sheet sample was welded to a hot rolled ASTM A36 steel base plate of 7/16 inch (11.10 mm) thickness. Both single and double sheet configurations were tested. The maximum thicknesses welded for single sheets were the 10 gauge samples at 0.138 inches (3.24 mm) thick, and 0.155 inches (3.94 mm) measured for two 14 gauge sheets (0.079 in, 1.90 mm) in a double sheet configuration. The single sheet configuration tested by Pekoz is depicted in Figure 2.1 below. All samples were welded with E6010 electrodes. Most samples were welded by a steel fabricator or in laboratory conditions, while 31 samples were welded in "field" conditions and consequently resulted in lesser quality welds.

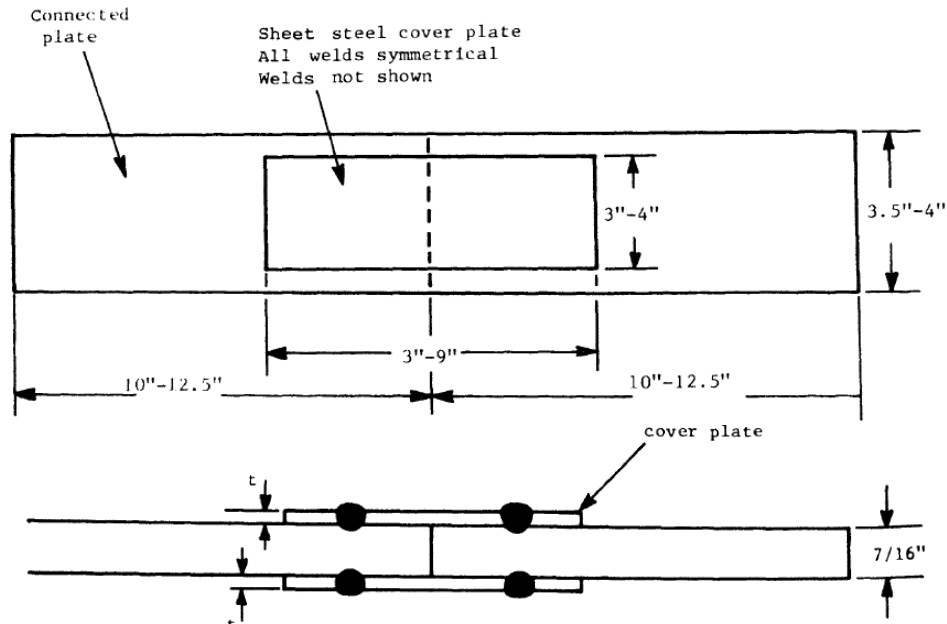


Figure 2.1: Single sheet configuration created by Pekoz (Pekoz, 1979).

Pekoz's work was initiated to codify sheet welding for the first time. His recorded failure modes and representative equations created the framework for what is currently codified in the AISI S100-12 standard for shear loaded sheet steel welds. Pekoz organized failure modes into three types: weld shear, sheet tearing, and sheet buckling. Most failures were preceded by out of plane sheet deformation. Weld shear failures were predicted with Equation 2-1, while all other failures were characterized by the ratio of weld diameter and sheet thickness (d_a/t) compared to ultimate strength of the sheet steel (F_u) and respectively predicted by either Equation 2-2 or 2-3. It should be noted that in the 1979 Pekoz report the equations are presented for two welds (as applicable to Pekoz's sample configuration), while the equations below are presented for a single weld.

$$P_n = \frac{\pi}{4} d_e^2 (0.75 F_{xx}) \quad (\text{Eq. 2-1})$$

For the range $140/\sqrt{F_u} \leq d_a/t \leq 240/\sqrt{F_u}$:

$$P_n = 0.280 \left[1 + \frac{960}{d_a \sqrt{F_u}} \right] t d_a F_u \quad (\text{Eq. 2-2})$$

For all other d_a/t ranges:

$$P_n = 1.40t d_a F_u \quad (\text{Eq. 2-3})$$

Pekoz also developed Equation 2-4 to represent the effective weld diameter (d_e), defined as the diameter of the weld at the shear plane. He also created Equation 2-5 to represent the average weld diameter (d_a); both equations are still specified in AISI S100-12.

$$d_e = 0.7d - 1.5t \quad (\text{Eq. 2-4})$$

$$d_a = d - t \quad (\text{Eq. 2-5})$$

Fung's 1978 report "Strength of Arc-Spot Weld in Sheet Steel Construction" was the first of its kind completed for the Canadian Steel Industry Construction Council (CSICC), as the design community began to consider arc-spot welds structurally important. Fung split his focus into three different test series which included 127 shear specimens and 128 tension specimens. All samples were manually created with an E6010 electrode with a 5/32 inch (3.96 mm) diameter. Weld diameters were specified to 0.75 inches (19.05 mm) (with exception of test series three). Sheet steel material was ASTM A446, G-90, of either Grade A ($F_y = 33$ ksi) or Grade D ($F_y = 50$ ksi). Sheet thicknesses ranged from 0.030 to 0.060 inches (0.726 to 1.524 mm). Sheets were welded to plates composed of CSA G40.21 44W ($F_y = 44$ ksi) steel which had thicknesses that varied from 0.125 to 1.00 inches (3.18 to 25.4 mm).

Test series one included 96 samples that focused on developing a standardized weld technique and explored relationships between weld machine settings, weld technique, sheet thickness, plate thickness, and weld diameter. Fung concluded that the ratio of plate to sheet thickness should be equal to or greater than 2.5 in order to achieve proper fusion and that weld

settings should be adjusted to achieve an effective weld diameter of at least 0.45 inch (11.43 mm) for a 0.75 inches (19.05 mm) specified visible weld diameter.

Test series two explored weld capacities for shear loading and tension loading (applied separately). Figure 2.2 depicts Fung's shear configuration (note that the sheet on top, is drawn thicker at the weld for understanding but is thinner than the plate, on bottom). Plate thickness was 0.5 inches (12.7 mm) for all test series two samples and sheets varied from 0.031 to 0.059 inches (0.787 to 1.499 mm) thick. Unfortunately, Fung did not report the failure mode of each sample, he did write that all shear samples experienced out of plane deformation and a majority of samples exhibited sheet tearing in front of the weld. Fung used AWS D1.3-77 equations (Equations 2-6 through 2-9 below) to predict shear strength which he found to be slightly conservative.



Figure 2.2: Shear specimen created by Fung (Fung, 1978).

$$\text{If } d/t < \frac{240}{\sqrt{F_y}} : P_n = 2.2t_d F_t \quad (\text{Eq. 2-6})$$

$$\text{Where } F_t = 0.4F_u \quad (\text{Eq. 2-7})$$

$$\text{If } d/t \geq \frac{240}{\sqrt{F_y}} : P_n = 1.4t_d F_t \quad (\text{Eq. 2-8})$$

$$P_n = \frac{\pi}{4} d_e^2 (0.30F_{xx}) \quad (\text{Eq. 2-9})$$

Test series three investigated several potential factors affecting weld strength which included: plate to sheet thickness ratios, strength of sheet material, weld size, surface coatings, initial gap between sheet and plate, different welders, and weld time. Specimens were prepared and tested in the same manner of test series two but varied the factors mentioned above. Fung found that heavily galvanized surfaces and air gaps lowered weld capacity, while strength of sheet material and welds larger than 0.75 inches (19.05 mm) had little effect on the weld capacity. Arc time was directly related to weld size and thereby load capacity in the case of welds smaller than

0.75 inches (19.05 mm). Therefore, shorter weld durations yielded smaller welds and lower strengths. Fung reported that a standardized weld technique proved to be the most important factor on weld capacity.

Peuler's 2002 report "Inelastic Response of Arc-Spot Welded Deck-to-Frame Connections for Steel Roof Deck Diaphragms" explored how to improve arc spot weld strength in a seismic environment. His research included 235 monotonic, cyclic and seismic shear loading tests. Within these loading types Peuler researched the effects of weld washers versus no reinforcement as well as different electrode types to produce the best arc spot weld. His sheets were composed of ASTM A635 steel and 16 gauge (0.060 inches, 1.52 mm), 18 gauge (0.052 inches, 1.21 mm), 20 gauge (0.036 inches, 0.91 mm) and 22 gauge (0.030 inches, 0.76 mm), three different plate sizes were used ranging from 1/8 to 1/2 inches (3.18 mm to 12.7 mm) thick, and three different weld washer shapes were tested. Figure 2.3 illustrates the shear test assembly employed by Peuler.

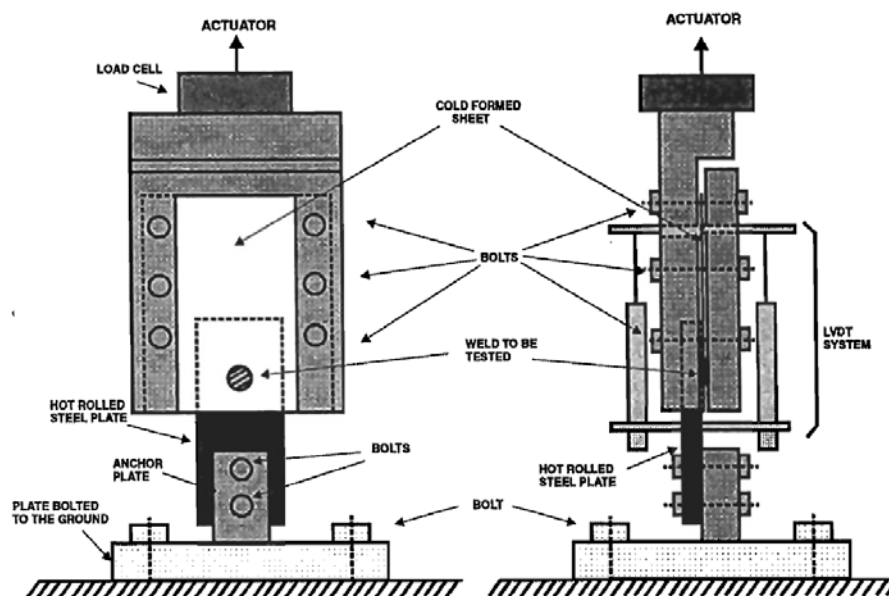


Figure 2.3: Shear test assembly used by Peuler (Peuler, 2002).

Although focused on seismic loading, Peuler's work included 49 monotonically loaded shear single sheet samples that were created without weld washers. These samples were created

with varied plate thicknesses and weld electrodes and are included in this analysis. Peuler had 4% of his samples fail through the weld, all of which included a weld washer. He measured the effective weld diameter of the failed samples and noted that Equation 1-5 was generally conservative. He also noted that E6011 electrodes exhibited the best penetrating power over E6010, E6022 and E7018 electrodes.

Easterling and Snow investigated reduced welding time and multi-sheet welding in their shear tests reported in the 2008, “Strength of Arc Spot Welds Made in Single and Multiple Steel Sheets”. Samples were welded with 1/8 inch (3.18 mm) diameter E6010 electrodes at full weld time, 2/3 weld time, and 1/3 weld time. Single, double, and four sheet thicknesses of ASTM A653 Grade 33 steel 16 to 22 gauge were welded and tested; making up the 138 specimens tested. Test results were then used to evaluate the 2001 AISI shear specifications for arc spot welds. Easterling’s specimen assembly tested is illustrated in Figure 2.4.

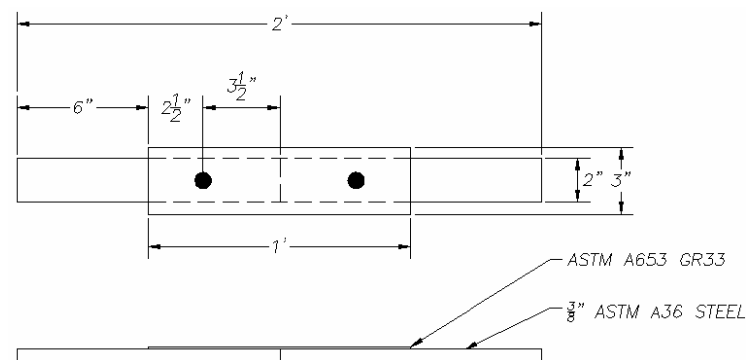


Figure 2.4: Specimen dimensions used by Easterling and Snow (Easterling and Snow, 2008).

Easterling and Snow found that the 2001 AISI shear strength equations were adequate when estimating the strength of the 2/3 and 1/3 weld time specimens by using the visual weld diameter. The test failure loads were on average 30% higher than the strength predicted by AISI S100-12 shear equations, but they found the accuracy of these equations diminished for thicker sheet samples and shorter weld durations. Easterling and Snow recommended that sheets with

combined thicknesses larger than 0.15 inches (3.81 mm) should not be used in arc spot welded connections. Note this was the conclusion when using E6010 electrodes.

Expanding from the scope of existing data, Guenfoud's 2010 report, "Experimental Program on the Shear Capacity and Tension Capacity of Arc-Spot Weld Connections for Multi-Overlap Roof Deck Panels" investigated shear and tension capacities for arc-spot welds through one to four sheet thicknesses. Welding through four sheets commonly occurs at the overlapping corners of four different deck panels as illustrated in Figure 2.5. Guenfoud performed monotonically loaded tension and shear tests as well as cyclic shear tests on a total of 179 specimens. Only the monotonic tests will be reviewed here.

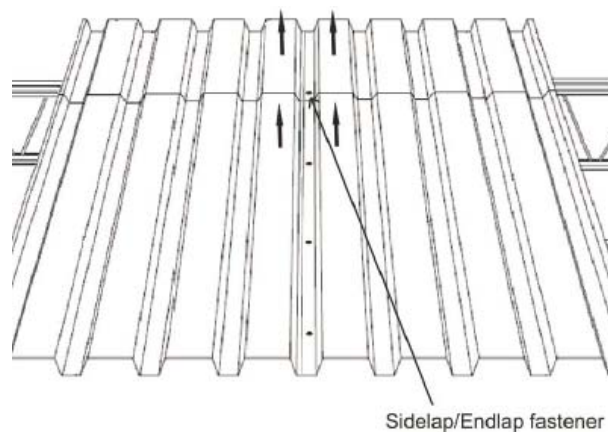


Figure 2.5: Arc-spot weld through four sheets as found in panel construction (Guendfoud, 2010).

Guenfoud paid particular attention to weld quality. E6011 electrodes with a 1/8 inch (3.18mm) diameter rod was chosen based on its ability to penetrate through thicker sheets as noted by Peuler's 2002 report. All of Guenfoud's samples were created by an experienced certified welder in collaboration with a weld engineer. Welds were circular with a visible diameter of 16 to 19 mm (0.63 to 0.75 inches). To maximize penetration and minimize porosity Guenfoud found that an AC current of 195 amps worked best for 16 and 18 gauge sheets while 160 amps was best for 20 and 22 gauge sheets.

The sheet material was ASTM A653 Grade 33 steel ($F_y = 33$ ksi, $F_u = 45$ ksi) for all 76 monotonically loaded shear samples. Sheet thicknesses were 16, 18, 20, and 22 gauge. Sheets were welded onto a Grade 350W CSA G40.21 hot rolled plate of either 6.4 or 3.2 mm (0.252 or 0.126 inch) thickness. Three different sheet configurations were tested in shear. A two sheet side-lap configuration, in which the shear plane was located between the sheets (design thickness equals one sheet). A four sheet configuration as shown in Figure 2.5 featured the shear plane in the middle of the four sheets (design thickness equals two sheets). The third configuration mimicked a perimeter end lap connection between two sheets where the shear plane was located between the hot rolled plate and the two sheets (design thickness equals two sheets). Figure 2.6 pictures the shear test assembly used by Guenfoud and Figure 2.7 presents the perimeter sheet configuration.

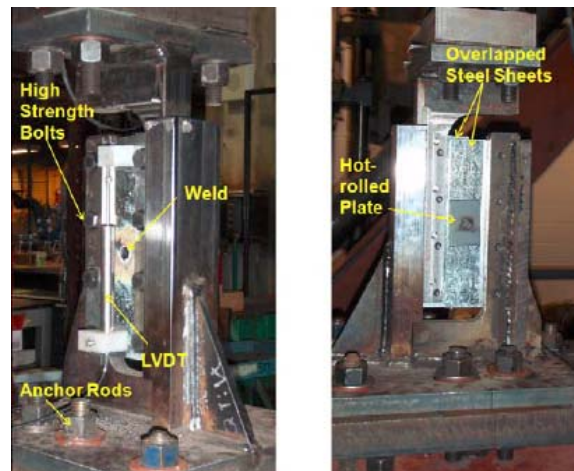


Figure 2.6: Shear test assembly used by Guenfoud (Guenfoud, 2010).

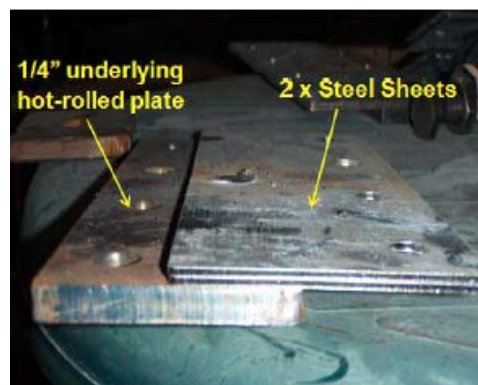


Figure 2.7: Perimeter shear configuration (Guenfoud, 2010).

Guenfoud recorded three different failure modes; shear failure through the weld, sheet tearing failure, and sheet bearing failure. For specimens that failed through the weld, Guenfoud was able to measure the effective weld diameter, d_e , with a vernier caliper. Guenfoud found that the current d_e equation (Equation 1-5) was conservative for welding through multiple sheet layers, particularly for connections with larger ratios of design thicknesses to weld diameter. Based on Guenfoud's analysis as depicted in Figure 2.8, he proposed Equation 2-10 as a modification to Equation 1-5.

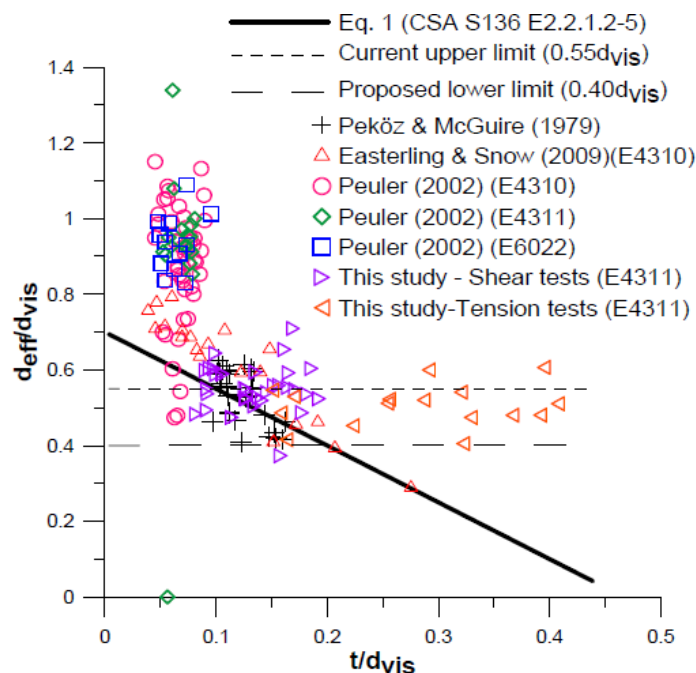


Figure 2.8: Shear weld failure samples from existing data base (Guendfoud, 2010).

$$d_e = 0.7d - 1.5t, \text{ with } 0.4d \leq d_e \leq 0.55d \quad (\text{Eq. 2-10})$$

All specimens with one sheet above the shear plane failed in either sheet tearing or bearing failure modes (the thinner design thickness, t , specimens). All 16 and 18 gauge four sheet specimens and perimeter two sheet specimens failed through the weld, a total of 33 samples, making Guenfoud the largest contributor to the shear weld failure data base. The two sheet design thickness and the thickest of the sheets tested appeared to increase sheet resistance and force failure

through the weld area. Alternatively, the 20 and 22 gauge specimens with four sheets resulted in various failure modes, but predominately sheet bearing failure.

Guenfoud's sheet failure specimens mostly fell into the category of AISI S100-12 equation E2.2.2.1-2 (Equation 1-2 above). He found Equation 2-11 to be the best fit for this category, the only change being a coefficient of 2.40 rather than 2.20. With this equation, Guenfoud recorded a measured to predicted ratio of 1.32, a coefficient of variation (COV) of 0.14 and a LSD resistance factor, ϕ , equal to 0.60.

$$\text{For } d_a/t < 0.815 \sqrt{E/F_y} : P_n = 2.40 t d_a F_u \quad (\text{Eq. 2-11})$$

Tension Tests

Tension tests, 128 total, were conducted in Fung's 1978 report in addition to shear in all three test series. All parameters were the same between shear and tension tests, with the addition of the tension test setup pictured in Figure 2.9. Tension loading deformed the channel section of the sheet away from the weld which created non-uniform and concentrated stresses along the weld perimeter closest to the channel walls. Fung described this failure mode as a peeling effect of the sheet as it tore around the weld perimeter.

Fung's conclusion provided design weld shear and tension capacities for sheet thickness and grade in a tabular form based on test results, but he did not produce prediction equations beyond AWS D1.3-77. At the time, AWS did not specify tensile capacity equations for arc-spot welds, but Fung found that the ratio of shear strength to tension strength was fairly constant for different sheet thicknesses with a ratio ranging from 2.5-2.8 for all samples.

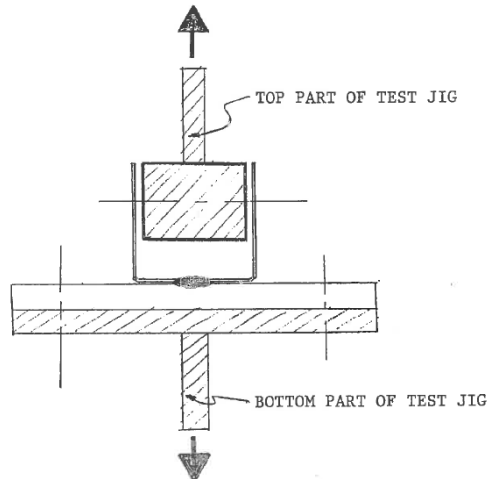


Figure 2.9: Tension specimen created by Fung (Fung, 1978).

In 1988, Albrecht's report "Developments and Future Needs in Welding Cold-Formed Steel" focused on analyzing Fung's tension data in order to develop a design equation for tensile strength of arc-spot welds. Albrecht proposed Equation 2-12 below for nominal tensile strength.

$$P_n = 0.9t_d F_u \quad (\text{Eq. 2-12})$$

This equation was further refined by Yu at the University of Missouri-Rolla in 1989. Yu modified Equation 2-12 to achieve a factor of safety equal to 2.5 which resulted in Equation 2-13. Following Yu's work, the American Iron and Steel Institute (AISI) adopted Equation 2-14 in a 1989 addendum to the 1986 Specification for the Design of Cold-Formed Steel Structural Members (LaBoube and Yu, 1991).

$$P_n = 0.66t_d F_u \quad (\text{Eq. 2-13})$$

$$P_n = 0.70t_d F_u \quad (\text{Eq. 2-14})$$

LaBoube and Yu's 1991 report "Tensile Strength of Welded Connections" published for the American Iron and Steel Institute expanded Fung's tensile data with 260 specimens composed of several different sheet configurations under tensile loading. These configurations are those commonly found in deck connection geometries that include single sheet interior welds, double

sheet interior welds, side-lap welds, eccentrically loaded single sheet perimeter welds as well as full-panel tests. The test assembly for the concentrically loaded samples is pictured in Figure 2.10 demonstrating a single sheet configuration while double sheet interior weld and side-lap weld configurations are sketched in Figure 2.11. Eccentrically loaded samples were tested similar to Figure 2.10 with the exception that only one side of the channel was bolted into the test apparatus.

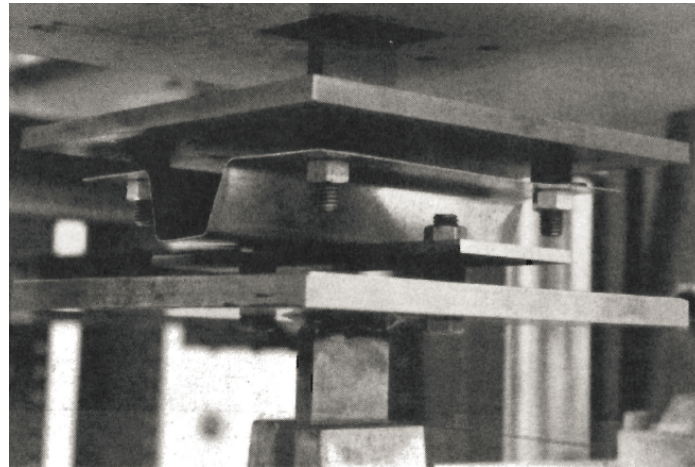


Figure 2.10: Single sheet configuration in tension test assembly (LaBoube and Yu, 1991).

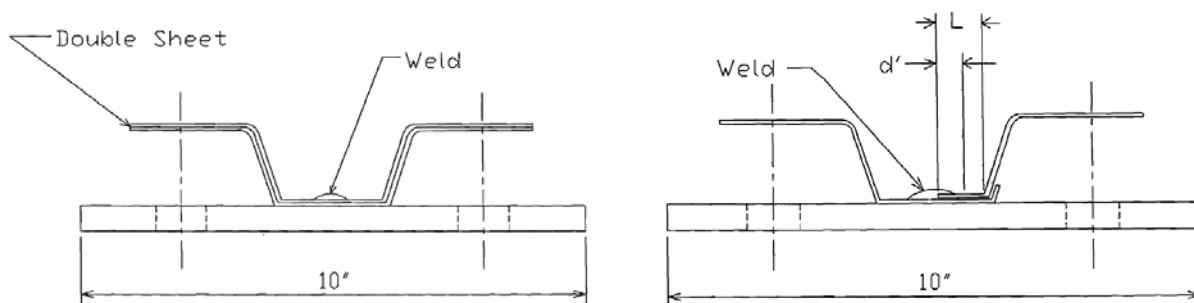


Figure 2.11: Double sheet interior weld and side-lap weld configurations (LaBoube and Yu, 1991).

In addition to these sheet configurations both stick and automatic welding procedures were investigated. For both processes an E70 electrode was used to create all samples. Sheet materials tested were ASTM A446 of either Grade C ($F_u = 50$ ksi) or Grade E ($F_u = 82$ ksi). The majority of samples were created with sheets 0.029 inches (0.737 mm) thick and a handful of specimens with 0.065 inches (1.651 mm) sheet thickness. Traditionally, weld washers were only used on sheets