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Structural Engineering and Materials

Research Report

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STRENGTH OF ARC SPOT WELDS MADE IN SINGLE AND MULTIPLE STEEL SHEETS

Abstract

The objective of this research was to establish a relationship between arc spot weld shear strength and the arc time used to form the weld. Lap shear tests were performed on both 3/4 in. and 5/8 in. nominal diameter welds. Each weld was formed in one-, two-, or four-layers of sheet steel ranging from 22 gauge (0.028 in.) to 16 gauge (.057 in.). Three distinct time series were tested for each unique weld size, thickness of sheet steel and layer configuration. The first of these series were the full-time welds. The two remaining series, 2/3-time and 1/3-time welds, had arc times equal to 2/3 and 1/3 of the average full-time weld arc time, respectively.

Both weld shear strength tests and weld sectioning were performed for each series of weld. Strength tests were performed on a minimum of three specimens from every weld series. If the strength of any specimen deviated by over ten percent from the mean strength, an additional specimen was tested, helping to better understand the true behavior of the weld. Comparisons were made between the strengths of full-time, 2/3-time and 1/3-time welds. Comparisons were also made between the observed strength of each weld and the strengths calculated using the 2001 AISI Specification.

Each sectioning test involved measuring and documenting the visual diameter, average diameter and effective diameter of the weld. Weld penetrations were also documented as sufficient or insufficient and any porosity was noted. A single sectioning test was performed for each full-time series, while three were performed for every 2/3-time and 1/3-time series.

The data taken from the strength tests and the sectioning samples proved that welds formed using reduced arc times were considerably smaller and weaker than full-time welds. The tests also proved that proper penetration is not dependent on the arc time, but is instead a function of the welding current and sheet steel thickness.

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d	=	Nominal Visual Diameter
d	=	Measured Visual Diameter
d_a	=	Average Diameter
d_e	=	Effective Diameter
e_{min}	=	Minimum Edge Distance
E	=	Modulus of Elasticity of Steel
F_u	=	Tensile Stress of Steel
F_{xx}	=	Tensile Stress of Electrode
F_y	=	Yield Stress of Steel
P_n	=	Design Strength
P_u	=	Required Stength
Pu	=	Ultimate Load
t	=	Total Sheet Steel Thickness
σ_u	=	Tensile Stress of Steel

Chapter 1: Introduction

1.1 Background

The ease with which cold formed steel can be manufactured, shipped and erected has made it an indispensable product in the modern construction industry. One of the most often used applications of cold formed steel is as steel deck. There are a number of different methods used to attach steel deck to hot-rolled steel. Perhaps the most common method is the use of arc spot welds, also known as puddle welds. Arc spot welds are produced by striking an arc on the upper sheet, forcing a hole to form, while the lower unit is raised to fusion temperature. With the attainment of proper temperature, the electrode is moved in a circular pattern until the hole is filled and fusion attained on the arc-puddle perimeter (Luttrell, 2004).

Steel decks frequently act as horizontal diaphragms, transmitting lateral loads to some lateral force resisting system. The amount of load that the diaphragm is able to transmit is dependent on the deck strength as well as the spacing and strength of the arc spot welds attaching it to the structure. If the weld strength is overestimated, too great of spacing between welds could be specified, thereby compromising the diaphragm strength and the lateral stability of the structure.

The current design strength equations for arc spot welds are based principally on research conducted at Cornell University by Pekoz and McGuire (1980) and research conducted by Blodgett (1978) of the Lincoln Electric Company. The equations used to predict the tearing and bearing at the weld contour limit state were first developed analytically by Blodgett (1978) in his report on Proposed Standards for Sheet Steel Welding. The equations were later supported through data collected by Pekoz and McGuire (1980). Pekoz and McGuire also developed an equation for the effective weld diameter, used to predict the weld shear failure limit state. Other limit states such as edge failure and net section failure are prevented by adhering to the minimum end and edge distance requirements given in section E2.2.1 of the 2001 AISI Specification (AISI, 2001).

During construction, situations regularly arise in which steel deck panels need to be lapped prior to welding. This results in four thicknesses of deck being lapped at the sheet corners. Pekoz and McGuire attempted to simulate these field conditions by conducting tests on both single and double layer steel sheets. Their test results indicated that the strength of an arc spot weld connection is dependent only on the total thickness of the sheet steels and not on the number of layers.

1.2 Objective

The objective of this research was to establish a relationship between arc spot weld shear strength and the arc time used while forming the weld. The results of the testing were also compared with the 2001 AISI Specification standard procedure for calculating arc spot weld shear strength. To achieve this objective, a test matrix encompassing a broad variety of welding scenarios was created. Arc times were broken down into three separate categories. The first category consisted of full-time welds, the second 2/3-time welds, and the third 1/3-time welds. The time spent making a full-time weld was defined as the minimum time required to produce visual, average and effective diameters consistent with the dimensions required by the 2001 AISI specification. Testing was performed on 22, 20, 18, and 16 gauge sheet steels. Each gauge material was tested in single-, double- and four-layer configurations. Both 3/4 in. and 5/8 in. diameter arc spot welds were tested. All three categories of arc times were tested for each unique sheet gauge, layer configuration and weld size. Every weld tested was formed by an AWS certified welder. Specimens from each series of arc time were loaded in shear in order to compare the differences in weld shear strength. Likewise, specimens from each series were also sectioned to compare differences in visual, average and effective weld diameters.

1.3 Scope

The sheet material chosen for the tests performed was ASTM A653 Gr. 33 galvanized sheet steel. Each sheet was sheared to a 3 in. by 12 in. area prior to testing. Strength Tests were conducted in both single- and double-layer configurations for each gauge material. Welds were also sectioned from single-, double- and four-layer sheet configurations. Every sheet was welded to an ASTM A36 3/8 in. thick steel plate. All welds were formed 2.5 in. from the sheet end and 1.5 in. from the sheet edge, providing adequate distance to prevent edge failure limit states. Both 3/4 and 5/8 in. welds were tested, each made with a 1/8 in. diameter E6010 electrode, as is commonly used in the construction industry for deck welding.

The testing process included testing material properties, documenting weld arc times, sectioning welds to determine their size and shape, and performing weld shear strength tests. All testing was completed at the Virginia Polytechnic Institute and State University Structures and Material Research Laboratory.

Tensile coupon tests were performed for each gauge sheet material used to determine their yield stress, tensile stress and percent elongation. These tests were performed in accordance with the ASTM E8-04 (2004) tensile coupon test procedure and their results are in Appendix C of this report.

A test series was defined as a specific combination of sheet gauge, layer configuration, weld size and arc time. Each test series was comprised of a minimum of three specimens. If any one of the specimen's shear strength deviated by more than ten percent from the mean shear strength, an additional specimen was tested. In all, strength tests were performed on 46 different test series. The complete test matrix is presented in Table A-1 of Appendix A.

1.4 Report Organization

A literature review summarizing previously conducted research and its conclusions is contained in Chapter 2 of this report. The research includes work done by Pekoz and McGuire at Cornell University and Omer Blodgett of the Lincoln Electric Company. The test setup, procedure and results from the lap shear tests are described in Chapter 3. These results include measured arc times, measured weld sections, observed strengths and comparisons made between the 2001 AISI Specification and recorded test results. A summary of the conducted research as well as conclusions that were drawn from the results are given in Chapter 4. Recommendations for improving the process of arc spot welding are also given in Chapter 4.

Chapter 2: Literature Review

The most common usage of arc spot welding is in the attachment of cold-formed steel roof deck to structural framing. Because the roof deck often acts as a horizontal diaphragm, transmitting lateral loads through shear into perpendicular lateral force resisting systems, it is important to know the exact shear strength of each diaphragm connection. Past research has focused on both the proper formation of arc spot welds and their ultimate strength.

In January of 1975, the AWS Structural Welding Committee set up a Task Group, now known as Subcommittee 11, to investigate the problem of sheet steel welding and to develop a proposed set of standards (Blodgett, 1978). The committee found that past efforts to study arc spot weld strength had been thwarted by a lack in understanding of how proper welds should be made. The four goals of the committee were as follows: (a) to establish when sheet steel welding is feasible, (b) investigate under what conditions good welds can be made, (c) to develop a proposed set of procedures, and (d) to test welds made with those procedures. The development of sound welds depends largely on adequate penetration into the supporting structural steel. Sufficient penetration, the committee found, is most dependent on the amount of current flowing through the welding electrode. If the critical current is not reached, heat simply flows through the sheet steel, forming a proper sized "puddle" in the sheet but with insufficient penetration into the structural steel underneath. Likewise, the committee also hypothesized that weld arc time affects only the visible weld diameter, and has little effect on the weld penetration or effective diameter. The committee went on to establish relationships between sheet thickness, electrode size, electrode melting rate (i.e. current), and visible to effective diameter ratio.

In 1975, the Canadian Steel Industries Construction Council (CSICC) began research project 175 "Strength of Arc Spot Weld in Sheet Steel Construction." The research was divided into three separate series. An in depth study on the basic parameters that affect the strength of the arc spot weld were carried out in Test Series I (Fung, 1978). These parameters included welding machine setting and technique, sheet thickness, plate thickness, and weld diameter. Ninety six welds were sectioned, etched and enlarged to evaluate the effect of the parameters. Findings for welding machine setting and technique were similar to those found by Blodgett (1978). It was also found that there was a substantial decrease in the effective diameter of the weld when the ratio of plate thickness to sheet thickness dropped below 2.5.

Test Series II evaluated the procedure of Test Series I under ideal conditions, while Test Series III evaluated the procedure under simulated field conditions. The simulated field conditions included surface coatings, gaps between sheet and plate, and variance in arc time. The results of Test Series II conformed reasonably well with the strength equations of AWS D1.3-77 (American Welding Society, 1977). These strength equations were developed by Omer Blodgett (see below) and are the basis for the strength equations used today by many specifications throughout the world. In Test Series III, the effect of surface coatings was varied. Primed surfaces and surfaces with lighter galvanizing (G-90) showed no significant signs of shear strength loss, while surfaces with heavier galvanizing (G-210) showed considerable losses in shear strength. Shims of 0.06 in., 0.10 in. and 0.13 in. thickness were used to separate the sheet from the plate to produce various gaps that might exist in the field (Fung, 1978). The test results showed the maximum permissible air gap to be 1/16 in. The increased volume of air present in gaps larger than 1/16 in. drew too much current away from the electrode, resulting in poor quality welds. The effect of increased arc time proved proportional to the arc spot weld shear capacity. In general, as arc time increased so did the weld diameter, resulting in a stronger weld.

A proper balance between the welding time and the electrode burn-off rate is essential to good quality welding (Luttrell, 2004). The Steel Deck Institute states that the settings should be such that burn-off rates are between 0.15 and 0.25 in. of rod per second in typical E60XX and E70XX 5/32 in. rods. Arc time is typically 3 to 6 seconds, but may be more depending on the properties of the sheet steel and hot rolled steel. “Spotty” contact between the weld and sheet steel may be indicative of an excessive power setting. Insufficient power will most likely result in poor penetration into the supporting member.

In many ways, the design of an arc spot weld is similar to an equivalent bolted connection as the failure modes are similar to those of mechanical connections (Hancock, 1998). Stark and Soetens (1980) summarize European research on welded connections in cold-formed sections. They indicate that arc spot welded connections subjected to shear will fail in one of four modes: tearing and bearing at the weld contour, edge failure, net section failure, or weld shear failure. All of these failure modes are the same as those seen in mechanical connections with the exception of two; *tearing and bearing at the weld contour* and *weld shear failure.*

Blodgett (1978) summarized the work of an AWS Subcommittee's investigation into the shear strength of arc spot welds. Based on the results of the investigation, Blodgett developed two separate equations used to predict the *tearing and bearing at weld contour* failure mode.

For $\frac{d_a}{t} < \frac{240}{\sqrt{\sigma_u}}$

$$Pu = 2.20 t_{av} \cdot d_a \cdot \sigma_u \qquad \text{(Eq 2.1)}$$

For $\frac{d_a}{t} \geq \frac{240}{\sqrt{\sigma_u}}$

$$Pu = 1.40 t_{av} \cdot d_a \cdot \sigma_u \qquad \text{(Eq 2.2)}$$

Where: d_a = the average visible diameter minus t_{av}

t_{av} = the average net sheet steel thickness

σ_u = the ultimate strength of the sheet steel

Pu = the ultimate load

The difference between Eq 2.1 and Eq 2.2 is attributed to the plate buckling theory. Equation 2.1 considers an arc spot weld perfectly bonded to a sufficiently thick sheet. As the connection is subjected to shear, the weld is pulled through the sheet. Blodgett pointed out that the stress in the material is a tensile stress at the leading edge, becoming a shear stress along the sides, and eventually becoming a compressive stress at the trailing edge of the weld (Yu, 2000). If, however, the plate is insufficiently thick, the compression side of sheet will buckle and provide little resistance against the weld's movement. Equation 2.2 above concerns an arc spot weld bonded to a sheet of minimal thickness such that any contributing compression forces may be neglected. An earlier book "Design of Weldments" (Blodgett 1963) indicates that the value of $240/(\sigma_u^{0.5})$ corresponds to the point at which the critical buckling stress of a plate, simply supported at both sides, transitions between inelastic and elastic behavior.

Test data later obtained at Cornell University by Pekoz and McGuire (1980) generally supported the findings of Blodgett. The tests were part of a research project "Welding of Sheet Steel," in which Pekoz and McGuire tested the shear strength of 126 different arc spot weld specimens. To better match the data however, a transition equation was added to the two equations suggested by Blodgett. Equations 2.3 through 2.5 are those suggested by Pekoz and McGuire to predict the *tearing and bearing at weld contour* failure mode. These equations are the basis of those currently in use by the American Iron and Steel Institute (AISI, 2001), the Steel Deck Institute (Luttrell, 2004), the American Welding Society (AWS, 1989), and the Australia/New Zealand Standard for Cold Formed Structures (Hancock, 1998).

For $\frac{d_a}{t} < \frac{140}{\sqrt{\sigma_u}}$

$$Pu = 2.20 t_{av} \cdot d_a \cdot \sigma_u \qquad \text{(Eq 2.3)}$$

For $\frac{d_a}{t} \geq \frac{240}{\sqrt{\sigma_u}}$

$$Pu = 1.40 t_{av} \cdot d_a \cdot \sigma_u \qquad \text{(Eq 2.4)}$$

For $\frac{140}{\sqrt{\sigma_u}} \leq \frac{d_a}{t} \leq \frac{240}{\sqrt{\sigma_u}}$

$$Pu = 0.28\left(1 + \frac{960 t_{av}}{d_a \sqrt{\sigma_u}}\right) t_{av} \cdot d_a \cdot \sigma_u \qquad \text{(Eq 2.5)}$$

Where:
d_a = the average visible diameter minus t_{av}
t_{av} = the average net sheet steel thickness
σ_u = the ultimate strength of the sheet steel
Pu = the ultimate load

Of the 126 welds tested by Pekoz and McGuire, 31 failed by *weld shear failure.* Many of the 31 failed welds contained substantial pitting and porosity (Pekoz and McGuire, 1980). The dimensions of these welds were then measured and a relationship between visible diameter, sheet thickness, and effective weld diameter was established (see Eq 2.6). The effective weld diameter was incorporated into the equation proposed for estimating the ultimate shear strength of arc spot welds (see Eq 2.7). Just as in Eqs 2.3 through 2.5, Eqs 2.6 and 2.7 are the basis of the equations currently used by the American Iron and Steel Institute (AISI, 2001), the Steel Deck Institute (Luttrell, 2004), the American Welding Society (AWS, 1989), and the Australia/New Zealand Standard for Cold Formed Structures (Hancock, 1998).

$$d_{en} = 0.7d - 1.5t \qquad \text{(Eq 2.6)}$$

$$P_u = \left(\frac{\pi \cdot d_{en}^{\ 2}}{4}\right) \cdot \left(\frac{3 \cdot \sigma_{uw}}{4}\right) \qquad \text{(Eq 2.7)}$$

Where: d = the visible diameter

d_{en} = the effective diameter

t = the sheet steel thickness

σ_{uw} = the weld electrode strength

Based on past research, the performance of arc spot welds subjected to shear in typical laboratory conditions is generally well documented and well understood. Performance of arc spot welds in simulated field conditions is, however, incomplete. The proposed research will document the effects of both reduced arc time and multiple sheet steel welding in an effort to better understand the actual behavior of arc spot welds as they are formed in today's construction industry.

Chapter 3: Test Setup and Results

The following chapter describes the testing procedure that was followed and the results that were taken from each test. Details related to the procedure such as specimen sizes, material properties and instrumentation are included. The results are presented in the same order in which testing was performed.

3.1 Test Parameters

Strength tests were performed on 46 different test series. Each specimen consisted of two ASTM A36 grade steel plates, two arc spot welds, and either a single- or double-layer of a specific thickness of ASTM A653 Gr. 33 sheet steel. The thicknesses of the sheet steel that were tested included 22, 20, 18 and 16 gauge material. The dimensions of the A36 grade steel plate used were 3/8 in. by 2 in. by 12 in. These dimensions were chosen so as to provide the welder with sufficient welding area while still adequately fitting into the grips of the testing machine. A 1/8 in. diameter E6010 electrode was used in the formation of every weld. Both 3/4 in. and 5/8 in. diameter arc spot welds were tested. The complete test matrix is listed in Appendix A of this document.

The current used in the formation of each weld varied depending on the specified diameter of the weld and the thickness of the sheet steel being welded. The lowest current setting, used for 5/8 in. welds in single-layer 22 gauge sheet steel, was 105 amps. The highest current setting, used for 3/4 in. welds in quadruple-layer 16 gauge sheet steel, was 200 amps. See Table 3-1 of Section 3.2 for the exact current used for each tests series.

Every weld was formed 2.5 in. from the sheet steel end and 1.5 in. from the sheet steel edge. These dimensions were in compliance with E2.2.1 of the 2001 AISI Specification, which dictates the minimum end and edge distances for arc spot welds loaded in shear. An example minimum end distance calculation using the AISI Specification can be seen in example B.2 of Appendix B of this document. Each piece of sheet steel was sheared to a 3 in. by 12 in. area, which adequately accommodated the minimum weld edge distances and end distances.

There is currently no standard test configurations used for testing the shear strength of arc spot welds. Instead, the configuration used was based on AISI TS-5-02 (AISI, 2002), which is the standard for testing the shear strength of mechanical fasteners used in connecting cold formed steel. The general layout of each specimen is illustrated in Figure 3-1.

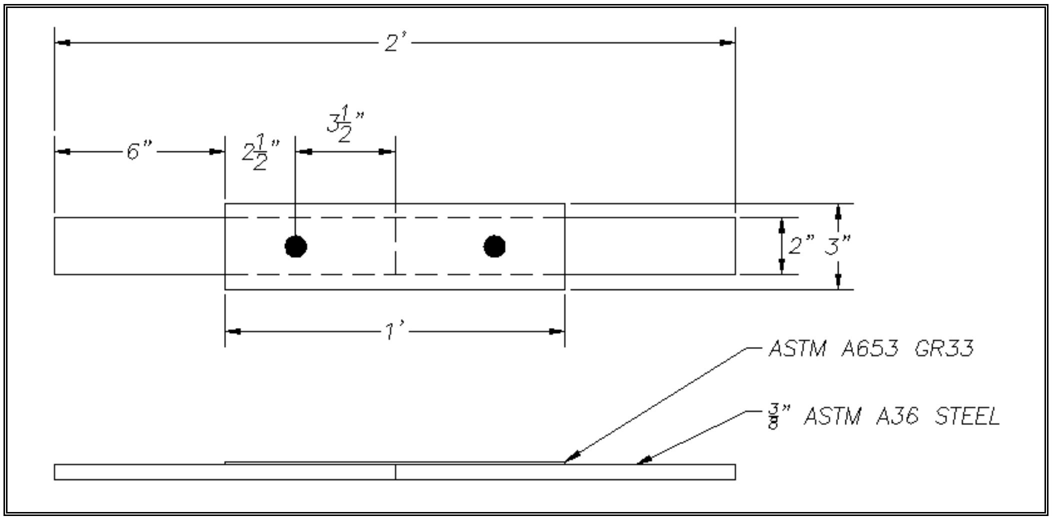

Figure 3-1: Test Specimen Configuration

3.2 Welding Procedure

The strength of arc spot welds is largely dependent on the skill of the person making the weld. Every weld formed in this research was performed by a single AWS certified welder. Current settings varied from 105 amps to 200 amps depending on the thickness of the sheet steel being welded. The melting rate was measured as the amount of electrode that would melt, or burn off, while forming a weld. The melting rates measured during this study varied between 10.5 in. per minute and 18 in. per minute. To choose the proper electrode and current/melting rate the welder used a combination of experience and experimentation. If the current was too low, insufficient penetration would be made into the supporting structural steel underneath. If the current was too high, the most likely result would be a substantial increase in porosity and inadequate contact with the surrounding sheet steel. Table 3-1 lists the currents and melting rates used for each test series.

Table 3-1: Current and Melting Rate

Thickness (gauge)	Weld Size (in)	Layer Configuration	Current (amps)	Melting Rate (in/min)
22	3/4	Single	105	10.00
20	3/4	Single	125	12.50
18	3/4	Single	135	13.25
16	3/4	Single	140	13.00
22	5/8	Single	105	10.00
20	5/8	Single	125	12.50
18	5/8	Single	135	13.25
16	5/8	Single	140	13.00
22	3/4	Double	135	14.50
20	3/4	Double	155	14.50
18	3/4	Double	165	16.00
16	3/4	Double	175	17.00
22	5/8	Double	140	13.50
20	5/8	Double	155	15.25
18	5/8	Double	165	16.00
16	5/8	Double	180	17.50
22	3/4	Four	180	17.50
20	3/4	Four	200	18.00
18	3/4	Four	200	18.00
16	3/4	Four	200	18.00

Once the proper current was determined the welder would begin forming the welds. The process of forming each weld started with an initial hole, which was burned through the sheet steel. For thicker sheet steels and multiple layers the current had to be increased to provide enough heat to burn through to the additional volume of material. Once this hole was formed, the electrode would begin to fuse with the supporting steel underneath. The welder then continued by spiraling the electrode out from the center of this hole, eventually over flowing it and forming the crown of the weld.

3.3 Material Properties

The materials used for the structural steel and sheet steel were ASTM A36 steel and ASTM A653 Gr. 33 galvanized sheet steel, respectively. Because the strength of the structural steel would not affect the strength of the arc spot welds, the material properties were not determined. Coupon tests following the ASTM E8-04 (2004) tensile coupon test procedure were performed for each thickness of sheet steel. The resulting stress vs.

strain plots are in Appendix C. Table 3-2 summarizes the average sheet steel properties determined from the testing.

Table 3-2: Average Material Properties

Gauge	Thickness (in)	Yield Stress (ksi)	Tensile Stress (ksi)	Percent Elongation (%)
22	0.028	47.5	55.3	37.0
20	0.046	47.6	55.0	37.7
18	0.034	48.7	58.7	31.9
16	0.057	54.4	61.2	29.0

3.4 Instrumentation

All strength tests were performed on an MTS Insight tensile testing machine with a load capacity of 30 kips. The MTS software TestWorks 4 was used to collect the measured displacements and loads. Displacements were measured between the grips of the MTS machine and not by an external extensometer or strain gauge device. Calipers accurate to the thousandth of an in. were used to measure sheet steel thicknesses, visual diameters, average diameters and effective diameters. The measurement of all full-time, 2/3-time and 1/3-time arc times was made with a standard stop watch. A digital video of every weld was recorded using a Sony DCR-HC40 digital camcorder.

3.5 Arc Time Results

Every full-time series was comprised of five specimens, each with two welds. The times spent making these ten welds were recorded and averaged. Times equal to 2/3 and 1/3 of this average were then used as the time cutoffs for the 2/3-time and 1/3-time series, respectively. Table 3-3 lists the average times used to form both 3/4 in. and 5/8 in. diameter full-time welds. Appendix D contains tabulated arc times for every full-time weld.

There were three variables associated with weld arc time; weld size, sheet steel thickness and the electrode current setting. The data indicates that the arc time required to form a given weld varies little with respect to sheet steel thickness or the electrode current setting. Arc time instead seems to be dependent only on the size of the weld.

Full-time 3/4 in. welds took an average of 12.8 seconds to form while full-time 5/8 in. welds took an average of 8.1 seconds to form.

Table 3-3: Full-Time Series Average Arc Times

Thickness (gauge)	Weld Size (in)	Layer Configuration	Total Thickness (in)	Full-Time Series Average Arc Time (sec)
22	3/4	Single	0.028	13.7
20	3/4	Single	0.034	12.8
18	3/4	Single	0.046	10.7
16	3/4	Single	0.057	12.8
22	5/8	Single	0.028	8.8
20	5/8	Single	0.034	7.2
18	5/8	Single	0.046	9.3
16	5/8	Single	0.057	8.3
22	3/4	Double	0.056	13.8
20	3/4	Double	0.068	11.2
18	3/4	Double	0.092	10.3
16	3/4	Double	0.114	14.7
22	5/8	Double	0.056	8.4
20	5/8	Double	0.068	7.7
18	5/8	Double	0.092	7.7
16	5/8	Double	0.114	8.8
22	3/4	Four	0.112	8.6
20	3/4	Four	0.136	7.8
18	3/4	Four	0.184	14.9
16	3/4	Four	0.228	16.5

Some of the arc times used were significantly different than the 3 to 6 seconds recommended by the SDI Diaphragm Design Manual (Luttrell, 2004). However, the 3 to 6 second time frame is based on the use of a 5/32 in. diameter electrode. These results indicate that welds made using 1/8 in. diameter rods take considerably longer to complete.

3.6 Specimen Sectioning and Test Procedure

The welding process began after the material properties were determined and the sheet steel was cut to the proper 3 in. by 12 in. dimension. The first step taken in the welding process was to form the initial full-time weld specimen. This specimen was then sectioned to determine if its dimensions met the requirements set forth by Section E2.2.1

of the 2001 AISI Specification and if sufficient penetration was formed in the hot-rolled steel. Weld penetration was considered insufficient if the weld material simply "pooled" on the surface of the hot-rolled steel and was considered sufficient if the weld material fused below the surface of the hot-rolled steel. If the specimen did not meet the dimension and penetration requirements, the current settings were adjusted and another specimen was made. The process was repeated until a weld with the proper dimensions and penetration was formed.

Once a proper sized full-time weld was created, the remaining four full-time specimens in the series were created using the same current setting, sheet steel thickness, layer configuration and weld size as the initial specimen. With a minimum of two welds formed in each specimen, a minimum of ten total full-time welds were created. The time required to form each weld was recorded and averaged. Two-thirds and one-third of this average time were then used as the cutoff times for 2/3-time welds and 1/3-time welds, respectively. A minimum of three 2/3-time and three 1/3-time specimens were formed. The same current setting that was used in the full-time series welds was used for both the 2/3-time and 1/3-time welds.

Full-time, 2/3-time and 1/3-time specimens were created for each unique combination of weld size, layer configuration and sheet steel thickness. Following their completion, shear strengths were determined for each specimen using a lap shear test. Each specimen was loaded beyond its ultimate shear strength to gain an accurate representation of the weld strength behavior.

The specimen sectioning portion of the study commenced after the shear strength tests were completed. One specimen was sectioned from every full-time series and three were sectioned from every 2/3-time and 1/3-time series. After each weld was sectioned, the average and effective weld diameters were measured and documented, the penetration was noted as sufficient or insufficient and any observed porosity was recorded. Digital photographs of each sectioned specimen were also taken in an effort to visually record the appearance of the weld cross section.

Using the strength data obtained from testing and the dimensional data obtained from sectioning, comparisons were made with the values predicted by the 2001 AISI Specification. The values obtained from the Specification were based on the measured visual diameters obtained during testing, which in many instances were significantly different than the intended nominal diameter.

3.7 Weld Diameter Results

3.7.1 General Findings

Results from each test series indicated a direct correlation between weld dimensions and arc time regardless of the thickness of the sheet steel or the number of layers being tested. It was discovered while welding the 2/3-time and 1/3-time series welds that the welder had to adjust his technique to form a visual diameter as consistent as possible with the nominal weld diameter. This adjustment was to form a smaller hole while initially burning through the sheet steel. The time saved burning a smaller hole allowed the welder to spend more time on the crown of the weld, which includes both the visual and average diameter.

The majority of 2/3-time welds tended to have visual and average diameters similar to those seen in full-time welds. However, because of the smaller initial hole in the sheet steel, they also tended to have smaller effective diameters. Full-time welds had visual diameters that were an average of 7 percent higher than those measured in the 2/3-time weld series. Effective diameters however, were an average of 22 percent higher in full-time welds. The average dimensions for full-time, 2/3-time and 1/3-time welds are displayed in Tables 3-4 through 3-6, respectively. Figure 3-2 illustrates the size difference between weld dimensions for each series of weld. Figures 3-2 and 3-3 illustrate the difference between the full-time, 2/3-time and 1/3-time weld diameters. Note in Figure 3-2 that the diameter, d, is a nominal value (e.g. 5/8 in. or 3/4 in.), while all values of "d" (d, d_a, d_e) in Figure 3-3 represent actual or measured values. A complete list of all weld sectioning data is in Appendix E of this document.

Despite saving time by starting with a smaller initial hole, most of the 1/3-time welds were found to be considerably undersized. The smaller initial hole meant that the effective diameter was undersized by an average of 36 percent when compared to full-time welds, while the visual diameter was undersized by an average of 21 percent.

Table 3-4: Average Dimensions of Full-Time Welds

Nominal Diameter (in.)	Sheet Thickness (gauge)	No. of Layers	Sheet Thickness (in.)	Measured Visual Diameter (in.)	Measured Average Diameter (in.)	Measured Effective Diameter (in.)
3/4	22	1	0.028	0.718	0.662	0.543
3/4	20	1	0.034	0.729	0.670	0.567
3/4	18	1	0.046	0.761	0.709	0.603
3/4	16	1	0.057	0.740	0.630	0.508
3/4	22	2	0.056	0.718	0.662	0.543
3/4	20	2	0.068	0.729	0.670	0.567
3/4	18	2	0.092	0.750	0.628	0.445
3/4	16	2	0.114	0.815	0.645	0.484
5/8	22	1	0.028	0.718	0.662	0.543
5/8	20	1	0.034	0.729	0.670	0.567
5/8	18	1	0.046	0.661	0.574	0.454
5/8	16	1	0.057	0.688	0.542	0.449
5/8	22	2	0.056	0.718	0.662	0.543
5/8	20	2	0.068	0.729	0.670	0.567
5/8	18	2	0.092	0.620	0.475	0.406
5/8	16	2	0.114	0.663	0.352	0.302
			3/4 Average	0.745	0.660	0.533
			5/8 Average	0.691	0.576	0.479

Table 3-5: Average Dimensions of 2/3-Time Welds

Nominal Diameter (in.)	Sheet Thickness (gauge)	No. of Layers	Sheet Thickness (in.)	Measured Visual Diameter (in.)	Measured Average Diameter (in.)	Measured Effective Diameter (in.)
3/4	22	1	0.028	0.630	0.541	0.396
3/4	20	1	0.034	0.687	0.574	0.407
3/4	18	1	0.046	0.659	0.602	0.456
3/4	16	1	0.057	0.730	0.561	0.368
3/4	22	2	0.056	0.697	0.607	0.386
3/4	20	2	0.068	0.711	0.611	0.456
3/4	18	2	0.092	0.735	0.606	0.350
3/4	16	2	0.114	0.714	0.616	0.380
5/8	22	1	0.028	0.595	0.537	0.304
5/8	20	1	0.034	0.597	0.517	0.314
5/8	18	1	0.046	0.624	0.524	0.385
5/8	16	1	0.057	0.650	0.567	0.361
5/8	22	2	0.056	0.617	0.528	0.333
5/8	20	2	0.068	0.615	0.479	0.361
5/8	18	2	0.092	0.600	0.450	0.315
			3/4 Average	0.695	0.590	0.400
			5/8 Average	0.614	0.515	0.339

Table 3-6: Average Dimensions of 1/3-Time Welds

Nominal Diameter (in.)	Sheet Thickness (gauge)	No. of Layers	Sheet Thickness (in.)	Measured Visual Diameter (in.)	Measured Average Diameter (in.)	Measured Effective Diameter (in.)
3/4	22	1	0.028	0.545	0.466	0.328
3/4	20	1	0.034	0.571	0.488	0.371
3/4	18	1	0.046	0.587	0.516	0.285
3/4	16	1	0.057	0.632	0.563	0.340
3/4	22	2	0.056	0.545	0.422	0.276
3/4	20	2	0.068	0.610	0.504	0.384
3/4	18	2	0.092	0.551	0.495	0.352
3/4	16	2	0.114	0.552	0.492	0.368
5/8	22	1	0.028	0.472	0.376	0.249
5/8	20	1	0.034	0.528	0.470	0.286
5/8	18	1	0.046	0.588	0.526	0.256
5/8	16	1	0.057	0.552	0.461	0.305
5/8	22	2	0.056	0.535	0.431	0.275
5/8	20	2	0.068	0.502	0.396	0.295
5/8	18	2	0.092	0.527	0.383	0.230
			3/4 Average	0.574	0.493	0.338
			5/8 Average	0.529	0.435	0.271

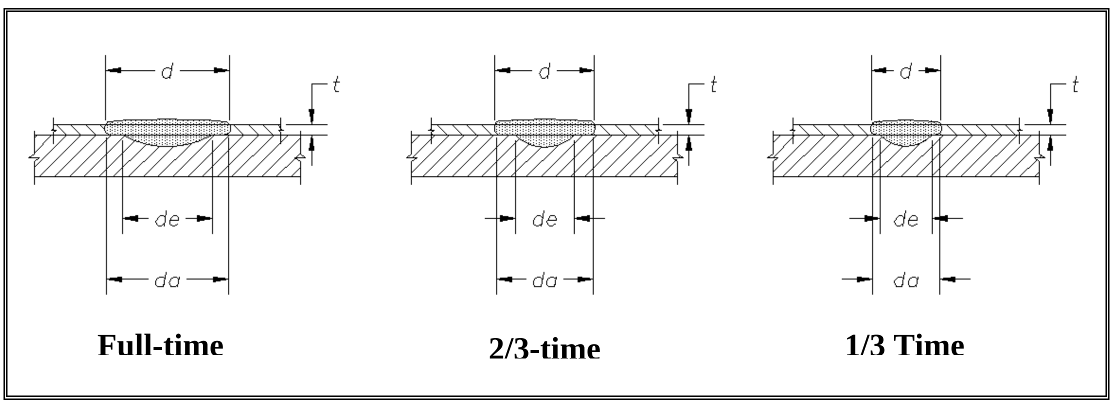

Figure 3-2: Common Weld Cross Sections

During the weld sectioning portion of the evaluations, it was found that some welds could not be satisfactorily created in certain layer configurations. When 5/8 in. welds were attempted in 16 gauge double layer conditions, three specimens had insufficient penetration and failed while sectioning. In an attempt to remedy the situation, the current was increased. Increasing the current however, also increased the initial hole, making it impossible to create any weld smaller than 3/4 in. in diameter. For this reason only the full-time series of 5/8 in. welds were tested for the 16 gauge double-layer configuration. Similarly, none of the four-layer configurations showed sufficient penetration into the structural steel underneath. The lack of penetration was a result of too much heat being absorbed by the sheet steel and layers of air between sheets. With the current already set at 200 amps (beyond the limit for a 1/8 in. diameter electrode), it was determined that neither a 5/8 in. or 3/4 in. diameter arc spot weld could be satisfactorily formed through four layers of sheet steel at any thickness. It should also be noted that the AWS does not certify welders to form arc spot welds through more than two layers of sheet steel.

3.7.2 Comparison between Weld Dimensions and the 2001 AISI Specification

Using the measured visual diameters and Section E2.2.1 of the 2001 AISI Specification, calculated average diameters were determined. The calculated average diameters were then compared with the measured average diameters obtained during the weld sectioning tests. Figure 3-3 illustrates the ratio of measured-to-calculated average diameters for full-time, 2/3-time and 1/3-time welds. Full-time welds had the lowest average ratio at 0.91 followed by 2/3-time welds at 0.92 and then by 1/3-time welds at 0.94. Standard deviation values for full-time, 2/3-time and 1/3-time welds were 0.08, 0.06 and 0.10, respectively. The relatively low standard deviation and ratios close to 1.0 suggest that the 2001 AISI Specification adequately predicts average diameters for both full-time and reduced time welds, given the known value of the visible diameters.

The effective diameters of all welds were evaluated using a process similar to the one used for average diameters. Using measured visual diameters and Section E2.2.1 of the 2001 AISI Specification, calculated effective diameters were determined for each sectioned specimen. Next, effective diameters measured during the weld sectioning procedure were compared to the calculated values. Figure 3-4 illustrates the differences between the measured and calculated values for full-time, 2/3-time and 1/3-time weld effective diameters. The measured-to-calculated effective diameter ratio for full-time welds averaged 1.3 for both 3/4 in. and 5/8 in. welds with a standard deviation of 0.11, indicating that the calculated values were slightly conservative. The effective diameter ratios for 2/3-time welds averaged approximately 1.0 with a standard deviation of 0.13

for both 3/4 in. and 5/8 in. welds. The value of 1.0 indicates that the measured effective diameters are consistent with those calculated using the 2001 AISI Specification, and are also slightly less than the ratio observed in full-time welds. The effective diameter ratio varied substantially more for 1/3-time welds than it did for either the full-time or 2/3-time welds. Although the average ratio was close to unity at 1.1, the standard deviation increased to 0.26.

Although Section E2.2.1 of the 2001 AISI Specification accurately predicts the average and effective diameters of both full-time and reduced-time welds, it is important to realize that the reduced time welds are still undersized. The measured-to-calculated ratio of 1.0 only indicates that the relationship between the measured visible diameter and other weld dimensions is accurate. It was often the case with reduced time welds that the measured visible diameter would be undersized and yet have measured-to-calculated dimension ratios of 1.0. This circumstance indicates that the entire weld is undersized, but that the relationship between the measured visual diameter and the remainder of the weld is consistent with the 2001 AISI Specification.

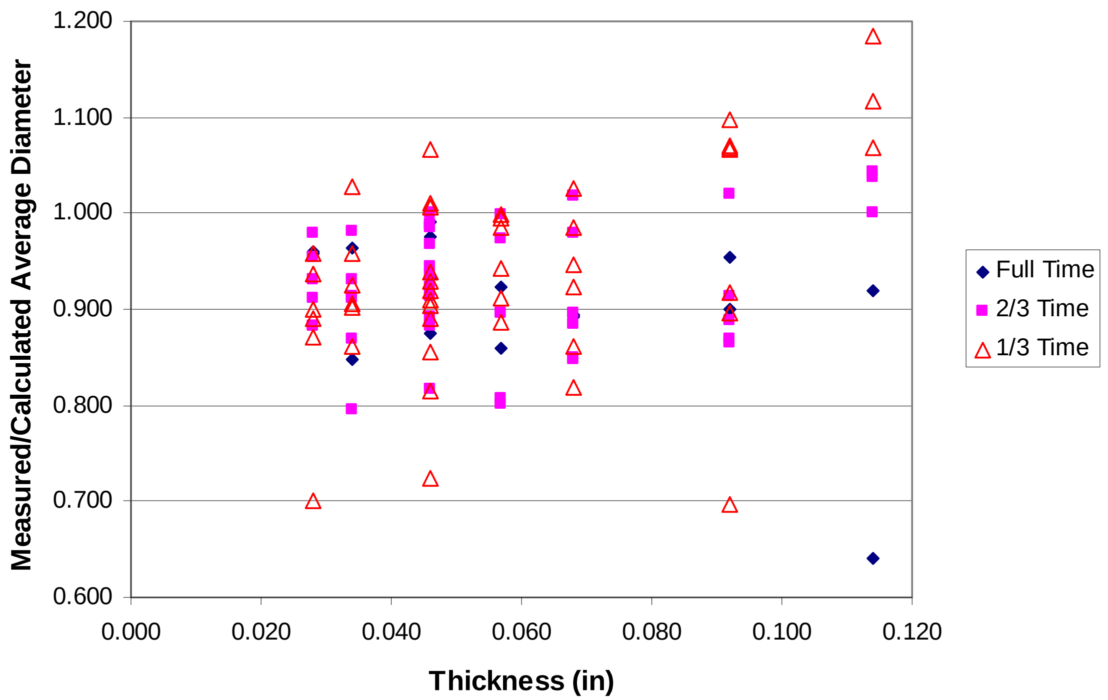

Figure 3-3: Measured/Calculated Average Diameters

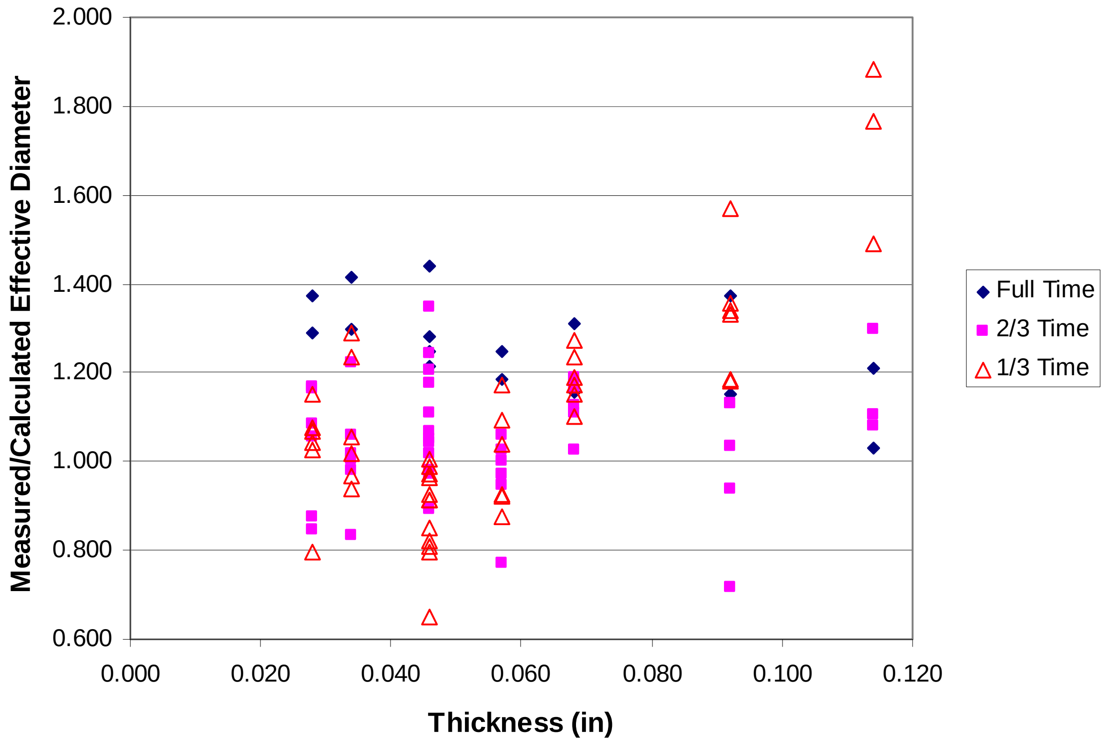

Figure 3-4: Measured/Calculated Effective Diameters

3.8 General Arc Spot Weld Failure Mode Results

Throughout the strength testing process, only two failure modes were observed. These failure modes included a ductile failure mode, sheet tear at the weld contour, and a brittle failure mode, weld shear failure through the fused area. The sheet tear at weld contour limit state controlled in conditions where the effective diameter to sheet steel thickness ratio was large. The tear always occurred at the tension side of the weld. The controlling parameter for this limit state was the average weld diameter. A larger average diameter meant a greater bonding area between the weld and the sheet steel. Increasing the bonding area decreased the stress in the sheet steel for a given applied load, resulting in a connection more resistant to sheet tear failure. The photograph in Figure 3-5 is an example of a 22 gauge sheet steel specimen failure due to sheet tear.

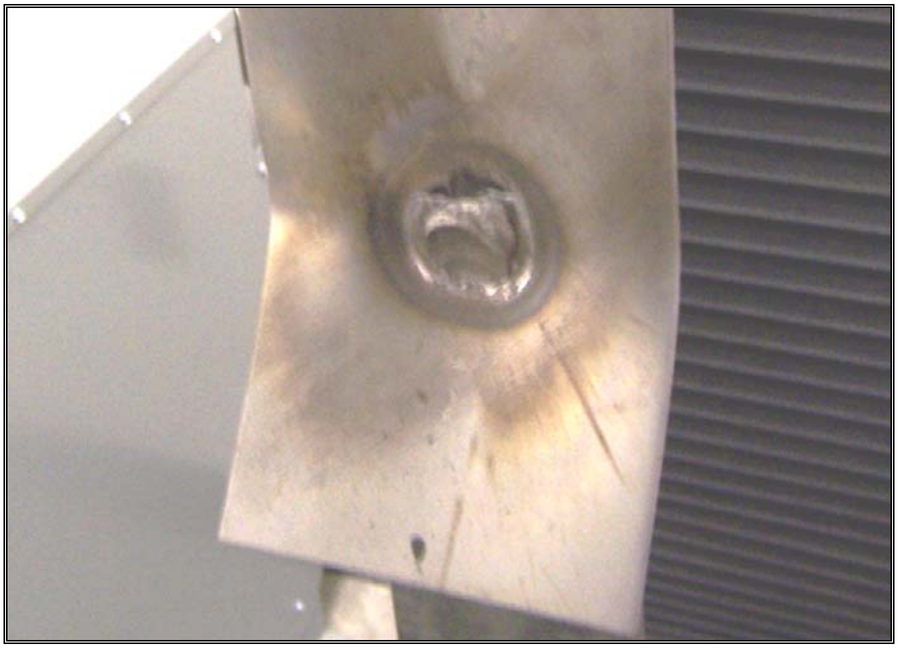

Figure 3-5: Sheet Tear Failure

Weld shear failure controlled in conditions where the effective diameter to sheet steel thickness ratio was small. When the critical load for weld shear failure was reached, the weld would shear directly through the effective diameter plane. The photograph in Figure 3-6 is an example of weld shear failure of a 3/4 in. weld made in 2-layers of 18 gauge sheet steel. Appendix F of this report contains a list of the observed failure modes.

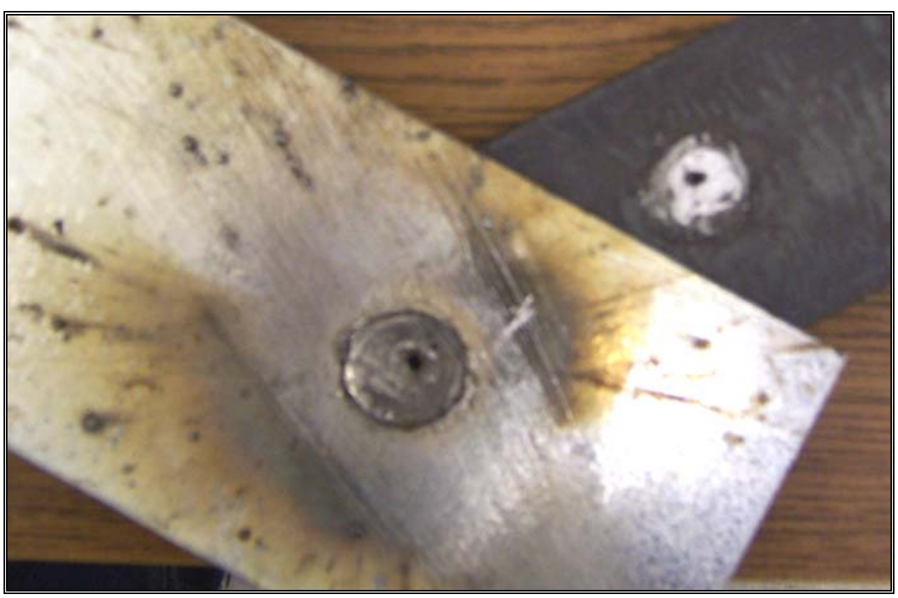

Figure 3-6: Weld Shear Failure

3.9 Individual Weld Shear Strength Results

Weld shear strength tests were performed on both 3/4 in. and 5/8 in. nominal diameter arc spot welds formed in a variety of sheet steel thicknesses and layers. In all, 155 strength tests were performed. Load vs. displacement graphs containing the results from each test are listed in Appendix G of this report. The following four sections describe the key results from the 155 tests.

3.9.1 Single Layer, 3/4 in. weld

The first set of weld shear strength tests was comprised of 3/4 in. welds formed in a single layer of sheet steel. This section describes the twelve test series included in the set. Each test series was comprised of either full-time, 2/3-time or 1/3-time welds and a single layer of 22, 20, 18 or 16 gauge sheet steel. As illustrated in Figure 3-7, full-time series welds are consistently stronger than other series made at a reduced arc time. However, the effect that time reductions have on weld strength varies between different gauge sheet steels. Time reductions had less influence on the weld shear strength for the 22 and 20 gauge sheets than for 18 and 16 gauge sheets. For this set of tests in general, full-time welds were an average of 11 percent stronger than 2/3-time welds and 20 percent stronger than 1/3-time welds.

Likewise, the failure modes differed depending on the thickness of sheet steel being used. For 22 and 20 gauge sheets, the failure modes were always sheet tear at the weld contour. As the thickness of the sheet steel increased, weld shear failure mode began to dominate in the 2/3 and 1/3-time welds. Table 3-7 highlights the typical failure modes for each of the single layer, 3/4 in. weld test series.

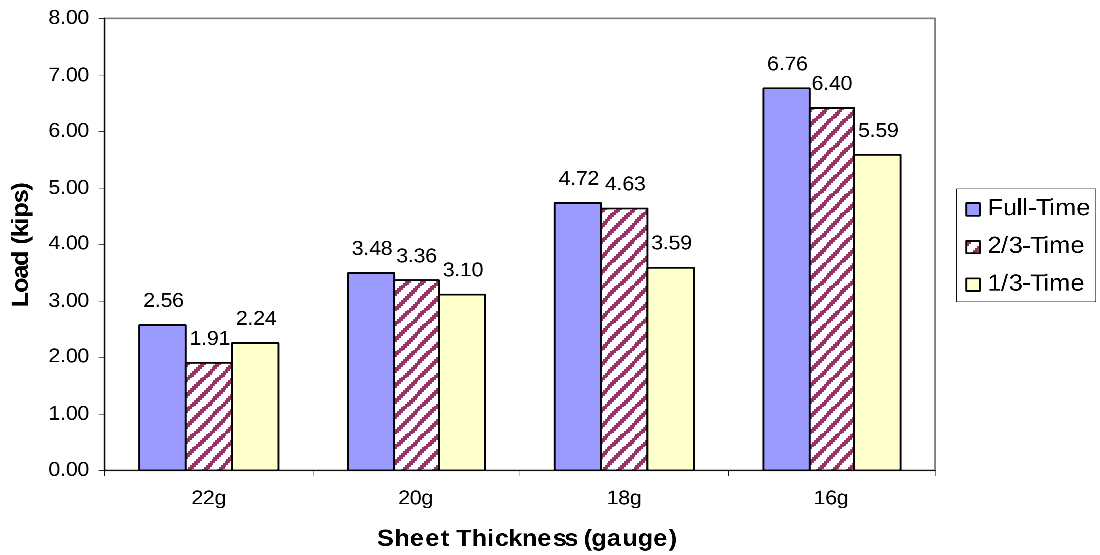

Figure 3-7: Average Shear Strength, Single Sheet, 3/4 in. Weld

Table 3-7: Single Layer, 3/4 in. Weld Typical Failure Modes

Weld Size (in)	Gauge	Layers	Welding Time	Typical Failure Mode
3/4	22	Single	Full	Sheet Tear
3/4	22	Single	2/3	Sheet Tear
3/4	22	Single	1/3	Sheet Tear
3/4	20	Single	Full	Sheet Tear
3/4	20	Single	2/3	Sheet Tear
3/4	20	Single	1/3	Sheet Tear
3/4	18	Single	Full	Sheet Tear
3/4	18	Single	2/3	Sheet Tear
3/4	18	Single	1/3	Weld Shear
3/4	16	Single	Full	Sheet Tear
3/4	16	Single	2/3	Weld Shear
3/4	16	Single	1/3	Weld Shear

3.9.2 Single Layer, 5/8 in. weld

The second set of tests was conducted on 5/8 in. arc spot welds formed in a single layer of sheet steel. This section describes results from the twelve test series included in the set. Each test series was comprised of either full-time, 2/3-time or 1/3-time welds and a single layer of 22, 20, 18 or 16 gauge sheet steel. Ultimate strengths for full-time and 2/3-time welds were similar, while strengths for the 1/3-time welds were substantially smaller. The results from these series of tests are displayed in Figure 3-8. Just as with the 3/4 in. welds, the strength difference between the full-time and 1/3-time 5/8 in. welds seemed to be dependent on the thickness of the sheet steel in which the welds were made. Thinner sheets (22 and 20 gauge) had average strength differences of 0.16 kips and 0.56 kips, respectively, while thicker sheets (18 and 16 gauge) had differences of 0.83 kips and 2.04 kips, respectively. For this set of tests in general, full-time welds were an average of 2.5 percent stronger than 2/3-time welds and 24 percent stronger than 1/3-time welds. The majority of the failure modes were sheet tear at the weld contour. However, weld shear failures did occur in the thicker sheet steels. Table 3-8 lists the failure modes for each test series included in this section.

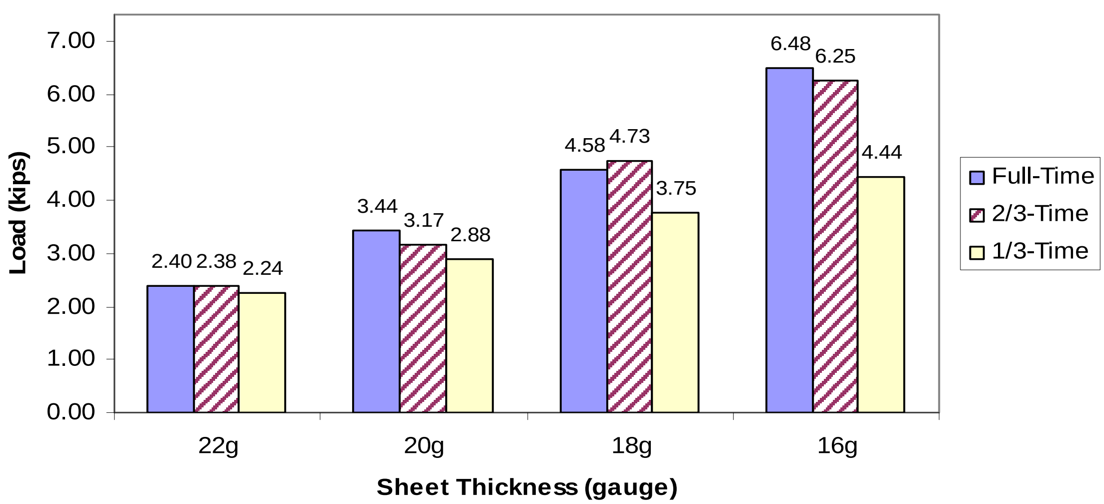

Figure 3-8: Average Shear Strength, Single Sheet, 5/8 in. Weld

Table 3-8: Single Layer, 5/8 in. Weld Typical Failure Modes

Weld Size (in)	Gauge	Layers	Welding Time	Typical Failure Mode
5/8	22	Single	Full	Sheet Tear
5/8	22	Single	2/3	Sheet Tear
5/8	22	Single	1/3	Sheet Tear
5/8	20	Single	Full	Sheet Tear
5/8	20	Single	2/3	Sheet Tear
5/8	20	Single	1/3	Sheet Tear
5/8	18	Single	Full	Sheet Tear
5/8	18	Single	2/3	Sheet Tear
5/8	18	Single	1/3	Weld Shear
5/8	16	Single	Full	Weld Shear
5/8	16	Single	2/3	Sheet Tear
5/8	16	Single	1/3	Weld Shear

3.9.3 Double Layer, 3/4 in. weld

The third set of tests was carried out on 3/4 in. arc spot welds formed in two layers of sheet steel. This section describes results from the twelve test series included in the set. Each test series was comprised of either full-time, 2/3-time or 1/3-time welds and two layers of 22, 20, 18 or 16 gauge sheet steel. The ultimate strengths from both the full-time and 2/3-time welds were similar, though the strengths of the full-time welds were consistently greater. The strength of 1/3-time welds was similar to the strength of full-time welds in 22 and 20 gauge sheet steels where the typical failure mode was sheet tear at the weld contour. However, for 18 and 16 gauge sheet steels, when weld shear was the typical failure mode, 1/3-time welds were considerably weaker than their full-time counterparts. For this set of tests in general, full-time welds were an average of 13 percent stronger than 2/3-time welds and 47 percent stronger than 1/3-time welds.

Figure 3-9 illustrates the differences in average shear strength for each of the twelve test series. Note that the strength in full-time welds consistently increases as the sheet steel thickness increases until the double layer of 16 gauge sheet steel is reached. The sudden decrease at this thickness can be attributed to the typical failure mode switching from sheet tear to weld shear failure. Weld shear failure is a function of the effective weld diameter which decreases as the sheet steel thickness increases. Therefore once the weld shear failure mode begins to dominate, increasing sheet steel thickness will result in decreased arc spot weld shear strength. Figure 3-10 illustrates how the estimated shear strength of a 3/4 in. arc spot weld varies with respect to sheet steel thickness. Equations E2.2.1-1 through E2.2.1-4 of the 2001 AISI Specification, which are based on Eqs 2.3 through 2.7 of this document, were used to calculate the estimated values used in the figure. Table 3-9 displays the typical failure modes for each test series.

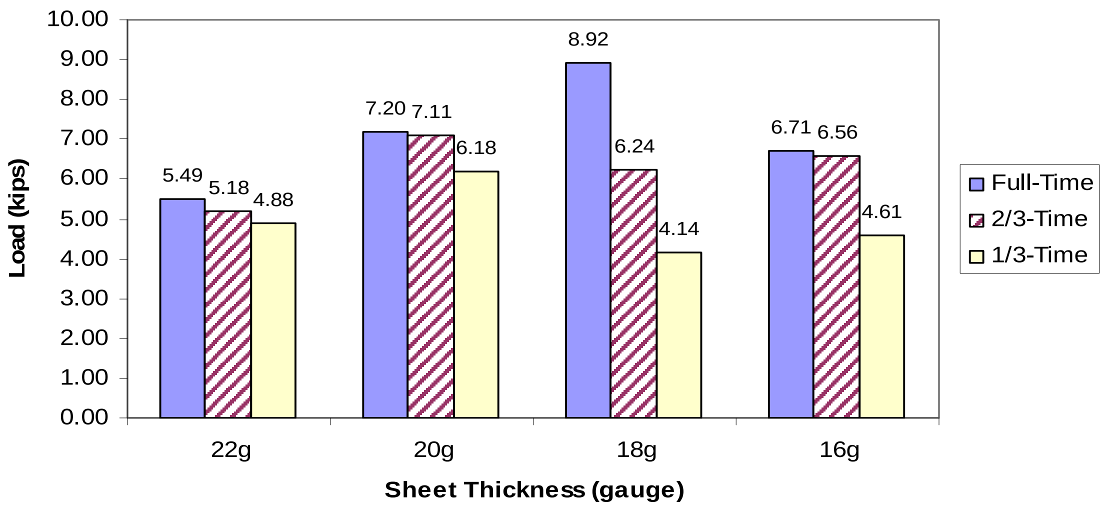

Figure 3-9: Average Shear Strength, Double Sheet, 3/4 in. Weld

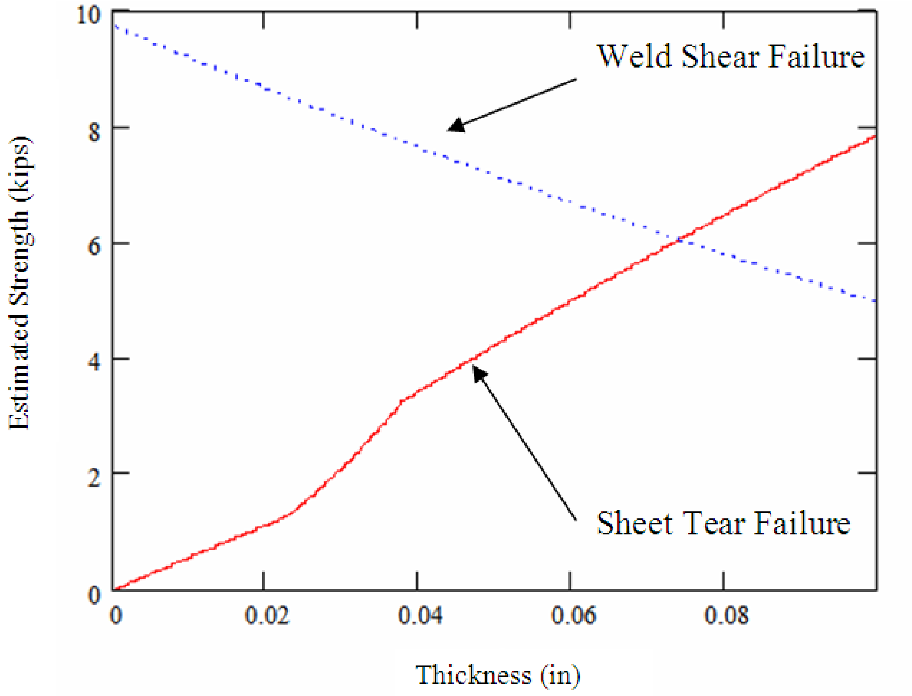

Figure 3-10: Weld Shear and Sheet Tear Strength vs. Sheet Thickness

Table 3-9: Double Layer, 3/4 in. Weld Typical Failure Modes

Weld Size (in)	Gauge	Layers	Welding Time	Typical Failure Mode
3/4	22	Double	Full	Sheet Tear
3/4	22	Double	2/3	Sheet Tear
3/4	22	Double	1/3	Sheet Tear
3/4	20	Double	Full	Sheet Tear
3/4	20	Double	2/3	Sheet Tear
3/4	20	Double	1/3	Weld Shear
3/4	18	Double	Full	Weld Shear
3/4	18	Double	2/3	Weld Shear
3/4	18	Double	1/3	Weld Shear
3/4	16	Double	Full	Weld Shear
3/4	16	Double	2/3	Weld Shear
3/4	16	Double	1/3	Weld Shear

3.9.4 Double Layer, 5/8 in. weld

The fourth set of tests was carried out on 5/8 in. arc spot welds formed in two layers of sheet steel. This section describes results from the ten test series included in the set. Each test series was comprised of either full-time, 2/3-time or 1/3-time welds and two layers of 22, 20, 18 or 16 gauge sheet steel. The strengths of full-time welds were consistently greater than both the 2/3-time and 1/3-time welds. With the exception of the 22 gauge sheets, none of the 2/3-time weld strengths were close to those of the full-time welds. For this set of tests in general, full-time welds were an average of 18 percent stronger than 2/3-time welds and 97 percent stronger than 1/3-time welds. Figure 3-11 displays the average shear strength for each of the ten series tested. Only the full-time welds were tested in double layered 16 gauge sheets. Insufficient penetration into the structural steel caused two of the full-time specimens to separate while sectioning. Based on the lack of penetration in the full-time series welds, it was decided not to attempt 2/3 and 1/3-time welds in the double layer 16 gauge sheet steel.

The typical failure mode for all 2/3 and 1/3-time welds was weld shear failure. Only full-time welds made in 22 and 20 gauge sheets had sheet tear at the weld contour as their typical failure modes. As with the 3/4 in. welds, once the weld shear failure limit state is reached, any increase in sheet steel thickness results in decreased arc spot weld shear strength. This can be attributed to the fact that the weld shear failure limit state is a function of the effective weld diameter, which decreases as the sheet steel thickness increases. The decrease in shear strength between the 20 gauge and 18 gauge full-time welds is shown in Figure 3-11. Table 3-10 displays the typical failure mode for the ten series tested.

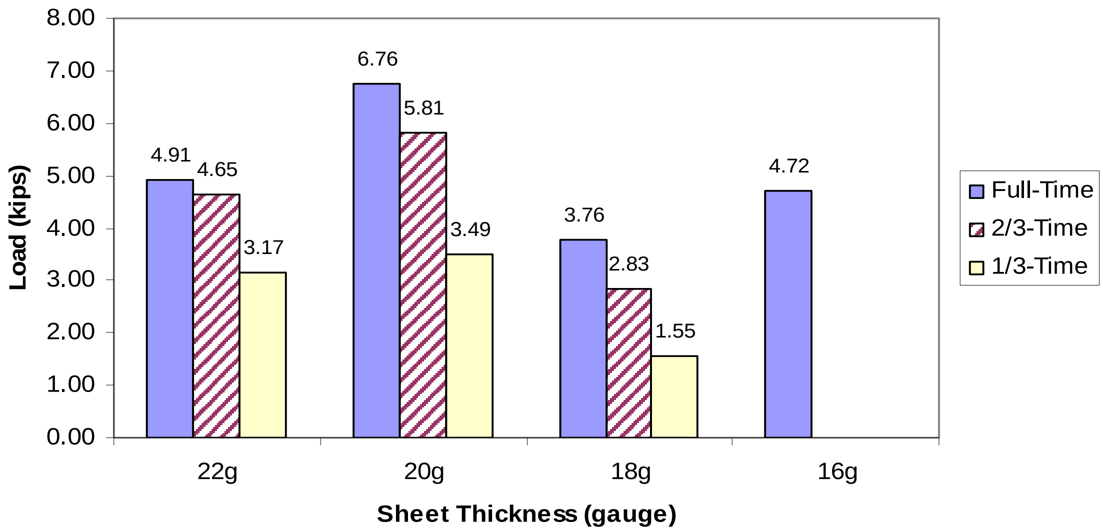

Figure 3-11: Average Shear Strength, Double Sheet, 5/8 in. Weld

Table 3-10: Double Layer, 5/8 in. Weld Typical Failure Modes

Weld Size (in)	Gauge	Layers	Welding Time	Typical Failure Mode
5/8	22	Double	Full	Sheet Tear
5/8	22	Double	2/3	Weld Shear
5/8	22	Double	1/3	Weld Shear
5/8	20	Double	Full	Sheet Tear
5/8	20	Double	2/3	Weld Shear
5/8	20	Double	1/3	Weld Shear
5/8	18	Double	Full	Weld Shear
5/8	18	Double	2/3	Weld Shear
5/8	18	Double	1/3	Weld Shear
5/8	16	Double	Full	Weld Shear

3.10 Comparison between Weld Shear Strength and the 2001 AISI Specification

From the results presented in section 3.9 or this report, it is apparent that the reduced-time welds are significantly weaker than full-time welds. Specimen sectioning results also indicate that reduced-time welds have consistently smaller dimensions.

Comparisons were made in this section of the report to determine how accurately equations E2.2.1-1 through E2.2.1-4 of the 2001 AISI Specification estimate reduced-time arc spot weld shear strength, given the smaller visual diameter of the welds.

For full-time welds, the average ratio of measured-to-calculated shear strength was 1.31 with a standard deviation of 0.26. The 2/3-time welds had an average ratio and a standard deviation of 1.25 and 0.26, respectively, and 1/3-time welds had an average ratio of 1.39 and a standard deviation of 1.56. Comparisons made between measured shear strengths and those calculated using the 2001 AISI Specification are illustrated in Figures 3-12, 3-13 and 3-14 for full-time, 2/3-time and 1/3-time welds, respectively. Appendix B contains an example shear strength calculation using the AISI Specification equations.

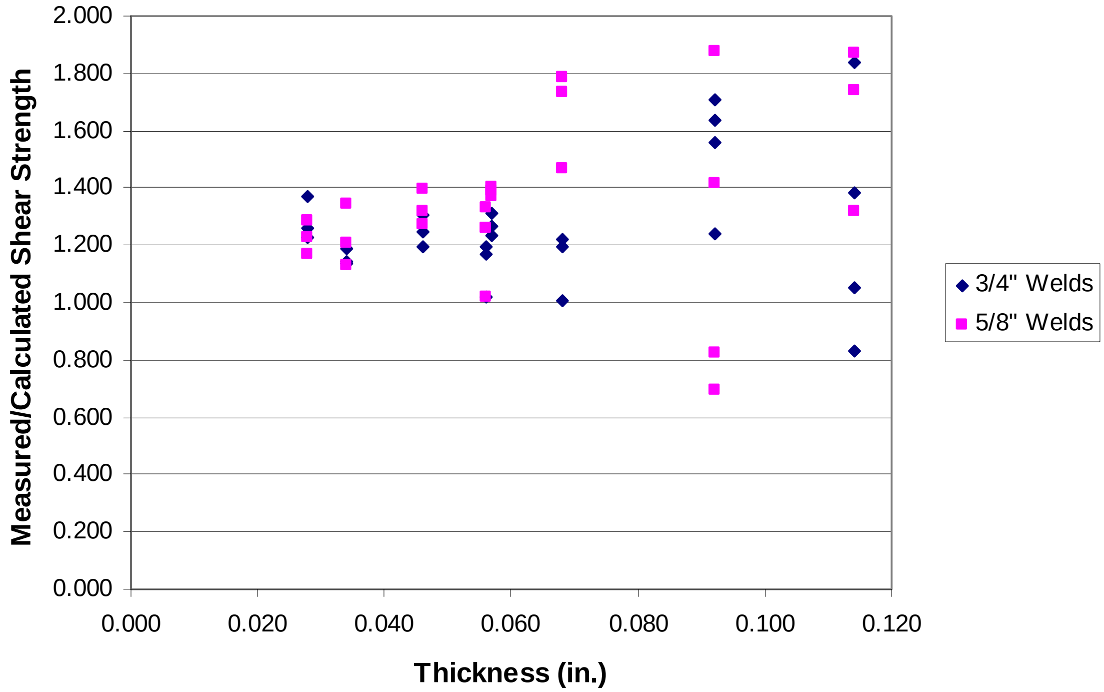

Figure 3-12: Comparison of Full-Time Weld Shear Strengths

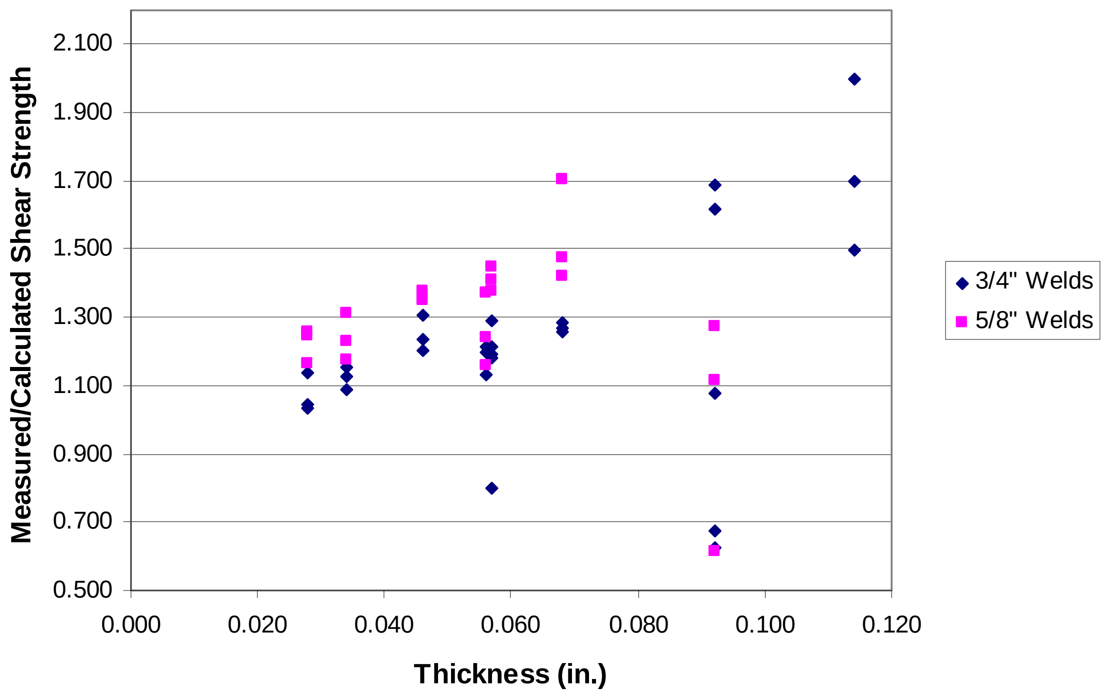

Figure 3-13: Comparison of 2/3-Time Weld Shear Strengths

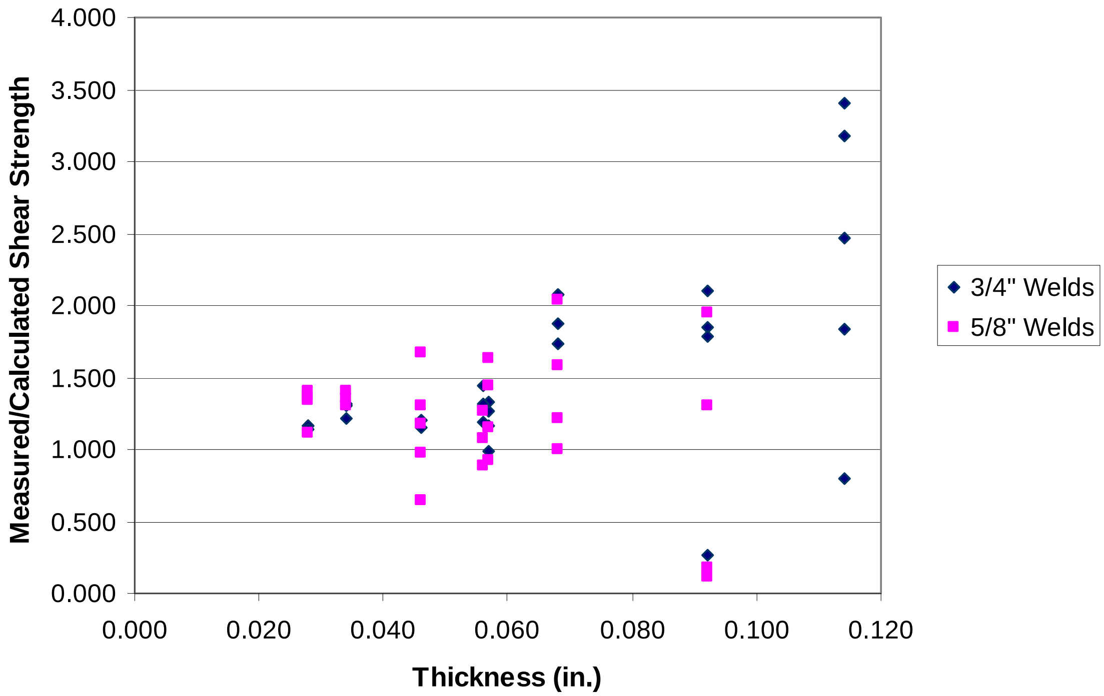

Figure 3-14: Comparison of 1/3-Time Weld Shear Strengths

The decreased strength of reduced-time welds was sufficiently estimated by equations E2.2.1-1 through E2.2.1-4 given in the 2001 AISI Specification, provided that the measured visual diameter of the reduced-time welds was used in the equations. Conversely, if the nominal visual diameter were to be used, the equations would have over estimated the shear strength of each reduced-time arc spot weld.

An increase in scatter can be observed in Figures 3-12 through 3-14 as the thickness of the sheet steel is increased. This trend can also be observed in Pekoz and McGuire's (1980) data and is likely caused by the unpredictability of the effective diameter of the weld. The area of the weld located at the effective diameter plane varies substantially, regardless of the sheet steel thickness (see Figure 3-4). Therefore the shear strength of the arc spot weld will vary significantly when weld shear failure, which is a function of the effective diameter, is the controlling limit state.

Weld shear strength comparisons were only made with the 2001 AISI Specification. Comparisons with other sources such as the SDI Diaphragm Design Manual (Luttrell, 2004) were considered unnecessary because their weld shear strength equations are based on those used by AISI.

3.11 Evaluation of Arc Time Results

The time required to form reduced-time welds was determined from the average time used to form each full-time weld. A total of 183 full-time welds were formed in sheet steel thicknesses of 22, 20, 18 and 16 gauge arranged in single-, double-, and quadruple-layers. As Figure 3-14 indicates, the arc time used in forming each weld varies little with respect to sheet steel thickness. This consistency can be attributed to the increased current setting used while forming welds in thicker layers of sheet steel. Arc time instead seems to only be a function of the weld diameter. The data taken suggests that full-time, 3/4 in. arc spot welds take approximately 12.8 seconds to form, while 5/8 in. diameter welds take approximately 8.1 seconds to form.

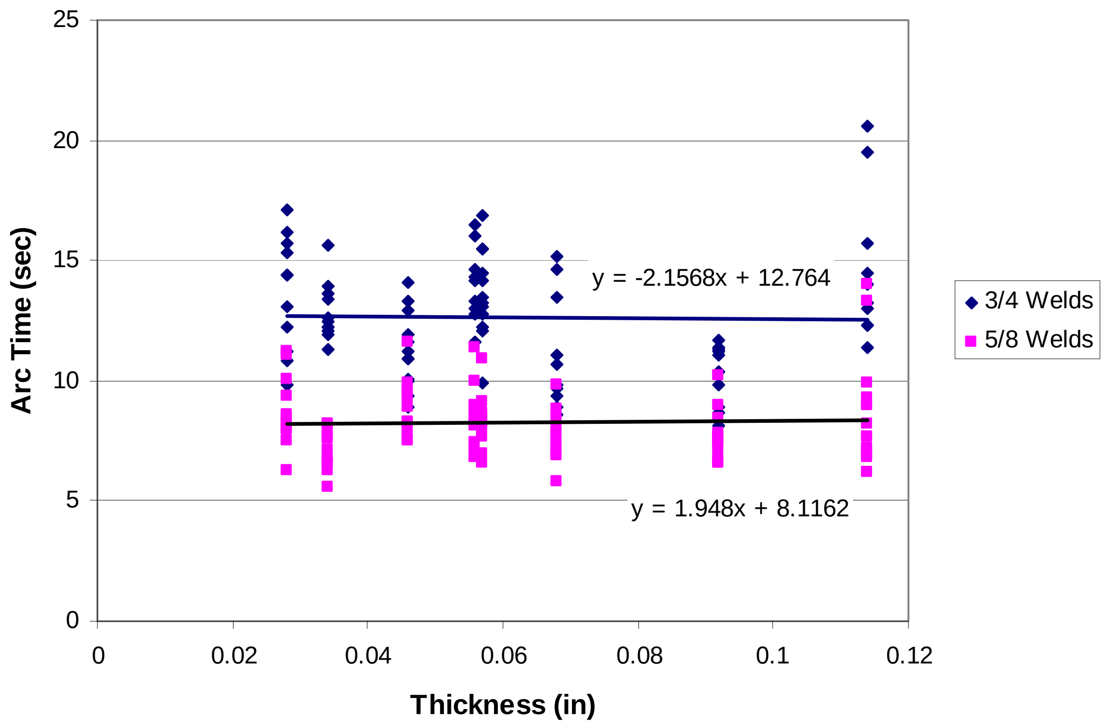

Figure 3-15: Arc Time vs. Sheet Thickness

3.12 Summary of Test Results

Cross sections taken during the testing process indicate a direct relationship between the dimensions of the weld and the time spent forming the weld. 2/3-time welds had visual and average diameters slightly smaller than those seen in full-time welds. The effective diameters were significantly smaller, however, by an average of 22 percent. The smaller effective diameter can be attributed to both the reduced arc time and the welding process. Because of the reduced time, the welder was forced to produce a smaller initial hole in the sheet steel when burning through to the structural steel underneath. The time saved producing a smaller hole can be used while making the crown of the weld, which includes the visual and average diameters. The additional time spent forming the crown allowed the welder to produce 2/3-time welds with visual diameters closely matching the nominal weld diameter. However, the smaller initial hole also meant a smaller effective diameter was formed. The smaller effective diameter resulted in reduced strength in the weld shear mode of failure for the 2/3-time welds. Overall, full-time welds were an average of 11 percent stronger than 2/3-time welds.

The effective diameters of 1/3-time welds also proved to be significantly less than their full-time counterparts. This can again be attributed to a reduced arc time and the technique used during the formation of the weld. On average the effective diameters of 1/3-time welds were 36 percent smaller than those measured in full-time welds. Unlike the 2/3-time welds however, the 1/3-time welds also had significantly smaller average and visual diameter when compared to full-time welds, by an average of 21 percent. The fact that both the average and effective diameters were undersized meant that the 1/3-time welds had a reduced strength for both the weld shear and sheet tear at the weld contour failure modes. Overall, full-time welds were an average of 44 percent stronger than 1/3-time welds.

Penetration into the structural steel underneath was affected most by current, the thickness of sheet steel, and number of layers used. If the current setting was too low, not enough heat would flow into the structural steel, which would not allow for adequate fusion between it and the electrode. Thicker sheets and multiple layers create a greater volume of material that had to be penetrated to contact the supporting hot-rolled steel underneath. The greater volume of material absorbs more heat from the electrode, thereby forcing the current setting to be increased to produce adequate penetration into the structural steel. It was found during the sectioning process that sufficient penetration from welds was not formed through four layers of 22, 20, 18 or 16 gauge sheet steel. The layers of sheet steel, combined with the layers of air trapped between, absorbed enough heat to cause insufficient penetration, despite the current being set at its maximum of 200 amps.

Chapter 4: Summary and Conclusions

4.1 Summary

Arc spot welds are used extensively in the construction industry for the attachment of cold-formed metal deck to structural steel. They can be used to temporarily hold the deck in place until a permanent attachment is made, as in composite construction. They can also be used as a permanent connection, as is often done with roof decks. When used as a permanent connection, the welds are relied upon to transfer lateral forces from the deck to parallel lateral force resisting systems through shear.

No previous research has been conducted on arc spot welds formed using a reduced arc time, making their exact strength and behavior uncertain. The primary focus of this research was to compare welds made under full-time conditions to those formed at reduced arc times of 2/3 of full-time and 1/3 of full-time. Comparisons were made between shear strength and weld geometry, including average diameter, effective diameter and penetration.

The testing matrix included a broad variety of weld sizes, sheet steel thicknesses and sheet steel layers. This was to insure that the results obtained and conclusions made were valid for arc spot welds formed in a variety of connection scenarios. Both 3/4 in. and 5/8 in. diameter welds were tested. Welds were made in single-, double-, or quadruple-layers of sheet steel. The sheet steel thicknesses were 22, 20, 18, and 16 gauge sheets.

Weld sectioning was used to determine the average diameter, effective diameter and penetration of welds from every time series. One weld was sectioned from every full-time series to insure compliance with the 2001 AISI Specification. Three welds from every 2/3-time series and every 1/3-time series were also sectioned. The average and effective diameters from each section were measured. Penetration was also noted as sufficient or insufficient.

Each specimen used for the shear strength tests was assembled in a lapped fashion with the sheet steel on top and two hot-rolled steel plates underneath. Two arc spot welds connected the sheet steel to the hot-rolled steel in every specimen. Only two failure modes were observed throughout the strength testing process; weld shear through the fused area and sheet tear at the weld contour. Weld shear failure was common among specimens with small effective diameter-to-sheet steel thickness ratios, while sheet tear failure was common among specimen with large effective diameter to sheet steel thickness ratios.

Although the strengths of 2/3-time and 1/3-time welds were significantly less than that observed in full-time welds, the strengths were in proportion to the measured visual diameter of each weld. Full-time welds were the strongest because they were consistently larger in diameter. When the visual diameter was used in place of the nominal diameter, equations E2.2.1-1 through E2.2.1-4 of the 2001 AISI Specification adequately estimated the weld shear strength capacity, making any modifications to the equations unnecessary.

4.2 Conclusions

This thesis summarizes the details of testing that was conducted on arc spot welds subjected to different time constraints. Conclusions, which are highlighted in the following sections, were drawn based on the data and results obtained from each test.

4.2.1 Weld Arc Time

- The three variables having the greatest influence on weld arc time were sheet steel thickness, current setting and weld size. A greater thickness of sheet steel requires more arc time than a thinner sheet for a given current setting and weld size. Higher current settings form larger welds in a smaller amount of time. And smaller weld sizes generally take less time to form than larger weld sizes.
- Testing showed that the time required to form full-time arc spot welds varies little with respect to the sheet steel thickness. This near constant behavior can be attributed to higher currents being used in thicker steel sheets. Because thicker sheets increase required arc time and higher current settings decrease it, the two essentially offset each other, leaving weld size as the only variable to have an actual effect on the required arc time.
- From the testing, the average time required to form a 3/4 in. weld is 12.8 seconds and that the average time required to make a 5/8 in. weld is 8.1 seconds.

4.2.2 General Weld Geometry

- Arc time has a significant impact on the overall size of a given weld. When the current setting and the electrode type are held constant, a reduction in arc time will always result in a smaller weld being formed, often far less than the intended nominal size. Measured visual diameters were an average of 7 percent smaller in 2/3-time welds and 21 percent smaller in 1/3-time welds than those measured in full-time welds.
- Depending on the weld size, layers of sheet steel and thickness of sheet steel, a current setting was found which would produce the optimal penetration. If the setting was too low, too much heat was absorbed by the sheet steel resulting in insufficient penetration into the supporting structural steel. If the setting were too high, substantial porosity appeared in the weld and sporadic contact was observed with the sheet steel at the weld perimeter.
- Every quadruple-layer specimen had unsatisfactory penetration into the supporting hot rolled steel. The total thicknesses of the sheet steel together with the added layers of air and galvanized coatings presumably all drew too much current away from the electrode to satisfactorily fuse with the structural steel.
- The 2001 AISI specification states that arc spot welds should not be made in layers of sheet steel totaling more than 0.15 in. in thickness but makes no mention to the maximum number of layers of sheet steel. Given the fact that insufficient penetration was observed in quadruple-layered steel as thin as 0.112 in. (4 layers of 22 gauge), it would be unreasonable to use 0.15 in. as the thickness upper limit for four or more layers of sheet steel.
- The testing performed in this study indicates that penetration is not directly affected by weld arc time. If the welder is allowed sufficient time to adequately burn through the sheet steel and the current setting is properly set, proper penetration will be achieved.

4.2.3 Comparison of Measured Diameters to the 2001 AISI Specification

- Although reducing the weld arc time significantly reduces the overall weld size, it has very little effect on the basic weld shape. Both 2/3-time and 1/3-time welds have approximately the same visual diameter-to-average diameter and visual diameter-to-effective diameter ratios as those observed in full-time welds. Using the measured visual diameter, comparisons were made between the measured average and effective diameters and those calculated using the 2001 AISI Specification. The comparisons prove that the Specification adequately estimates average and effective weld diameters regardless of arc time, given a known visual diameter.

4.2.4 General Weld Shear Strength

- Arc time had a significant impact on weld strength. Full-time welds were an average of 11 percent stronger than 2/3-time welds and 44 percent stronger than 1/3-time welds.
- Differences between the strength of full-time welds and reduced-time welds increase as the sheet steel thickness is increased. This can be attributed to the slightly smaller effective diameter observed in reduced time welds.

4.2.5 Comparison between measured strength and the 2001 AISI Specification

- The lower shear strength observed in reduced-time welds is directly proportional to the decreased size of the welds. Using the measured visual diameter and not the nominal diameter, the 2001 AISI Specification provisions adequately estimate the strength of full-time welds, 2/3-time welds, and 1/3-time welds.
- The test results show that full-time welds, 2/3-time welds, and 1/3-time welds all averaged approximately 30 percent higher strengths than their estimated values. This conservatism is consistent with Pekoz and McGuire's (1980) data, where tested strengths averaged as much as 22 percent higher than the estimated values.
- The accuracy with which the 2001 AISI Specification could estimate weld strength diminished as the thickness of the sheet steel increased for both full-time and reduced-time welds. This can be attributed to the failure mode switching from sheet tear failure to weld shear failure for thicker sheet steels.

4.3 Recommendations

4.3.1 Requirements for Weld Arc Time

This research has proven that arc time has a tremendous influence on arc spot weld shear strength. It is therefore imperative that measures be taken to insure welds formed in the field are completed using the proper arc time.

Naturally, every welder has a slightly different technique and may require slightly different amounts of time to complete an arc spot weld. The variation in required arc time from welder to welder was not accounted for in this research. Therefore it is not recommended that either the 12.8 second 3/4 in. welds or 8.1 second 5/8 in. welds used by the welder in this research be set as any sort of standard. Instead, a new procedure must be devised that will accommodate a welders individual technique and required arc time.

Currently, welders must be certified at the beginning of each project they undertake that involves deck welding. This certification involves forming an arc spot weld in the same sheet material used on the project. The welder must form the weld using the same electrode and current setting that will be used during the remainder of the project. This weld is then inspected by an AWS certified professional who deems the quality of the weld to be sufficient or insufficient. Provided the weld is sufficient, the welder is allowed to proceed with welding arc spot welds for the project. The major recommendation concerning the certification process is that it be modified to include arc time. This would give the welder three items to hold constant: the electrode, the current setting and the arc time (within a certain tolerance). Holding these three items constant would ensure that welds consistent in quality with the initially inspected weld are formed throughout the project.

4.3.2 Arc Spot Welds made in Multiple Layers of Sheet Steel

The 2001 AISI Specification states that arc spot welds should not be formed in sheet steel totaling more than 0.15 in. in thickness. This research suggests that while single and double layered sheets may be adequately welded up to 0.15 in. in thickness, quadruple layers can not be. Insufficient penetration was observed from welds made in quadruple layer sheets as thin as 0.112 in. (4-layers of 22 gauge). The additional layers of air and surface coatings draw too much heat from the electrode, preventing it from fusing with the supporting hot rolled steel. Due to lack of penetration, it is recommended that arc spot welding not be permitted in situations involving four or more layers of sheet steel.

More research is required to determine if arc spot welds can be adequately created in three layers of sheet steel. In practice however, situations involving welds made through three layers are extremely rare.

References

1. American Iron and Steel Institute, AISI (2001). "North American Specification for the Design of Cold-Formed Steel Structural Members," 2001 Edition, With 2004 Supplement, Washington D.C.

2. American Iron and Steel Institute, AISI (2002). "Cold-formed Steel Design Manual," 2002 Edition, Washington DC

3. American Society for Testing and Materials (2004). "ASTM E8-04: Standard Test Method for Tension Testing of Metallic Materials", *Annual Book of ASTM Standards 2004,* 03.01, 62 – 85.

4. American Welding Society, AWS D1.3-89 (1989), "Structural Welding Code – Sheet Steel," 550 N.W. LeJune Road, Miami, Florida.

5. American Welding Society, AWS D1.3-77 (1977), "Specification for Welding Sheet Steel in Structures," 550 N.W. LeJune Road, Miami, Florida.

6. Blodgett, Omer W. (1963). Design of Weldments. Cleveland, Ohio: The James F. Lincoln Arc Welding Foundation.

7. Blodgett, O.W. (1978). "Report on Proposed Standards for Sheet Steel Structural Welding," Proceedings, Fourth International Specialty conference on Cold formed Steel Structures, University of Missouri – Rolla.

8. Fung, C. (1978). "Strength of Arc-Spot Weld in Sheet Steel Construction," Final Report on CSICC Industry Research Project 175, Westeel-Rosco, Ltd., Canada.

9. Hancock, Gregory J. (1998). Design of Cold-Formed Steel Structures (to Australian/New Zealand Standard AS/NZS 4600:1996). Third Edition. North Sydney, Australia: Australian Institute of Steel Construction.

10. Luttrell, L.D. (2004). "Diaphragm Design Manual." Third Edition. Steel Deck Institute. Fox River Grove, IL.

11. Pekoz, T. and McGuire, W. (1980). "Welding of Sheet Steel," Proceedings, Fifth International Specialty Conference on Cold-Formed Steel Structures, St. Louis, Missouri.

12. Stark, J.W.B. and Soetens, F. (1980). "Welded Connections in Cold-Formed Sections," Proceedings, Fifth International Specialty Conference on Cold-Formed Steel Structures, St. Louis, Missouri.

13. Yu, W. W. (2000). Cold-Formed Steel Design. Third Edition. New York, New York: John Wiley and Sons, Inc.

Appendix A: Test Matrix

Table A-1: Test Matrix

Test Series	Deck Gauge	Galv.	Layer Condition	Welding Time	Effective Weld Size (in.)	No. Welds to determine Full Time Average	No. of Samples
1	22	Yes	Single Lap	Full Time	3/4	10 (5 sets of 2 welds)	3 sets of 2 welds
2	22	Yes	Single Lap	2/3 Time	3/4	-	3 sets of 2 welds
3	22	Yes	Single Lap	1/3 Time	3/4	-	3 sets of 2 welds
4	20	Yes	Single Lap	Full Time	3/4	10 (5 sets of 2 welds)	3 sets of 2 welds
5	20	Yes	Single Lap	2/3 Time	3/4	-	3 sets of 2 welds
6	20	Yes	Single Lap	1/3 Time	3/4	-	3 sets of 2 welds
7	18	Yes	Single Lap	Full Time	3/4	10 (5 sets of 2 welds)	3 sets of 2 welds
8	18	Yes	Single Lap	2/3 Time	3/4	-	3 sets of 2 welds
9	18	Yes	Single Lap	1/3 Time	3/4	-	3 sets of 2 welds
10	16	Yes	Single Lap	Full Time	3/4	10 (5 sets of 2 welds)	3 sets of 2 welds
11	16	Yes	Single Lap	2/3 Time	3/4	-	3 sets of 2 welds
12	16	Yes	Single Lap	1/3 Time	3/4	-	3 sets of 2 welds
13	22	Yes	Single Lap	Full Time	5/8	10 (5 sets of 2 welds)	3 sets of 2 welds
14	22	Yes	Single Lap	2/3 Time	5/8	-	3 sets of 2 welds
15	22	Yes	Single Lap	1/3 Time	5/8	-	3 sets of 2 welds
16	20	Yes	Single Lap	Full Time	5/8	10 (5 sets of 2 welds)	3 sets of 2 welds
17	20	Yes	Single Lap	2/3 Time	5/8	-	3 sets of 2 welds
18	20	Yes	Single Lap	1/3 Time	5/8	-	3 sets of 2 welds
19	18	Yes	Single Lap	Full Time	5/8	10 (5 sets of 2 welds)	3 sets of 2 welds
20	18	Yes	Single Lap	2/3 Time	5/8	-	3 sets of 2 welds
21	18	Yes	Single Lap	1/3 Time	5/8	-	3 sets of 2 welds
22	16	Yes	Single Lap	Full Time	5/8	10 (5 sets of 2 welds)	3 sets of 2 welds
23	16	Yes	Single Lap	2/3 Time	5/8	-	3 sets of 2 welds
24	16	Yes	Single Lap	1/3 Time	5/8	-	3 sets of 2 welds

Table A-1 (cont.): Test Matrix

Test Series	Deck Gauge	Galv.	Layer Condition	Welding Time	Effective Weld Size (in.)	No. Welds to determine Full Time Average	No. of Samples
25	22	Yes	2 - Lap	Full Time	3/4	10 (5 sets of 2 welds)	3 sets of 2 welds
26	22	Yes	2 - Lap	2/3 Time	3/4	-	3 sets of 2 welds
27	22	Yes	2 - Lap	1/3 Time	3/4	-	3 sets of 2 welds
28	20	Yes	2 - Lap	Full Time	3/4	10 (5 sets of 2 welds)	3 sets of 2 welds
29	20	Yes	2 - Lap	2/3 Time	3/4	-	3 sets of 2 welds
30	20	Yes	2 - Lap	1/3 Time	3/4	-	3 sets of 2 welds
31	18	Yes	2 - Lap	Full Time	3/4	10 (5 sets of 2 welds)	3 sets of 2 welds
32	18	Yes	2 - Lap	2/3 Time	3/4	-	3 sets of 2 welds
33	18	Yes	2 - Lap	1/3 Time	3/4	-	3 sets of 2 welds
34	16	Yes	2 - Lap	Full Time	3/4	10 (5 sets of 2 welds)	3 sets of 2 welds
35	16	Yes	2 - Lap	2/3 Time	3/4	-	3 sets of 2 welds
36	16	Yes	2 - Lap	1/3 Time	3/4	-	3 sets of 2 welds
37	22	Yes	2 - Lap	Full Time	5/8	10 (5 sets of 2 welds)	3 sets of 2 welds
38	22	Yes	2 - Lap	2/3 Time	5/8	-	3 sets of 2 welds
39	22	Yes	2 - Lap	1/3 Time	5/8	-	3 sets of 2 welds
40	20	Yes	2 - Lap	Full Time	5/8	10 (5 sets of 2 welds)	3 sets of 2 welds
41	20	Yes	2 - Lap	2/3 Time	5/8	-	3 sets of 2 welds
42	20	Yes	2 - Lap	1/3 Time	5/8	-	3 sets of 2 welds
43	18	Yes	2 - Lap	Full Time	5/8	10 (5 sets of 2 welds)	3 sets of 2 welds
44	18	Yes	2 - Lap	2/3 Time	5/8	-	3 sets of 2 welds
45	18	Yes	2 - Lap	1/3 Time	5/8	-	3 sets of 2 welds
46	16	Yes	2 - Lap	Full Time	5/8	10 (5 sets of 2 welds)	3 sets of 2 welds
47	22	Yes	4 - Lap	Full Time	3/4	N/A	N/A
48	20	No	4 - Lap	Full Time	3/4	N/A	N/A
49	22	No	4 - Lap	Full Time	3/4	N/A	N/A
50	20	No	4 - Lap	Full Time	3/4	N/A	N/A

Appendix B: Sample Calculations

B.1 Calculating arc spot weld *shear strength* using the 2001 AISI Specification

d = Measured Visual Diameter = *0.7 in*

t = Total Sheet Steel Thickness = *0.046 in*

F_u = Sheet Steel Tensile Strength = *55.0 ksi*

E = Modulus of Elasticity = *29500 ksi*

F_{xx} = Electrode Tensile Strength = *60 ksi*

d_a = Average Diameter = $d - t = 0.654$ *in*

d_e = Effective Diameter = $0.7d - 1.5t \leq 0.55d = 0.385$ *in*

Design Strength:

$$\frac{d_a}{t} = 14.2 < 0.815\sqrt{\frac{E}{F_u}} = 18.9$$

$$\therefore \quad P_n = 2.20 \cdot t \cdot d_a \cdot F_u = 3.64 \quad kips$$

B.2 Calculating arc spot weld *end distance* using the 2001 AISI Specification

Using the same weld specified in example E.1

F_u = Sheet Steel Tensile Strength = *55.0 ksi*

F_y = Sheet Steel Yield Strength = *47.6 ksi*

$F_u/F_y = 1.16 > 1.08$

$\therefore \quad \phi = 0.70$

P_u = Required Strength transmitted by weld = *3.64 kips (from example E.1)*

t = Total Sheet Steel Thickness = *0.046 in*

Minimum End Distance:

$$e_{\min} = \frac{P_u}{\phi F_u t} = 2.06 \quad in$$

Appendix C: Material Properties

Results from the performed tensile coupon tests are presented in the following section. Each test was completed in accordance with the ASTM E8-04 (2004) *Standard Test Methods for Tension Testing of Metallic Materials* procedure. The sheet steel material used in this research was ASTM A653 Grade 33 galvanized in 22, 20, 18, and 16 gauge thicknesses. Every specific thickness of sheet steel was obtained from the same coil, making it possible to only test three tensile coupons for each gauge of sheet steel.

Prior to testing, one coupon from each gauge of sheet steel was placed in a hydrochloric acid bath to remove the galvanized coating. With the galvanized coating removed, the thickness of the material was measured with calipers accurate to 1/1000 in. This thickness was used as the thickness for each test coupon and the sheet steel in each test specimen. After the widths and thicknesses of the coupons were determined, each was marked with a 2 in. gauge length. The tests were performed using an MTS Insight computer-controlled mechanical testing machine. Stress vs. strain data as well as yield stress, tensile stress and percent elongation were measured for every test coupon. The strain data used in the stress vs. strain curves was based on the extension of the testing machine grips and is not the true strain of the specimen.

Table C-1: Material Properties Summary

Specimen No.	Gauge	Thickness (in)	Width (in)	Galvanized	Yield Stress (ksi)	Tensile Stress (ksi)	Percent Elongation (%)
1	22	0.028	0.491	Yes	47.9	55.3	37.5
2	22	0.028	0.491	Yes	47.5	55.3	39.0
3	22	0.028	0.498	Yes	47.1	55.3	34.6
1	20	0.034	0.500	Yes	48.3	58.3	30.4
2	20	0.034	0.500	Yes	48.7	58.9	34.0
3	20	0.034	0.501	Yes	49.2	58.9	31.4
1	18	0.046	0.491	Yes	47.9	55.8	37.1
2	18	0.046	0.492	Yes	47.2	54.1	37.9
3	18	0.046	0.492	Yes	47.6	55.2	38.2
1	16	0.057	0.500	Yes	55.6	61.7	27.0
2	16	0.057	0.501	Yes	53.0	60.4	31.7
3	16	0.057	0.498	Yes	54.5	61.6	28.4

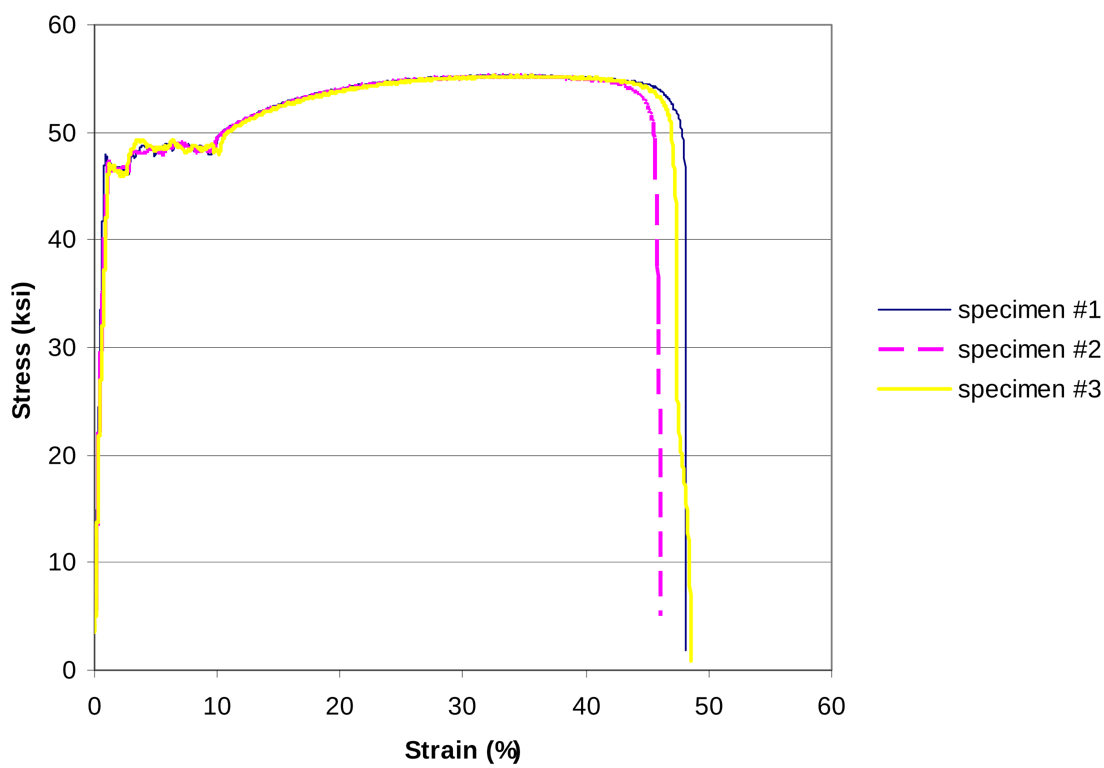

Figure C-1: 22 gauge coupon Stress vs. Strain Curve

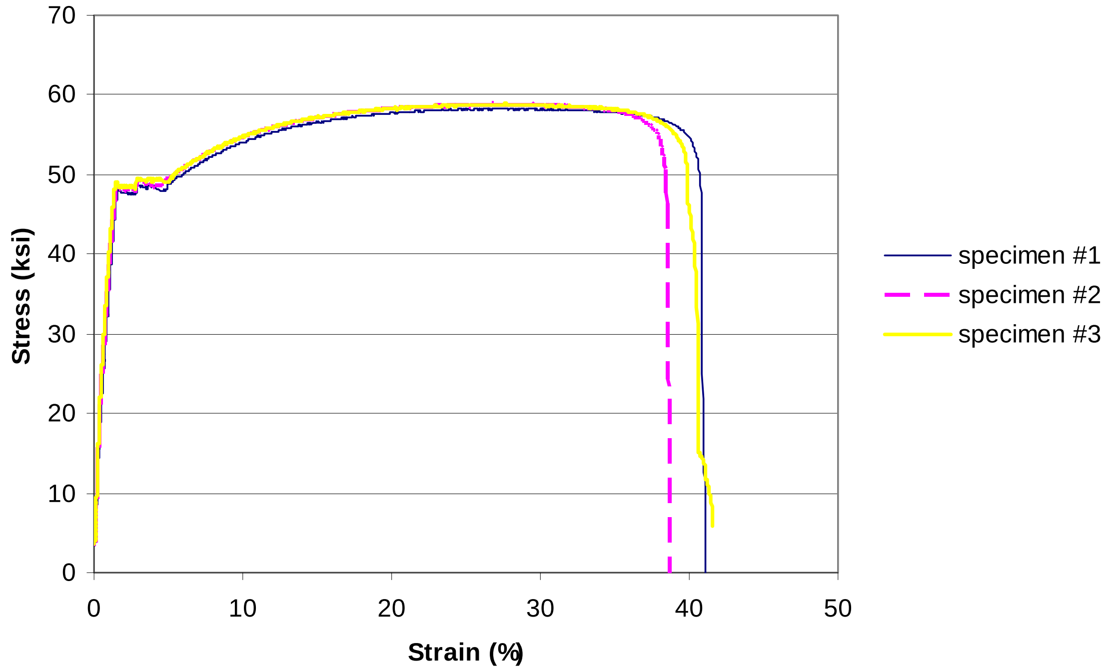

Figure C-2: 20 gauge coupon Stress vs. Strain Curve

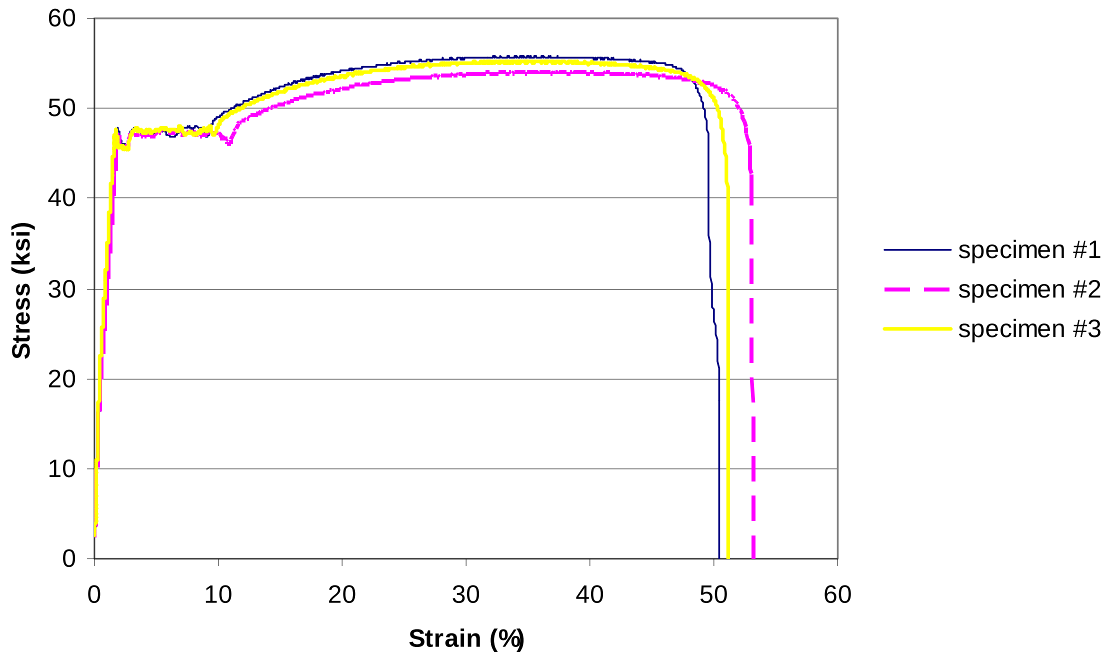

Figure C-3: 18 gauge coupon Stress vs. Strain Curve

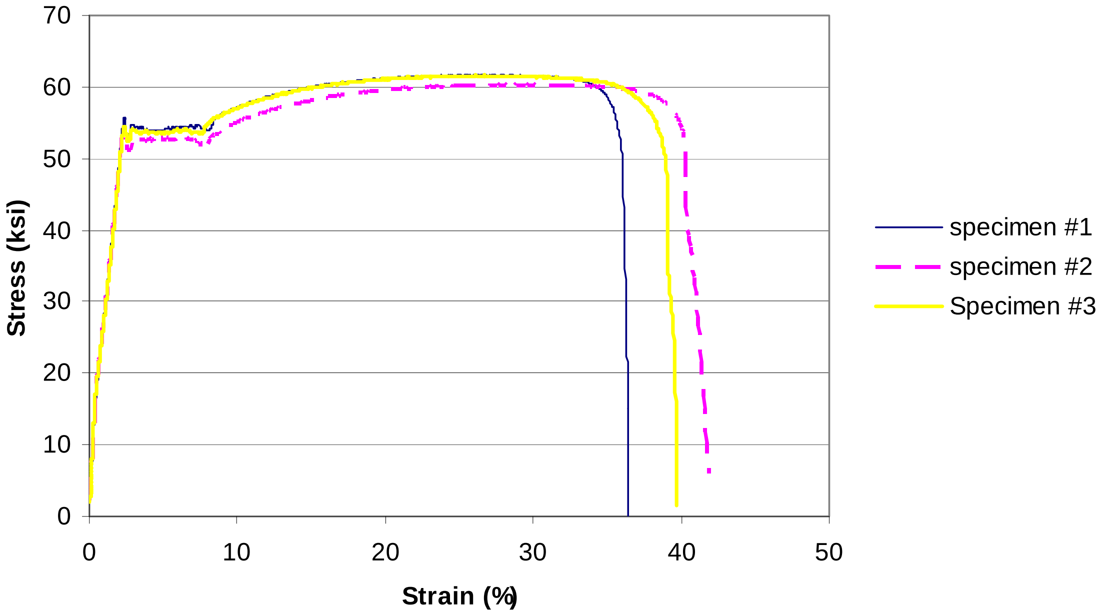

Figure C-4: 16 gauge coupon Stress vs. Strain Curve

Appendix D: Full-Time Weld Arc Times

The following section contains tabulated weld arc times for every full-time weld specimen. The arc time spent on each particular weld was measured with the use of a standard stop watch. The arc time from a minimum of ten full-time welds was measured and averaged for each full-time series. A value of 2/3 of the average was used as the cutoff for 2/3-time welds and a value of 1/3 of the average was used for 1/3-time welds.

Table D-1: Full-time weld Arc Times

Nominal Weld Size (in.)	Thickness (gauge)	Total Thickness (in.)	Layer Configuration	Full Time Series Arc Times (sec)
3/4	22	0.028	Single	10.9
3/4	22	0.028	Single	13.1
3/4	22	0.028	Single	15.3
3/4	22	0.028	Single	9.8
3/4	22	0.028	Single	11.2
3/4	22	0.028	Single	14.4
3/4	22	0.028	Single	14.4
3/4	22	0.028	Single	15.7
3/4	22	0.028	Single	12.2
3/4	22	0.028	Single	16.2
3/4	22	0.028	Single	17.1
3/4	20	0.034	Single	12.2
3/4	20	0.034	Single	11.3
3/4	20	0.034	Single	13.4
3/4	20	0.034	Single	12.1
3/4	20	0.034	Single	12.5
3/4	20	0.034	Single	11.9
3/4	20	0.034	Single	12.6
3/4	20	0.034	Single	15.6
3/4	20	0.034	Single	13.6
3/4	20	0.034	Single	13.9
3/4	20	0.034	Single	12.2
3/4	18	0.046	Single	13.3
3/4	18	0.046	Single	9.4
3/4	18	0.046	Single	8.9
3/4	18	0.046	Single	11.9
3/4	18	0.046	Single	10.0
3/4	18	0.046	Single	14.1
3/4	18	0.046	Single	11.6
3/4	18	0.046	Single	12.9
3/4	18	0.046	Single	10.9
3/4	18	0.046	Single	11.2
3/4	18	0.046	Single	10.1
3/4	18	0.046	Single	10.9

Table D-1 (cont.): Full-time weld Arc Times

Nominal Weld Size (in.)	Thickness (gauge)	Total Thickness (in)	Layer Configuration	Full Time Series Arc Times (sec)
3/4	16	0.057	Single	12.2
3/4	16	0.057	Single	13.5
3/4	16	0.057	Single	15.5
3/4	16	0.057	Single	13.2
3/4	16	0.057	Single	15.5
3/4	16	0.057	Single	13.1
3/4	16	0.057	Single	12.8
3/4	16	0.057	Single	16.9
3/4	16	0.057	Single	14.2
3/4	16	0.057	Single	14.5
3/4	16	0.057	Single	9.9
3/4	16	0.057	Single	12.1
5/8	22	0.028	Single	10.1
5/8	22	0.028	Single	8.0
5/8	22	0.028	Single	11.2
5/8	22	0.028	Single	8.2
5/8	22	0.028	Single	8.6
5/8	22	0.028	Single	7.5
5/8	22	0.028	Single	8.4
5/8	22	0.028	Single	11.1
5/8	22	0.028	Single	9.4
5/8	22	0.028	Single	6.3
5/8	22	0.028	Single	8.0
5/8	20	0.034	Single	8.2
5/8	20	0.034	Single	6.3
5/8	20	0.034	Single	7.6
5/8	20	0.034	Single	6.6
5/8	20	0.034	Single	6.6
5/8	20	0.034	Single	7.1
5/8	20	0.034	Single	5.6
5/8	20	0.034	Single	6.7
5/8	20	0.034	Single	7.7
5/8	20	0.034	Single	8.0
5/8	20	0.034	Single	8.2

Table D-1 (cont.): Full-time weld Arc Times

Nominal Weld Size (in.)	Thickness (gauge)	Total Thickness (in)	Layer Configuration	Full Time Series Arc Times (sec)
5/8	18	0.046	Single	8.9
5/8	18	0.046	Single	8.3
5/8	18	0.046	Single	8.3
5/8	18	0.046	Single	9.5
5/8	18	0.046	Single	9.9
5/8	18	0.046	Single	11.6
5/8	18	0.046	Single	7.5
5/8	18	0.046	Single	7.8
5/8	18	0.046	Single	7.5
5/8	18	0.046	Single	8.2
5/8	18	0.046	Single	9.6
5/8	18	0.046	Single	9.3
5/8	16	0.057	Single	10.9
5/8	16	0.057	Single	6.6
5/8	16	0.057	Single	8.1
5/8	16	0.057	Single	8.3
5/8	16	0.057	Single	7.7
5/8	16	0.057	Single	7.0
5/8	16	0.057	Single	8.6
5/8	16	0.057	Single	8.4
5/8	16	0.057	Single	8.0
5/8	16	0.057	Single	8.7
5/8	16	0.057	Single	9.1
3/4	22	0.056	Double	12.8
3/4	22	0.056	Double	13.0
3/4	22	0.056	Double	11.6
3/4	22	0.056	Double	14.3
3/4	22	0.056	Double	14.6
3/4	22	0.056	Double	16.0
3/4	22	0.056	Double	13.3
3/4	22	0.056	Double	11.6
3/4	22	0.056	Double	14.2
3/4	22	0.056	Double	16.5

Table D-1 (cont.): Full-time weld Arc Times

Nominal Weld Size (in.)	Thickness (gauge)	Total Thickness (in)	Layer Configuration	Full Time Series Arc Times (sec)
3/4	20	0.068	Double	14.6
3/4	20	0.068	Double	11.1
3/4	20	0.068	Double	9.7
3/4	20	0.068	Double	9.4
3/4	20	0.068	Double	8.9
3/4	20	0.068	Double	15.2
3/4	20	0.068	Double	13.5
3/4	20	0.068	Double	9.8
3/4	20	0.068	Double	10.7
3/4	20	0.068	Double	8.6
3/4	18	0.092	Double	8.1
3/4	18	0.092	Double	8.7
3/4	18	0.092	Double	11.2
3/4	18	0.092	Double	10.4
3/4	18	0.092	Double	11.4
3/4	18	0.092	Double	9.8
3/4	18	0.092	Double	8.9
3/4	18	0.092	Double	11.7
3/4	18	0.092	Double	10.4
3/4	18	0.092	Double	11.1
3/4	18	0.092	Double	11.3
3/4	16	0.114	Double	19.5
3/4	16	0.114	Double	14.5
3/4	16	0.114	Double	12.3
3/4	16	0.114	Double	12.3
3/4	16	0.114	Double	13.2
3/4	16	0.114	Double	20.6
3/4	16	0.114	Double	15.7
3/4	16	0.114	Double	11.4
3/4	16	0.114	Double	14.0
3/4	16	0.114	Double	13.0

Table D-1 (cont.): Full-time weld Arc Times

Nominal Weld Size (in.)	Thickness (gauge)	Total Thickness (in)	Layer Configuration	Full Time Series Arc Times (sec)
5/8	22	0.056	Double	8.2
5/8	22	0.056	Double	8.6
5/8	22	0.056	Double	7.3
5/8	22	0.056	Double	7.4
5/8	22	0.056	Double	7.0
5/8	22	0.056	Double	10.0
5/8	22	0.056	Double	9.0
5/8	22	0.056	Double	6.8
5/8	22	0.056	Double	8.6
5/8	22	0.056	Double	8.1
5/8	22	0.056	Double	11.4
5/8	20	0.068	Double	7.5
5/8	20	0.068	Double	9.8
5/8	20	0.068	Double	5.8
5/8	20	0.068	Double	7.3
5/8	20	0.068	Double	7.8
5/8	20	0.068	Double	8.8
5/8	20	0.068	Double	8.4
5/8	20	0.068	Double	7.0
5/8	20	0.068	Double	6.9
5/8	20	0.068	Double	8.0
5/8	18	0.092	Double	10.2
5/8	18	0.092	Double	7.7
5/8	18	0.092	Double	7.5
5/8	18	0.092	Double	7.7
5/8	18	0.092	Double	6.6
5/8	18	0.092	Double	7.8
5/8	18	0.092	Double	7.2
5/8	18	0.092	Double	6.8
5/8	18	0.092	Double	7.4
5/8	18	0.092	Double	8.4
5/8	18	0.092	Double	6.6
5/8	18	0.092	Double	9.0
5/8	16	0.114	Double	7.1
5/8	16	0.114	Double	7.7

Table D-1 (cont.): Full-time weld Arc Times

Nominal Weld Size (in.)	Thickness (gauge)	Total Thickness (in)	Layer Configuration	Full Time Series Arc Times (sec)
5/8	16	0.114	Double	8.2
5/8	16	0.114	Double	6.8
5/8	16	0.114	Double	6.9
5/8	16	0.114	Double	9.9
5/8	16	0.114	Double	9.0
5/8	16	0.114	Double	9.0
5/8	16	0.114	Double	6.2
5/8	16	0.114	Double	9.3
5/8	16	0.114	Double	7.7
5/8	16	0.114	Double	7.2
5/8	16	0.114	Double	13.3
5/8	16	0.114	Double	14.0
3/4	22	0.112	Four	8.6
3/4	20	0.136	Four	7.8
3/4	18	0.184	Four	14.9
3/4	16	0.228	Four	16.5

Appendix E: Arc Spot Weld Dimensions

The following section contains the data taken from the weld sectioning portion of testing. All dimensions were measured with the use of calipers accurate to the thousandth of an in. One weld was sectioned from each full-time series, while three were sectioned from every 2/3-time and 1/3-time series.

The process of weld sectioning involved first saw cutting through the center of the given weld. To bring out the contrast between the weld and the remaining steel, a nitric acid solution was applied which turned the weld a dark black color (see Figure E-1). With the weld visible, the visual, average and effective diameters were measured.

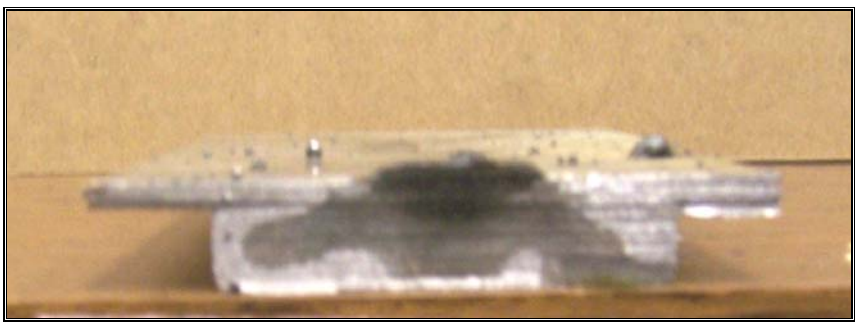

Figure E-1: Arc-spot weld section

Some welds that failed under weld shear failure were not sectioned in this same manor. Weld shear failures allow an observer to measure the weld dimensions without the need for saw cutting. The effective weld diameter can be measured as the diameter of the weld through the failure plane. The average diameter can be measured by averaging the visual weld diameter located at the top of the sheet steel with the weld diameter at the bottom of the sheet steel.

Table E-1: Dimensions of 3/4 in. arc spot welds in single layer sheet steel

Nominal Weld Size (in.)	Thickness (gauge)	Thickness (in.)	Welding Time	Layer	Specimen No.	d (in.)	da (in.)	de (in.)
3/4	22	0.028	Full	Single	#1	0.718	0.662	0.543
3/4	22	0.028	2/3	Single	#1	0.664	0.592	0.427
3/4	22	0.028	2/3	Single	#2	0.670	0.567	0.429
3/4	22	0.028	2/3	Single	#3	0.555	0.465	0.331
3/4	22	0.028	1/3	Single	#1	0.601	0.510	0.380
3/4	22	0.028	1/3	Single	#2	0.475	0.389	0.273
3/4	22	0.028	1/3	Single	#3	0.560	0.498	0.332
3/4	20	0.034	Full	Single	#1	0.729	0.670	0.567
3/4	20	0.034	2/3	Single	#1	0.715	0.592	0.400
3/4	20	0.034	2/3	Single	#2	0.654	0.608	0.440
3/4	20	0.034	2/3	Single	#3	0.692	0.523	0.382
3/4	20	0.034	1/3	Single	#2	0.590	0.502	0.401
3/4	20	0.034	1/3	Single	#3	0.562	0.506	0.398
3/4	20	0.034	1/3	Single	#4	0.562	0.455	0.314
3/4	18	0.046	Full	Single	#1	0.761	0.709	0.603
3/4	18	0.046	2/3	Single	#1	0.684	0.618	0.507
3/4	18	0.046	2/3	Single	#2	0.642	0.590	0.415
3/4	18	0.046	2/3	Single	#4	0.652	0.598	0.446
3/4	18	0.046	1/3	Single	#1	0.580	0.540	0.315
3/4	18	0.046	1/3	Single	#2	0.557	0.470	0.248
3/4	18	0.046	1/3	Single	#3	0.625	0.538	0.293
3/4	16	0.057	Full	Single	#1	0.740	0.630	0.508
3/4	16	0.057	2/3	Single	#1	0.759	0.562	0.395
3/4	16	0.057	2/3	Single	#2	0.698	0.575	0.296
3/4	16	0.057	2/3	Single	#3	0.732	0.545	0.414
3/4	16	0.057	1/3	Single	#1	0.656	0.598	0.334
3/4	16	0.057	1/3	Single	#2	0.636	0.546	0.322
3/4	16	0.057	1/3	Single	#3	0.605	0.545	0.364

Table E-2: Dimensions of 5/8 in. arc spot welds in single layer sheet steel

Nominal Weld Size (in.)	Thickness (gauge)	Thickness (in.)	Welding Time	Layer	Specimen No.	d (in.)	da (in.)	de (in.)
5/8	22	0.028	Full	Single	#1	0.615	0.562	0.436
5/8	22	0.028	2/3	Single	#1	0.609	0.554	0.353
5/8	22	0.028	2/3	Single	#2	0.551	0.512	0.266
5/8	22	0.028	2/3	Single	#3	0.626	0.545	0.292
5/8	22	0.028	1/3	Single	#1	0.512	0.436	0.289
5/8	22	0.028	1/3	Single	#2	0.488	0.322	0.214
5/8	22	0.028	1/3	Single	#3	0.415	0.371	0.244
5/8	20	0.034	Full	Single	#1	0.628	0.504	0.449
5/8	20	0.034	2/3	Single	#1	0.604	0.531	0.352
5/8	20	0.034	2/3	Single	#2	0.616	0.530	0.283
5/8	20	0.034	2/3	Single	#3	0.570	0.490	0.307
5/8	20	0.034	1/3	Single	#2	0.520	0.450	0.268
5/8	20	0.034	1/3	Single	#3	0.555	0.472	0.295
5/8	20	0.034	1/3	Single	#4	0.510	0.489	0.296
5/8	18	0.046	Full	Single	#1	0.661	0.574	0.454
5/8	18	0.046	2/3	Single	#1	0.646	0.554	0.373
5/8	18	0.046	2/3	Single	#2	0.610	0.498	0.373
5/8	18	0.046	2/3	Single	#4	0.615	0.520	0.408
5/8	18	0.046	1/3	Single	#1	0.572	0.561	0.288
5/8	18	0.046	1/3	Single	#2	0.588	0.509	0.265
5/8	18	0.046	1/3	Single	#3	0.605	0.508	0.216
5/8	16	0.057	Full	Single	#1	0.688	0.542	0.449
5/8	16	0.057	2/3	Single	#1	0.656	0.598	0.351
5/8	16	0.057	2/3	Single	#2	0.655	0.582	0.360
5/8	16	0.057	2/3	Single	#3	0.640	0.522	0.373
5/8	16	0.057	1/3	Single	#1	0.515	0.406	0.323
5/8	16	0.057	1/3	Single	#2	0.541	0.441	0.304
5/8	16	0.057	1/3	Single	#3	0.600	0.535	0.289

Table E-3: Dimensions of 3/4 in. arc spot welds in double layer sheet steel

Nominal Weld Size (in.)	Thickness (gauge)	Thickness (in.)	Welding Time	Layer	Specimen No.	d (in.)	da (in.)	de (in.)
3/4	22	0.056	Full	Double	#1	0.802	0.662	0.565
3/4	22	0.056	2/3	Double	#1	0.634	0.579	0.363
3/4	22	0.056	2/3	Double	#2	0.726	0.556	0.388
3/4	22	0.056	2/3	Double	#3	0.730	0.685	0.408
3/4	22	0.056	1/3	Double	#1	0.580	0.387	0.254
3/4	22	0.056	1/3	Double	#2	0.535	0.492	0.296
3/4	22	0.056	1/3	Double	#3	0.520	0.386	0.278
3/4	20	0.068	Full	Double	#1	0.795	0.648	0.505
3/4	20	0.068	2/3	Double	#1	0.735	0.653	0.455
3/4	20	0.068	2/3	Double	#2	0.698	0.535	0.457
3/4	20	0.068	2/3	Double	#3	0.701	0.644	0.456
3/4	20	0.068	1/3	Double	#2	0.526	0.470	0.329
3/4	20	0.068	1/3	Double	#3	0.675	0.523	0.434
3/4	20	0.068	1/3	Double	#4	0.629	0.518	0.390
3/4	18	0.092	Full	Double	#1	0.750	0.628	0.445
3/4	18	0.092	2/3	Double	#1	0.722	0.576	0.415
3/4	18	0.092	2/3	Double	#2	0.722	0.560	0.264
3/4	18	0.092	2/3	Double	#4	0.760	0.681	0.370
3/4	18	0.092	1/3	Double	#1	0.540	0.492	0.320
3/4	18	0.092	1/3	Double	#2	0.548	0.488	0.385
3/4	18	0.092	1/3	Double	#3	0.566	0.506	0.350
3/4	16	0.114	Full	Double	#1	0.815	0.645	0.484
3/4	16	0.114	2/3	Double	#1	0.736	0.623	0.372
3/4	16	0.114	2/3	Double	#2	0.695	0.603	0.409
3/4	16	0.114	2/3	Double	#3	0.710	0.622	0.360
3/4	16	0.114	1/3	Double	#1	0.540	0.505	0.390
3/4	16	0.114	1/3	Double	#2	0.556	0.472	0.325
3/4	16	0.114	1/3	Double	#3	0.560	0.498	0.390

Table E-4: Dimensions of 5/8 in. arc spot welds in double layer sheet steel

Nominal Weld Size (in.)	Thickness (gauge)	Thickness (in.)	Welding Time	Layer	Specimen No.	d (in.)	da (in.)	de (in.)
5/8	22	0.056	Full	Double	#1	0.602	0.542	0.402
5/8	22	0.056	2/3	Double	#1	0.612	0.535	0.330
5/8	22	0.056	2/3	Double	#2	0.620	0.512	0.305
5/8	22	0.056	2/3	Double	#3	0.620	0.538	0.364
5/8	22	0.056	1/3	Double	#1	0.551	0.450	0.280
5/8	22	0.056	1/3	Double	#2	0.551	0.432	0.292
5/8	22	0.056	1/3	Double	#3	0.502	0.412	0.252
5/8	20	0.068	Full	Double	#1	0.630	0.502	0.444
5/8	20	0.068	2/3	Double	#1	0.631	0.498	0.395
5/8	20	0.068	2/3	Double	#2	0.581	0.460	0.338
5/8	20	0.068	2/3	Double	#3	0.632	0.478	0.350
5/8	20	0.068	1/3	Double	#2	0.494	0.403	0.310
5/8	20	0.068	1/3	Double	#3	0.530	0.378	0.296
5/8	20	0.068	1/3	Double	#4	0.482	0.408	0.280
5/8	18	0.092	Full	Double	#1	0.620	0.475	0.406
5/8	18	0.092	2/3	Double	#1	0.615	0.455	0.331
5/8	18	0.092	2/3	Double	#2	0.584	0.426	0.280
5/8	18	0.092	2/3	Double	#4	0.602	0.468	0.335
5/8	18	0.092	1/3	Double	#1	0.525	0.388	0.272
5/8	18	0.092	1/3	Double	#2	0.554	0.322	0.130
5/8	18	0.092	1/3	Double	#3	0.503	0.438	0.287
5/8	16	0.114	Full	Double	#1	0.663	0.352	0.302

Table E-5: Dimensions of 3/4 in. arc spot welds in quadruple layer sheet steel

Nominal Weld Size (in.)	Thickness (gauge)	Thickness (in.)	Welding Time	Layer	Specimen No.	d (in.)	da (in.)	de (in.)
3/4	22	0.112	Full	Four	#1	0.738	0.469	0.302
3/4	20	0.136	Full	Four	#1	0.710	0.449	0.328
3/4	18	0.184	Full	Four	#1	0.889	0.506	0.350
3/4	16	0.228	Full	Four	#1	0.828	0.452	0.239

Appendix F: Strength Test Failure Modes

Throughout this study, only two different failure modes observed were observed during the strength test portion of testing. One of these failure modes was sheet tear failure, which occurred when the effective weld diameter to sheet steel thickness ratio was high. The other observed failure mode was weld shear failure, which was more prevalent in welds with small effective diameter to sheet steel thickness ratios. The following section lists the observed failure modes for each strength test performed.

Table F-1: Strength Test Failure Modes

Weld Size (in)	Gauge	Layers	Welding Time	Typical Failure Mode *				
Specimen No.				1	2	3	4	5
3/4	22	Single	Full		ST	ST		ST
3/4	22	Single	2/3	ST	ST	ST		
3/4	22	Single	1/3	ST	ST	ST		
3/4	20	Single	Full		ST	ST	ST	
3/4	20	Single	2/3	ST	ST	ST		
3/4	20	Single	1/3		ST	ST	ST	
3/4	18	Single	Full		ST	ST	ST	
3/4	18	Single	2/3	ST	ST		ST	
3/4	18	Single	1/3	WF	WF	WF		
3/4	16	Single	Full		ST	ST	ST	
3/4	16	Single	2/3	WF	WF	WF	ST	ST
3/4	16	Single	1/3	WF	WF	ST	WF	
5/8	22	Single	Full		ST	ST	ST	
5/8	22	Single	2/3	ST	ST	ST		
5/8	22	Single	1/3	ST	ST	ST	ST	
5/8	20	Single	Full		ST	ST	ST	
5/8	20	Single	2/3	ST	ST	ST		
5/8	20	Single	1/3	ST	ST	ST		
5/8	18	Single	Full		ST	ST	ST	
5/8	18	Single	2/3	ST	ST	ST		
5/8	18	Single	1/3	ST	WF	ST	WF	WF
5/8	16	Single	Full	WF	ST	WF		
5/8	16	Single	2/3	WF	ST	ST		
5/8	16	Single	1/3	WF	WF	WF	WF	
3/4	22	Double	Full		ST	ST	ST	
3/4	22	Double	2/3	ST	ST	ST		
3/4	22	Double	1/3	ST	ST	WF	ST	
3/4	20	Double	Full		WF	ST	ST	
3/4	20	Double	2/3		ST	ST	ST	
3/4	20	Double	1/3	WF	ST	ST	WF	
3/4	18	Double	Full		WF	WF	WF	ST
3/4	18	Double	2/3	WF	WF	WF	WF	WF
3/4	18	Double	1/3	WF	WF	WF	WF	
3/4	16	Double	Full		WF	WF	WF	WF
3/4	16	Double	2/3	WF	WF	WF		
3/4	16	Double	1/3	WF	WF	WF	WF	WF

Table F-1 (cont.): Strength Test Failure Modes

Weld Size (in)	Gauge	Layers	Welding Time	Typical Failure Mode *				
Specimen No.				1	2	3	4	5
5/8	22	Double	Full		ST	WF	ST	ST
5/8	22	Double	2/3	WF	WF	ST		
5/8	22	Double	1/3	WF	WF	WF		
5/8	20	Double	Full		ST	ST	WF	
5/8	20	Double	2/3	WF	WF	WF		
5/8	20	Double	1/3	WF	WF	WF	WF	
5/8	18	Double	Full	WF	WF	WF	WF	
5/8	18	Double	2/3	WF	WF	WF	WF	
5/8	18	Double	1/3	WF	WF	WF	WF	
5/8	16	Double	Full		WF	WF	WF	

* ST = Sheet Tear Failure
WF = Weld Shear Failure

Appendix G: Shear Strength Tests

The following section contains data illustrating the load vs. extension relationship for all performed lap shear tests. A summary of weld shear strengths is given first then followed by load vs. extension plots for all tests. A minimum of three specimens were tested for each series of welds. If the shear strength of any of these three specimen deviated by over ten percent from the mean strength, an additional specimen was tested in order to gain a more accurate representation of the series shear strength.

Tests were performed on 22, 20, 18, and 16 gauge sheet steels arranged in single-, double-, and quadruple-layers. Each specimen contained two welds with either 5/8 in. or 3/4 in. nominal diameters. Each test was performed using an MTS Insight computer-controlled mechanical testing machine. The load and extension data were both recorded using the TestWorks 4 software program.

Table G-1 Weld Shear Strength Data

Weld Size (in)	Gauge	Layers	Welding Time	Weld Shear Strength (kips)				
Specimen No.				1	2	3	4	5
3/4	22	Single	Full		2.5	2.45		2.73
3/4	22	Single	2/3	2.04	1.86	2.19		
3/4	22	Single	1/3	2.27	2.26	2.2		
3/4	20	Single	Full		3.43	3.39	3.62	
3/4	20	Single	2/3	3.46	3.26	3.37		
3/4	20	Single	1/3		3.14	3.1	3.06	
3/4	18	Single	Full		4.65	4.78	4.74	
3/4	18	Single	2/3	4.71	4.56		4.61	
3/4	18	Single	1/3	3.58	3.28	3.9		
3/4	16	Single	Full		6.53	6.97	6.78	
3/4	16	Single	2/3	6.42	3.93	6.22	6.6	6.36
3/4	16	Single	1/3	5.83	4.36	5.84	5.09	
5/8	22	Single	Full		2.27	2.42	2.51	
5/8	22	Single	2/3	2.43	2.45	2.27		
5/8	22	Single	1/3	2.22	1.81	2.26	2.24	
5/8	20	Single	Full		3.38	3.59	3.36	
5/8	20	Single	2/3	3.25	3	3.25		
5/8	20	Single	1/3	2.95	2.92	2.77		
5/8	18	Single	Full		4.71	4.58	4.46	
5/8	18	Single	2/3	4.76	4.62	4.82		
5/8	18	Single	1/3	3.96	3.45	4.62	2.97	2.02
5/8	16	Single	Full		6.12	6.6	6.71	
5/8	16	Single	2/3	6.34	6.35	6.05		
5/8	16	Single	1/3	3.27	4.38	4.4	4.55	
3/4	22	Double	Full		5.36	5.48	5.64	
3/4	22	Double	2/3	5.08	5.38	5.08		
3/4	22	Double	1/3	4.82	5.04	3.92	4.78	
3/4	20	Double	Full		6.78	7.41	7.4	
3/4	20	Double	2/3		6.99	7.21	7.13	
3/4	20	Double	1/3	5.19	6.38	6.24	5.92	
3/4	18	Double	Full		8.13	9.84	7.92	9.8
3/4	18	Double	2/3	7.24	4.1	7.71	2.98	5.9
3/4	18	Double	1/3	0.87	4.28	3.95	4.2	
3/4	16	Double	Full		5.62	6.38	8.12	3.77
3/4	16	Double	2/3	6.27	7.04	6.38		
3/4	16	Double	1/3	5.16	4.15	5.49	1.48	3.64

Table G-1 (cont.) Weld Shear Strength Data

Weld Size (in)	Gauge	Layers	Welding Time	Typical Failure Mode				
Specimen No.				1	2	3	4	5
5/8	22	Double	Full		5.5	3.9	4.63	4.6
5/8	22	Double	2/3	4.7	4.45	4.8		
5/8	22	Double	1/3	3.45	2.86	3.19		
5/8	20	Double	Full		6.78	7.04	6.45	
5/8	20	Double	2/3	6.02	5.59	5.81		
5/8	20	Double	1/3	4.27	3.12	3.09	2.18	
5/8	18	Double	Full	4.39	6.24	3.5	3.4	
5/8	18	Double	2/3	5.59	1.99	2.89	3.61	
5/8	18	Double	1/3	2.42	0.39	0.25	3.15	
5/8	16	Double	Full		3.91	5.55	4.7	

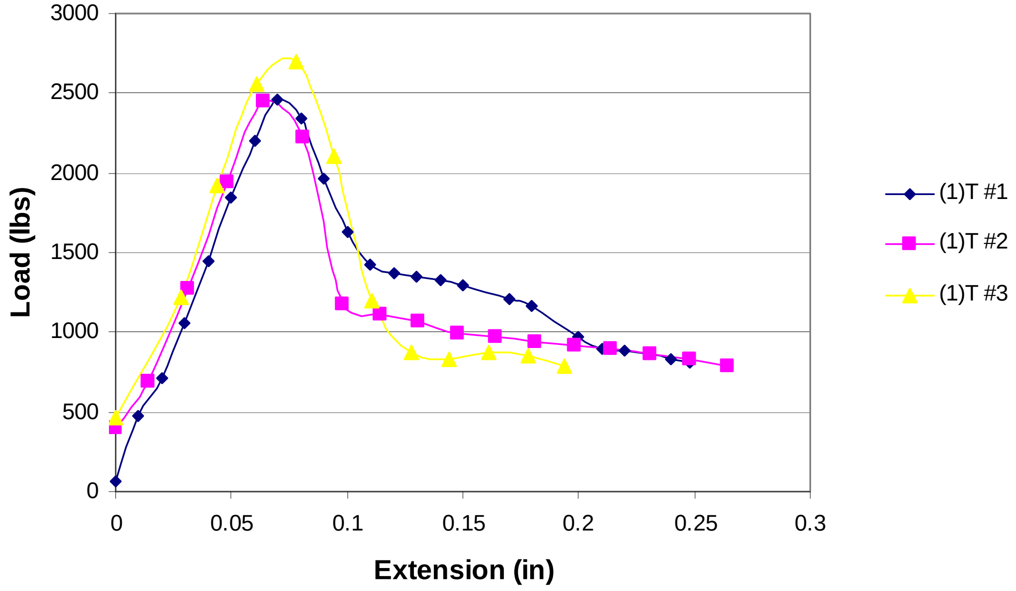

Figure G-1: Full-time 3/4 in. welds in a single 22g sheet steel layer

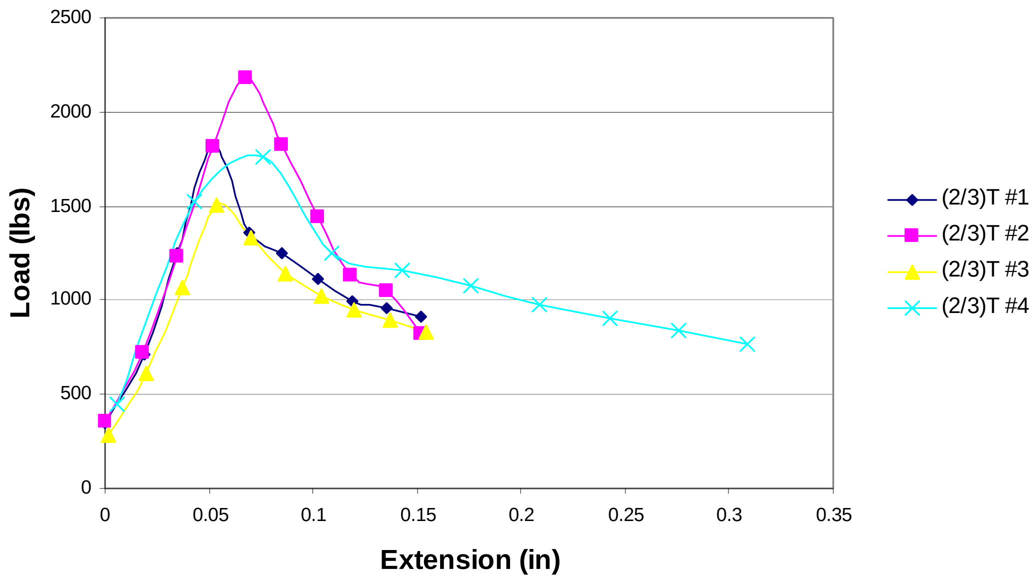

Figure G-2: 2/3-time 3/4 in. welds in a single 22g sheet steel layer

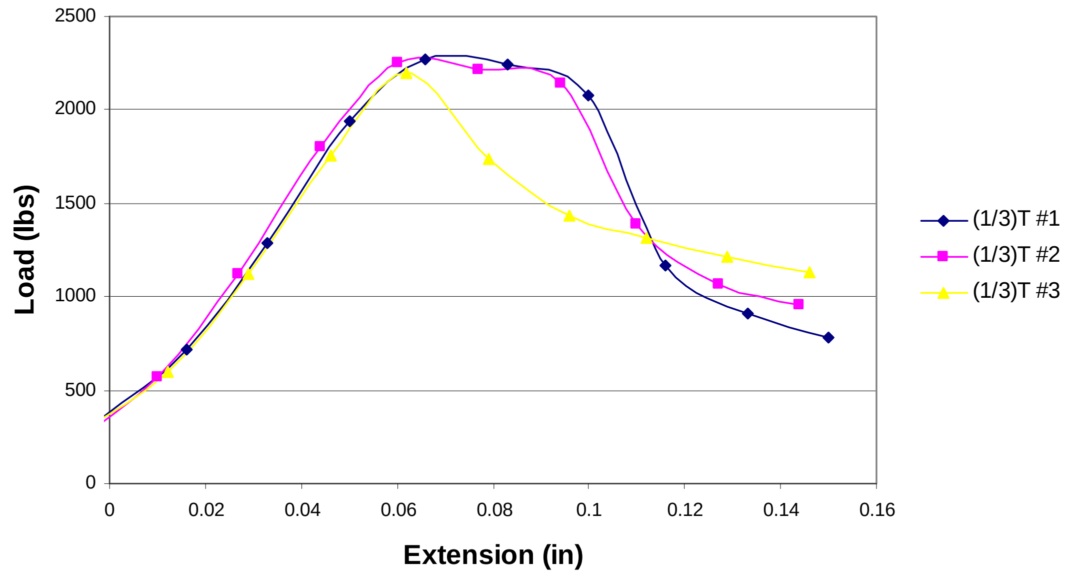

Figure G-3: 1/3-time 3/4 in. welds in a single 22g sheet steel layer

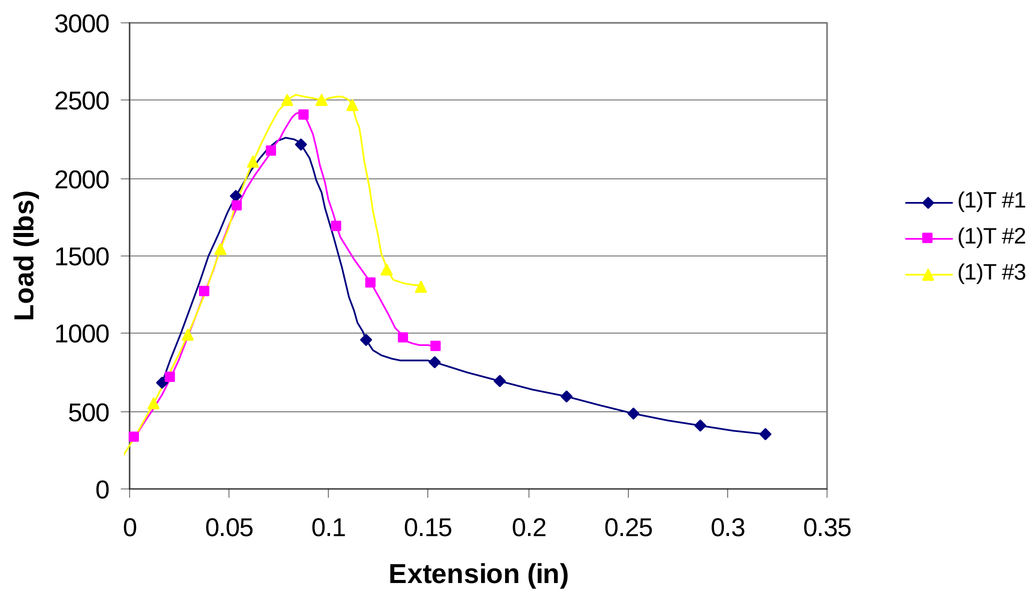

Figure G-4: Full-time 5/8 in. welds in a single 22g sheet steel layer

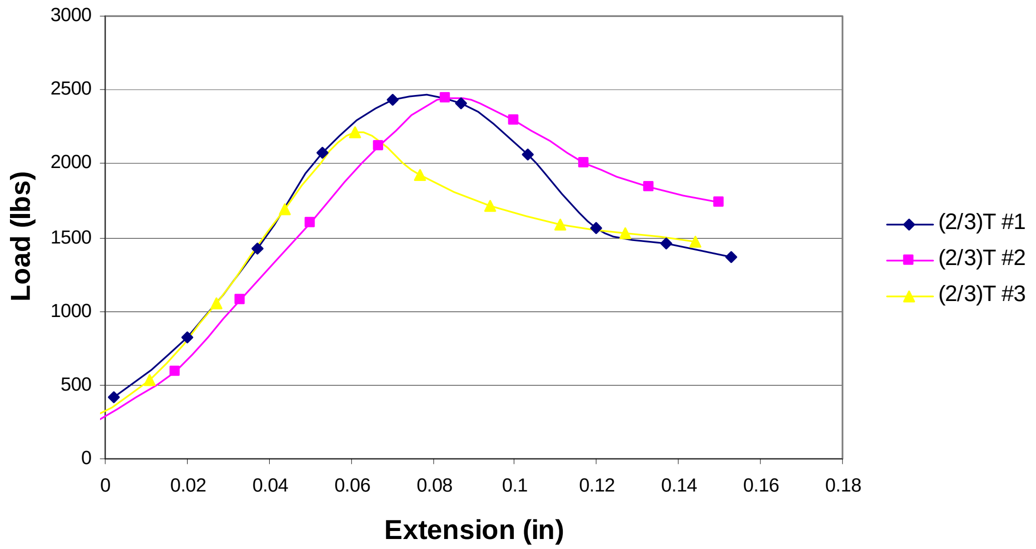

Figure G-5: 2/3-time 5/8 in. welds in a single 22g sheet steel layer

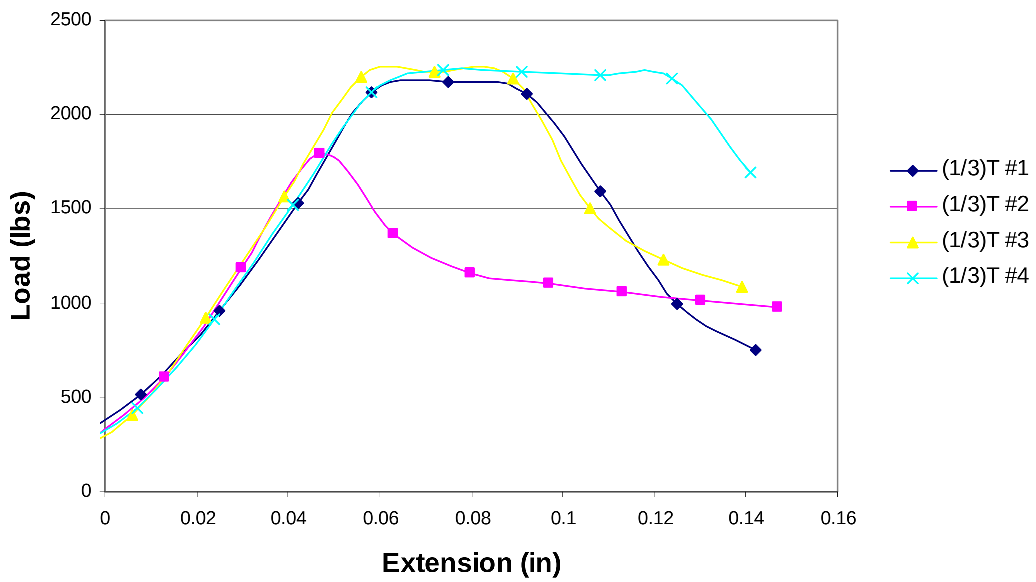

Figure G-6: 1/3-time 5/8 in. welds in a single 22g sheet steel layer

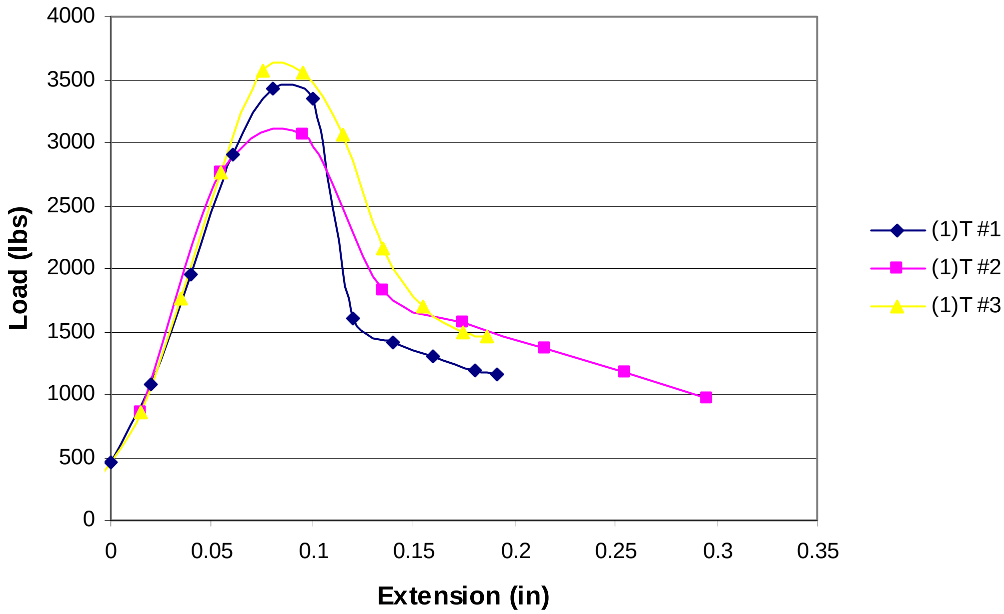

Figure G-7: Full-time 3/4 in. welds in a single 20g sheet steel layer

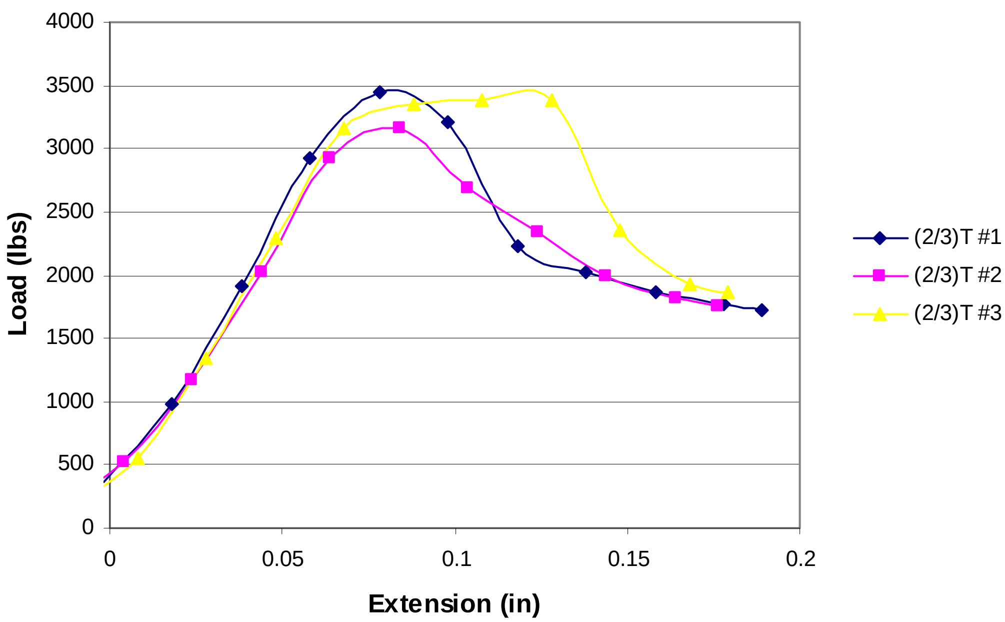

Figure G-8**: 2/3-time 3/4 in. welds in a single 20g sheet steel layer**

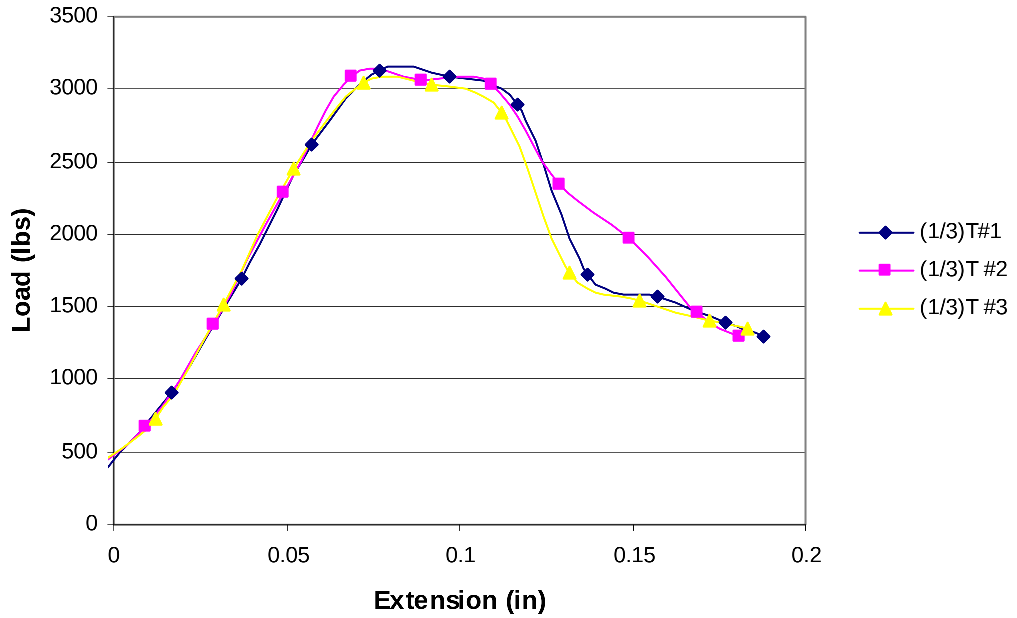

Figure G-9: 1/3-time 3/4 in. welds in a single 20g sheet steel layer

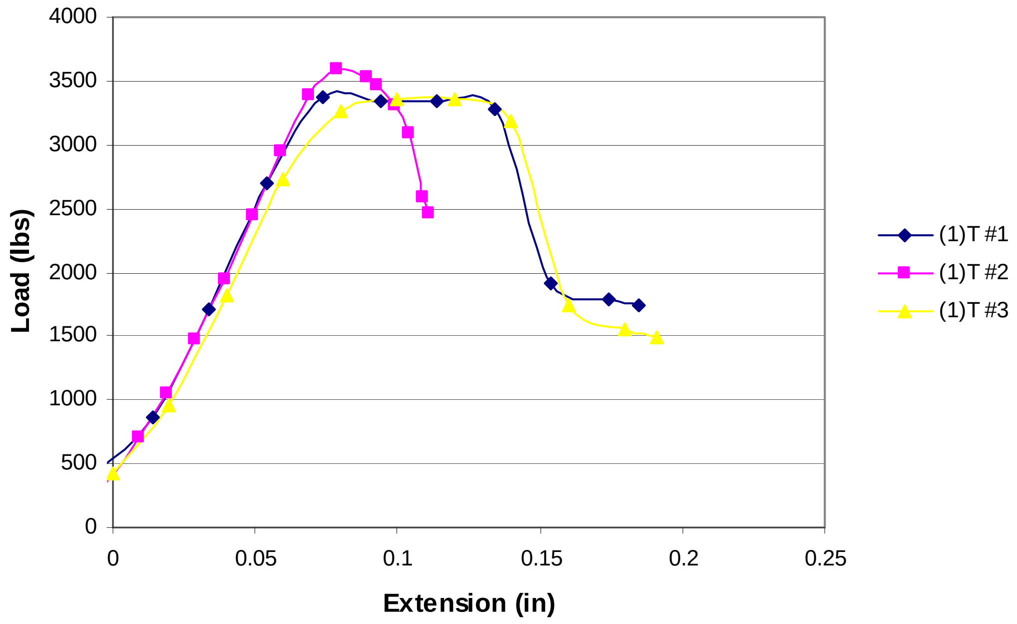

Figure G-10: Full-time 5/8 in. welds in a single 20g sheet steel layer

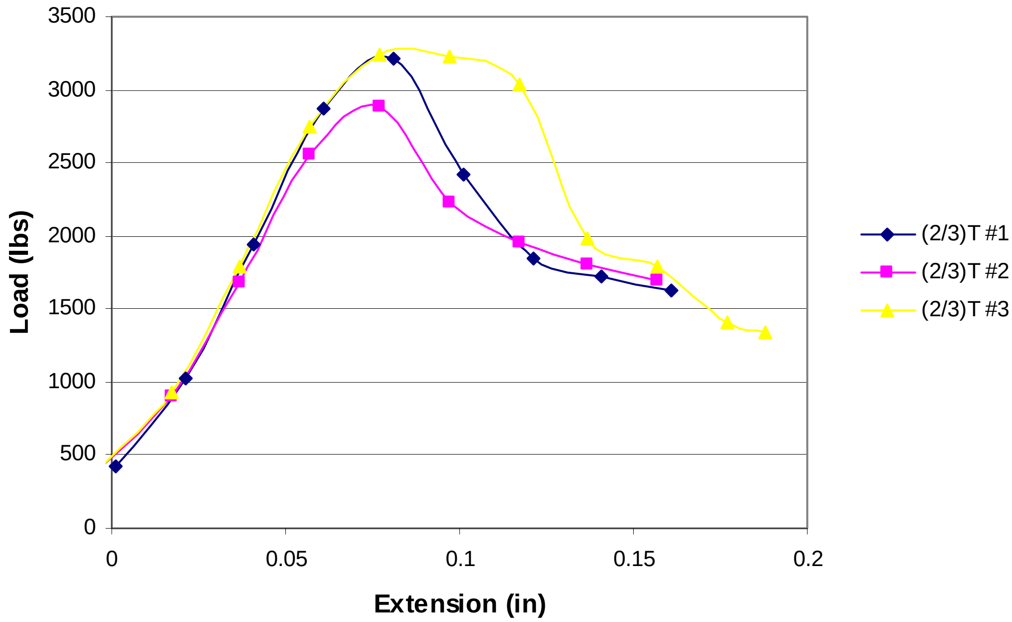

Figure G-11: 2/3-time 5/8 in. welds in a single 20g sheet steel layer

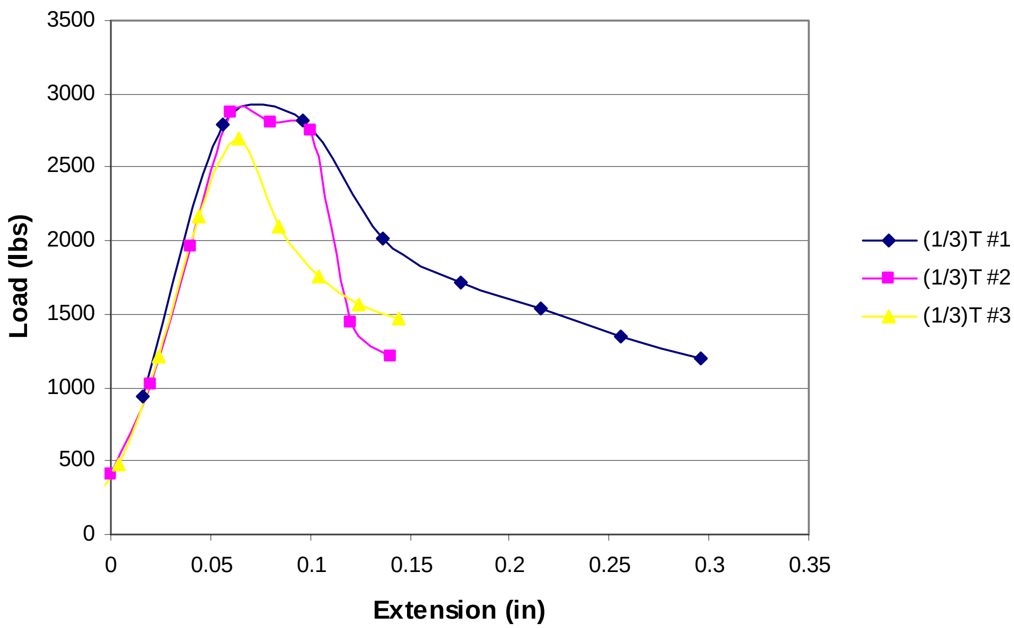

Figure G-12: 1/3-time 5/8 in. welds in a single 20g sheet steel layer

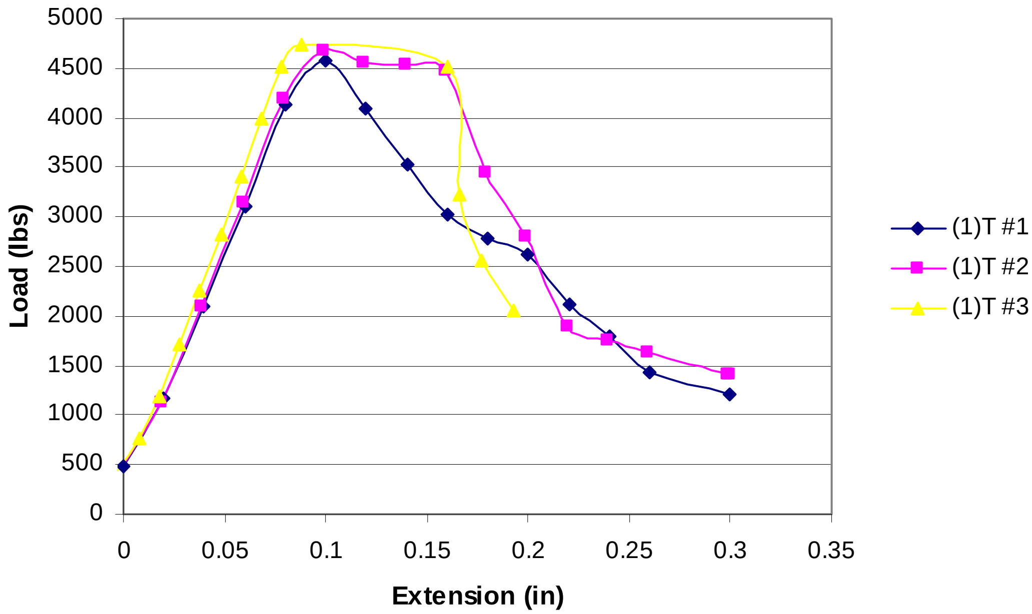

Figure G-13: Full-time 3/4 in. welds in a single 18g sheet steel layer

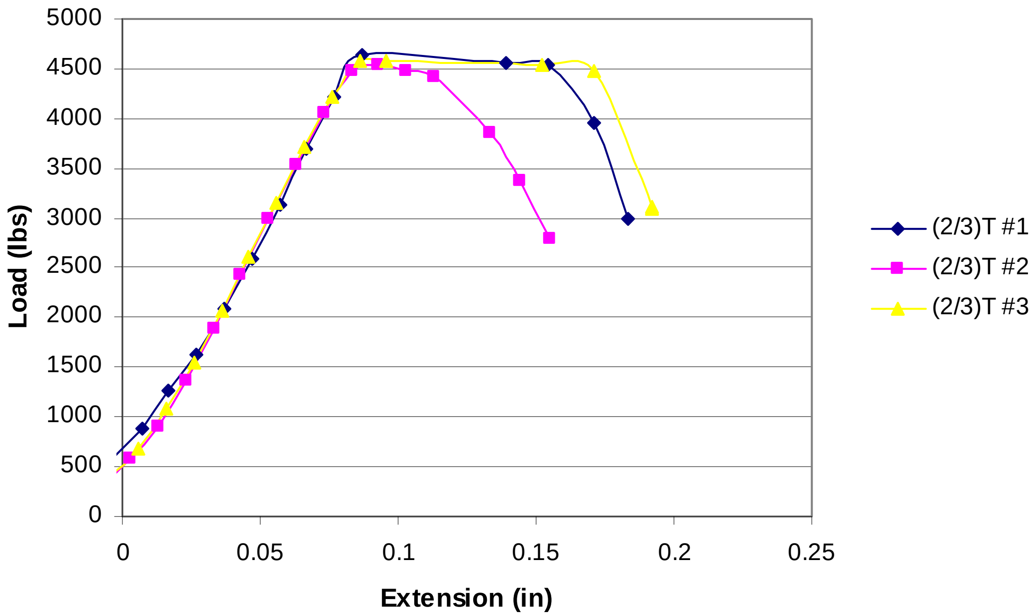

Figure G-14: 2/3-time 3/4 in. welds in a single 18g sheet steel layer

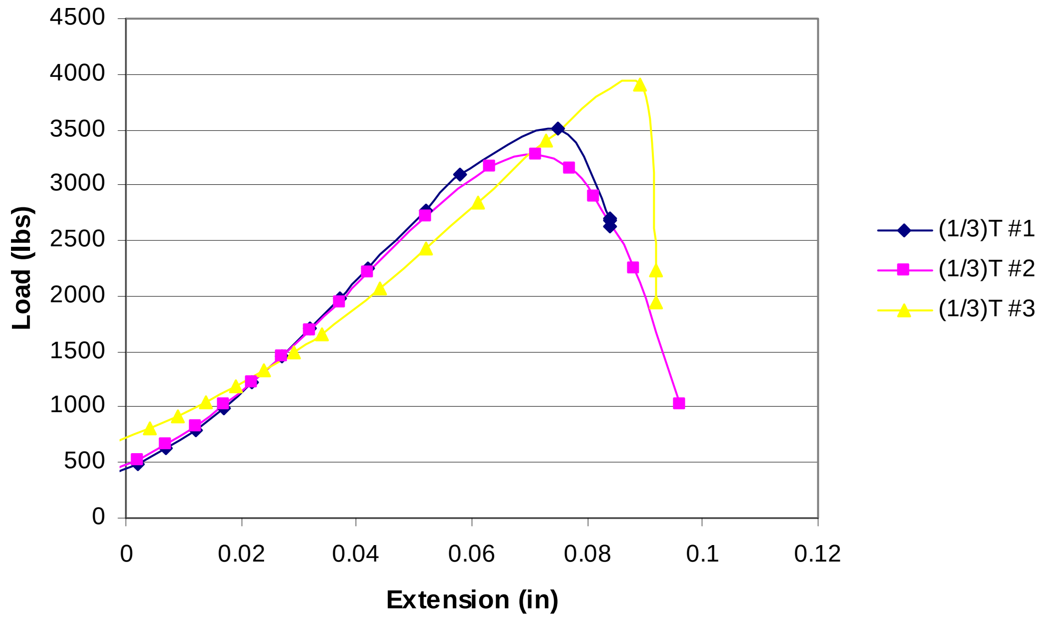

Figure G-15: 1/3-time 3/4 in. welds in a single 18g sheet steel layer

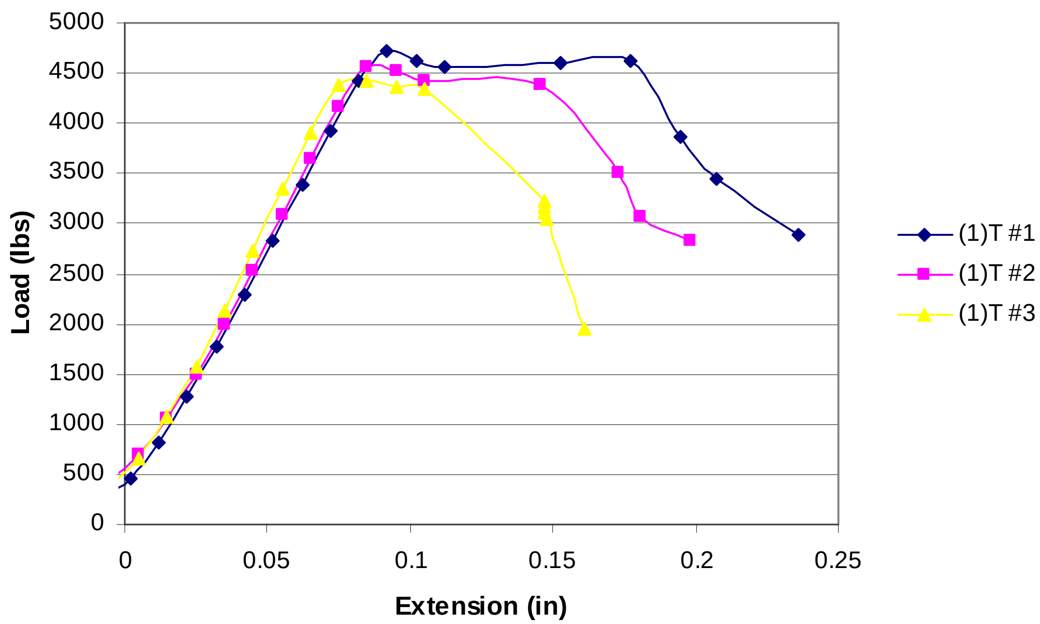

Figure G-16: Full-time 5/8 in. welds in a single 18g sheet steel layer

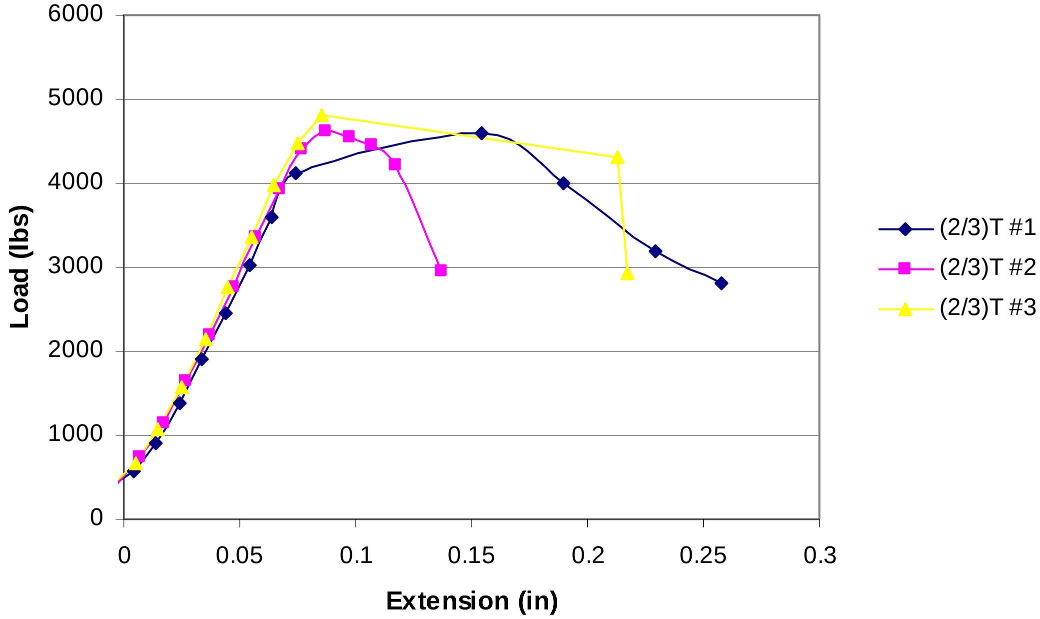

Figure G-17: 2/3-time 5/8 in. welds in a single 18g sheet steel layer

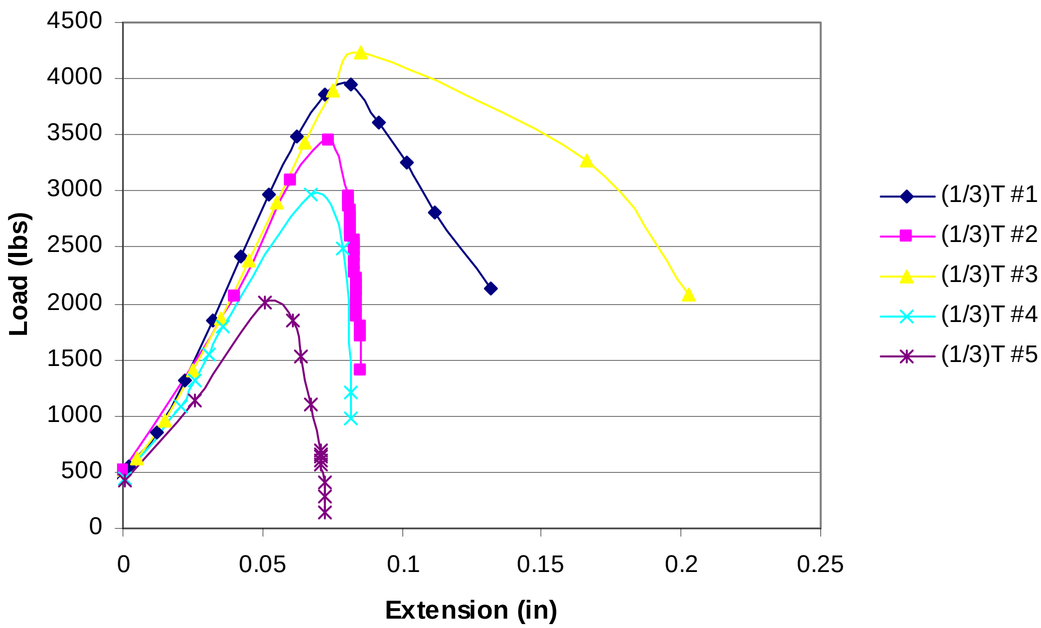

Figure G-18: 1/3-time 5/8 in. welds in a single 18g sheet steel layer

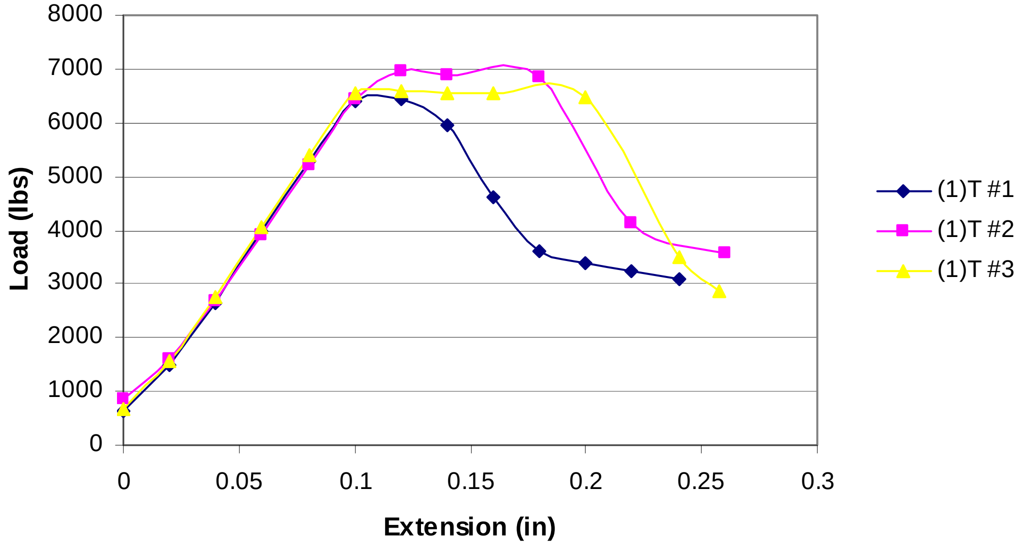

Figure G-19: Full-time 3/4 in. welds in a single 16g sheet steel layer

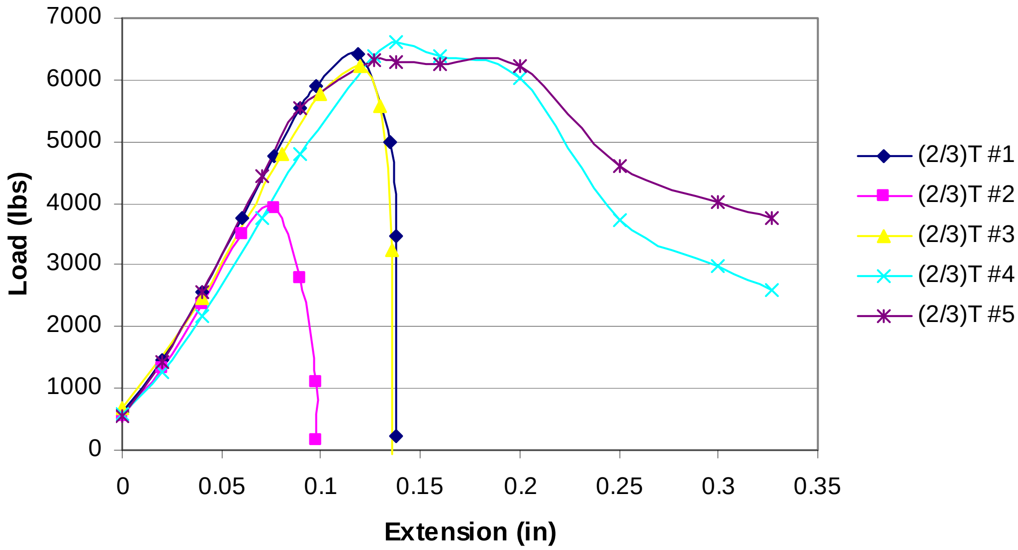

Figure G-20: 2/3-time 3/4 in. welds in a single 16g sheet steel layer

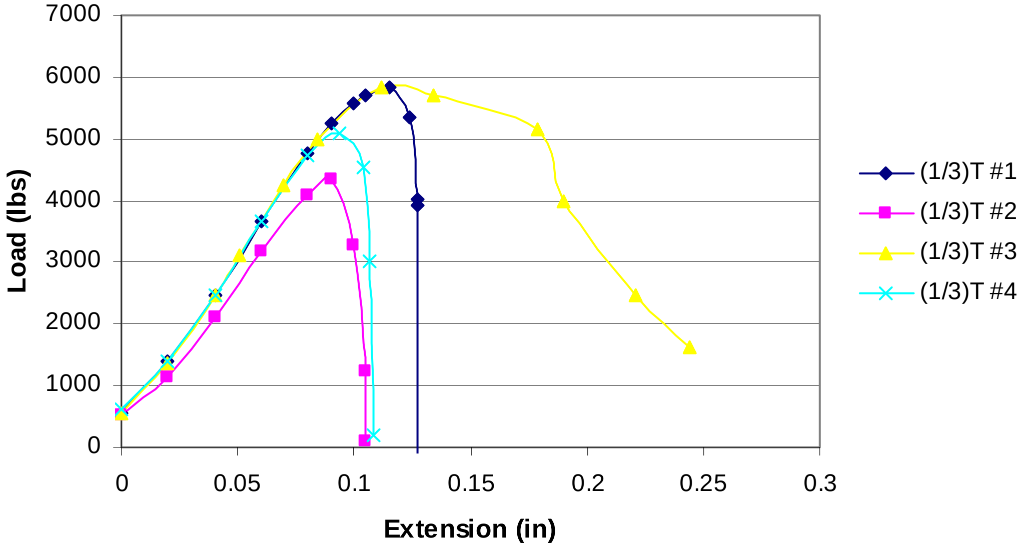

Figure G-21: 1/3-time 3/4 in. welds in a single 16g sheet steel layer

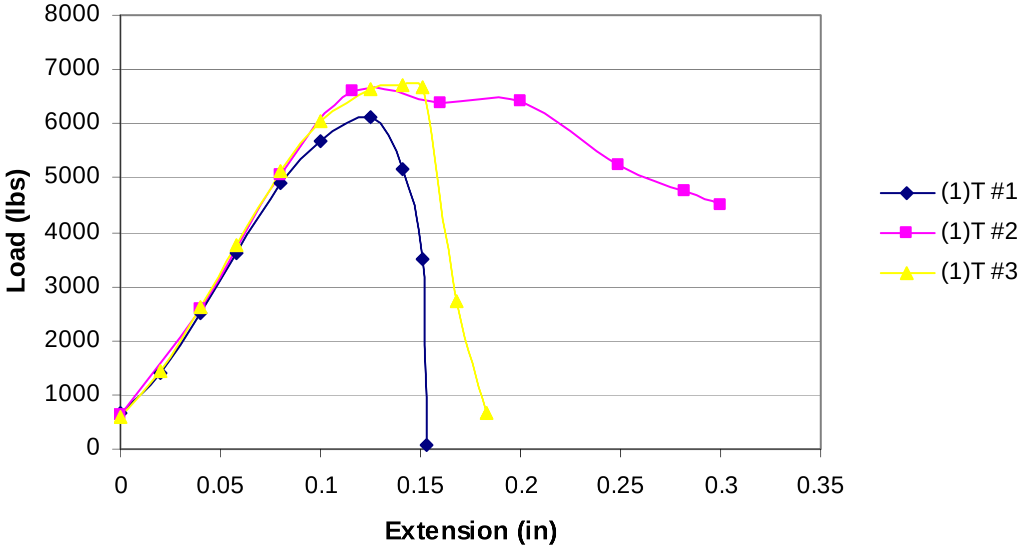

Figure G-22: Full-time 5/8 in. welds in a single 16g sheet steel layer

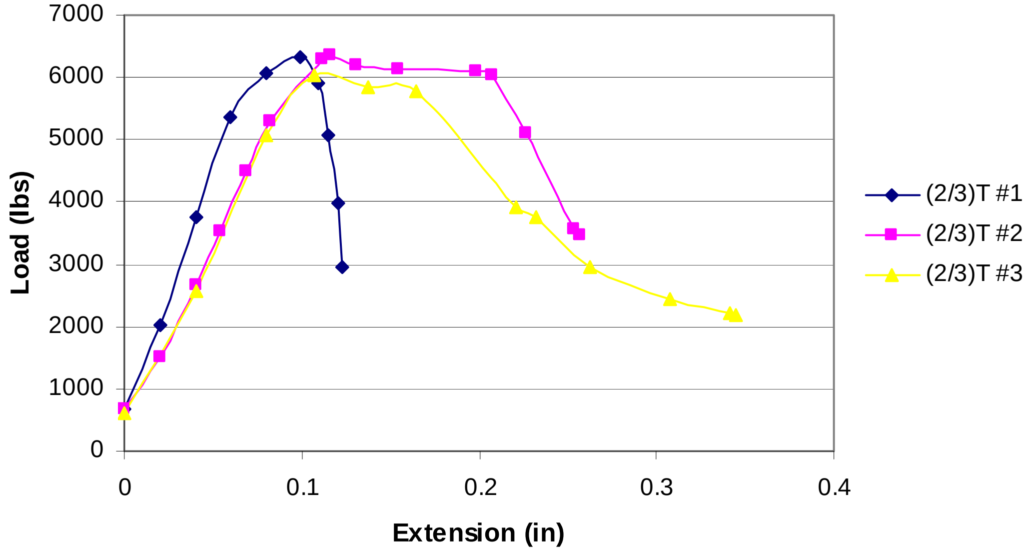

Figure G-23: 2/3-time 5/8 in. welds in a single 16g sheet steel layer

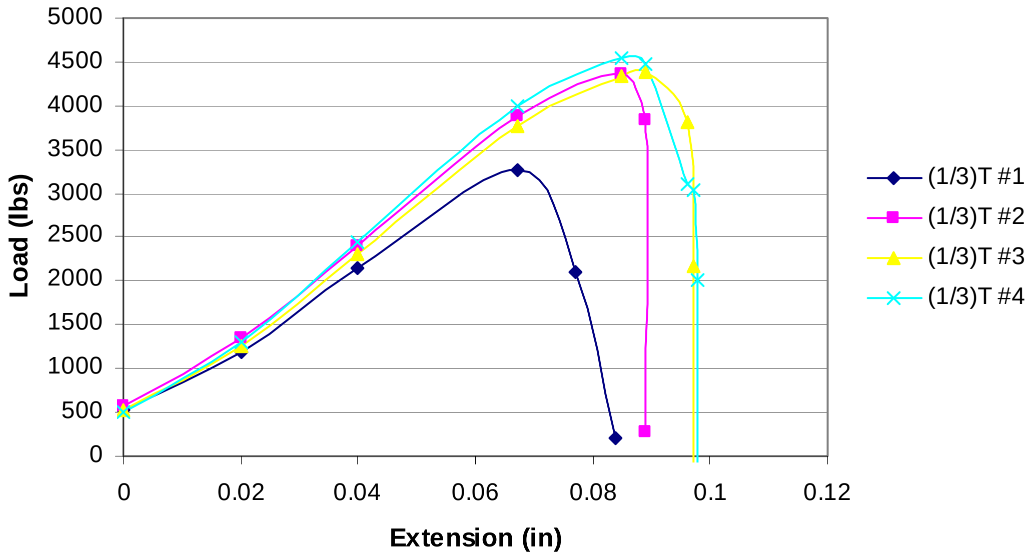

Figure G-24: 1/3-time 5/8 in. welds in a single 16g sheet steel layer

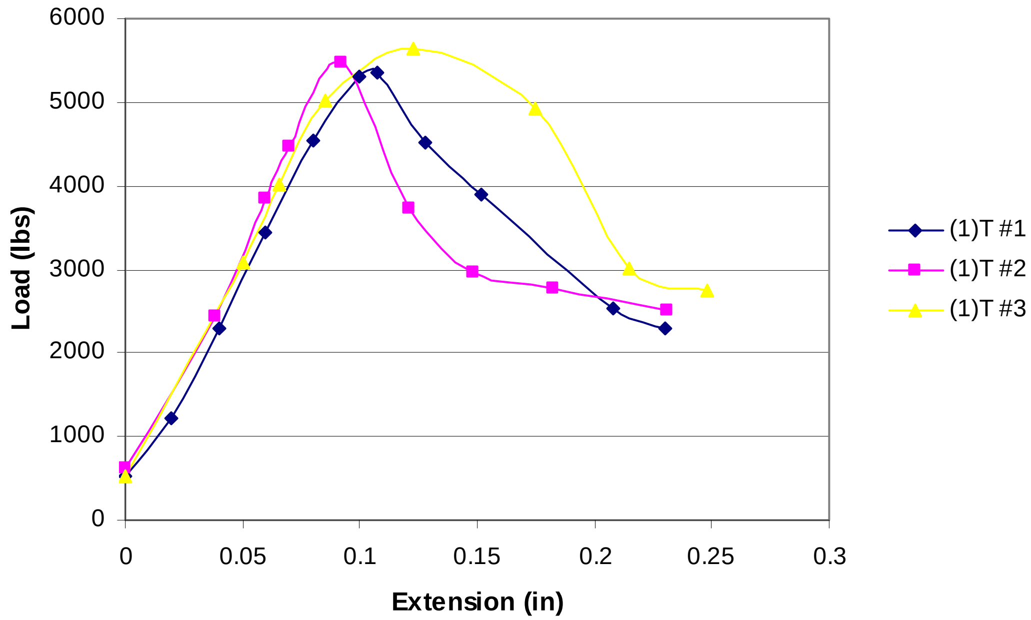

Figure G-25: Full-time 3/4 in. welds in a double 22g sheet steel layer

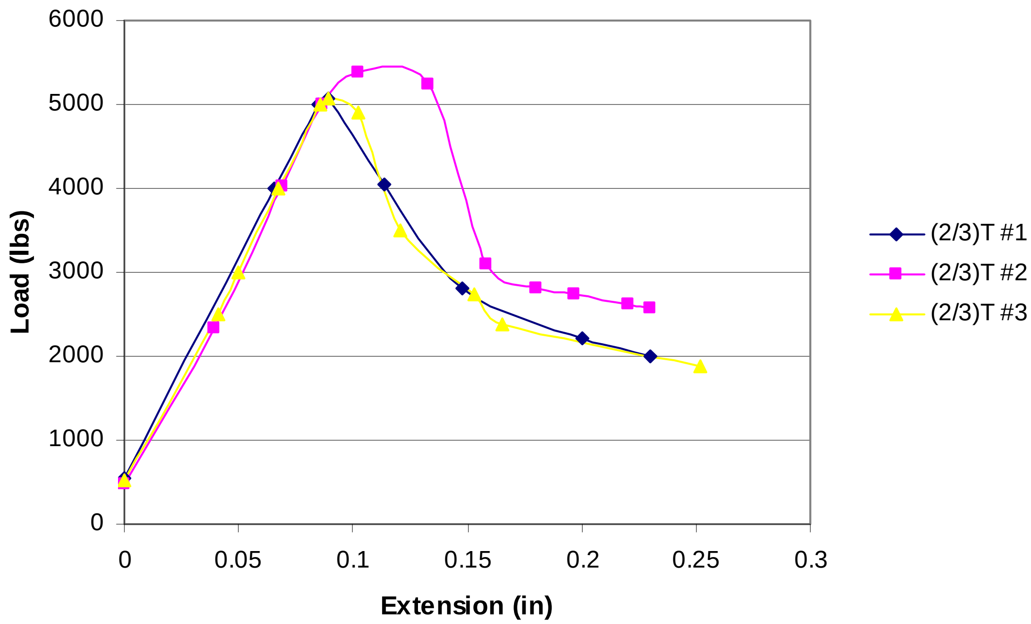

Figure G-26: 2/3-time 3/4 in. welds in a double 22g sheet steel layer

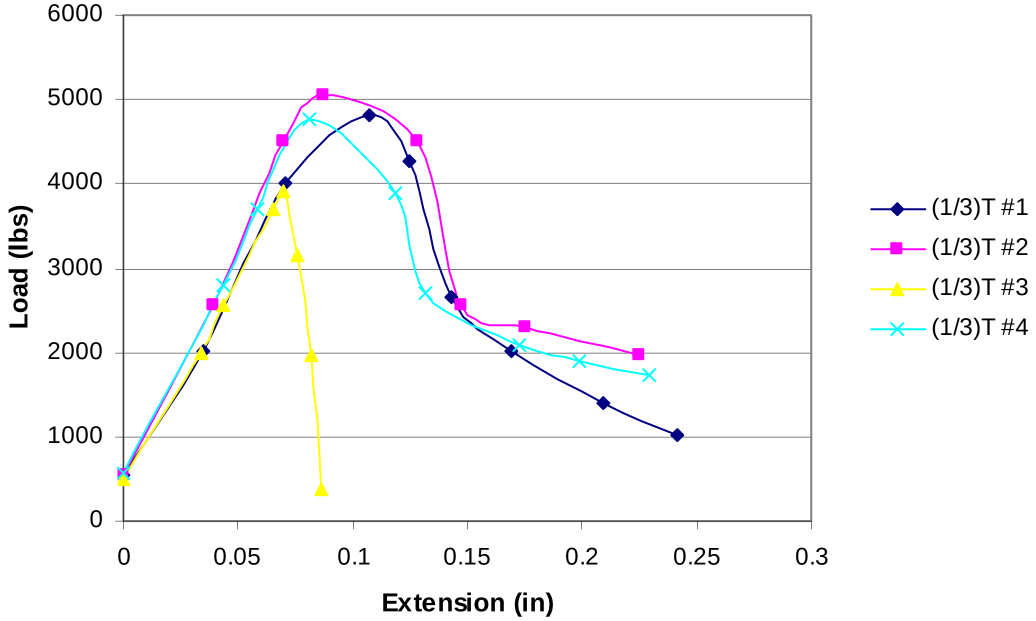

Figure G-27: 1/3-time 3/4 in. welds in a double 22g sheet steel layer

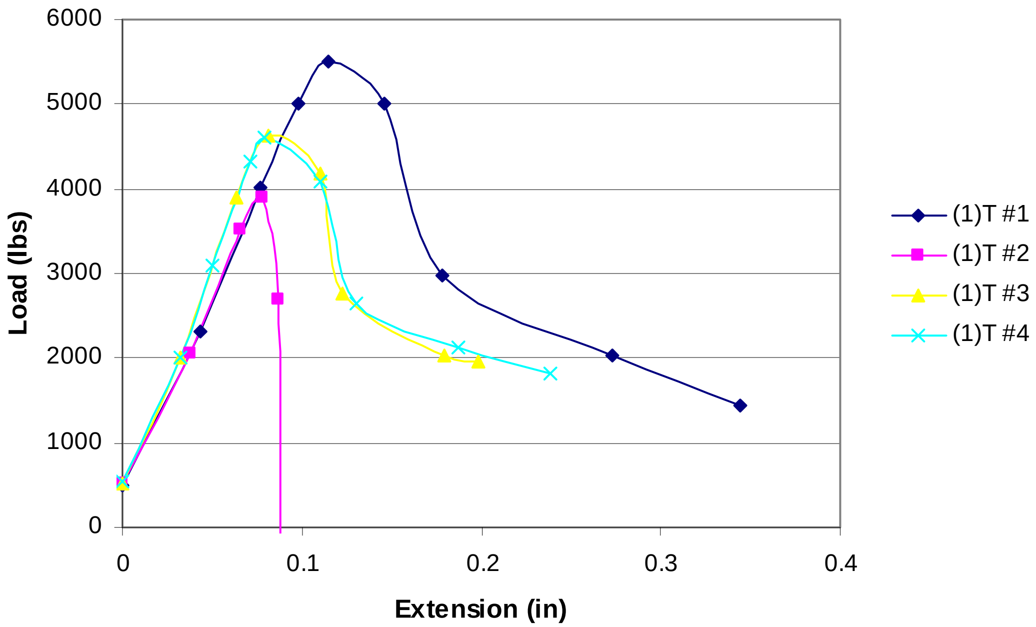

Figure G-28: Full-time 5/8 in. welds in a double 22g sheet steel layer

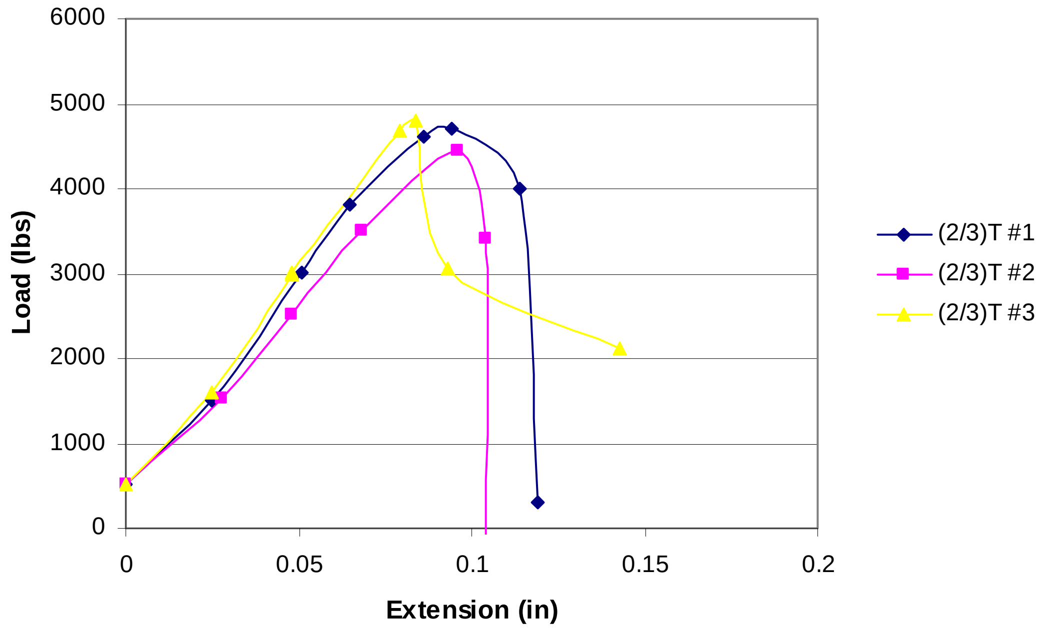

Figure G-29: 2/3-time 5/8 in. welds in a double 22g sheet steel layer

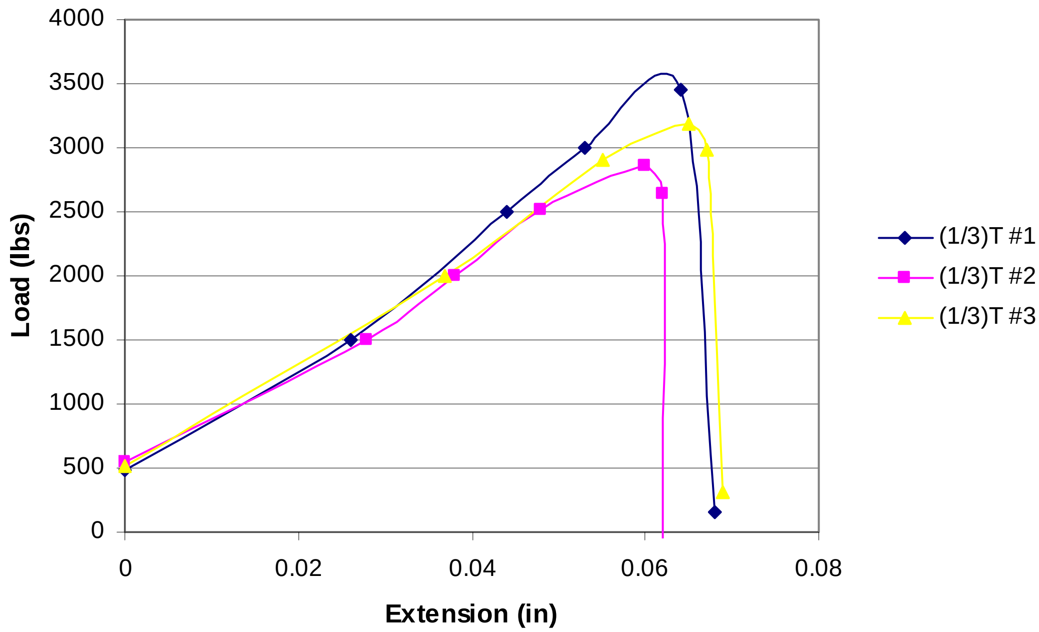

Figure G-30: 1/3-time 5/8 in. welds in a double 22g sheet steel layer

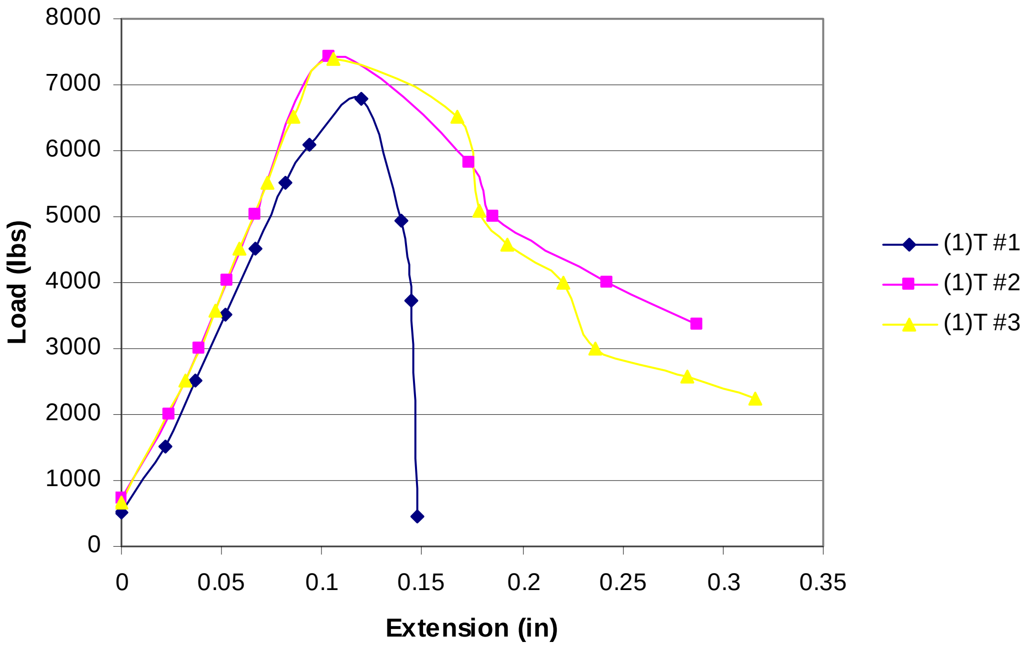

Figure G-31: Full-time 3/4 in. welds in a double 20g sheet steel layer

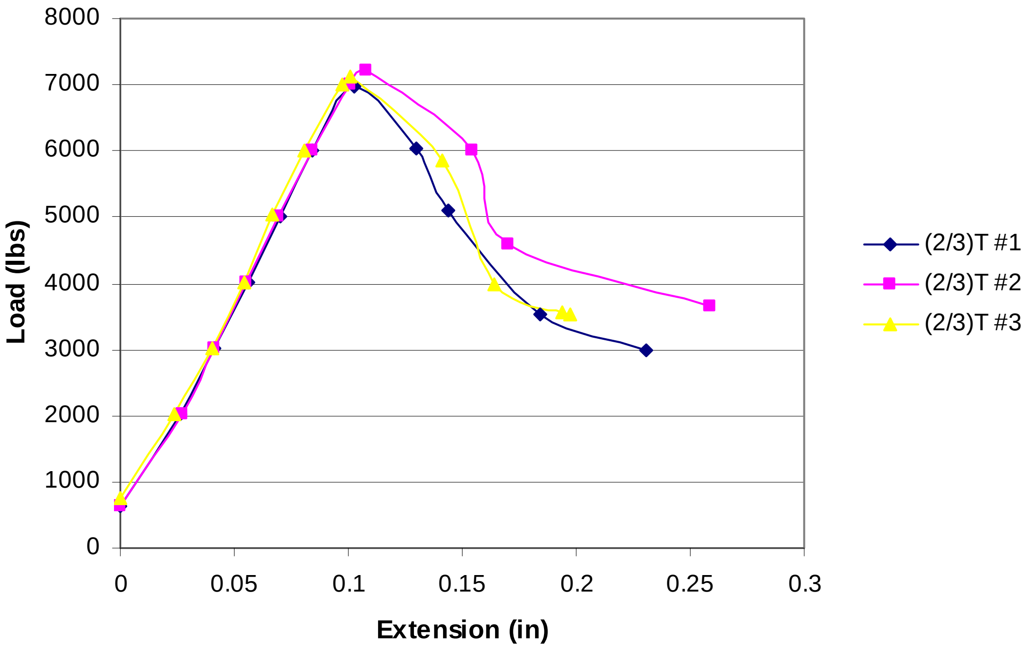

Figure G-32: 2/3-time 3/4 in. welds in a double 20g sheet steel layer

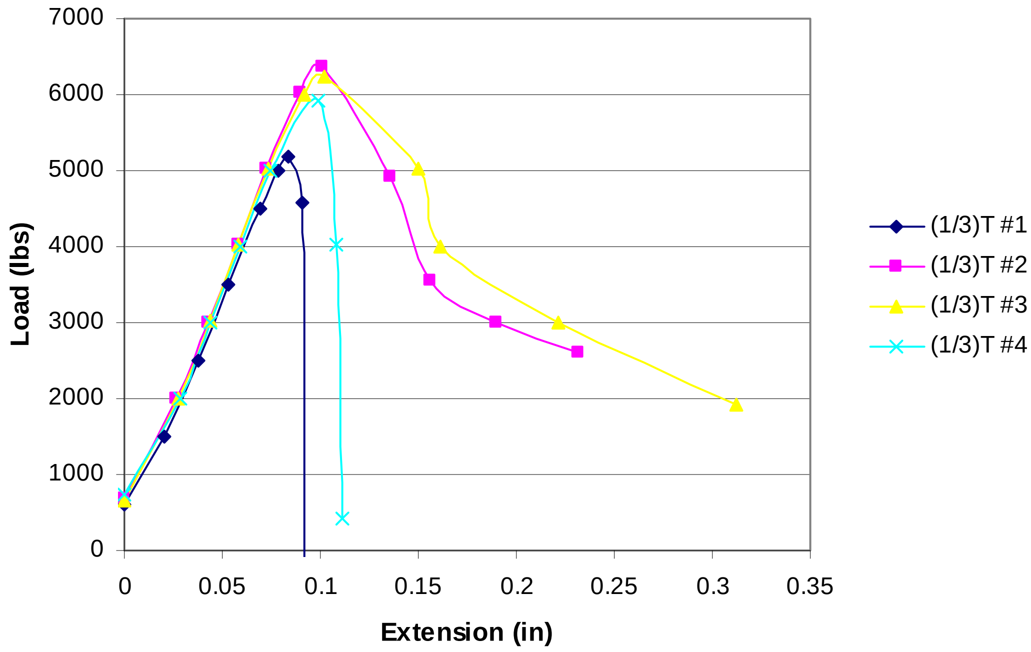

Figure G-33: 1/3-time 3/4 in. welds in a double 20g sheet steel layer

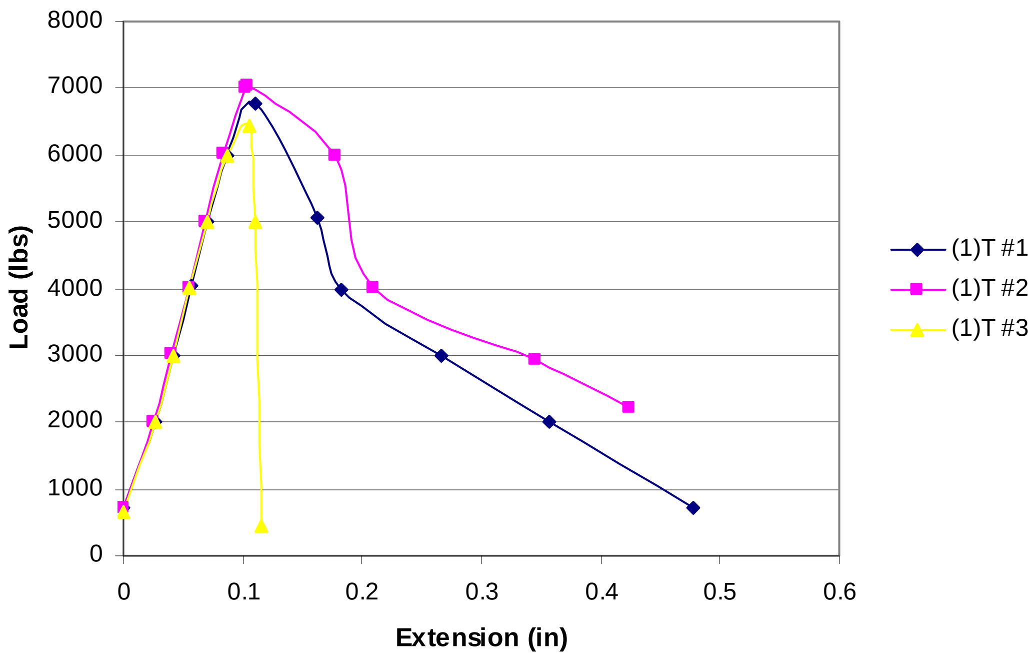

Figure G-34: Full-time 5/8 in. welds in a double 20g sheet steel layer

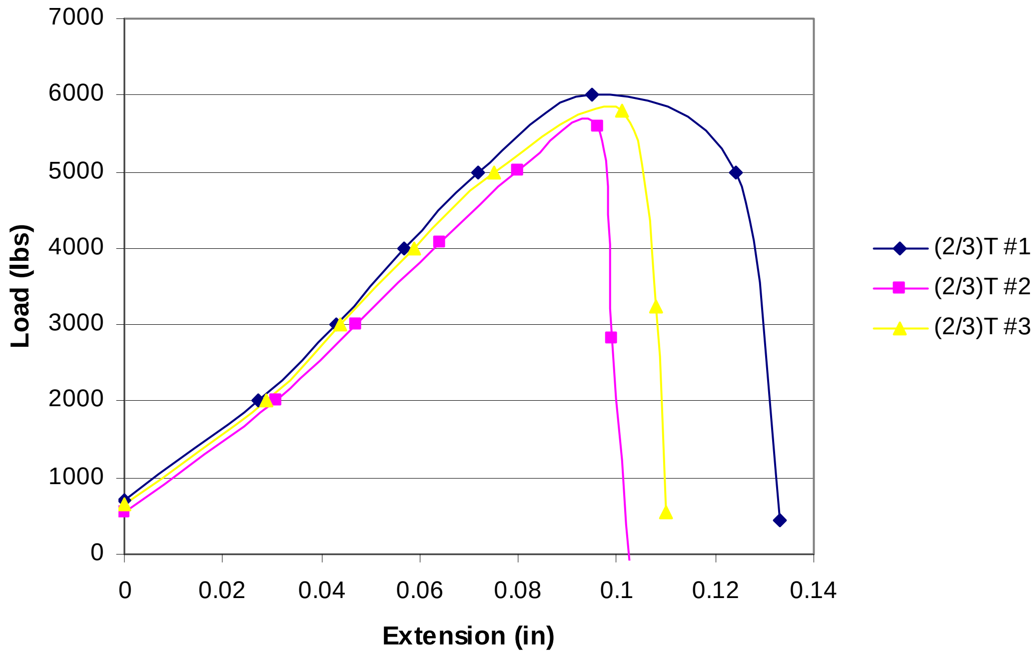

Figure G-35: 2/3-time 5/8 in. welds in a double 20g sheet steel layer

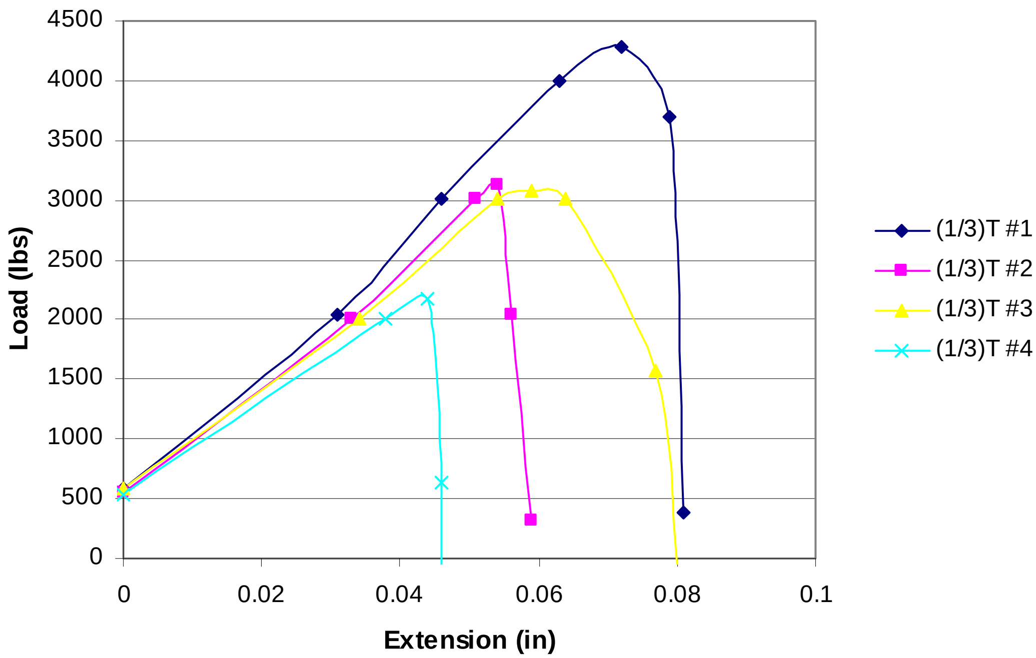

Figure G-36: 1/3-time 5/8 in. welds in a double 20g sheet steel layer

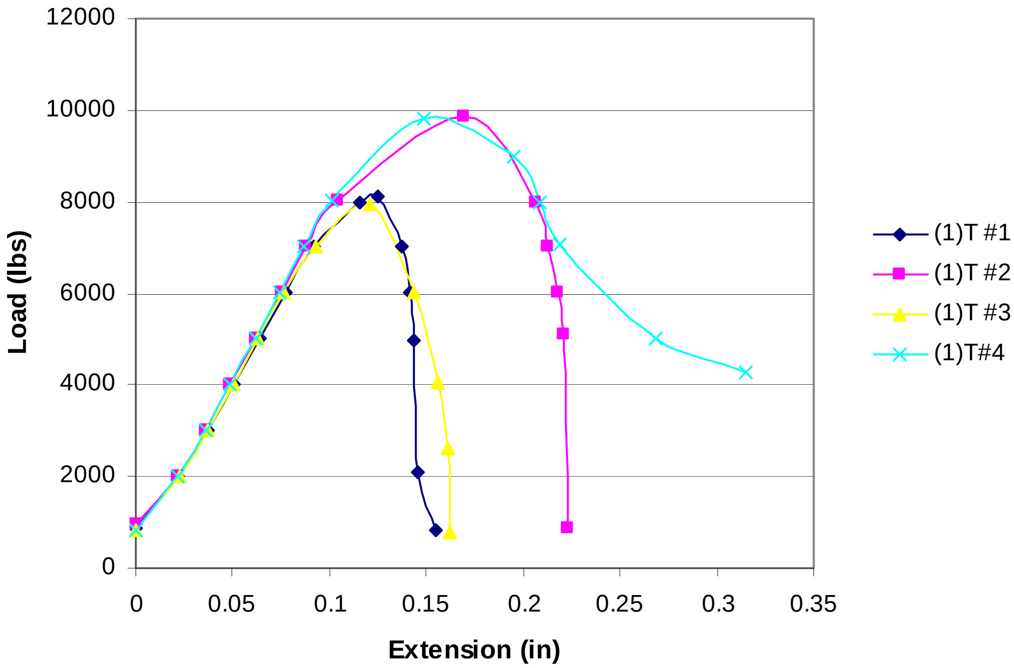

Figure G-37: Full-time 3/4 in. welds in a double 18g sheet steel layer

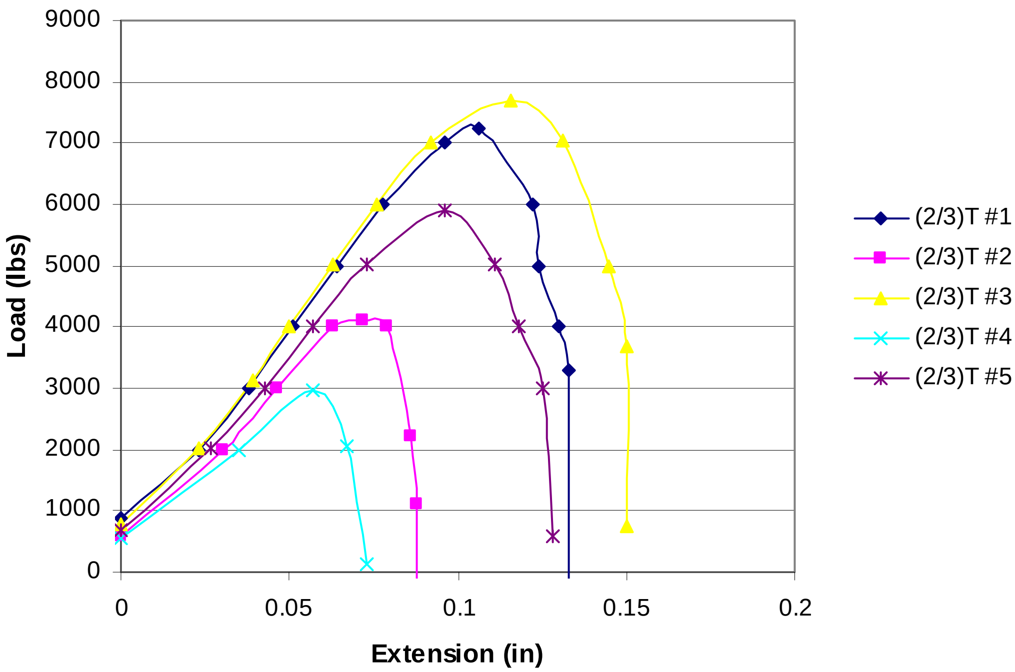

Figure G-38: 2/3-time 3/4 in. welds in a double 18g sheet steel layer

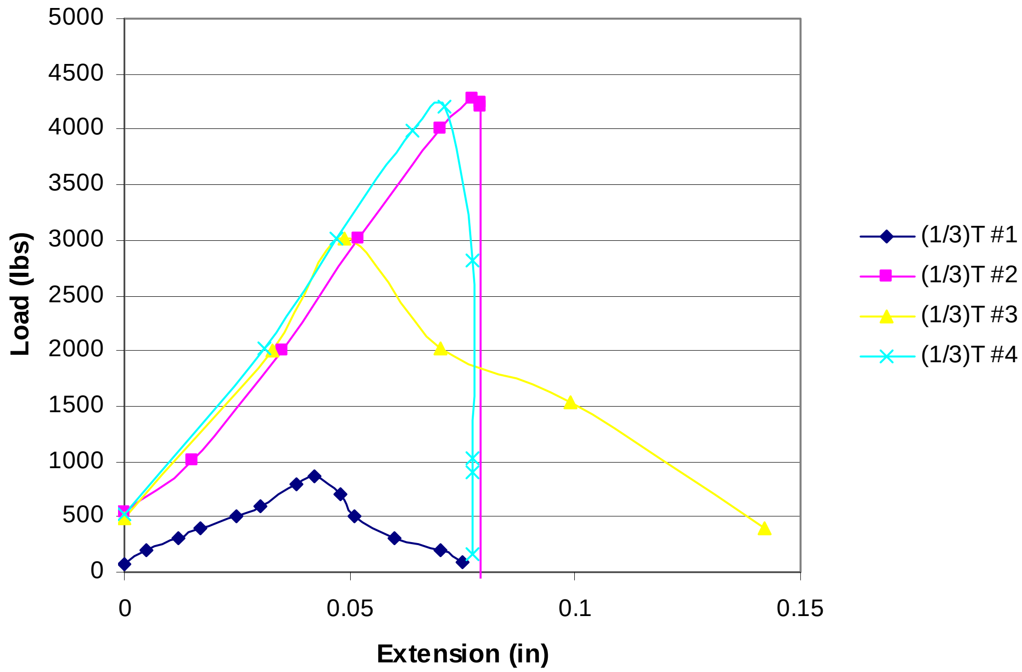

Figure G-39: 1/3-time 3/4 in. welds in a double 18g sheet steel layer

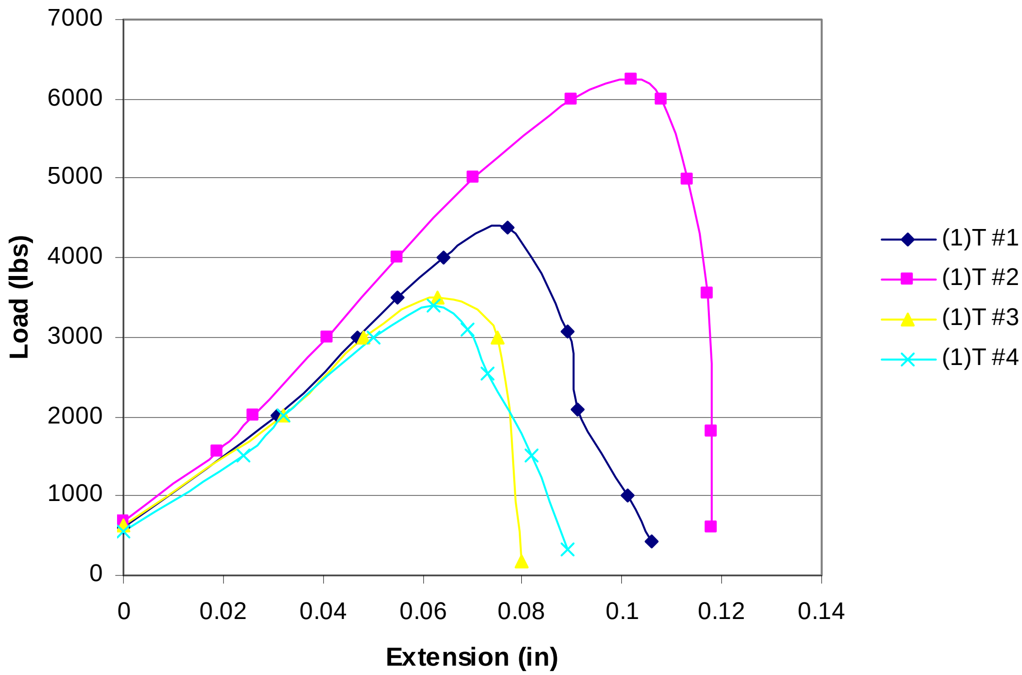

Figure G-40: Full-time 5/8 in. welds in a double 18g sheet steel layer

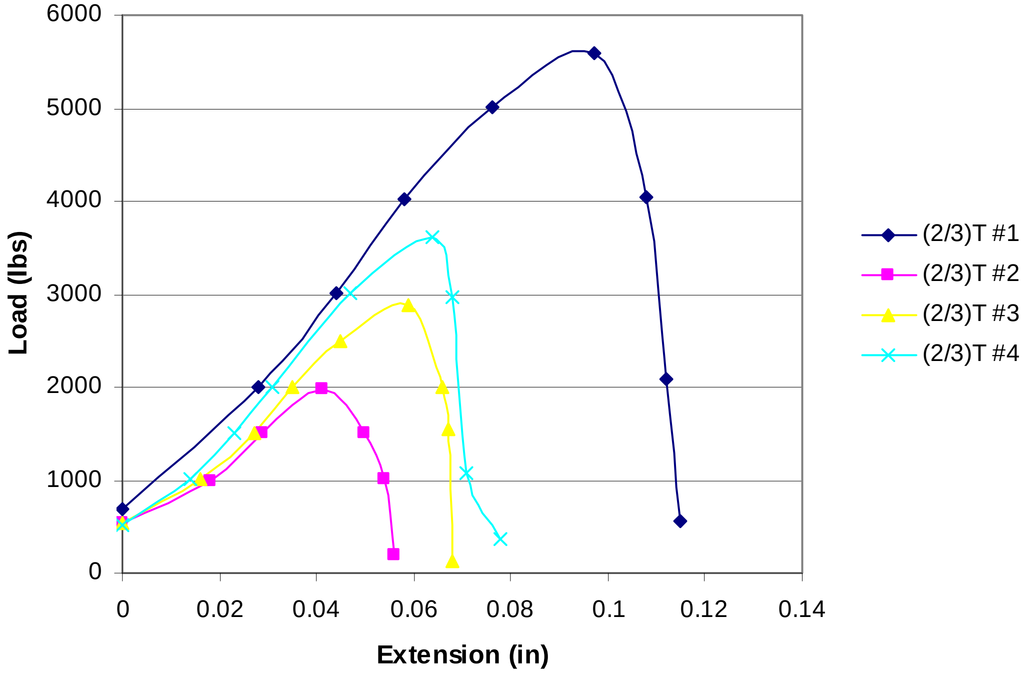

Figure G-41: 2/3-time 5/8 in. welds in a double 18g sheet steel layer

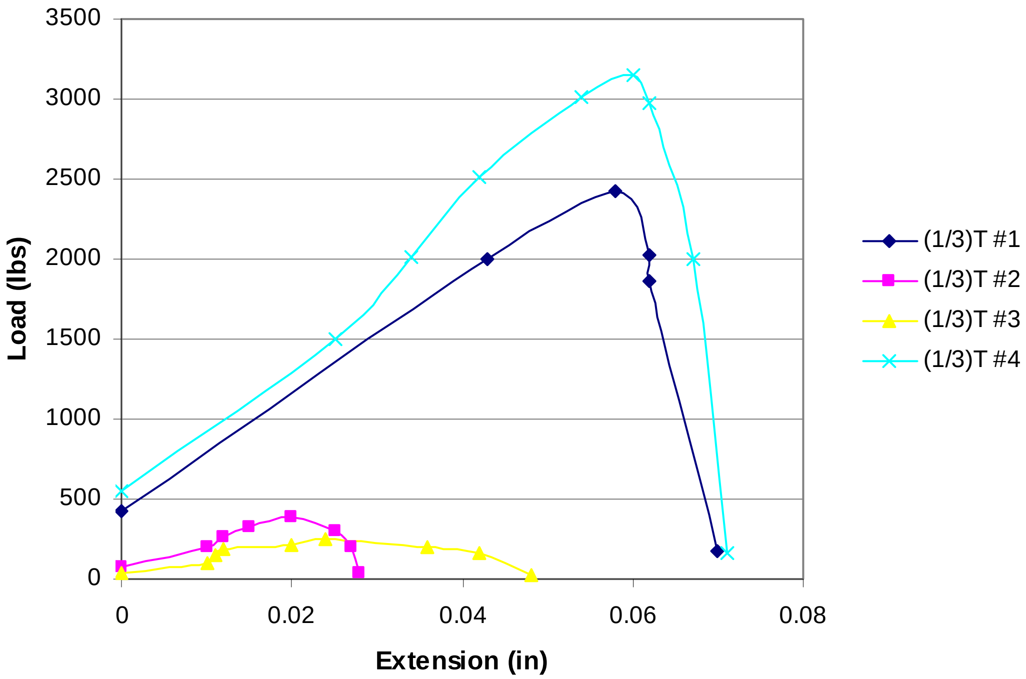

Figure G-42: 1/3-time 5/8 in. welds in a double 18g sheet steel layer

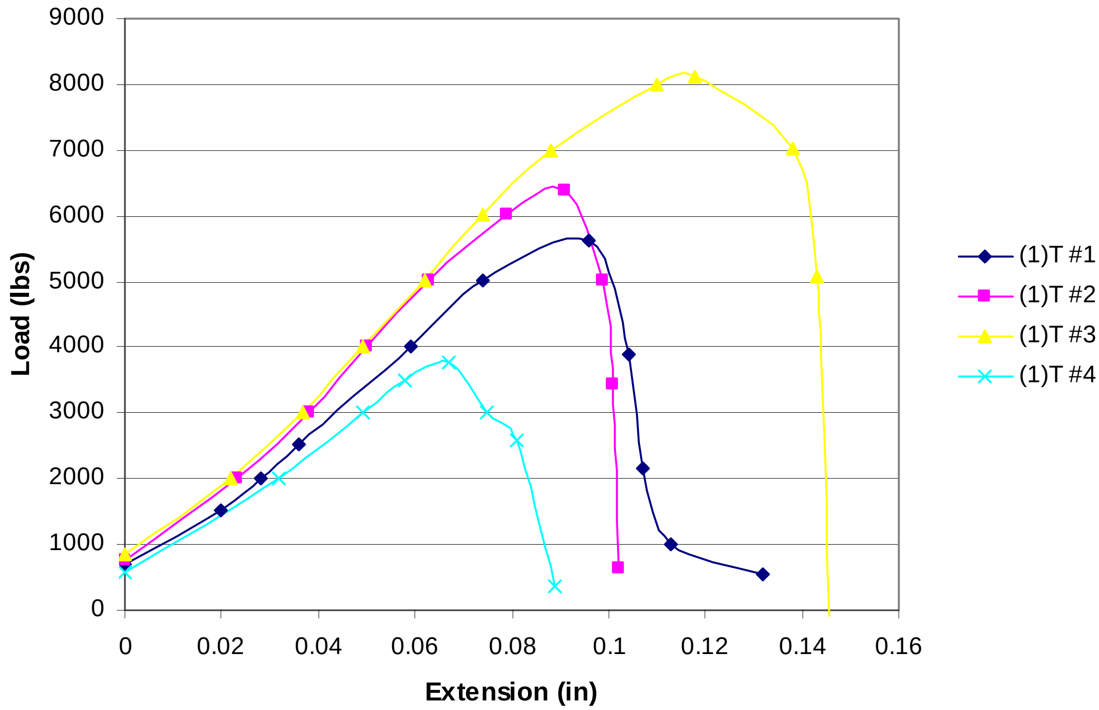

Figure G-43: Full-time 3/4 in. welds in a double 16g sheet steel layer

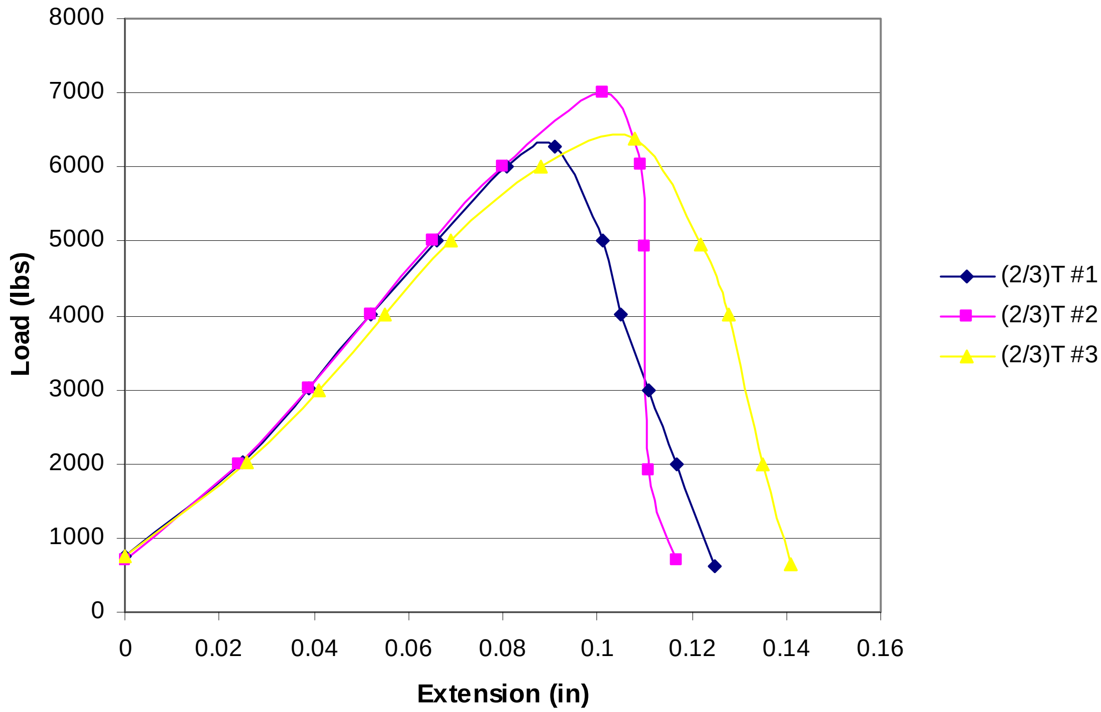

Figure G-44: 2/3-time 3/4 in. welds in a double 16g sheet steel layer

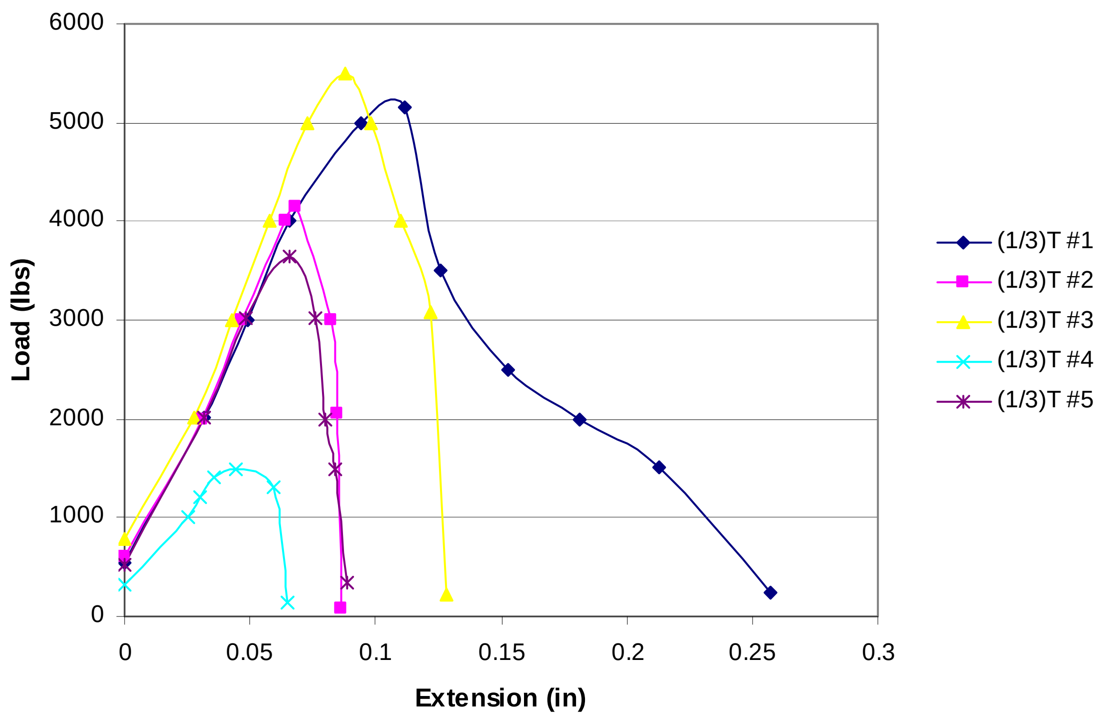

Figure G-45: 1/3-time 3/4 in. welds in a double 16g sheet steel layer

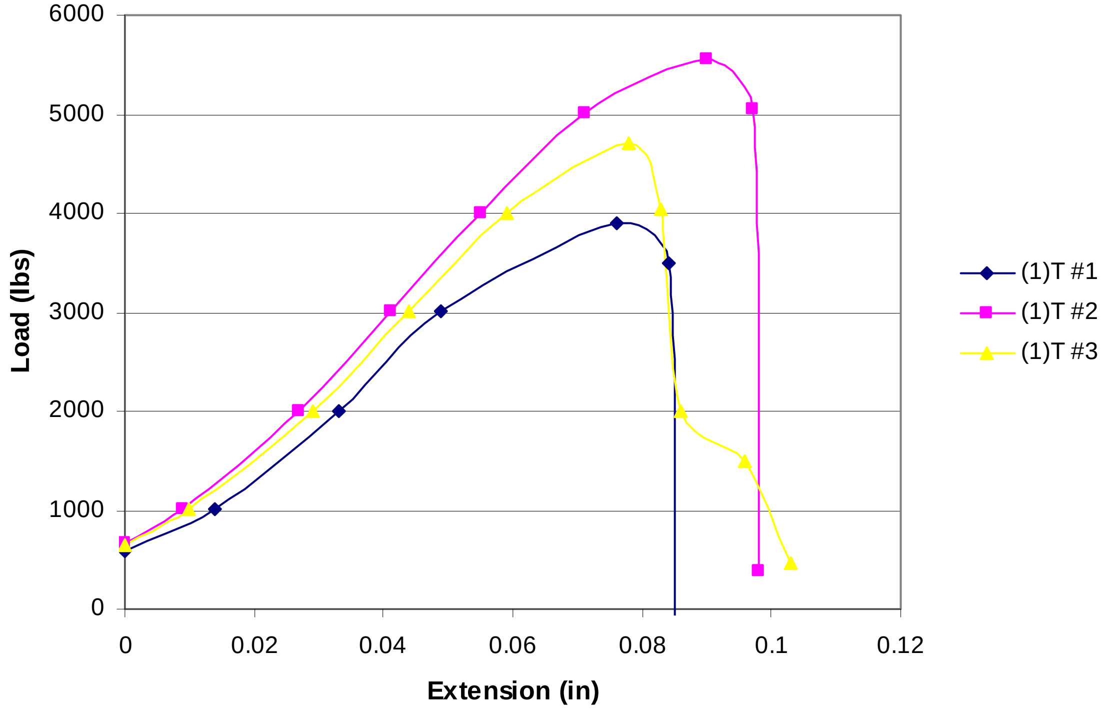

Figure G-46: Full-time 5/8 in. welds in a double 16g sheet steel layer