key words;
1- welds, fillet
2- welded conn's

THE EFFECT OF PROFILE AND ROOT GEOMETRY ON THE STRENGTH OF FILLET WELDS

Volume I

A Thesis Submitted to the Faculty

of

Purdue University

by

Brian P. Quinn - author

In Partial Fulfillment of the

Requirements for the Degree

of

Master of Science in Civil Engineering

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I wish to express my sincere appreciation to my major professor, Dr. Mark D. Bowman for his constant guidance and assistance as well as his eagerness to help whenever it was requested throughout the project. I also thank the other two members of my committee, Professors J.T. Gaunt and C.D. Sutton.

Funding for this project has been partially provided by a 1989 American Institute of Steel Construction educational fellowship. I wish to thank Raymond H. R. Tide of Wiss, Janney, Elstner Associates for his insights and interest in the project.

In addition, I wish to thank Chicago Bridge and Iron for their excellent quality workmanship in welding all of the specimens for this project, free of charge. Special thanks go to Ned A. Bacon of CBI Technical Services as well as Robert E. Klippel of CBI Services for their assistance in arranging for the welding of all the specimens. Also, I wish to thank James A. Brennan of CBI Services who oversaw all of the welding and was most helpful in insuring all of the welding was done as I had wished. Finally, I wish to thank Ivaldo Basso and Dennis Hornback for setting up and welding all of the specimens at CBI Services in Bourbonnais, Illinois.

Further thanks must be expressed to the Purdue University Central Machine Shop and Charlie Crow in particular for his help in the preparation of the specimens and for the use of Central Machine Shop equipment.

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AMERICAN INSTITUTE OF STEEL CONSTRUCTION, INC.

TO: N. Iwankiw ***DATE:*** December 12, 1991

FROM: R. Lorenz RFL

SUBJECT: "Strength of Fillet Welds"--Fellowship Thesis: Brian Quinn

==

Attached is the two volumes which cover the work of Brian Quinn, a Purdue Fellowship winner. This effort shows very good correlations with the work of Kulak, Preece and others regarding fillet weld strength, but does raise a few questions that may influence ϕ-factor values for connections or possibly improved procedural recommendations. Also, the apparent discrepancy between ASD and LRFD predictions of weld strength (see bottom of page 148) may need further study.

RFL/ag
Attachments
cc: G. Haaijer
L. Brunner
F. Rosenberg

cc (with copies) to R.H.R. Tide + G. Kulak

PURDUE UNIVERSITY

SCHOOL OF CIVIL
ENGINEERING

December 5, 1991

Mr. Robert F. Lorenz
Director of Education & Training
American Institute of Steel Construction
One East Wacker Drive, Suite 3100
Chicago, Illinois 60601-2001

Dear Mr. Lorenz:

Enclosed herewith please find a copy of the thesis prepared by Brian P. Quinn for his MSCE degree at Purdue University. As you know, Brian received an AISC fellowship and was conducting a series of tests on fillet welded lap joints. Please accept this copy of his thesis as the summary report of his work.

I would like to take this opportunity to thank AISC for the financial support that was given to Mr. Quinn. I know that Brian is very proud of fellowship that he received and the experimental work that the fellowship allowed him to complete. I believe this pride is reflected in the quality of the thesis that Brian prepared.

Brian and I will be working together in the next couple of months to prepare a summary paper of his research findings for submission to a technical journal. We will let you know more about this when the paper is completed.

Finally, best wishes to you and the staff at AISC for a happy holiday season.

Sincerely yours,

Mark D. Bowman

Mark D. Bowman
Associate Professor
of Civil Engineering

Encl.

CIVIL ENGINEERING PURDUE UNIVERSITY

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ABSTRACT

Quinn, Brian P. MSCE, Purdue University, December 1991. The Effect of Profile and Root Geometry on the Strength of Fillet Welds. Major Professor: Mark D.Bowman.

The objective of this research study was to investigate a few of the critical parameters which affect fillet weld strength. These parameters include: the effect of weld nugget geometry, the effect of fabrication gaps, the difference in strength of longitudinal and transverse fillet welds, and finally, the load-deformation behavior of both longitudinal and transverse fillet welds.

Eighteen primary test matrix specimens consisting of nine longitudinal and nine transverse fillet weld specimens were tested in this study. Additionally, three weld electrode coupon specimens were fabricated and tested to determine the weld electrode strength. Furthermore, three macroetch specimens were fabricated for the investigation of weld penetration into the base metal. 'Dentist' type plaster molds were also made of one of the test welds for each of the primary test matrix specimens, with the exception of the first specimen. These specimens gave an

indication of the 'reinforcement' weld distance due to the convexity of the weld profile.

The exposed weld profile had the most significant effect on the strength of the fillet welds, for a given weld leg size and weld electrode. The 1/2 inch leg size longitudinal weld specimens demonstrated a significant decrease in strength over the predicted values obtained from extrapolating 1/4 inch test results.

Root penetration had little effect on the weld strength. The fabrication gaps induced on some of the specimens also had minimal effect on the weld strength because the weld material was allowed to 'flow' into the gap area.

All of the transverse welds were stronger per square inch of weld than similar longitudinal specimens, with corresponding decreased weld deformation, as was expected. Load-deformation data were closer to AISC ASD Specification curves than to the more recent LRFD Specification curves.

CHAPTER 1

INTRODUCTION

1.1 General Remarks

Fillet welding is a process for joining metals which is affected by many variables. There are several critical variables which determine the strength of the deposited weld metal.

One of these variables is the welding process which is employed. A number of different welding processes are commonly used for structural applications, including shielded metal arc welding (SMAW), submerged arc welding (SAW), flux cored arc welding (FCAW), and gas metal arc welding (GMAW), just to name a few. Each of these processes utilize uniquely different electrodes. There are even different types of electrodes, within each process, that have the same minimum tensile strength, but which produce different properties of the deposited weld metal. For example, if shielded metal arc welding was being used different strengths of electrodes could be chosen, such as E60xx or E70xx. If E70xx was chosen, then there are more choices for what class within E70xx such as either E7018 or

E7024. Both of these electrodes have the same minimum tensile strength and the same design strength, but the welds they produce may vary. Different base metals which are fused together with the weld electrode also affect the weld strength.

The type of welding equipment being used also influences the quality of the deposited weld metal. AC or DC welding equipment with varying voltage and amperage can affect the weld. Furthermore, the experience of the welder is important for the quality of weld produced. Qualification tests are normally required of all welders, but different welders have different styles of welding which inevitably make welds slightly different for each individual welder.

An additional input variable that affects the type of weld produced is the weld geometry. As a result of variations in the fillet welding process, the weld profile is variable over the length of the weld. Fillet welds can be convex or concave in profile, with different top and bottom leg sizes. Various degrees of root penetration and fusion may also affect the weld strength. Erection procedures may also introduce gaps between the steel members or plates to be joined, which may compromise strength when welded.

Because of the variations in the profile of fillet welds and the variations introduced in the welding process, it is not easy to exactly define the strength of fillet welds. Even in laboratory conditions, there are many aspects of fillet welds which are difficult to control and measure. Further complicating the analysis of fillet welds is the fact that they have a different behavior when loaded in shear than when loaded in compression or tension. For a shear type loading, the fillet weld strength depends upon the orientation of the load relative to the weld. Therefore, it is important to consider the numerous critical aspects which influence the behavior of fillet welds when trying to characterize the strength parameter. It is often difficult to quantify all of these important variables, even in a laboratory setting.

Current design practice defines weld strength based on an allowable stress on the effective area of the weld. For fillet welds, this effective area is the effective throat thickness times the length of the weld. The allowable stress for fillet welds is currently based on the ultimate tensile strength of the weld metal times a constant which takes into account a safety factor and a reduction in strength assuming the weld to be loaded in shear. For weld electrodes with the same minimum ultimate tensile strength, this allowable stress is constant for any weld size, loaded at any angle.

1.2 Purpose and Scope

This experimental study is an attempt to investigate a few of the critical parameters which affect fillet weld strength. The primary objectives of this study are the following:

1. To determine the effect of weld nugget geometry on fillet weld strength.
2. To determine the effect of fabrication gaps on fillet weld strength.
3. To determine how the strength of longitudinal fillet welds differs from the strength of transverse fillet welds.
4. To investigate the load-deformation response of longitudinal and transverse fillet welds.

A review of literature on the strength of fillet welds is presented in Chapter 2. Test results from a few key studies have been used as the basis in developing current design expressions and requirements for fillet welded connections. Furthermore, previous research which has investigated the effect of weld profile on fillet weld strength as well as load-deformation response is reviewed.

Chapter 3 describes the experimental test program which was conducted on a series of filled welded lap connections to examine fillet weld behavior. In-depth detail is provided concerning specimen design, fabrication, instrumentation, and testing.

The results of this series of tests are presented in Chapter 4. An analysis of the experimental test results was conducted and is also described in Chapter 4 where the variables affecting fillet weld strength which were isolated are discussed in detail.

Chapter 5 presents a summary of the report and conclusions which were drawn from the analysis of the data collected from the experimental test program. The need for additional research on fillet welds is also discussed.

Finally, appendices with raw data from the test series are included.

CHAPTER 2

LITERATURE REVIEW

2.1 Historical Background

The art of fusion welding in the United States has been popular since the United States military started using this technique on ships during World War I. The post World War I days sparked interests by industry in using this technique to join steel. Fillet and butt welds were two popular types of welds used in the structural building industry. Early tests on these types of welds were merely aimed at proving the welds were stronger than the base metal they attached. Thus, most experimental tests simply loaded a welded connection until fracture occurred in the base metal. This then proved that the weld was stronger than the base metal and was deemed sufficient to allow a similar weld to be used in a structure.

During the late 1920's, structural engineers began to question whether their designs involving welds were economically efficient. It was realized that in many fillet welded connections, the base metal tensile strength was not necessarily the governing design parameter. Thus, many of the welds in connections were over-designed. Therefore, tests were conducted in the United States and Great Britain during the late 1920's and into the 1930's to examine the actual strength of the welds. These tests were set up to have failure induced in the welds so an allowable stress for welds could be defined for design. The allowable stresses determined from these tests were slightly revised in the 1940's to account for the use of covered electrodes and these values were then used until the early 1970's. The introduction of new electrodes and stronger steels sparked further testing of fillet welds in the late 1960's. The allowable stresses were increased as a result of these tests and are still used by the American Institute of Steel Construction (AISC) for Allowable Stress Design (ASD) of fillet welds in shear. The weld strength expression in the Load and Resistance Factor Design Manual (LRFD,1986) has taken into account recent research in Canada and has been partially modeled after the Canadian Institute of Steel Construction (CISC) limit states design which was implemented in the 1970's.

Other research studies have been conducted which investigate the various other properties of fillet welds. From the 1940's thru the 1960's, this research concentrated on specific types of connections. Most of these tests were not concerned with the shear strength of the weld, but rather with the connection strength for a particular weld arrangement.

Recent research of the 1970's and 1980's has been directed towards establishing an ultimate strength design method for welded connections under combined shear and moment. Elastic design methods generally produce relatively high and variable factors of safety. The new methods are concerned with determining the strength of the connection based on the orientation of the weld to the load, since it is known that weld strength is a function of weld orientations.

In this chapter, several important issues relating to fillet welds will be reviewed. These topics include the development of code expressions for fillet weld shear strength, the effects of leg size, root penetration, and plate stress on weld strength, and the load-deformation response of fillet welds. Existing literature available on these topics will be presented and discussed.

2.2 Fillet Weld Shear Strength

This section will review the development of fillet weld shear strength and the factors which influence its strength. Parameters which will be discussed include the effects of weld leg size, weld profile, and root penetration as reported by previous research. An in-depth chronological development of current design practices for fillet weld shear strength is also provided.

2.2.1 Development of Fillet Weld Shear Strength

After World War I, commercial welding became increasingly popular in the United States for joining metals. The use of arc welding for structural building construction created the need for experimental tests to insure the safety of these welded connections. In 1928, the American Welding Society published a "Code for Fusion Welding and Gas Cutting in Building Construction." This code specified allowable stresses based upon a section through the weld throat for different loadings as follows:

Shear .... 11.3 ksi
Tension .... 13.0 ksi
Compression ..... 15.0 ksi

These stresses were based on minimal experimental data existing at the time. Because these data were scattered and could not be correlated well due to differing test situations, there was a need to perform additional tests. As a result, the Structural Steel Welding Committee of the American Bureau of Welding was formed by the American Welding Society in 1926. Since the Research Committee of the American Institute of Steel Construction was also considering similar weld testing, these committees decided to collaborate and work together in the study.

2.2.1.1 Structural Steel Welding Committee (1931)

The aims of this committee were threefold: to determine safe allowable stresses for the design of welds as applicable to different loadings and joints, to determine if welder qualification tests reflected the actual quality of the welder, and to investigate the scatter which could be expected in weld strength for specimens welded at different fabrication shops. As a result, several different types of specimens and specimen configurations were fabricated throughout the Midwest and Eastern United States. A total of 1395 main specimens for testing were fabricated, which included 169 sizes of welds in 55 different types of joints. In addition, 1098 welder qualification tests were conducted. The full details of this study are given in the Committee Report entitled "Report of Structural Steel Welding Committee" (1931).

There were several different types of fillet welded connections tested in this matrix. These included both longitudinal and transverse fillet welds used in both symmetric and unsymmetric connections. Furthermore, intermittent fillet weld configurations were tested to compare their strength to continuous welds. Figure 2.1

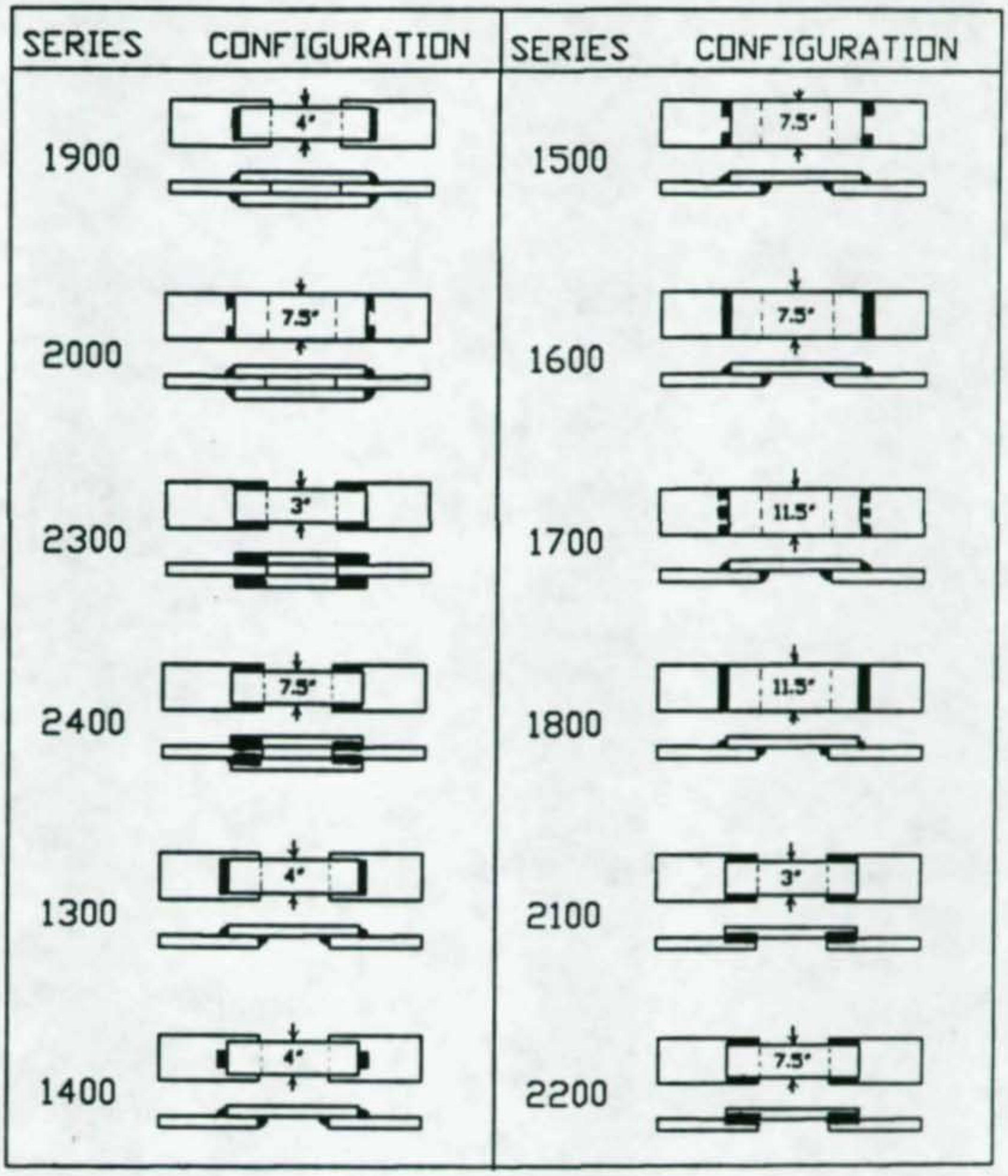


Figure 2.1 Specimen Configurations (from "Report of Structural Steel Welding Committee", 1931)

shows some of the fillet welded connections tested. All steel used for the specimens was ASTM A9. There were two types of welding rods used, bare wire arc welding rods (AWS class E-1-A or E-1-B) and gas welding rods. Weld coupon tests were conducted on both the arc welded and the gas welded electrodes. Qualification tests required the arc welded electrodes to average 45 ksi with no single coupon test falling below 40 ksi. No actual electrode strengths were given in the report because the committee was mainly concerned that welders only satisfy these minimum requirements.

Various weld dimensions were measured for each specimen. Both the horizontal and vertical legs as well as the throat thickness were measured with a set of weld gages. Minimum and maximum sizes were prescribed by the committee for the various fabricators who produced the specimens. No start-up or run-off tabs were used during the welding. Instead, an "effective length" of weld was used for analysis. The effective length of weld was the full length minus 1/4 inch. This accounts for 1/8 inch for start-up to full throat and also considering the last 1/4 inch being only half effective. The sizes of the welds ranged from 1/4 inch to 3/4 inch in increments of 1/8 inch.

The committee compared its results with those published in the American Welding Society fusion welding code as reported earlier. Since it was common to have a factor of safety of 3 1/3 for connections, the committee tabulated factors of safety for its tests in reference to the allowable stresses for welds reported by the welding code. These results were tabulated for the symmetrical and unsymmetrical connections. The safety factors reported by the committee are shown in Table 2.1.

These tests produced a factor of safety ranging from 3.01 to 4.70 based on an allowable stress of 11.3 ksi. The minimum factor of safety was 3.01 for the specimens reported in Table 2.1. (Additional specimens were tested with Tee type joints as well as with combined longitudinal and transverse fillet welds. The results of these tests have not been reproduced in Table 2.1) The committee felt that their factors of safety compared well with those given in the fusion welding code. Secondly, the eccentrically loaded specimens were considerably weaker than the symmetrical joints (up to 35%), but no suggestions for a decrease in allowable stress were given. Thirdly, the end fillet welds averaged 35% stronger than the side fillet welds, but they also exhibited more scatter. It was also noted that the larger size welds were slightly weaker but not enough to change the allowable stresses (This weld size effect is discussed in Section 2.2.3). Finally, the intermittent fillet welds were as strong as continuous welds, when evaluated on a per inch of weld basis.

Table 2.1 Safety Factors (from "Report of Structural Steel Welding Committee", 1931)

SYMMETRICAL			
LOCATION OF WELDS	SERIES	FACTOR OF SAFETY BASED ON STRESS OF 11.3 KIPS/SQ. INCH THROAT	
		AVERAGE	MINIMUM
END	1900	4.63	2.92
	2000	4.70	3.18
SIDE	2300	3.62	2.84
	2400	3.28	2.84

NON-SYMMETRICAL			
LOCATION OF WELDS	SERIES	FACTOR OF SAFETY BASED ON STRESS OF 11.3 KIPS/SQ. INCH THROAT	
		AVERAGE	MINIMUM
END	1300	4.09	3.54
	1400	4.36	3.98
	1500	4.55	3.10
	1600	4.06	3.18
	1700	4.48	3.72
	1800	3.81	3.02
SIDE	2100	3.30	2.48
	2200	3.01	2.39

The large database of this test matrix gave additional confidence to the allowable stress values already prescribed for fillet welds. As was mentioned earlier, the weld electrodes used in these tests were bare wire. However, in the early 1930's covered electrodes, which introduced shielding gases, became popular. As a result, additional tests were conducted to determine if the use of covered electrodes produced stronger welds. Important test results were published by Godfrey and Mount (1940) on covered electrodes which caused future revisions in weld allowable stresses.

2.2.1.2 Godfrey and Mount (1940)

The test results presented by Godrey and Mount (1940) prompted the American Welding Society to increase the allowable stresses for welds in shear through the effective throat from 11.3 ksi to 13.6 ksi. The specimen arrangements for this test matrix are shown in Figure 2.2. Grade 10 covered wire electrodes were used on all specimens. Weld metal coupons made from the covered wire electrodes exhibited tensile strengths between 66.7 and 80 ksi. This was significantly higher than the ASTM required tensile strength of 60 ksi.

The weld sizes tested were 1/4 inch, 1/2 inch, and 3/4 inch fillet welds. No information is given on either weld

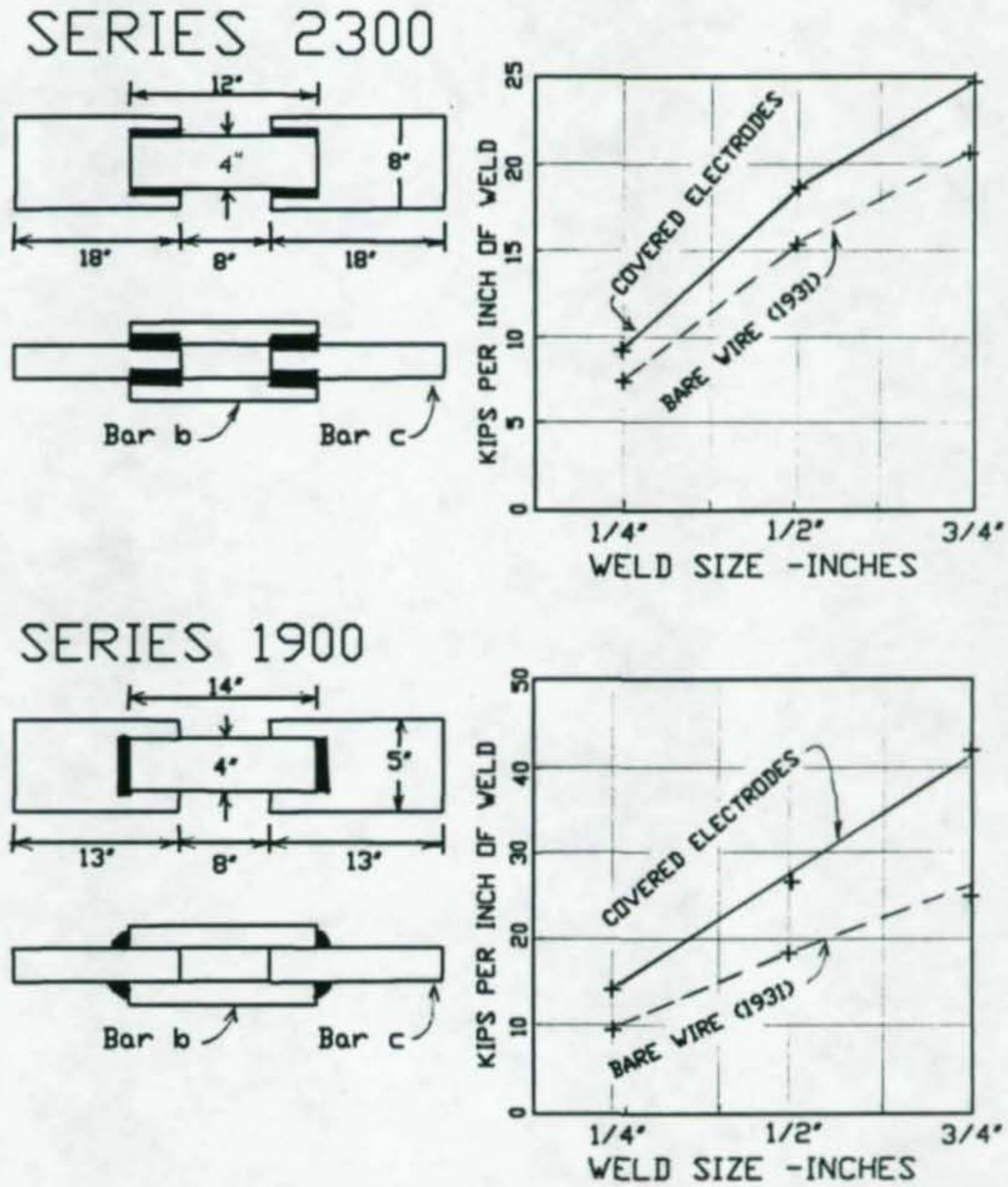


Figure 2.2 Specimen Configurations (from Godfrey and Mount, 1940)

size or throat measurement. Both longitudinal and transverse welds were tested. The strengths of two series of tests are also shown in Figure 2.2. The symmetrical transverse welded joints were approximately 1.5 times as strong as the longitudinal welded joints. As a result of the increased weld metal tensile strength, and the corresponding increase in fillet weld shear strength the allowable stress for fillet welds in shear was increased from 11.3 ksi to 13.6 ksi.

In 1963 the AISC 6th Edition ASD Code revised allowable stresses for welds in compression and tension to meet base metal strengths, but the shear strength allowable stress was kept constant at 13.6 ksi for E60xx electrodes. However, the code permitted an allowable stress of 15.8 ksi for E70xx and higher tensile strength electrodes. This value was simply obtained by multiplying 13.6 ksi times 70/60.

2.2.1.3 Higgins and Preece (1969)

Due to new developments in steels and welding electrodes, further research was conducted by Higgins and Preece (1968,1969) to account for steels with strengths up to 100 ksi and corresponding high strength electrodes. The main objectives of this research were to determine the effect of base metal dilution with weld metal and to determine the effect of using stronger electrodes for fillet welds. Additional variables that were evaluated include the root penetration profile, the failure surface orientation, and a statistical study into the actual fillet weld size versus the specified size.

The actual experimental investigation was conducted by F.R. Preece of Testing Engineers, Inc., for a joint AWS-AISC Task Group. The specimens were fabricated in two shops, one from the Eastern United States and one from the Western United States. A total of 132 specimens were fabricated. The tests included longitudinal and transverse fillet welds with varying base metal strength, electrode strength, and weld sizes. Figure 2.3 shows the specimen dimensions used in this study. The weld sizes used were 1/4", 3/8", and 1/2" for the longitudinal welds and only 1/4" for the transverse welds. AWS class E60xx, E70xx, E90xx, and E110xx electrodes were used for placement of the SMAW welds. Base metal was ASTM A-36, A-441, and A-514. The matrix of specimens tested is shown in Table 2.2.

The weld lengths were measured to the nearest 1/100 of an inch with a machinists scale. All welds were full length throughout because, as shown in Figure 2.3, saw cuts near the ends of the splice plates isolated the test weld. The longitudinal specimens were saw cut across a section so that four cross sections of the weld could be measured. For each of these four welds, both the horizontal and vertical leg sizes were measured, as well as the theoretical throat, and

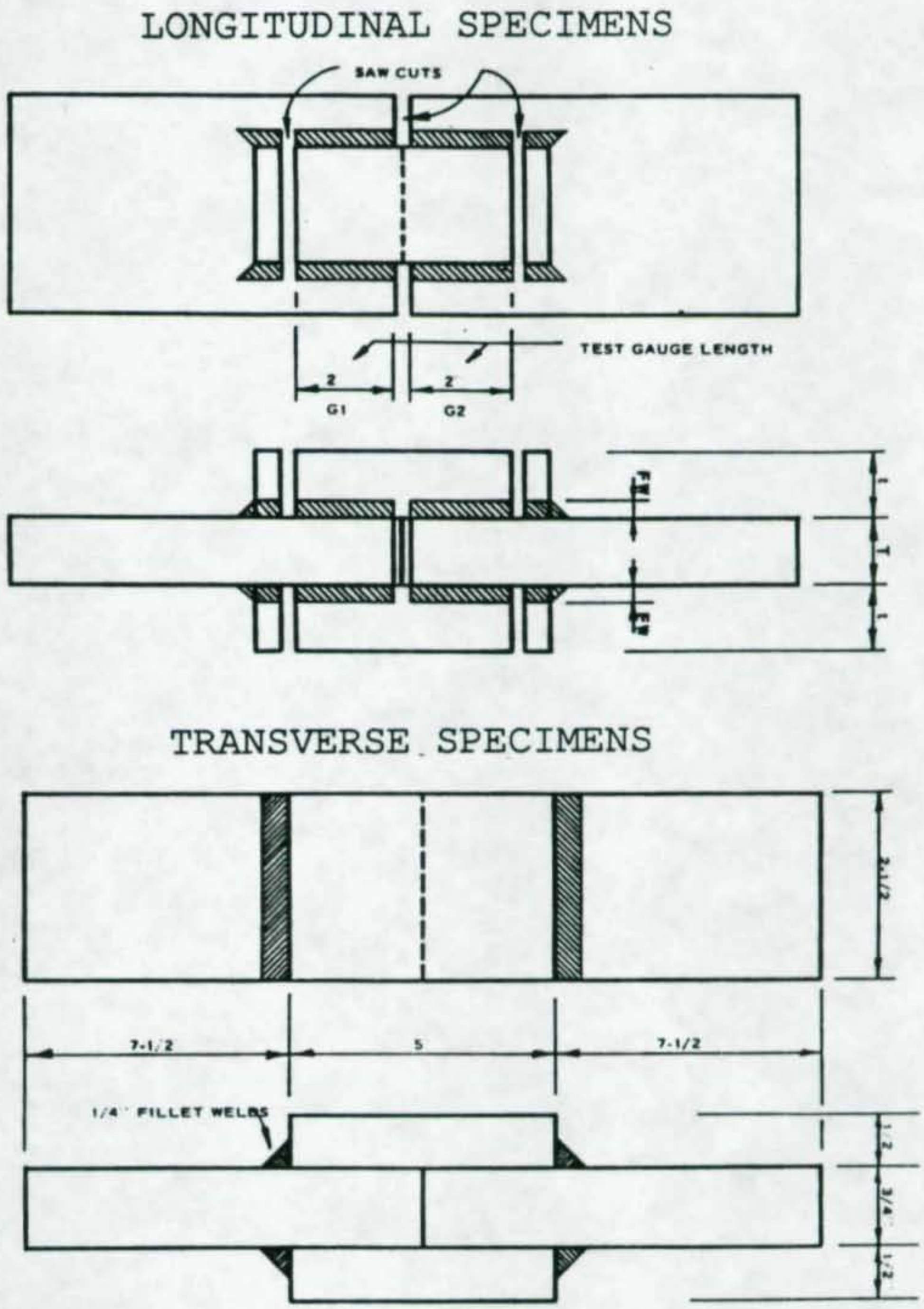


Figure 2.3 Specimen Configurations (from Preece and Testing Engineers, Inc., 1968)

Table 2.2 Test Matrix of Fillet Weld Specimens (from Preece and Testing Engineers, Inc., 1968)

	ELECTRODE	E-6012		E-7018			E-9018			E-11018		
FABRICATOR	BASE METAL / WELD SIZE	1/4"	3/8"	1/4"	3/8"	1/2"	1/4"	3/8"	1/2"	1/4"	3/8"	1/2"
WEST COAST (W)	A-36	W362A	W363A	W372A	W373A	W374A	W392A					
		W362B	W363B	W372B	W373B	W374B	W392B	NOTE: NO TEST REQUIRED				
		W362C	W363C	W372C	W373C	W374C	W392C					
	A-441			W472A	W473A	W474A	W492A	W493A	W494A	W412A		
				W472B	W473B	W474B	W492B	W493B	W494B	W412B		
				W472C	W473C	W474C	W492C	W493C	W494C	W412C		
	A-514			W572A	W573A	W574A	W592A	W593A	W594A	W512A	W513A	W514A
				W572B	W573B	W574B	W592B	W593B	W594B	W512B	W513B	W514B
				W572C	W573C	W574C	W592C	W593C	W594C	W512C	W513C	W514C
EAST COAST (E)	A-36											
	A-441		ALL IDENTIFICATION NUMBERS ARE THE SAME AS ABOVE EXCEPT THE FABRICATOR IDENTIFICATION. 'W' IS TO BE REPLACED BY 'E'									
	A-514											

NOTE – ONLY 1 SPECIMEN REQUIRED OF EACH IDENTIFICATION NUMBER

IDENTIFICATION NUMBER KEY

1ST DIGIT – FABRICATOR IDENTIFICATION – "W" OR "E"
2ND DIGIT – BASE METAL IDENTIFICATION – 3 = A-36, 4 = A-441, 5 = A-514
3RD DIGIT – ELECTRODE TYPE – 7 = E70, 9 = E90, 1 = E110
4TH DIGIT – WELD SIZE – 2 = 1/4", 3 = 3/8", 4 = 1/2
5TH DIGIT – SEQUENCE OF SAMPLE PREPARATION FOR EACH TYPE SPECIMEN – A, B & C

also the shortest distance along a 45 degree angle from the weld to the center plate. Additionally, the actual failure throat "W" was measured. Figure 2.4 shows the measurements taken for the longitudinal and transverse welds. Each of these sections was acid etched with a 20% solution of ammonium persulphate to observe root penetration. The exact same measurements were taken on the transverse specimens except that eight unfailed sections of the welds were examined. In all of the weld size measurements, the dimensions were taken on unstressed sections of the weld.

The failure stresses on the welds were computed for the theoretical throat "T", the least distance "P", and the actual measured failure throat "W" as shown in Figure 2.4. The stresses computed using the measured failure width "W" were reported as being the most consistent when comparing East and West coast fabricators. Once again, factors of safety were computed to determine if the current allowable stresses for welds in shear of 13.6 ksi for E60xx electrodes and 15.8 ksi for E70xx electrodes could be modified. These factors of safety were computed by dividing the actual failure load with the weld length to get a strength per inch of weld. These values were then compared with the code allowable stresses based on the design theoretical throat. The factors of safety reported by the AWS-AISC Fillet Weld Study (1968) are reproduced in Tables 2.3 and 2.4.

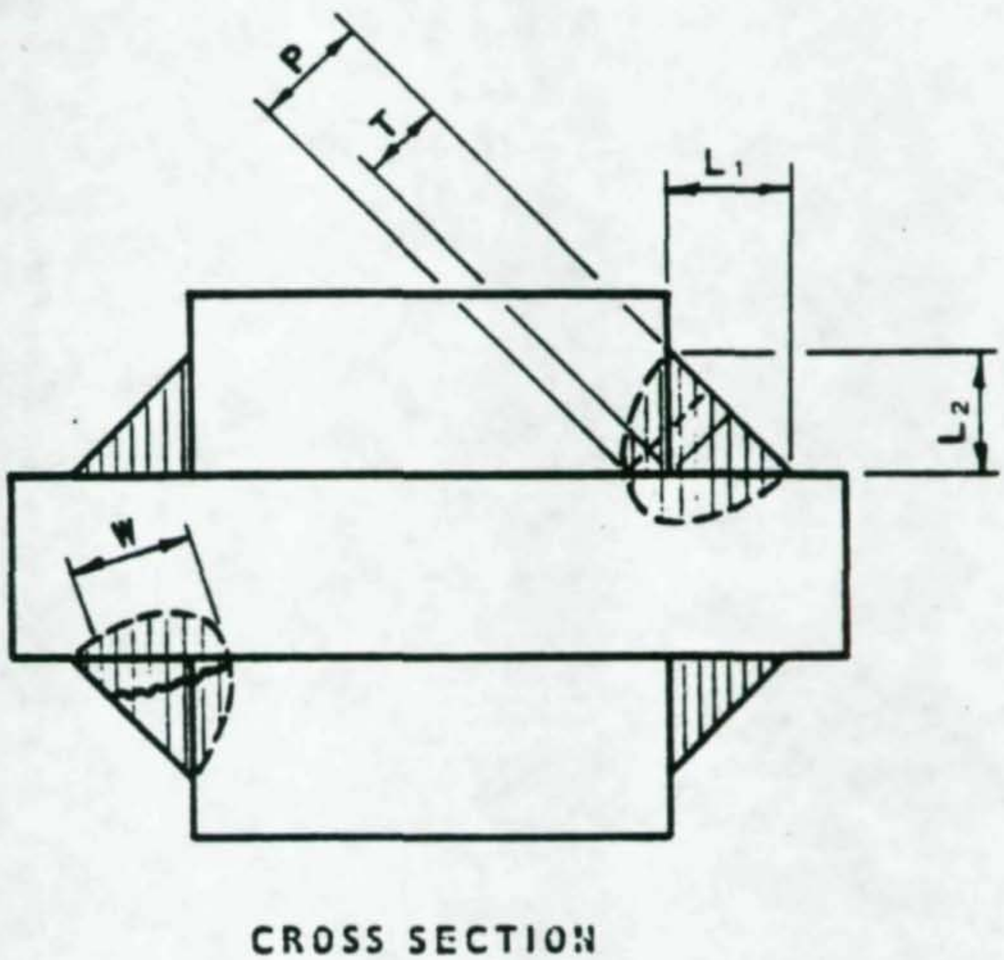


Figure 2.4 Cross Section Measurements (from Preece and Testing Engineers, Inc., 1968)

Table 2.3 Safety Factors for Longitudinal Specimens (from Preece and Testing Engineers Inc.,1968)

Factors of Safety Longitudinal Fillet Welds

Based on Existing Code Values 13.6 k/sq. in. for E60
15.8 k/sq. in. for all others

Material Combination Base Material & Electrodes		1/4" Fillets A	B	3/8" Fillets A	B	1/2" Fillets A	B
A36	E60	4.8	4.3	4.4	4.3	---	---
	E70	5.3	5.1	4.6	4.4	4.2	4.2
A441	E70	5.3	5.0	4.8	4.4	4.1	3.8
	E90	5.5	4.7	5.2	5.0	4.5	4.3
A514	E70	5.2	4.6	4.9	4.5	4.2	3.8
	E90	6.1	5.3	5.5	5.1	5.0	4.4
	E110	6.6	5.6	6.1	5.3	5.7	5.1

Notes:

Column A is based on the Average ultimate strength (in kips per lin. inch) for 6 test specimens.

Column B is based on the Minimum ultimate strength (in kips per lin. inch) for 6 test specimens.

Factor of Safety is determined by dividing the ultimate shear strength (in kips/lin.) inch by the allowable shear value (in kips per lin. inch).

Table 2.4 Safety Factors for Transverse Specimens (from Preece and Testing Engineers Inc.,1968)

Factors of Safety Transverse Fillet Welds

Based on Existing Code Values - 15.8 k/sq. in.

Material Combination Base Material & Electrode		1/4" Fillets Average A	Minimum B
A36	E70	8.2	7.6
A441	E70	9.0	8.5
A514	E70	8.5	7.2
A441	E90	8.4	6.8
A514	E90	9.6	8.6
A514	E110	11.5	9.7

As a result of these test results, some important tentative conclusions were reached from this study. These conclusions were reported by F.R.Preece from Testing Engineers, Inc. as follows:

> 1. "Factors of safety for fillet welds appear to decrease with increasing weld size and do not increase in direct proportion to an increase in specified tensile strength of the materials used.
>
> 2. Fillet weld size (strength) appears to be more closely related to the weld metal's ability to accomodate large shearing and bending strains rather than its being related to an arbitrary shear stress calculated on theoretical throat dimensions.
>
> 3. The larger the size of manual fillet welds, the closer the average measured size is to the specified size and the greater tendency there is for undersize welds.
>
> 4. Nevertheless, there appears to be ample room in the present factor of safety for a substantial increase in allowable stresses for fillet welds and to include the new high strength steels and electrodes now available, provided:
>
> a. Adequate controls are exercised over dimension profile shape and other quality requirements.
>
> b. Proper identification of base metals and electrodes is maintained during fabrication.
>
> 5. It is apparent that if higher allowable stresses are permitted for fillet welds, smaller weld sizes would result, and size probably would be governed by the present requirements for minimum weld size as related to thickness of material used. Additional research is needed therefore, to establish a more rational basis for specifying this relationship. The need for such research, however, should not affect present

deliberations on increasing allowable stresses."

As a result of these tests, Higgins and Preece (1969) suggested that fillet weld allowable stresses should be a function of the tensile strength of the electrode used. They were able to correlate their factors of safety with previous results of Godfrey and Mount (1940) as well as the Structural Steel Welding Committee (1931) by using an allowable stress of 0.3 times the electrode tensile strength. As a result of these tests, AISC changed the allowable stress for fillet welds in shear to 0.3 times the electode tensile strength. This is still the method used today for allowable stress design of fillet welds within the United States.

2.2.1.4 Load and Resistance Factor Design

The AISC Load and Resistance Factor Design Specification (LRFD, 1986) departs from allowable stress design in that an ultimate resistance, in units of force, is calculated for fillet welds in shear. The factored resistance for a fillet weld in shear is given as:

$$\phi R_n = \phi (0.6\ Fexx) A_w$$

where ϕ= resistance factor for material imperfections, the importance of the member under consideration, and previous experience. For fillet welds = 0.75

Fexx= ultimate tensile strength of the electrode

A_W= the effective area of the weld

The effective area of the weld, A_W, is taken as the length of the weld times the effective throat thickness. The 0.6 Fexx factor is the result of earlier testing results which have been interpreted conservatively. It is also based on the distortion energy criterion which describes the condition of plastic flow and also the Von Mises yield criterion for shear. An in depth explanation of the present LRFD design method for connectors is given in Fisher, et al (1978). In order to compare LRFD and ASD design requirements, the LRFD equation can be converted to a stress on the effective area of the weld. This stress would be expressed as:

$$\phi(0.6 \text{ Fexx}), \quad \text{with } \phi = 0.75$$
$$= 0.45 \text{ Fexx}$$

This expression cannot be directly compared with the AISC ASD Specification because the LRFD Specification incorporates load factors which are not considered in allowable stress design. Different load factor combinations for different loading situations cause the factor of safety to be variable. For simple live plus dead loading, the load factor for dead load is 1.2 and the factor for live load is 1.6. Using an average load factor of 1.5 and dividing 0.45 Fexx by 1.5, produces an allowable stress of 0.30 Fexx.

Therefore, the LRFD equation gives a similar weld design strength to allowable stress design. It must be remembered that a direct comparison to the ASD Specification would require knowledge of the loading condition for each design situation.

The LRFD design equation for fillet welds has also been based on the recent research work of Kulak, et al (1971, 1972, 1974, 1984) in Canada from which the Canadian Limit States Design of Steel Structures Specification (1989) was developed. This specification defines fillet weld strength as:

$$V_r=\phi_w(0.67\ X_u)A_w$$

where X_u= ultimate tensile strength of the weld metal

A_w= effective area of the weld

ϕ_w= resistance factor (= 0.67 for weld metal)

The 0.67 X_u factor relates weld metal shear strength to electrode ultimate strength. Multiplying 0.67 x ϕ_w (=0.67) gives *0.4489* which is approximately equal to *0.45. Thus,* the LRFD factor of 0.75 x 0.60 = 0.45 is the same essentially as the Canadian limit states design. However, the Canadian load factors used in the 1989 Limit States Design Specification are slightly different than the LRFD Specification load factors.

2.2.1.5 Early Developments in Great Britain

The Welding Panel of the Steel Structures Research Committee organized a series of longitudinal and transverse fillet weld tests during the 1930's. These specimens were welded in the horizontal, vertical, and overhead positions. The objective of this study was to examine the strength and reliability of fillet welds made according to common fabrication practice at the time in Great Britain. An attempt was made to determine whether the skill of the welder or the type of electrode used was more critical for the strength of the joint. No qualification tests were required of welders in England during the 1930's so it was thought important to determine how the skill of the welder related to the weld strength. The full report of this committee is contained in the "Report of the Welding Panel of the Steel Structures Research Committee" (1938). There are four major parts to this report:

A. "Statistical examination of the strength of welded joints.
B. Investigation of non-destructive methods of testing welds.
C. Research on the fatigue resistance of welded joints.
D. Survey of existing published information on the design of welded joints."

A sketch of the experimental test specimens utilized for the investigation of the static strength of fillet welds is shown in Figure 2.5. These specimens were fabricated by 61

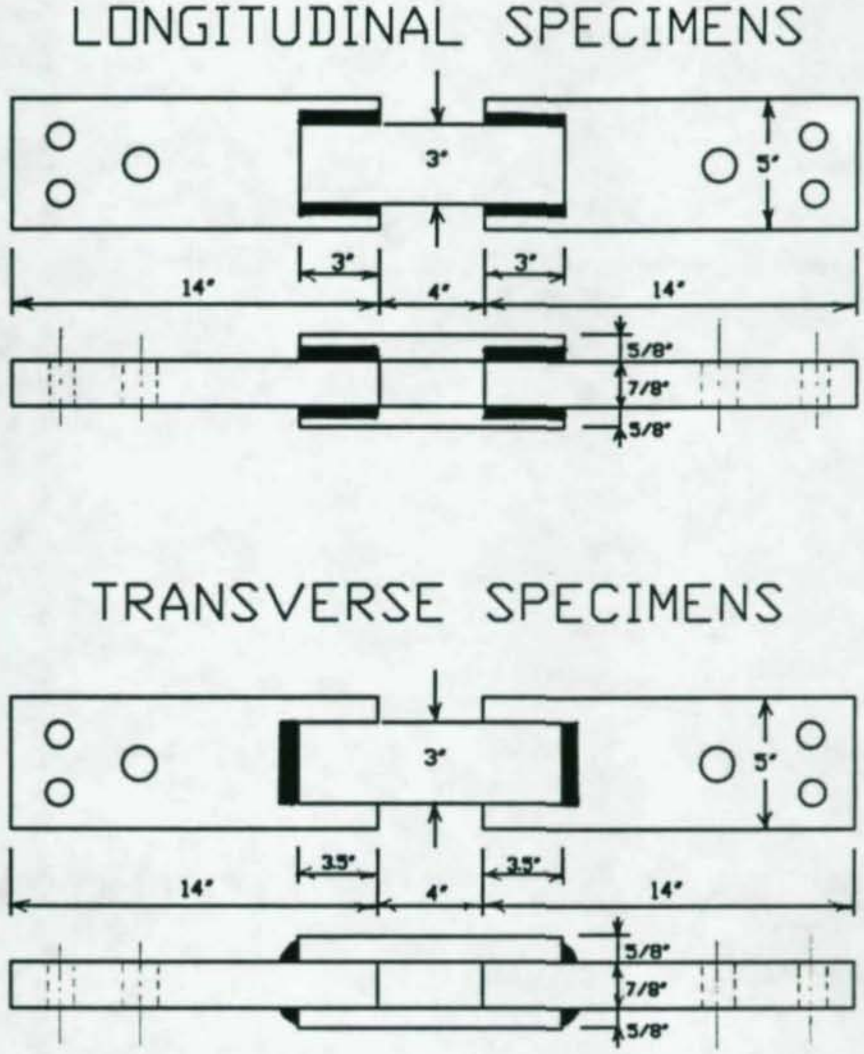


Figure 2.5 Specimen Configurations (from "Report of the Welding Panel of the Steel Structures Research Committee", 1938)

firms throughout Great Britain in the early part of 1935 with representative electrodes of current practice. No specific requirements were put on the electrodes, but from the analysis of the weld metal coupon tests, they were divided up into two classes: Grade A and non-Grade A electrodes. Grade A electrodes had a minimum tensile strength of 62.7 ksi (28 British tons per square inch) and 20% minimum elongation; the non-Grade A electrodes were any electrodes whose properties fell below these minimums.

A total of 423 transverse and 426 longitudinal specimens were fabricated. No leg sizes are reported but actual throat depths are given as measured by a set of fillet weld gages. All specimens appear to be approximately 1/4 inch leg sizes. It was also noted that the specimens welded vertically were not as strong as the others, probably due to welder inexperience with this welding position. The average weld strengths for all of the specimens are given in Table 2.5. Based on the the results of the static tests, the following observations were made:

A. As has been reported by other researchers, the transverse fillet welds were stronger than the longitudinal specimens by a factor of approximately 1.4. Also, the transverse specimen strengths exhibited more scatter.

B. For all fillet weld specimens grouped as a whole, the quality of the electrode material influenced the strength more than the skill of the welder.

Table 2.5 Weld Strengths (from "Report of the Welding Panel of the Steel Structures Research Committee", 1938)

MAXIMUM LOAD PER INCH OF WELD (kips/inch)						
TYPE OF WELD	WELDING POSITION	NO. OF TESTS	LOWEST VALUE	HIGHEST VALUE	MEAN VALUE	STANDARD DEV.
END	HORIZONTAL	187	5.53	20.88	14.04	2.60
	VERTICAL	123	3.16	18.23	11.42	3.05
	OVERHEAD	113	4.73	20.70	12.79	2.96
SIDE	HORIZONTAL	189	2.15	12.45	9.50	1.46
	VERTICAL	123	3.83	13.31	9.18	1.77
	OVERHEAD	114	5.06	14.96	9.30	1.70
MAXIMUM WELD STRESS (ksi)						
TYPE OF WELD	WELDING POSITION	NO. OF TESTS	LOWEST VALUE	HIGHEST VALUE	MEAN VALUE	STANDARD DEV.
END	HORIZONTAL	187	26.7	114.2	74.6	15.0
	VERTICAL	123	15.5	101.2	60.9	17.7
	OVERHEAD	113	30.7	145.4	72.1	17.9
SIDE	HORIZONTAL	189	11.4	69.7	48.8	7.2
	VERTICAL	123	19.3	73.7	47.7	10.1
	OVERHEAD	114	22.0	77.5	51.1	10.3

C. For specimens welded with Grade A electrodes, the workmanship of the welder was more important. The tests with Grade A electrodes also showed less scatter and had very few specimens with low strength.

D. Variations in the size of fillet welds over their length are relatively unimportant in comparison with the other factors controlling the strength of fillet welds.

Additional research was conducted by Gardner (Jan.,1939) to determine the strength of fillet welds. A total of 43 longitudinal and 29 transverse specimens were prepared according to the configurations shown in Figure 2.6. One end of the specimen was a test end while the other end was an anchor end with larger welds to insure failure in the test end. The welding electrodes used were heavy coated electrodes with a tensile strength of 62.7 to 67.2 ksi (28-30 Brit.tons per square inch) and 30-35% elongation, as determined from a series of weld metal coupon tests. The weld leg sizes ranged from 1/4 inch to 3/4 inch. These leg sizes along with the average throat thickness were reported to be measured carefully, but no specific details of the measurement were given. Stresses on both the miter throat (theoretical throat based on leg size) and the gross throat (actual throat) at failure are indicated in Figure 2.6.

At the time of Gardner's tests, Great Britain allowed separate design of transverse and longitudinal fillet welds. In fact, Gardner (Jan., 1939) reported that only the United States, Germany, and Poland were using the same allowable

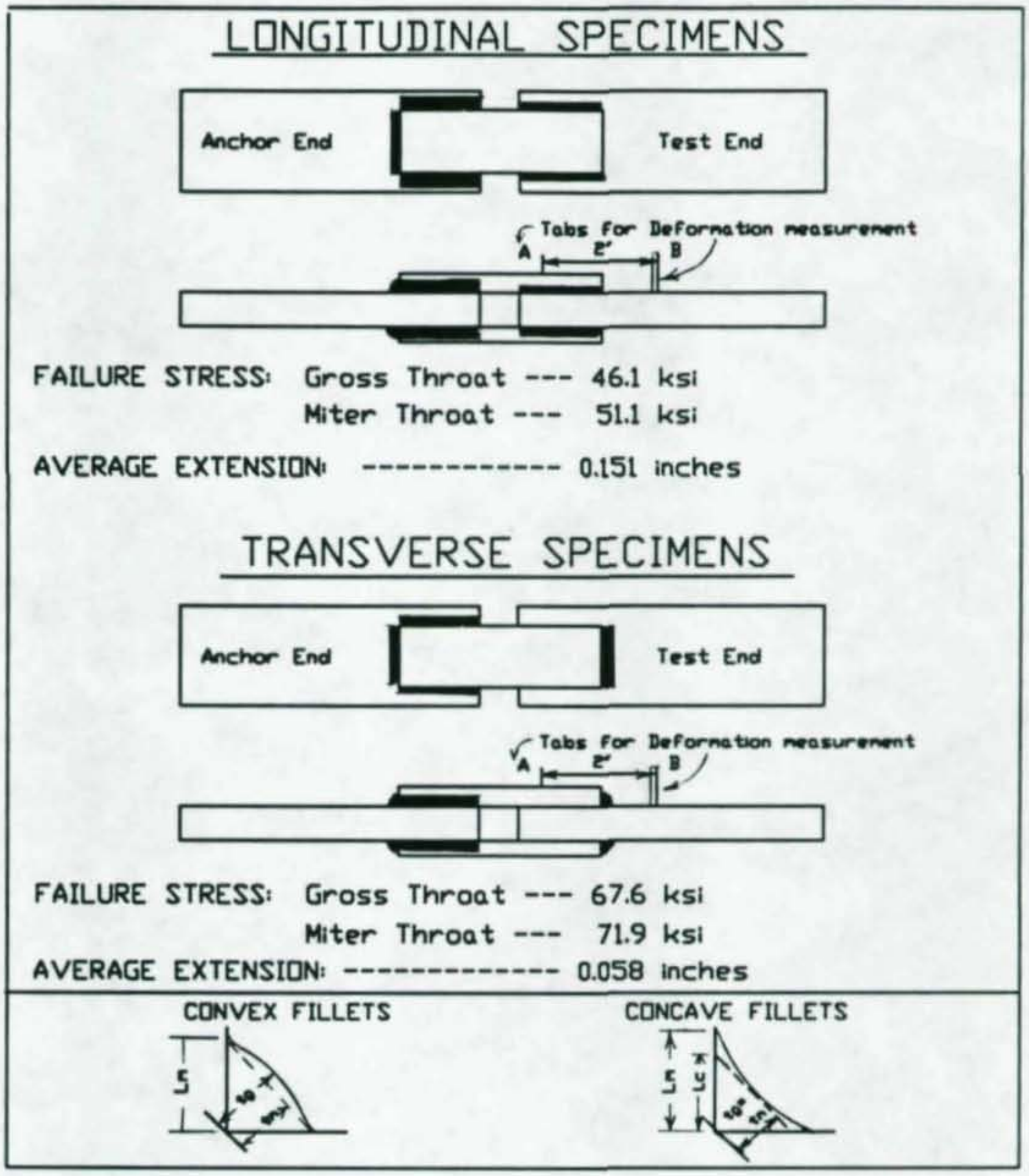


Figure 2.6 Specimen Configurations (from Gardner, 1939)

stresses for both conditions. Gardner's tests confirmed that the stresses used in Great Britain for longitudinal and transverse welds were reasonable. The stresses used at that time were 60.5 ksi (27 Br.tons per square inch) for transverse fillet welds and 40.3 ksi (18 Br.tons per square inch) for longitudinal fillet welds. This provision allowed for a 50% strength increase when using transverse welds.

2.2.1.6 Spraragen and Claussen (1942)

Spraragen and Claussen published an extensive review of existing literature on fillet welds in 1942 in which all of the relevant literature concerning the static strength of fillet welds from 1932 to 1940 was discussed. Since the results from the U.S. Structural Steel Welding Committee were published in 1931, this data was not discussed by Spraragen. However, an excellent review of the work done in Great Britain by the Steel Structures Research Committee as well as by Gardner was included. Furthermore, many other smaller experimental programs were also discussed. An extensive bibliography was also provided.

2.2.1.7 Research During the 1970's and 1980's

Professor Geoffrey Kulak of the University of Alberta has conducted several series of tests on fillet welds beginning in the early 1970's in Canada. The main emphasis of these tests was to determine fillet weld strength as a function of the loading angle to the weld. The results of these tests were then used to predict the ultimate strength of an eccentrically loaded welded connection using the instantaneous center of rotation method. This method is similar to that which had been developed for bolts, except the design procedure takes into account the deformation response of the weld as a function of the loading angle. (The topic of load-deformation response of welds is discussed in Section 2.3). Kulak's investigation of fillet weld strength also involved the testing of fillet weld shear coupons similar to those of previous researchers. Therefore, these tests provide additional data which are informative because of the use of newer electrodes and steels which have replaced earlier materials. A brief summary of each of these investigations is provided.

Butler and Kulak (1971) conducted a series of coupon tests to examine the influence of weld inclination, relative to the applied load, on the load-deformation response. A total of 23 test specimens were fabricated using 1/4 inch (E60xx) fillet welds placed at inclinations of 0°.30°, 60°, or

90° to the longitudinal (loading direction) axis. The steel plate used was CSA G40.12 with a minimum yield stress of 44 ksi and tensile strength of 62 ksi. No measured leg sizes or throat sizes are reported. However, it is stated that all welds were made as uniform as possible by using the same welder for all the specimens. The specimen configuration as well as the mean strengths are given in Figure 2.7. Butler and Kulak's results showed that the transverse welds were about 44% stronger than longitudinal welds but had only one quarter of the deformation capacity. Results for the specimens at angles of 30° and 60° fell in between those for the transverse and longitudinal specimens.

Butler, Pal, and Kulak (1972) used the results from Butler and Kulak's (1971) coupon tests to develop the instantaneous center of rotation ultimate strength design for eccentrically loaded fillet welds. This design used the load-deformation response from the coupon tests to determine the strength of fillet welds under combined shear and twisting moment. Full size connections using framing angles were tested. Since no additional coupon tests were performed, this paper does not present any new information on fillet weld shear strength.

Dawe and Kulak (1974) continued the study of eccentrically loaded fillet welds to investigate welds which are not free to rotate in the compression zone. Additional

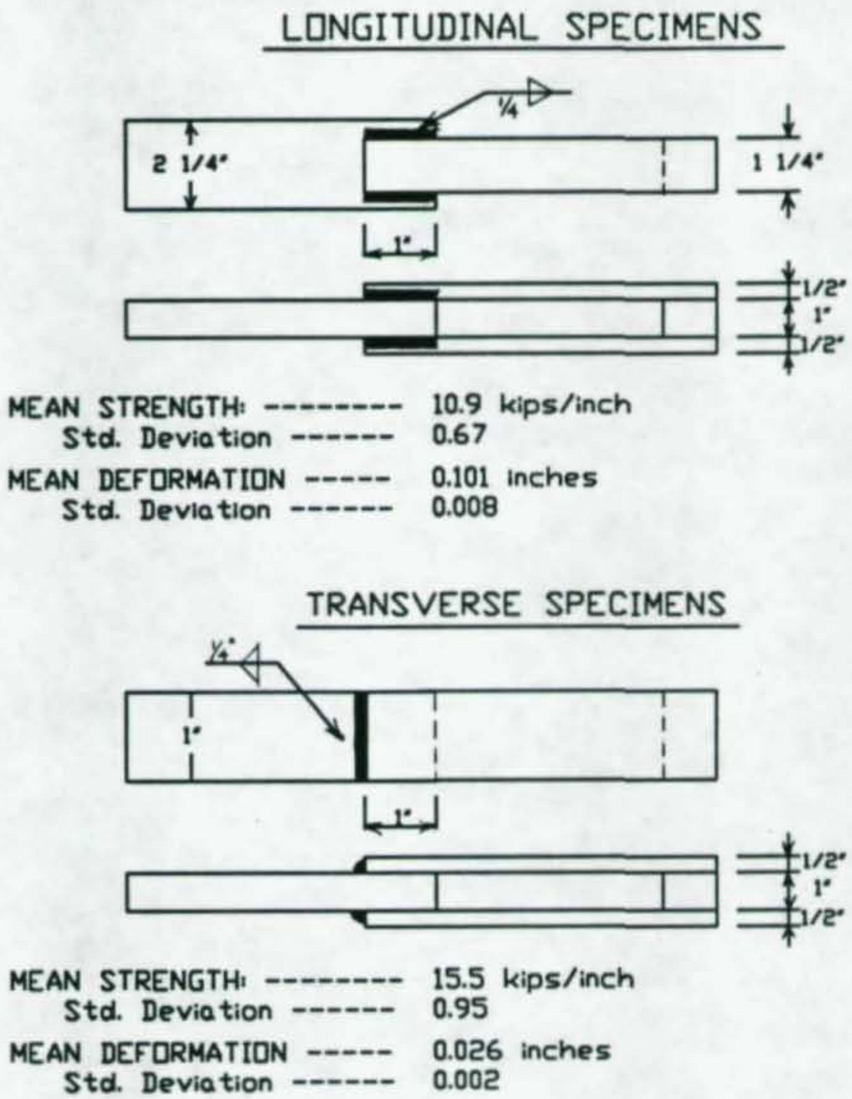


Figure 2.7 Specimen Configurations (from Butler and Kulak, 1971)

weld coupon tests were conducted with 1/4 inch longitudinal fillet welds, made with AWS E60xx electrodes, used to attach the ASTM A36 steel test plates. Once again, no mention is made of any weld size measurements, but all specimens were welded by the same welder. Three separate series, with five weld coupons in each series, for a total of fifteen coupons were tested. The average load deformation response was then reported for each of the three series. No coupon dimensions are reported. The results, reproduced from Dawe and Kulak (1974) are shown in Figure 2.8. The strengths of the longitudinal welds appear to range from about 9 kips/inch to 10.5 kips/inch.

Further tests were conducted by Kulak and Timler (1984) to determine the fillet weld strength for a connection where the welds are arranged horizontally. Five weld coupon specimens with 1/4 inch longitudinal fillet welds, similar in configuration to those tested by Butler and Kulak (1971), were fabricated with E480 (70 ksi) electrodes and tested to failure. Leg sizes were measured from plaster casts of the weld. One inch thick steel was used. The results of these five tests, reproduced from Kulak and Timler (1984), are shown in Table 2.6.

As a result of Kulak's work, the Canadian Institute of Steel Construction (CISC) has expressed the basic fillet weld strength as :

$$V_r = \phi_w (0.67 X_u) A_w$$

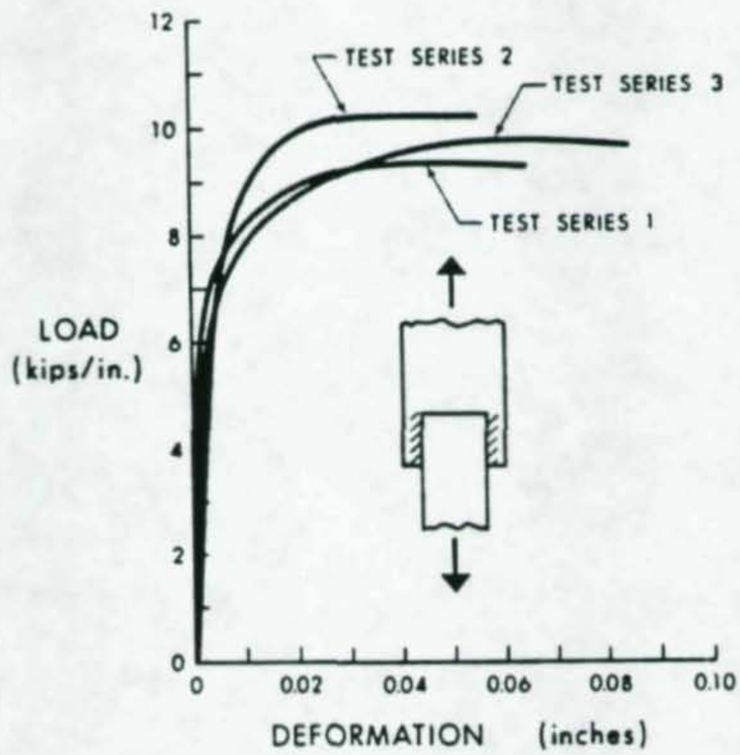


Figure 2.8 Load-Deformation Behavior (from Dawe and Kulak, 1974)

Table 2.6 Longitudinal Weld Coupon Strengths (from Kulak and Timler, 1984)

FILLET WELD COUPON TESTS				
COUPON NO.	WELD LENGTH (inches)	AVERAGE LEG SIZE (inches)	ULTIMATE STRENGTH (kips/inch)	ULTIMATE DEFORM. (inches)
1	5.08	0.33	10.40	0.076
2	4.48	0.35	9.66	0.151
3	4.55	0.34	9.54	0.123
4	4.76	0.35	9.37	0.111
5	4.23	0.34	9.83	N.A.

NOTES

A. Ultimate strengths are based on 1/4" leg size

B. The mean ultimate strength is .... 9.77 kips/inch

C. The mean ultimate deformation is... 0.115 inches

The explanation of this equation has already been given in Section 2.2.1.4. This equation is based on tests of longitudinal fillet welds and does not incorporate the additional strength of the weld for different orientations.

2.2.2 The Effect of Weld Size

There has been a great deal of discussion, dating back to the 1930's about the influence of weld size on the strength of fillet welds. The test results in "Report of Structural Steel Welding Committee" (1931) demonstrate a slight influence of weld size, but it was not significant enough to change the allowable stresses. Weld leg sizes in 1/8 inch increments from 1/4 inch to 3/4 inch welds were tested. The average strength of these welds as a percent of the overall strength average was reported, with the 5/8" and 3/4" welds having the lowest failure stresses at 95% of the overall average. The committee noted that for welds made with the same number of passes, the larger weld was not as strong per square inch of effective area. The results comparing stresses for each leg size are shown in Table 2.7.

Gardner (Jan.,1939) reports that both Poland and Italy used lower allowable stresses for larger welds at the time of his study. Gardner tested fillet welds ranging from 1/4 inch to 3/4 inch and determined that the weld size did not have any effect on the gross throat stress of the weld at

Table 2.7 Effect of Leg Size (from "Report of Structural Steel Welding Committee", 1931)

WELD STRENGTH -- KIPS PER SQ. IN. THROAT						
SERIES	SIZE OF WELD -- INCHES					AVERAGE
	1/4	3/8	1/2	5/8	3/4	
1000	41.7	36.2	39.0	36.8	35.6	37.9
1300	46.3	44.5	41.7	40.5	39.6	42.5
1900	52.5	51.0	51.0	45.0	47.0	49.3
2100	42.8	34.6	38.6	36.6	35.3	37.6
2300	44.6	37.8	44.3	39.1	39.6	41.1

STRENGTH OF EACH SIZE AS % OF AVERAGE						
SERIES	SIZE OF WELD -- INCHES					
	1/4	3/8	1/2	5/8	3/4	
1000	110	95	103	97	94	
1300	109	105	98	95	93	
1900	106	104	104	92	96	
2100	114	92	103	97	94	
2300	109	92	108	95	96	
GRAND AVG.	110	97	103	95	95	

failure. In this study, Gardner discusses the research of Hohn (1930) and Bryla (1934) who had reported a decrease in weld strength with increasing size. Upon review of Hohn's results, Gardner felt the evidence was insufficient to determine if the weld strength decreased with leg size. The reason for this is that Hohn based his strength on the fillet weld leg sizes. Thus, the effect of weld profile was not considered. Gardner states that weld convexity could have increased the throat size for the smaller weld sizes, which was not considered in the strength analysis. Since the larger size welds generally are not nearly as convex in profile, and may even be concave, it is hard to determine if there actually was any effect of weld size. In reviewing Bryla's investigation (1934), Gardner notes that the weld stress values obtained were based on the area of fracture of the fillet weld after the test. There was significant variance in the measured fracture throat and the theoretical throat. Therefore, Gardner did not feel there was sufficient evidence in Hohn and Bryla's investigations to claim that fillet weld strength decreases with size. Because Gardner actually measured the gross throat and still found no variation in throat stress, there was not a move to decrease fillet weld allowable stresses for larger size welds.

Spraragen (1942), in his review of fillet weld literature, discussed the influence of weld size. In his review, he stated that several investigators in addition to Hohn and Bryla have reported decreasing stress with weld size. However, many of these reports did not give details on how some of the data were measured. Spraragen states that the evidence showing fillet weld stress being independent of weld size is much more convincing.

Several other studies have also discussed variations in fillet weld stress for various sizes of welds. Godfrey and Mount (1940) show little decrease in stress for larger weld sizes in their pilot tests. F.R.Preece and Testing Engineers, Inc. (1968) reported a decrease in factors of safety for increasing weld size. (This statement is given in section 2.2.1.3., part 1.) Recent research by Kulak has utilized 1/4 inch weld coupons only, so no information about the effect of weld size can be extracted. Thus, there have been many different opinions about the effect of weld size on the strength of fillet welds since the 1930's.

2.2.3 The Effect of Root Penetration

There has been little discussion about the effect of root penetration on the strength of fillet welds. Gardner (April,1939) conducted a series of tests on longitudinal and transverse fillet welds to determine the effect of root penetration. Cut sections were polished and etched and then measurements taken to determine the amount of root penetration. In his investigation, Gardner reports that root penetration should not be less than 0.039 inches in both the horizontal and vertical directions or else weld strength may be compromised. Gardner goes on to discuss required electrode and weld sizes for single pass fillet welds which produce adequate penetration. There appears to be little increase in strength for penetrations larger than the minimum size Gardner states.

Persson (1970) conducted a series of tests on vertically welded fillet welds. He found that the depth of the fusion zone did not have any effect on the strength of the weld. Preece (1968) examined etched sections of welds for leg size measurements, but did not investigate the effect of the root penetration, except to note that many of the etched sections had little root penetration. Thus, there has been little published information on the effect of root penetration.

2.2.4 The Effect of Fabrication Gaps

Minimal literature concerning the effects of fabrication gaps on the strength of fillet welded connections was obtained. Current AWS Structural Welding Code Specifications (Section 3.3.1, 1990) require an increased weld leg size equal to the gap size for connections where the fabrication gap exceeds 1/16".

Alternately, the contractor may demonstrate that the required throat has been achieved. Also, gaps may not exceed 3/16" for fillet welded joints. No reference to previous literature has been given by AWS to validate these specification requirements.

2.2.5 The Effect of Plate Stress

There has been some discussion concerning the level of stress in connecting plates for experiments designed for weld failure. In general, most experimental studies have designed the connecting plates large enough to keep the stresses within the elastic range. "Real-world" connnections are more economically designed for a "balanced" condition where failure would simultaneously occur in both the connecting plates and the welds. In such a connection, yielding would occur in the plates at failure and could possibly cause a somewhat different behavior of the welds than expected. Therefore, it is important to understand the behavior of the connection when the plates yield.

In the "Report of Structural Steel Welding Committee" (1931) it was reported that by increasing plate size the failure load increased, for the same size weld. It was thought that the additional stiffness of the joint increased the strength. It is uncertain if the plates actually yielded, but it does give an indication that thicker plates increase the stiffness and, therefore, the strength of the connection.

In the literature review contained in the "Report of the Welding Panel of the Steel Structures Research Committee" (1938), Denaro reports that "local yielding in the parent metal adjacent to the welds has been shown to have an unfavourable effect on the strength of welds", which had been reported by Jezek (1933).

Gardner (Jan.,1939) investigated the influence of plate stress by designing some specimens to reach stresses as high as 67,000 psi in the connecting plates, while the other specimens were to have lower stresses, around 33,500 psi. Gardner, unlike other researchers, found no effect of plate stress on the maximum gross throat stresses in the fillet welds:

> "...it will be noted that the maximum gross throat stresses of both the 'end' and 'side' fillet welds do not appear to have been influenced by the variations in the plate stress intensities."

Spraragen and Claussen (1942) in their review of published literature found that Vandeperre and Joukoff reported that the maximum throat stress decreased when the stress in the connecting plates was increased, possibly because friction did not have as much as an effect.

The work of Kulak, et al (1971,1974,1984) was designed to insure failure in the welds with no mention of plate stresses given. The weld deformations, which were measured with dial gages, probably included some minimal plate deformation. If the plates would yield, considerably more plate deformation would be included in the dial gage readings. From the overall small deformations measured by the dial gages, it appears that the connecting plates were not yielding.

Recent tests by Miazga and Kennedy (1989) to determine the strength of fillet welds based on the weld orientation have been designed to prevent yielding of the connecting plates.

Thus, there are conflicting views on the effects of plate stress on fillet weld strength. Gardner's extensive test series found that plate stress had no effect on weld strength, but other researchers have reported a decrease in fillet weld strength with increasing plate stress. There are very few reports which investigate the effect of plate stress that could be found. Most previous research has tried to eliminate this variable, so test specimens have been designed to keep connecting plates within the elastic stress range. However, this variable remains important because balanced design procedures will usually produce a weld size and configuration such that the parent base metal will be yielding at incipient failure, and perhaps even controlling the failure.

2.3 Load-Deformation Response of Fillet Welds

Researchers dating back to the late 1930's have tried to analyze the load-deformation response of fillet welds. All of the studies have shown longitudinal welds to be much more ductile than transverse welds, but the studies also have shown a reduced strength for longitudinal welds. Early experiments tried to establish qualitative load-deformation behavior because measurement techniques were not refined enough to isolate the weld deformation alone. Recent research during the 1970's and 1980's has been able to achieve a more quantitative understanding of load-deformation behavior. Many tests have been designed to specifically analyze this load-deformation response to predict the ultimate strength of eccentric fillet welded connections.

Gardner (Jan.,1939) qualitatively measured the load-deformation response of both transverse and longitudinal fillet welds. Tabs were placed on each side of the weld and the deformations measured with an Avery extensometer. Thus, these measurements included some of the plate deformation since a two inch gage length was used. The maximum extension averages for the longitudinal and transverse specimens were 0.151 inches and 0.058 inches, respectively. There was significant scatter in the results, especially for the longitudinal deformations.

Butler and Kulak (1971) conducted a series of 23 coupon tests on 1/4 inch fillet welds oriented at 0°, 30°, 60°, and 90° to the loading angle to measure the load-deformation response. The test set-up was described in Section 2.2.1.7 and is also shown in Figure 2.7. Two 0.001 inch dial gages were mounted on the specimens at the center of the weld and the corresponding deformations measured up to the peak load, at which point the gages were removed as the load fell. The mean maximum deformations were 0.101 inches for the longitudinal specimens and 0.026 inches for the transverse specimens. The deformations for weld orientations between these two extremes were in between these values. With these data, Butler and Kulak (1971) used the expression for bolt load-deformation response and adapted it for welded connections. The general fastener group expression as reported by Fisher (1965) is:

$$R=R_{ult}(1-e^{-\mu\Delta})^{\lambda}$$

where R = fastener load at any given deformation, Δ
Δ = shearing, bending, and bearing deformation of the connected plate
μ,λ = regression coefficients
e = base of natural log (2.718)

Based on their load-deformation data, Butler and Kulak developed expressions for R_{ult}, Δ_{max}, μ, and λ. These coefficients are functions of the angle of the weld to the load, θ. The specimens for these tests were fabricated with E60xx electrodes.

Butler, Pal, and Kulak (1972) used the results of Butler and Kulak (1971) to develop the instantaneous center of rotation ultimate strength design approach for fillet welds. This method predicts the ultimate strength of an eccentric fillet welded connection based on an incremental length of weld reaching its maximum deformation first. The formulation and expressions developed by Butler, Pal, and Kulak for this ultimate strength analysis are reproduced in the eighth and ninth editions of of the AISC ASD manual.

Kulak and Timler (1984) revised the load-deformation coefficients to reflect the behavior of 70 ksi strength electrodes. The revised strength equation along with the revised coefficients presented by Kulak and Timler are incorporated in the AISC LRFD (1986) manual. Using these equations, maximum deformations for longitudinal welds and transverse welds are computed to be 0.11" and 0.028", respectively. The equations used to obtain these values are obtained from equations which have been curve fit from data.

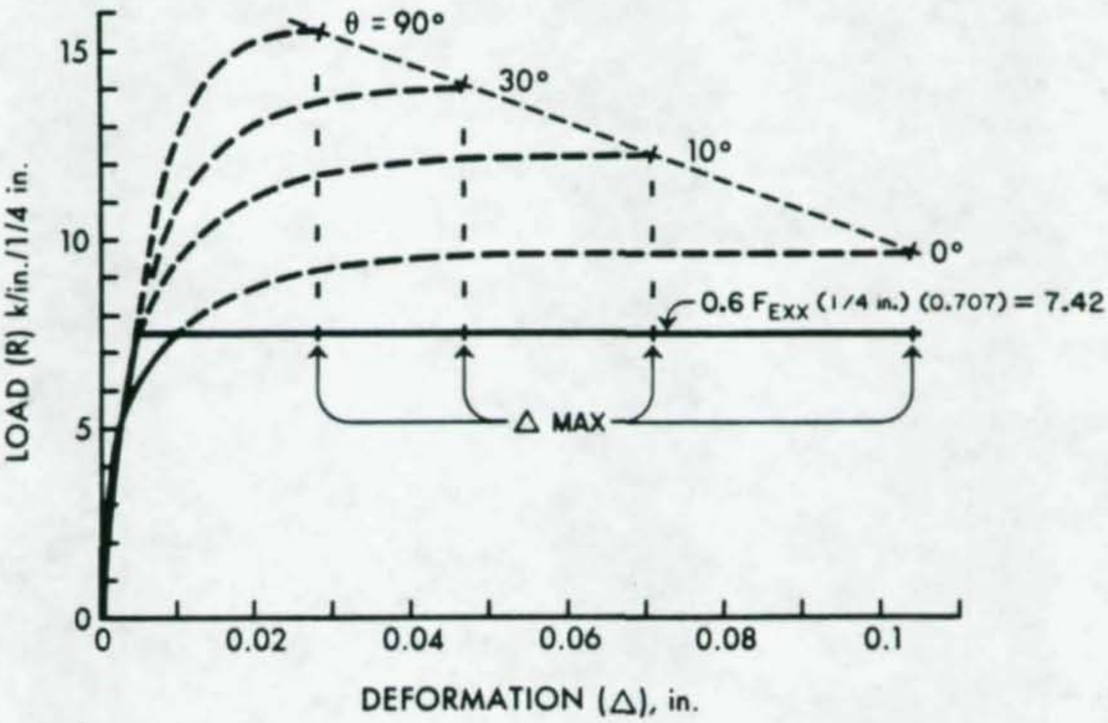
The plot of the load-deformation strength equation developed by Kulak and Timler (1984) is reproduced in Figure 2.9. Additionally, a comparision of the load-deformation equations presented in both the AISC ASD Ninth Edition Specification (1989) and the AISC LRFD Specification (1986) is included. Both of these specifications limit the maximum strength which can be utilized for any fillet weld. In the LRFD Specification, this maximum strength value is given by:

$$R_{w_{max}} = (0.6\ F_{EXX})A_w$$

This equation is plotted in Figure 2.9 for a 1/4 inch fillet weld. The ASD Specification (1989) expression for the maximum weld strength which can be developed is given by:

$$R_{w_{max}} = (0.3\ F_u)A_w$$

Even though the ASD Ninth Edition Specification was published three years after the LRFD Specification, it maintained the same load-deformation equations as the eighth edition manual. It is unclear why the ASD Ninth Edition Specification does not incorporate the results of the 1984 Kulak and Timler report because these results were included in the 1986 LRFD Specification.



ASD (1989)	LRFD (1986)
$R=R_{ult}(1-e^{-\mu\Delta})^{\lambda}$	$R=R_{ult}(1-e^{(-k1\Delta/\Delta o)})^{k2}$
$\Delta_{max}=0.225(\Theta+5)^{-0.47}$	$\Delta_{max}=\Delta_o(\Theta/5\ +1)^{-0.47}$
$R_{ult}=\dfrac{10+\Theta}{0.92+0.0603\Theta}$	$R_{ult}=\dfrac{(10+\Theta)}{10+0.582\Theta}(0.791F_{EXX}t)$
$\mu=75e^{0.0114\Theta}$	$k1=8.274e^{0.0114\Theta}$
$\lambda=0.4e^{0.0146\Theta}$	$k2=0.4e^{0.0146\Theta}$
$\Delta=(r/r_{max})\Delta_{max}$	$\Delta=(r/r_{max})\Delta_{max}$

Figure 2.9 AISC Load-Deformation Curves and Equations (from AISC ASD Specification, 1989, and LRFD Specification, 1986)

CHAPTER 3

EXPERIMENTAL PROGRAM

3.1 Introduction

This chapter describes in detail the experimental test program conducted on a series of fillet welded connections fabricated to investigate weld strength and ductility. The design, fabrication, measurement, instrumentation, and test procedure of these fillet welded connections is reviewed.

3.2 Specimen Design

To achieve the objectives outlined in Section 1.2, several different sizes and types of specimens were designed. The first set of specimens will be referred to as the "primary test matrix." This set of specimens consisted of fillet welded lap connections tested to failure. Most of the variables being investigated were isolated in the primary test matrix. Two other groups of specimens were designed to investigate variables which could not be isolated in the primary test matrix. The first of these two groups will be referred to as "coupon specimens." This group consisted of both all-weld-metal coupons and a base metal coupon specimen for determining material properties. The second group will be referred to as "macroetch specimens." These specimens were required to determine weld fusion and root penetration. The design for all of these groups of specimens is reviewed subsequently.

3.2.1 Primary Test Matrix

3.2.1.1 Overview

The primary test matrix consisted of eighteen lap connections welded using the shielded metal arc welding process (SMAW). The specimens were designed to examine the effects of three primary variables which influence fillet weld strength: weld leg size, weld orientation, and fabrication gaps. Weld electrode strength was not chosen as a test variable due to the limited nature of the testing program.

All of the specimens were designed to induce failure in the welds to isolate the weld strength parameter. Varying weld sizes of 1/4 inch, 3/8 inch, and 1/2 inch were selected to determine the effect of leg size. Due to the capacity of the testing machine, fabrication costs, and steel costs, 1/2 inch was the largest leg size chosen. To investigate the effects of fabrication gaps, spacer rods of 1/16 inch and 1/8 inch were placed in some of the specimens to create a gap between the two steel plates joined. A total of eighteen specimens were designed for the primary test matrix. Nine of these were fabricated with the welds longitudinal (0°) to the direction of loading, while the other nine specimens had welds oriented transverse (90°) to the loading direction. The same sizes of welds and fabrication gaps were used on both the longitudinal and transverse specimens.

A numbering system consisting of two numbers, a letter, and another number (i.e. 1-2-L-0) was stamped on all specimens to identify the properties of that specimen. The first digit refers to the specimen number in the test matrix, used for quick referencing. The second digit indicates the weld leg size in eighths of an inch. Thus, the number '2' would represent a 1/4 inch weld. The subsequent letter refers to a specimen with either a longitudinal or a transverse weld. A longitudinal weld specimen would have the letter 'L' while a transverse weld specimen the letter 'T'. The final number represents the fabrication gap induced, in sixteenths of an inch. Therefore, the number '2' would represent a 1/8 inch gap while the number '0' would represent a specimen with no gap. Table 3.1 provides a listing of the specimens in the primary test matrix.

To reduce the weld profile measurements, failure was designed for one end of the specimen, called the 'test end'. The other end was called the 'anchor end' and had

Table 3.1 Primary Test Matrix Specimens

SPECIMEN #	WELD SIZE (inches)	WELD ORIENTATION (Long. or Trans.)	GAP SIZE (inches)
1-2-L-0	1/4	LONGITUDINAL	NONE
2-2-L-0	1/4	LONGITUDINAL	NONE
3-3-L-0	3/8	LONGITUDINAL	NONE
4-3-L-0	3/8	LONGITUDINAL	NONE
5-4-L-O	1/2	LONGITUDINAL	NONE
6-4-L-0	1/2	LONGITUDINAL	NONE
7-2-T-0	1/4	TRANSVERSE	NONE
8-2-T-0	1/4	TRANSVERSE	NONE
9-3-T-0	3/8	TRANSVERSE	NONE
10-3-T-0	3/8	TRANSVERSE	NONE
11-4-T-0	1/2	TRANSVERSE	NONE
12-4-T-0	1/2	TRANSVERSE	NONE
13-2-L-1	1/4	LONGITUDINAL	1/16
14-2-L-2	1/4	LONGITUDINAL	1/8
15-4-L-1	1/2	LONGITUDINAL	1/16
16-2-T-1	1/4	TRANSVERSE	1/16
17-2-T-2	1/4	TRANSVERSE	1/8
18-4-T-1	1/2	TRANSVERSE	1/16

ALL SPECIMENS: E7018 Electrodes
SMAW Process
A572 Gr.50 Steel

significantly larger welds to prevent failure from occurring at this end. Figures 3.1 and 3.2 show the longitudinal and transverse weld specimen configurations, respectively, as well as the specimen numbering system.

3.2.1.2 Test Specimen Design Criteria

The testing machine used to load the specimens had a rated load capacity of 600 kips. A reasonably accurate estimate of the expected weld strength had to be calculated so that the test specimens could be designed without exceeding the limitations of the testing machine. The current LRFD Specification (1986) defines unfactored fillet weld strength as:

$$R_w = 0.6\ F_{EXX}\ A_w$$

where F_{EXX} = weld electrode tensile strength

A_w = effective area of the weld, = throat thickness times the weld length

0.6 = factor to account for shear loading

This equation is a conservative estimate of fillet weld strength. Therefore, previous test results were used to estimate a modified factor, which would also account for the weld orientation, to replace the 0.6 shear factor. Based on previous test results discussed in Chapter 2, two similar equations to the LRFD Specification equation, but with

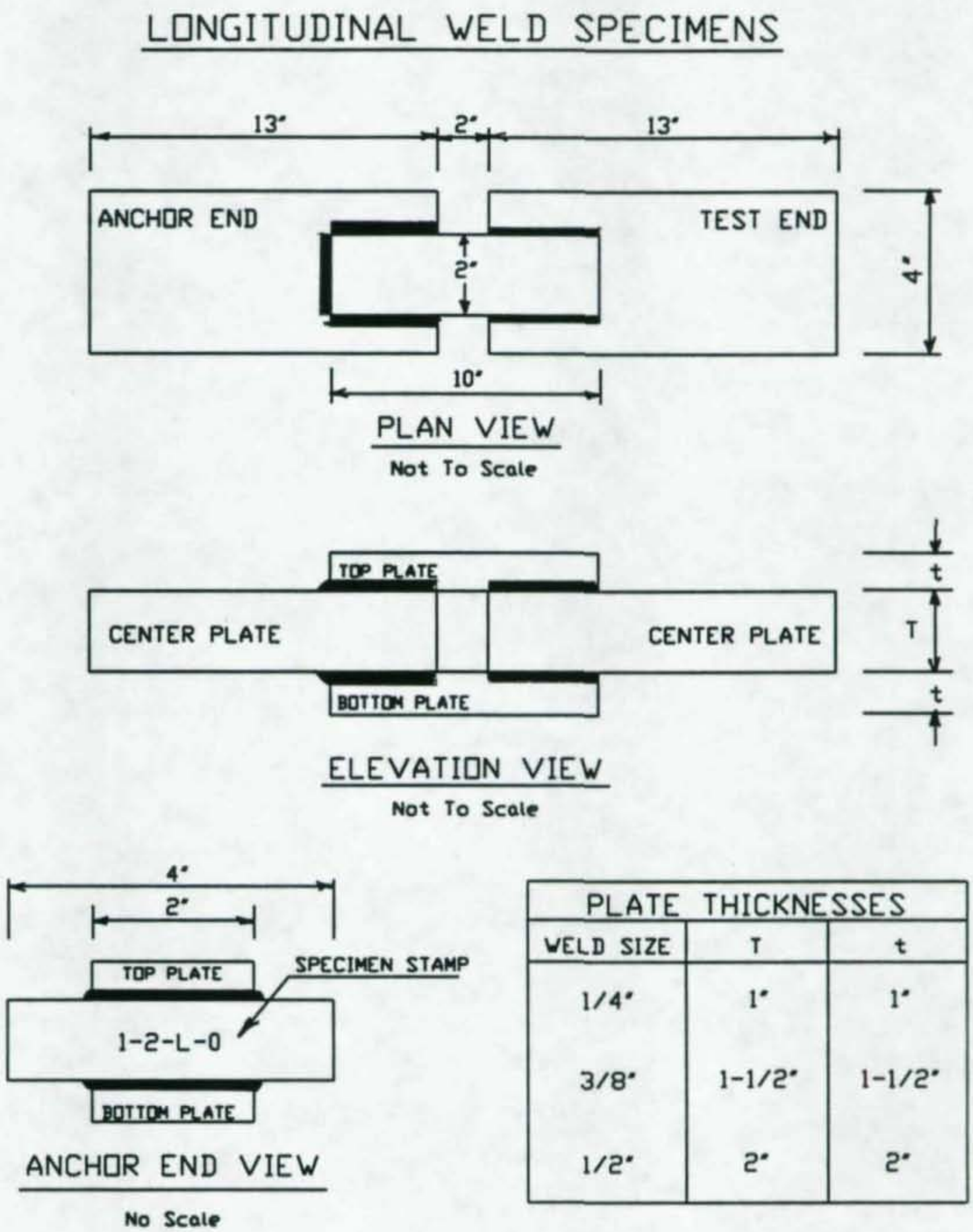


PLATE THICKNESSES		
WELD SIZE	T	t
1/4"	1"	1"
3/8"	1-1/2"	1-1/2"
1/2"	2"	2"

Figure 3.1 Typical Longitudinal Weld Specimens

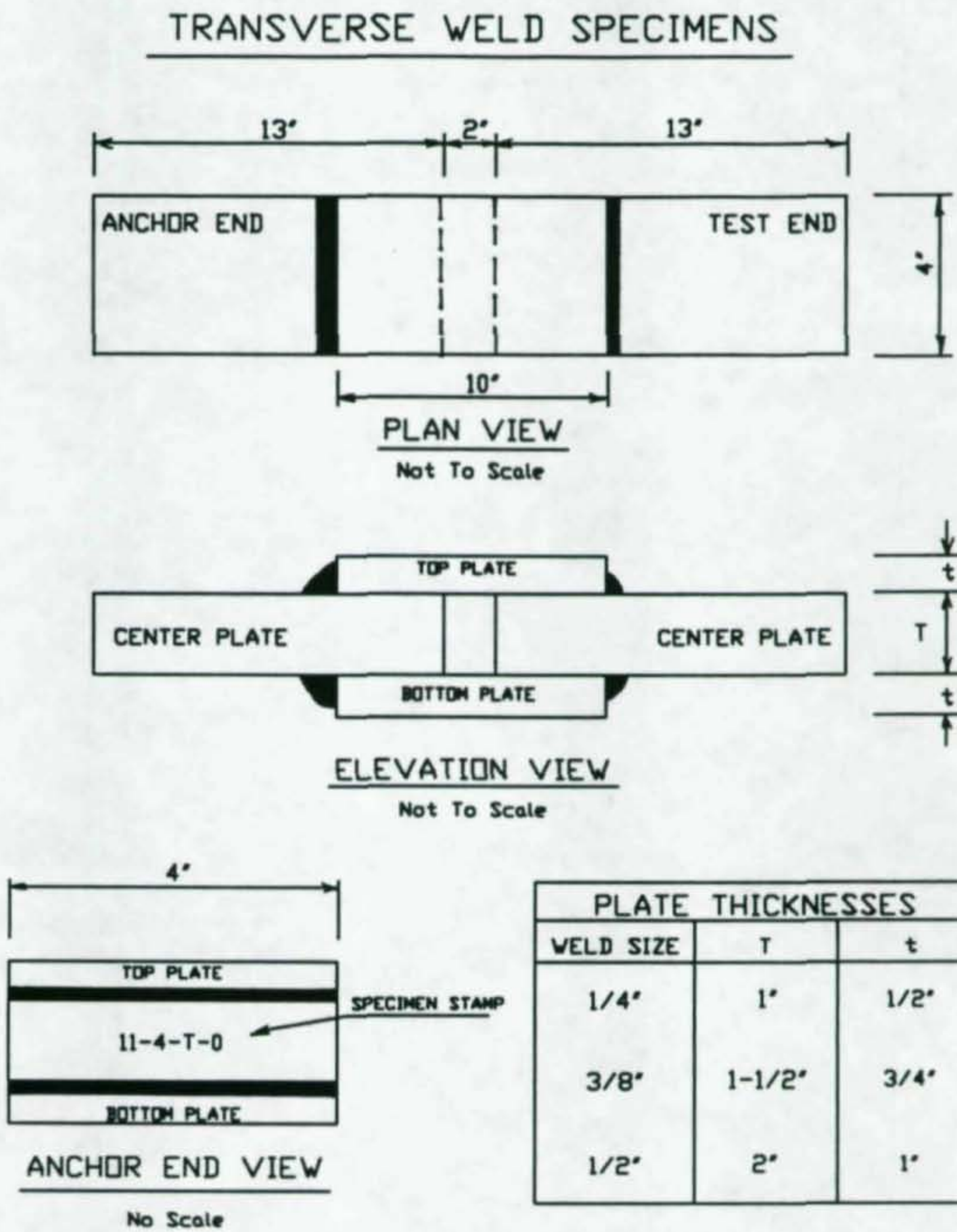


PLATE THICKNESSES		
WELD SIZE	T	t
1/4"	1"	1/2"
3/8"	1-1/2"	3/4"
1/2"	2"	1"

Figure 3.2 Typical Transverse Weld Specimens

modified shear factors, were used to estimate the strengths of the longitudinal and the transverse welds. These equations were:

$$R_w = 0.9\ F_{EXX}\ A_w \quad \text{for longitudinal welds}$$

$$R_w = 1.6\ F_{EXX}\ A_w \quad \text{for transverse welds}$$

The significantly larger factor for the transverse welds takes into account the well known fact that transverse fillet welds are stronger than longitudinal welds.

A common electrode was desired for the welding, so E70xx electrodes were selected. Therefore, F_{EXX} was taken as 70 ksi in the strength equations given previously. The effective area of the weld for fillet welds is the effective throat thickness times the effective weld length. The theoretical throat thickness of 0.7071 times the leg size was used as the effective throat for design purposes. The effective length was taken as the design length of the weld.

Several factors were considered in designing the length of the fillet welds. First of all, it was desired to minimize the start-up and end lengths of the weld as a percentage of the entire weld length. Secondly, to avoid possible shear lag effects given in LRFD Specification Section B3 (1986), the weld length should be greater than twice the width of the connecting plate. Both of these factors encourage long weld lengths. However, a trade-off had to be made since the testing machine capacity was only

600 kips. To keep the welds far enough apart for the longitudinal specimens, the width of the top and bottom lap plates was designed for two inches, as shown in Figure 3.1. To avoid possible shear lag effects, the weld length was chosen as four inches. While this is not strictly greater than two times the lap plate width, no shear lag effects with a four inch weld length were anticipated. The specimens with longitudinal welds were designed for four equal length (four inch) fillet welds, for a total of sixteen inches of weld on the test end of the specimen. The anchor end of the longitudinal specimens had larger weld leg sizes and was also welded across the back of the top and bottom plates to prohibit failure from occurring at this end.

For the specimens with transverse welds, the weld length was maintained at four inches, so the width of the top and bottom lap plates was designed for the length of the weld. Thus, there was a total of eight inches of weld for the test end of the transverse specimens. The anchor end of these specimens was to have larger weld leg sizes to insure failure at the test end.

Based on these lengths of welds, the weld leg sizes were then designed to keep the strength of the weld within the capacity of the testing machine. Therefore, the largest weld size chosen was 1/2 inch. The strength of the longitudinal specimen with 1/2 inch welds was the greatest and was estimated to be 356 kips (0.9 * 70 ksi* 1/2" *0.7071*16"). At first glance this appears to be significantly lower than the 600 kip capacity of the testing machine. However, for safety purposes, the largest load desired was to be below 500 kips. Additionally, it was anticipated that the weld leg size could be slightly larger than the prescribed 1/2 inch, and the weld electrode tensile strength could also be greater than 70 ksi. Therefore, the 1/2 inch leg size was the largest size chosen.

Varying leg sizes were required to investigate the leg size effect on the weld strength parameter. Therefore, 1/2 inch, 3/8 inch, and 1/4 inch weld leg sizes were selected for both the longitudinal and transverse specimens. Two transverse and two longitudinal specimens with each leg size were selected. Thus, a total of twelve specimens without fabrication gaps were designed.

Six additional primary test matrix specimens were designed to include fabrication gaps. Section 3.3.1 of the AWS Structural Welding Code Specification (1990) states that fabrication gaps up to 1/16 inch are tolerated without any reduction in the design strength. Thus, four specimens were designed to incorporate a 1/16 inch gap. This gap was included on a longitudinal and transverse specimen with 1/4 inch welds and also a longitudinal and transverse specimen with 1/2 inch welds, for a total of four specimens. A 1/8 inch gap was introduced in both a longitudinal and a transverse specimen with 1/4 inch welds. These 1/8 inch gaps were chosen to investigate the effect of exceeding the AWS prescribed limits without increasing the weld size. Therefore, six specimens with gaps were designed along with the other twelve non-gapped specimens for a total of eighteen specimens in the primary test matrix.

Once the failure load of the weld was estimated, the steel connecting plates were designed. The principal design criterion for the plates was to keep the stress in the plates within the elastic region until the weld failed. Thus, the yield stress and thickness of the plate were the two variables which could be adjusted to prevent yielding of the plates. The width of the plates was already fixed by the weld length selected. The type of steel had to be a 'matching' steel for the E70xx electrodes and it was also desired to use a common structural grade steel. Therefore, ASTM A572 Grade 50 steel was selected to minimize the plate thicknesses while still utilizing a common grade of structural steel.

The following tension yield design equation was used to predict the steel plate thicknesses:

$$\phi F_y (A_{pl}) >= R_w$$

where ϕ = 0.90 for tension members

F_y = yield stress of plate, taken as 50 ksi

A_{pl} = cross sectional area of plate

R_w = weld strength, as computed earlier

It was anticipated that this equation would be conservative because steel yield stresses are generally higher than the minimum value specified, and a strength reduction factor (ϕ) of 0.9 was also used. The thicknesses of plate used as determined from this equation were given previously in Figures 3.1 and 3.2.

Several factors influenced the selection of plate lengths. First of all, the center plates were to be gripped in the test machine, so six inches of grip length was allotted. An additional minimum of three inches was desired between the end of the gripped section and the beginning of the weld, which would allow for the stress in the plate to become more uniformly distributed between the weld and the grip. Finally, four inches of plate from the weld to the end of the plate was used since the welds were four inches long. Thus the total center plate length was 6"+3"+4"= 13". The length of the top and bottom lap plates was determined by the opening required between the two center plates. To achieve a more uniform stress distribution and provide enough space for weld run-off tabs, an opening of two inches between the center plates was selected. Four inches of plate overlap onto the center plate was determined previously. Therefore, the cover plate length was 4"+2"+4" = 10". Plate dimensions are shown in Figures 3.1 and 3.2.

3.2.2 Coupon Specimens

Two different types of coupon specimens were designed for testing. The first type of coupon consisted of all-weld-metal coupon specimens and the second type was a piece of the ASTM A572 Grade 50 steel which was prepared for testing to obtain the stress-strain properties of the base metal.

3.2.2.1 All-Weld-Metal Coupon Specimens

Three all-weld-metal coupons (called 'A505' specimens) were designed to determine the material properties of the weld metal. The ultimate tensile strength and the percent elongation were the two primary properties to be obtained from these tests. The all-weld-metal coupons were prepared according to the requirements given in the AWS Structural Welding Code for weld metal tension tests. The all-weld-metal coupons were extracted from a single-V groove weld, which was used to join two one inch thick plates. Figures 3.3 and 3.4 show the butt welded specimen and the all-weld-metal specimen extracted from it.

3.2.2.2 Base Metal Coupon Specimen

A single 15-1/2 inch length of one inch thick A572 Grade 50 steel was saved for a coupon test on the base

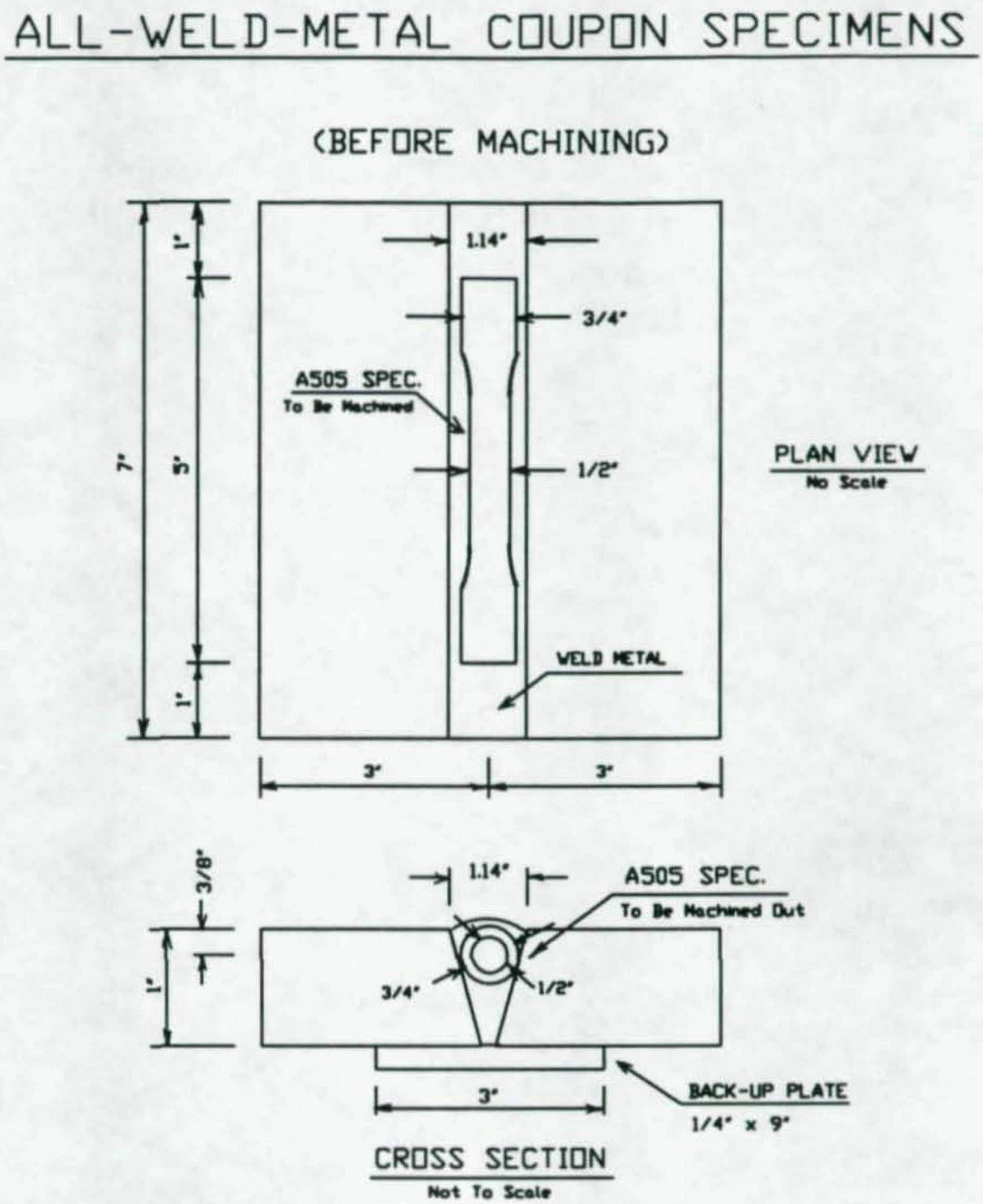


Figure 3.3 All-Weld-Metal Coupon Specimen Before Machining

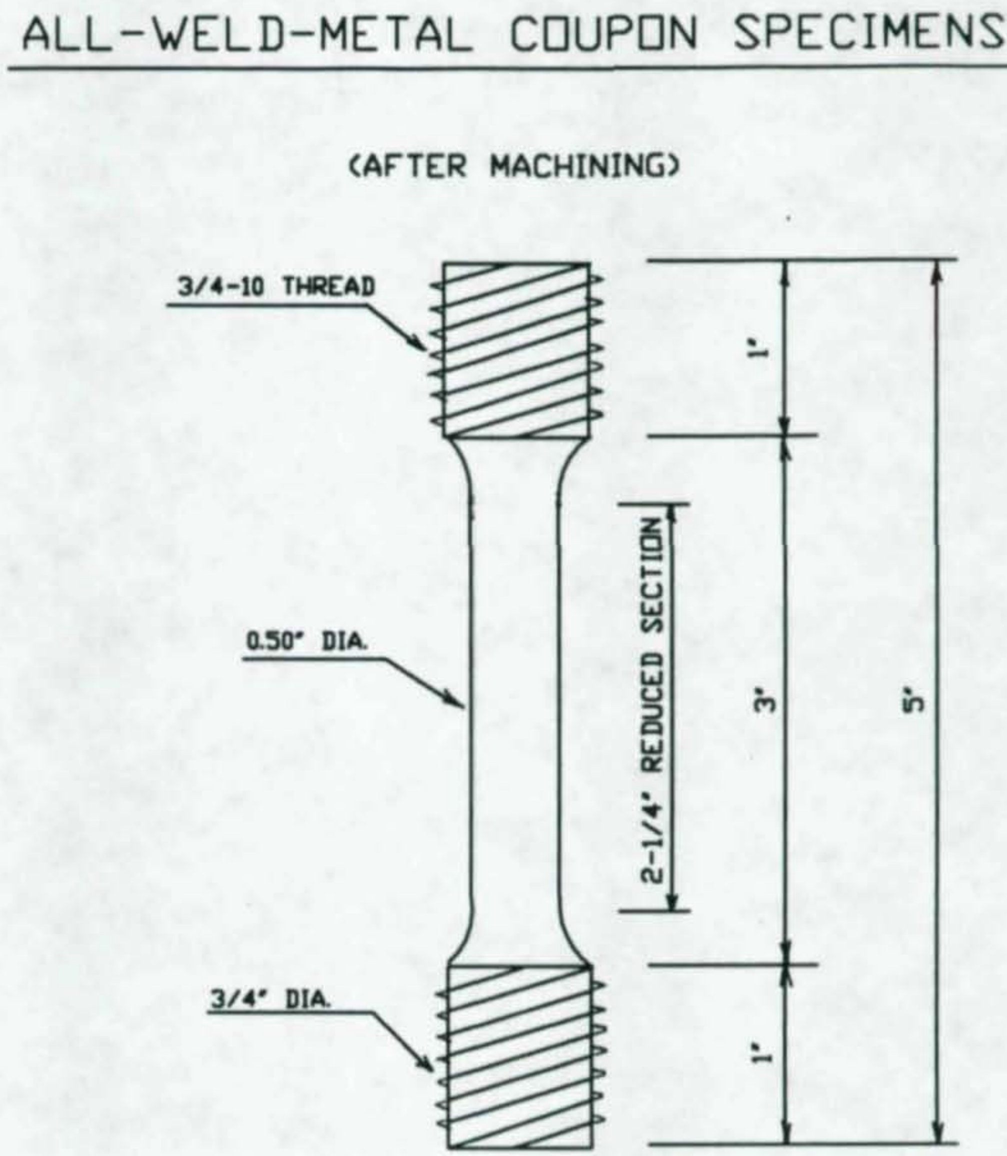


Figure 3.4 All-Weld-Metal Coupon Specimen After Machining

metal. This specimen was to be tested to failure to obtain its material properties such as yield stress, ultimate strength, elastic modulus, and percent elongation. There was not enough leftover steel to perform a coupon test on all of the thicknesses of steel. However, mill reports for the steel were obtained and are included in Appendix F. Figure 3.5 shows dimensions of the base metal coupon specimen. The actual width and thickness were measured in the middle of the gage section of the specimen. The thickness was measured with a micrometer while a vernier caliper was used to measure the width.

3.2.3 Macroetch Specimens

Three macroetch specimens were designed to investigate weld fusion and root penetration. Each macroetch was designed to have representative welds of the specimens in the primary test matrix. Therefore, 1/2 inch, 3/8 inch, and 1/4 inch weld leg sizes were selected. Additionally, gaps were introduced to model the gaps produced on some of the specimens in the primary test matrix. Figure 3.6 shows the dimensions and weld sizes of the three macroetch specimens.

3.3 Specimen Fabrication

All of the specimens were fabricated by CBI Services in Bourbonnais, Illinois from May 14, 1990 through May 16,

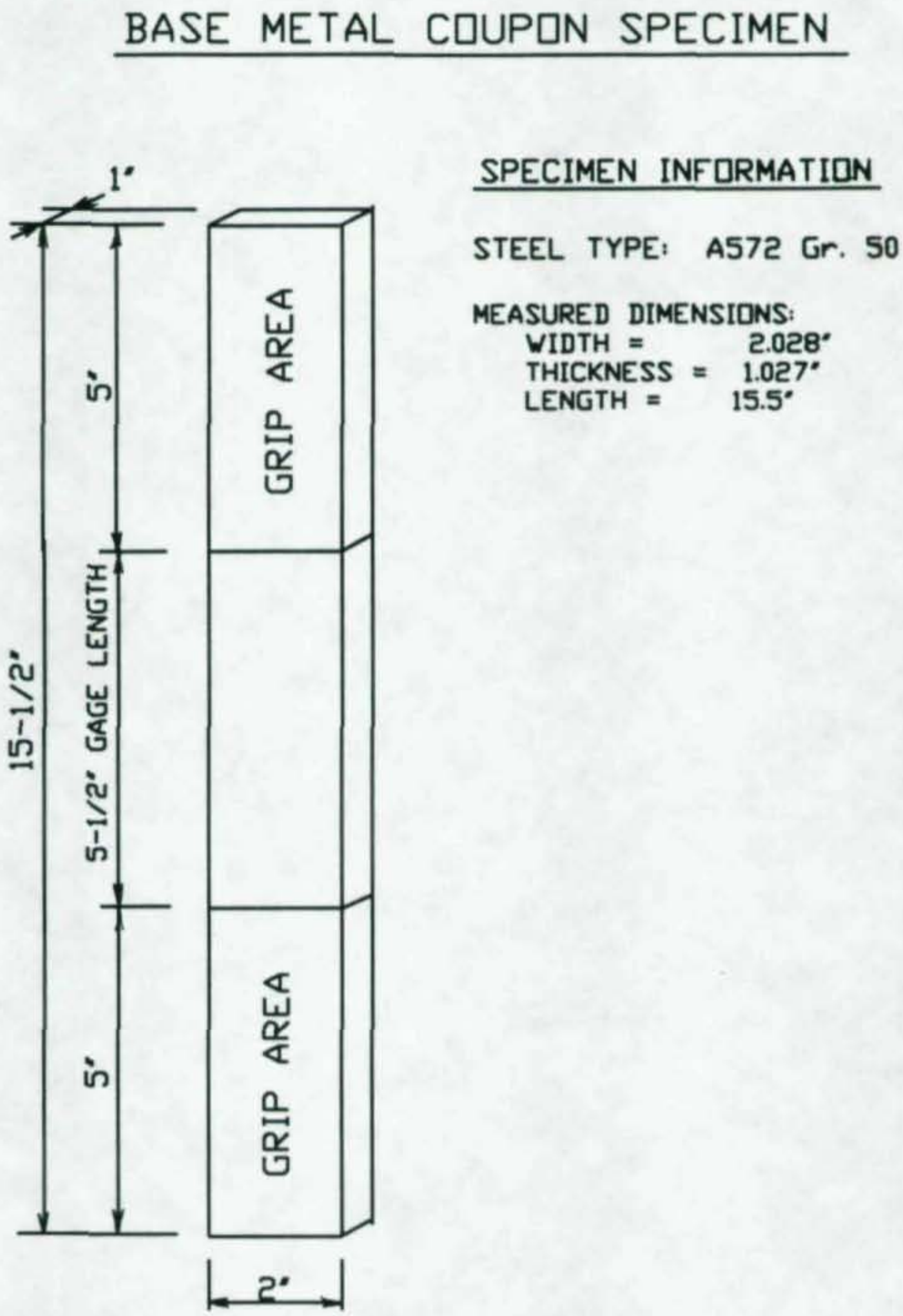
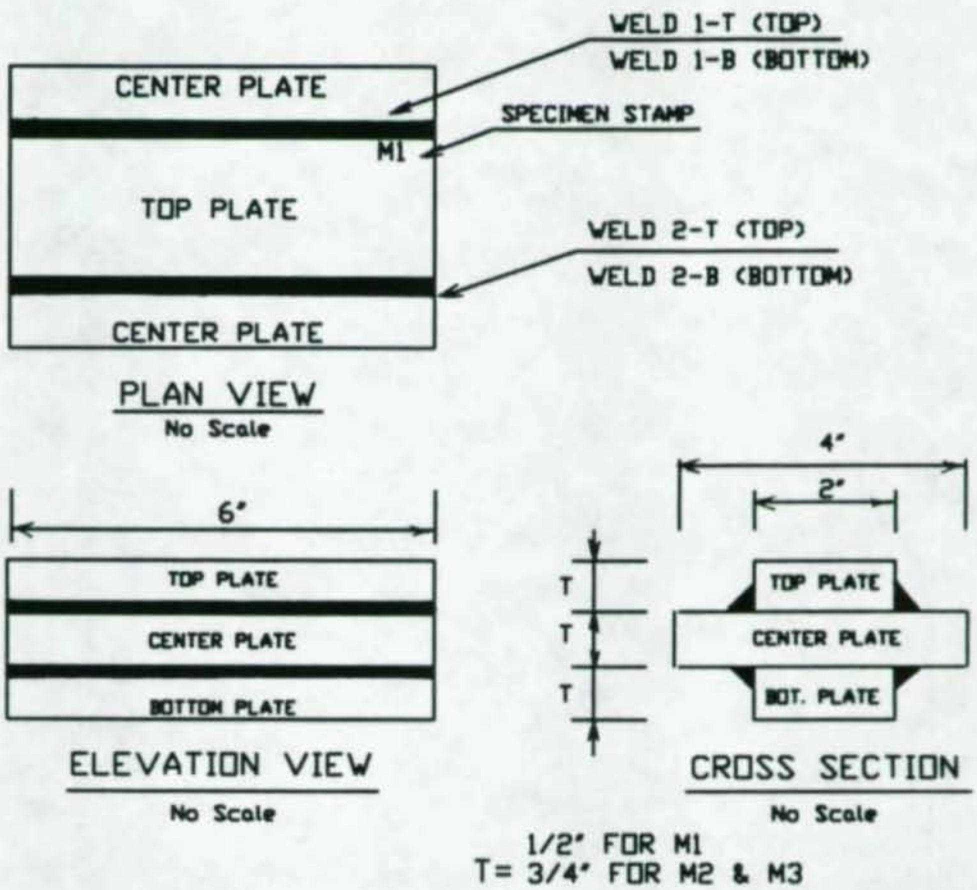


Figure 3.5 Base Metal Coupon Specimen

MACROETCH SPECIMENS



MACROETCH SPECIMEN DIMENSIONS						
	M1		M2		M3	
WELD LOCATION	WELD SIZE	GAP SIZE	WELD SIZE	GAP SIZE	WELD SIZE	GAP SIZE
1-T	1/4'	NONE	3/8'	NONE	3/8'	1/8'
1-B	1/4'	1/16'	1/2'	1/16'	1/4'	1/8'
2-T	1/4'	NONE	1/2'	NONE	1/2'	1/8'
2-B	1/4'	1/16'	3/8'	1/16'	1/4'	1/8'

Figure 3.6 Macroetch Specimens

1990. The welding was all performed by the same welder to achieve uniformity. Atom Arc E7018 Alpha, low hydrogen, 3/16 inch electrodes were used for all of the welding. The electrodes were stored overnight in an oven as recommended by the AWS Structural Welding Code. A Westinghouse D.C. shielded metal arc welding (SMAW) machine was used for the welding. The machine amperage was constant for all of the welding at approximately 240 amps as measured with an ammeter. The voltage fluctuated between 19 and 22 volts, as measured with a voltmeter. None of the steel was preheated and there was no control over the interpass temperature. All slag was removed between passes with a sputter gun and wire brush.

3.3.1 Primary Test Matrix

As stated before, the primary test matrix consisted of nine specimens with longitudinal welds and nine specimens with transverse welds. Weld sizes were 1/2 inch, 3/8 inch, and 1/4 inch. Some specimens had gaps of either 1/16 inch or 1/8 inch induced between the plates. Details of the fabrication procedure for each of these eighteen specimens are provided in the following sections.

3.3.1.1 Longitudinal Weld Specimens

All nine longitudinal specimens had run-off plates in the center section of the specimen to avoid arc-blow at the end of the weld. After fabrication, the weld metal on the run-off plate was isolated with a saw cut. No start-up tabs were used because excess weld metal was pooled at the beginning of the weld, slightly wrapping around the end of the cover plate. This allowed for the weld to have a full throat thickness at the edge of the plate. The excess weld metal which ran past the end of the cover plate was later saw cut and filed off. Prior to welding, the specimens were clamped and tack-welded on the anchor end, with additional tack welds being placed at the junction of the run-off plate, cover plate, and center plate. The direction of welding, as well as the placement of tack welds and run-off tabs are shown in Figure 3.7. Details of the fabrication of the specimens are presented below.

3.3.1.1.1 Specimens 1-2-L-0 and 2-2-L-0

Specimens 1-2-L-0 and 2-2-L-0 were fabricated with 1/4 inch longitudinal fillet welds and no fabrication gap. A single weld pass with the 3/16 inch electrode was sufficient to attain the desired leg size and throat thickness. The specimens were tilted for welding in a V-groove position, as shown in Figure 3.8. The reason for using this position was

FABRICATION - LONGITUDINAL WELD SPECIMENS

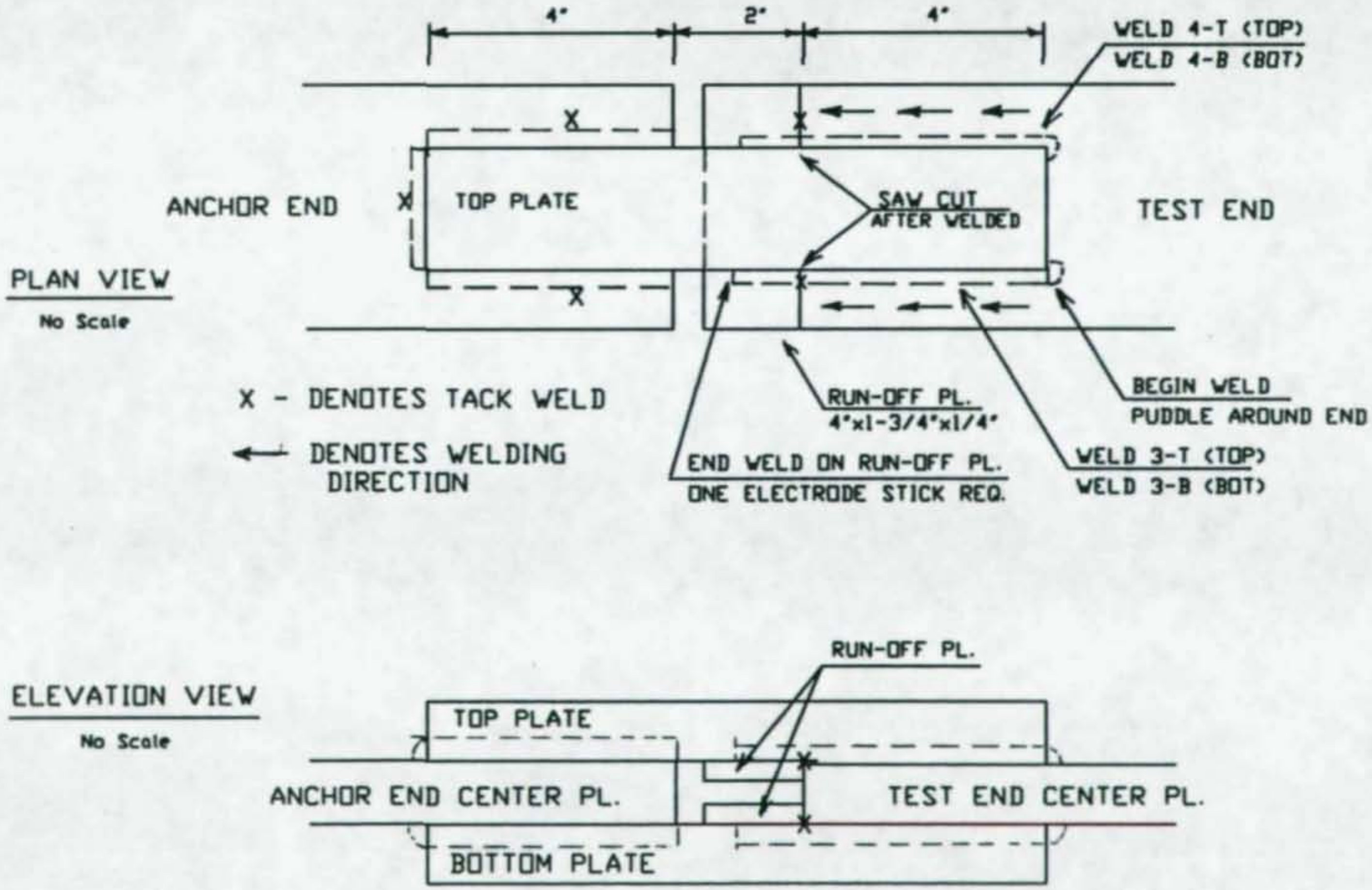


Figure 3.7 Fabrication of Longitudinal Specimens

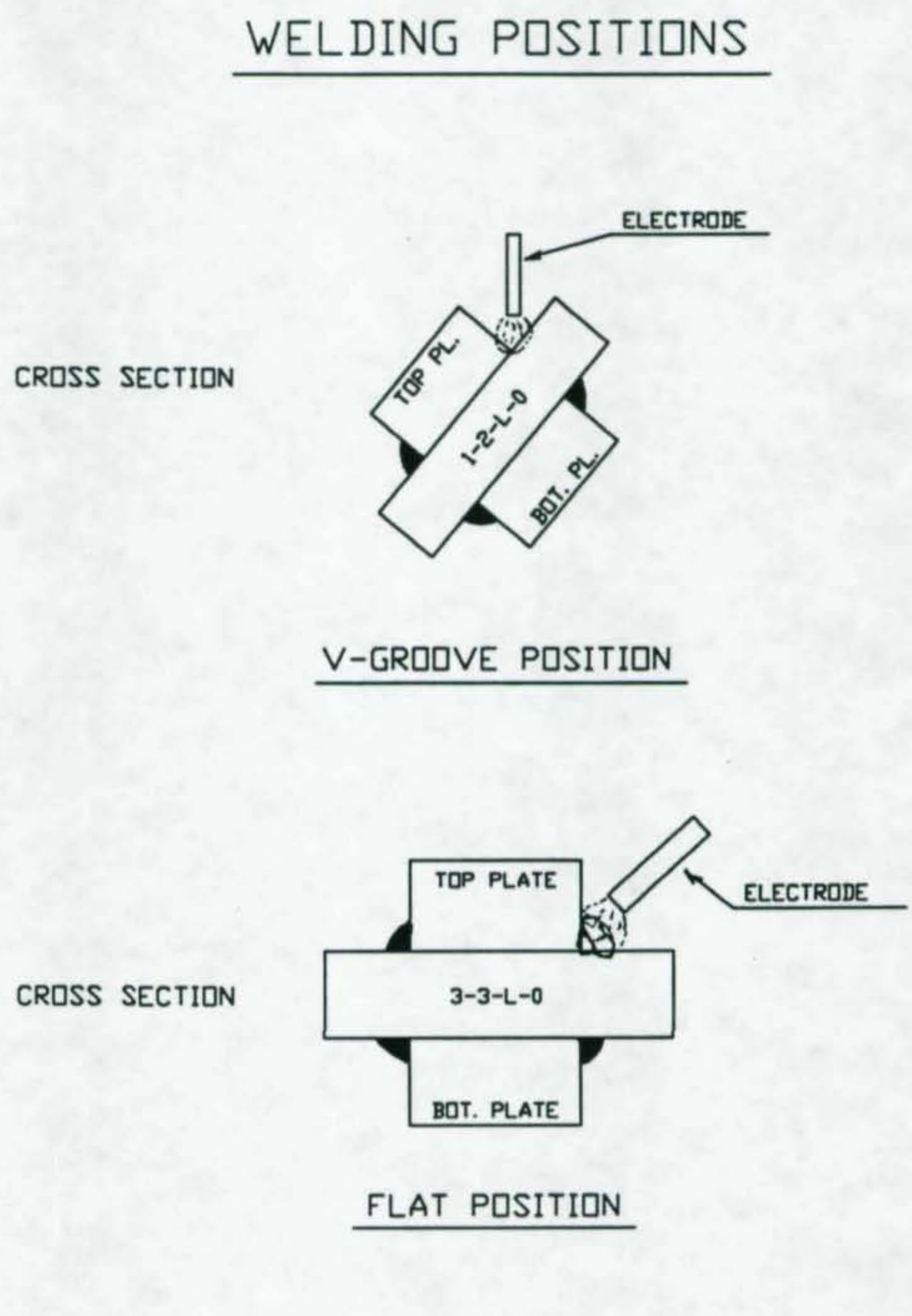


Figure 3.8 Welding Positions

two-fold. First of all, it was thought that the welder would be more successful in producing top and bottom leg sizes with similar dimensions using this position, thereby making the weld more symmetric. Secondly, the fabricator stated they like to use this position whenever possible because it allows the welder to get better penetration on the root pass.

3.3.1.1.2 Specimens 3-3-L-0 and 4-3-L-0

Specimens 3-3-L-0 and 4-3-L-0 were fabricated with 3/8 inch longitudinal fillet welds and no fabrication gap. Two weld passes were required to attain the required leg size and throat thickness. The first pass was a root pass and the second pass was a 'weave' pass. Both passes were welded in the V-groove position.

3.3.1.1.3 Specimen 5-4-L-0

Specimen 5-4-L-0 was fabricated with 1/2 inch longitudinal fillet welds and no fabrication gap. A single weld pass was placed around the entire specimen to prevent warping of the specimen on subsequent passes. Welds 3T, 4T, and 4B (shown in Figure 3.7) all required three weld passes, but weld 3B needed one extra weld pass. The weld sizes were measured during fabrication with a fillet weld gage. All of the root pass welds for specimen 5-4-L-0 were fabricated in the V-groove position. The second pass, however, was welded in a flat position, as shown in Figure 3.8. Pass 3 was welded in the V-groove position, weaving the electrode, because it was anticipated that three passes would produce the correct leg size. This was not the case for weld 3B, and a fourth pass was required. The fourth pass on weld 3-B was welded in the V-groove position. The welding positions were varied to try to achieve the required weld size with the fewest weld passses.

3.3.1.1.4 Specimen 6-4-L-0

Specimen 6-4-L-0 was fabricated with 1/2 inch longitudinal fillet welds and no fabrication gap. Once again, to prevent warping a single pass was initially welded for each section of weld in the V-groove position. The second pass was welded in a flat position, while passes three and four were weaved in the V-groove position.

3.3.1.1.5 Specimen 13-2-L-1

Specimen 13-2-L-1 was fabricated with 1/4 inch longitudinal fillet welds and a 1/16 inch fabrication gap. The gap was produced by removing the covering from 1/16 inch electrodes and placing the bare wire rods between the cover plate and the center plate. Figures 3.9 and 3.10 show the placement of spacer rods for the longitudinal specimens. A single

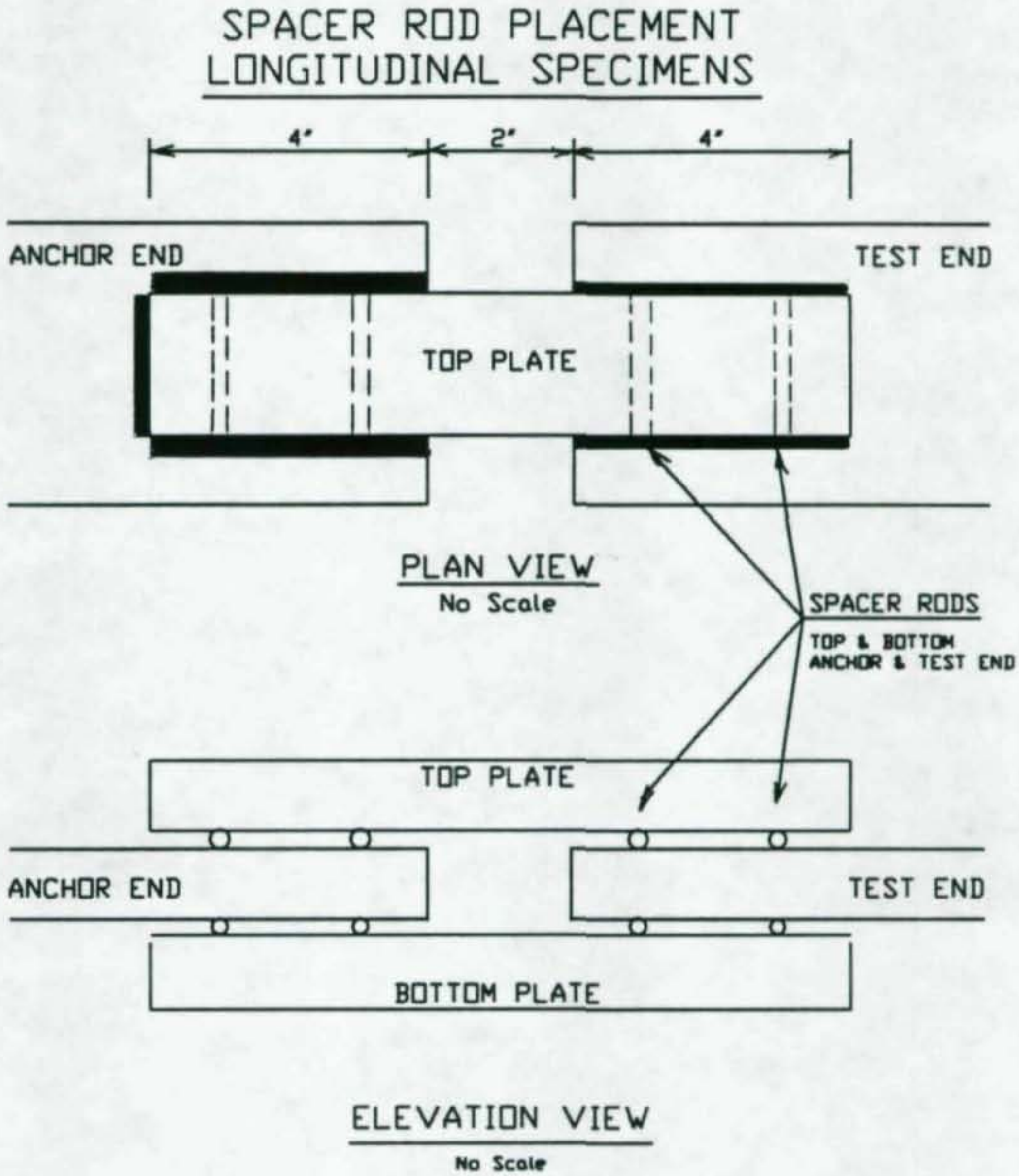


Figure 3.9 Spacer Rod Placement for Longitudinal Specimens

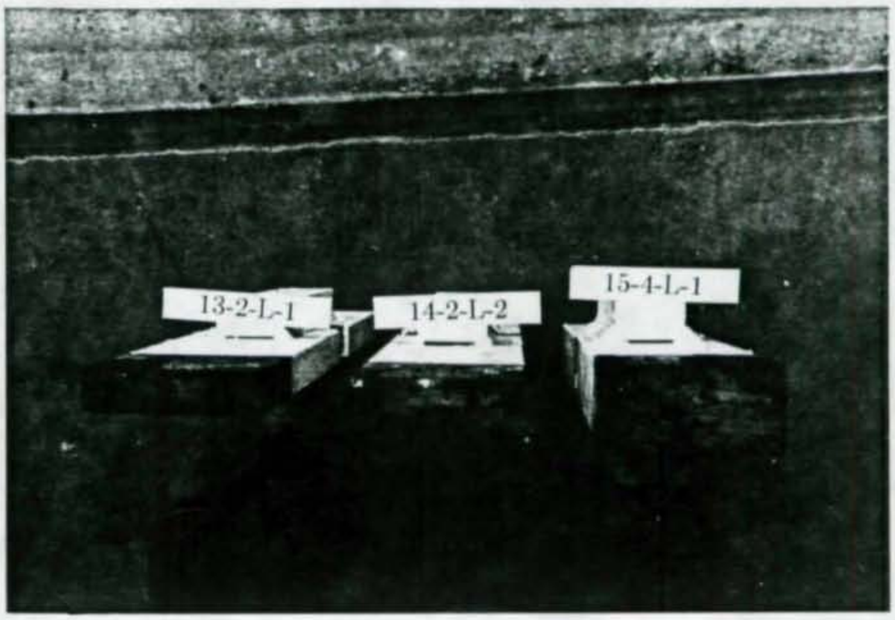


Figure 3.10 Photograph of Longitudinal Specimens with Fabrication Gaps

weld pass in the V-groove position provided adequate throat thickness and leg size.

3.3.1.1.6 Specimen 14-2-L-2

Specimen 14-2-L-2 was fabricated with 1/4 inch longitudinal fillet welds and a 1/8 inch fabrication gap. The covering was removed from 1/8 inch electrodes and the remaining bare wire part of the electrode was used as a spacer rod as was previously shown in Figure 3.9. A single pass welded in the V-groove with the 3/16 inch electrode was required, but was run at a slower rate than the other specimens because some of the molten weld metal was 'flowing' under the gap.

3.3.1.1.7 Specimen 15-4-L-1

Specimen 15-4-L-1 was fabricated with 1/2 inch longitudinal fillet welds and a 1/16 inch fabrication gap. Four passes with the 3/16 inch electrode were required. The first pass was welded in a V-groove position but the subsequent three passes were welded in a flat position, with the fourth and final pass being weaved. Once again, 1/16 inch electrodes with the covering removed were used as spacer rods.

3.3.1.2 Transverse Weld Specimens

The nine primary test matrix specimens with transverse welds were fabricated with run-off angles on both ends of the two test welds. After fabrication the run-off angles were gouged off and the ends of the welds were ground smooth with the connecting plates. The anchor end did not have any run-off tabs because the weld sizes were to be enlarged to ensure failure at the test end. The specimens were clamped and tack-welded at the anchor end and also at the junction of the run-off angle, center plate, and lap plate. The location of tack welds, run-off angles, as well as the weld numbering system is shown in Figure 3.11. Details of each transverse weld specimen are given below.

3.3.1.2.1 Specimens 7-2-T-0 and 8-2-T-0

Specimens 7-2-T-0 and 8-2-T-0 were fabricated with 1/4 inch transverse fillet welds with no fabrication gap. A single weld pass using the 3/16 inch electrode in the V-groove position provided adequate leg size and throat thickness.

3.3.1.2.2 Specimens 9-3-T-0 and 10-3-T-0

Specimens 9-3-T-0 and 10-3-T-0 were fabricated with 3/8 inch transverse fillet welds with no fabrication gap. Two

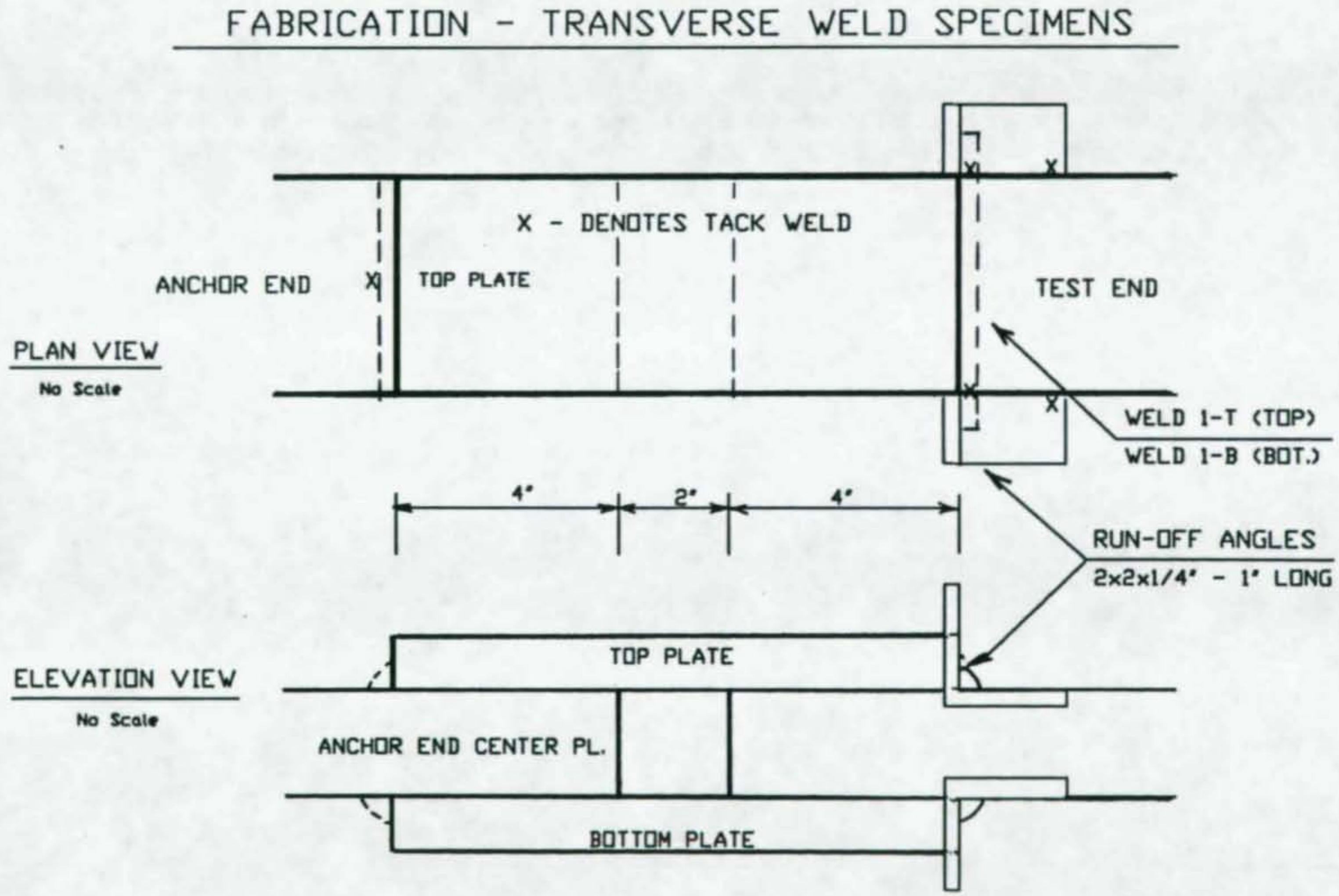


Figure 3.11 Fabrication of Transverse Weld Specimens

weld passes in the V-groove position were required. The first pass was a slow root pass while the second pass was weaved.

3.3.1.2.3 Specimens 11-4-T-0 and 12-4-T-0

Specimens 11-4-T-0 and 12-4-T-0 were fabricated with 1/2 inch transverse fillet welds without a fabrication gap. Four weld passes were needed to achieve the desired leg size and throat thickness. The first pass was a slow root pass welded in the V-groove position while the subsequent three passes were welded in the flat position. This procedure seemed to provide the best 1/2 inch weld, after earlier experimentation with specimens 5-4-L-0 and 6-4-L-0.

3.3.1.2.4 Specimen 16-2-T-1

Specimen 16-2-T-1 was fabricated with 1/4 inch transverse fillet welds with a 1/16 inch gap between the top and bottom plates and the center plate. The covering was removed from 1/16 inch electrodes and the bare wire used as spacer rods as shown in Figures 3.12 and 3.13. Only a single weld pass was required in the V-groove position.

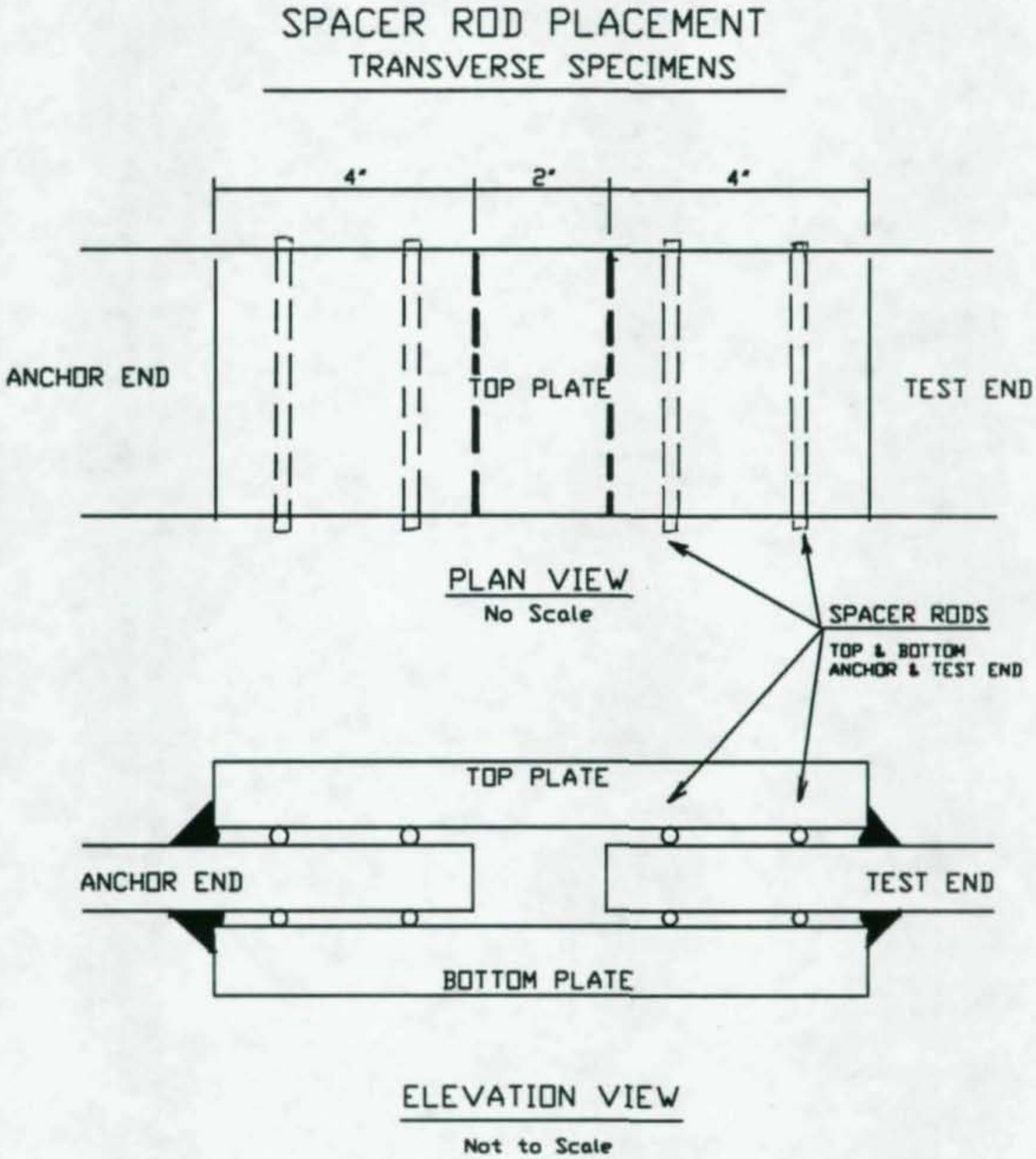


Figure 3.12 Spacer Rod Placement for Transverse Specimens

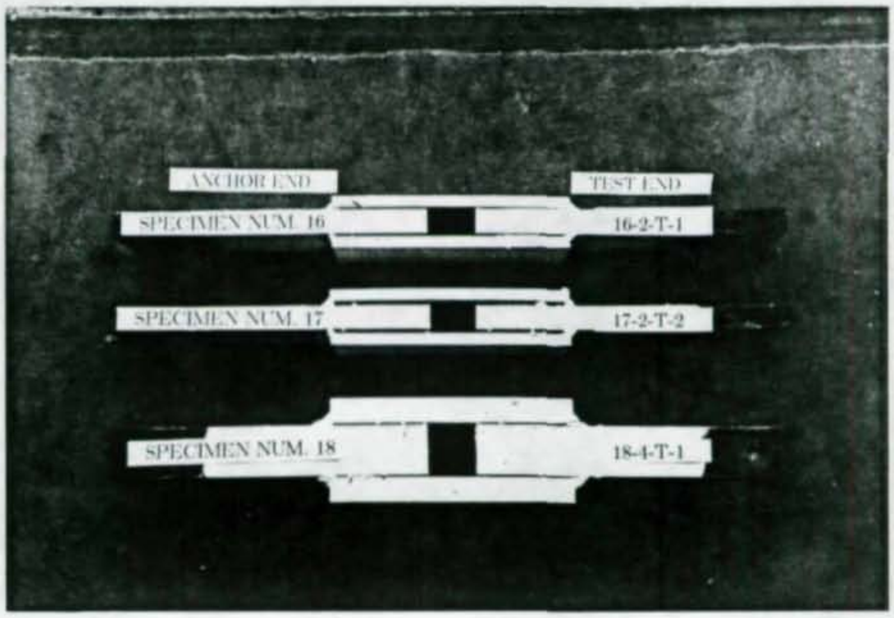


Figure 3.13 Photograph of Transverse Specimens with Fabrication Gaps

3.3.1.2.5 Specimen 17-2-T-2

Specimen 17-2-T-2 was fabricated with 1/4 inch transverse fillet welds with a 1/8 inch plate gap. Spacer rods made by removing the covering from 1/8 inch electrodes were used as was previously shown in Figure 3.11. A single weld pass placed in the V-groove position with a 3/16 inch electrode provided sufficient leg size and throat thickness.

3.3.1.2.6 Specimen 18-4-T-1

Specimen 18-4-T-1 was fabricated with 1/2 inch transverse fillet welds with a plate gap of 1/16 inch. One root pass in the V-groove was welded around the entire specimen first, to prevent warping, and then three subsequent passes were welded in the flat position.

3.3.2 Coupon Specimens

The three butt welded all-weld-metal 'A505' specimens were fabricated by the same welder, using the same welding machine, amperage, and electrodes as the primary test matrix specimens. Weld passes were deposited one after another, without controlling the interpass temperature. The number of weld passes required to fill the single-V groove in the one-inch thick plates varied for the three specimens. A505 number 1 required 25 passes while A505 numbers 2 and 3 required 29 and 23 passes, respectively.

The specimens became very hot from the repeated continuous welding and A505 specimen number 3 (which was welded first) began to warp after nine passes. To eliminate this warping, steel plates which would not interfere with the deposited weld metal were welded to the bottom of the specimen as shown in Figure 3.14. A505 specimen numbers 1 and 2 were attached back to back as shown in Figure 3.14 and welded alternately to prevent the warping encountered in A505 specimen number 3.

After returning from the fabrication shop, the A505 specimens were machined from the groove welded section of the plates, being careful to extract only weld metal in the reduced section of the specimens.

The steel plate coupon specimen was taken from excess one inch thick A572 Grade 50 steel used in fabricating the primary test matrix specimens. The specimen dimensions are shown in Figure 3.5. No fabrication was necessary for this specimen.

3.3.3 Macroetch Specimens

The three macroetch specimens, whose configurations were given in Figure 3.6, were designed to model the test welds on the primary test matrix specimens. Therefore, the

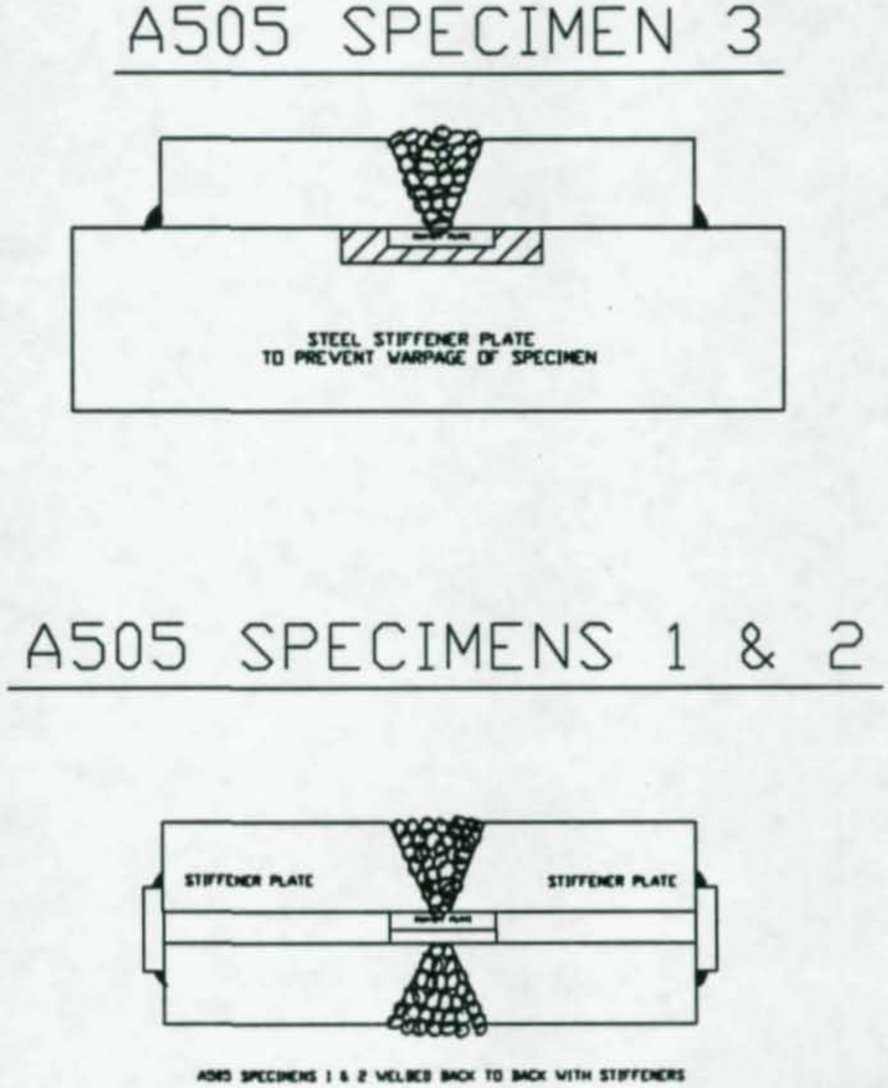


Figure 3.14 Fabrication of All-Weld-Metal Coupon Specimens

procedures used to weld these specimens were the same as was used for the specimens in the primary test matrix. For example, most of the 1/2 inch leg size specimens required four weld passes, with the first pass being welded in the V-groove and the subsequent three passes in a flat position. The corresponding 1/2 inch welds on the macroetch were welded in the same manner.

3.4 Weld Measurements

Several different dimensions of the deposited fillet welds were recorded. These measurements include weld length, weld leg size, exposed weld profile, root penetration, and weld failure angles.

3.4.1 Weld Length

The test end weld lengths for the specimens in the primary test matrix were measured to the nearest 0.001 inches using a vernier calipers. Only one measurement for each weld length was taken.

3.4.2 Leg Size

Both the top and bottom weld leg sizes were measured and recorded to the nearest 0.01 inches using a 'telemicroscope' apparatus. This apparatus consisted of a

Gaertner 10x telescope (Model M511) mounted on a Velmex A2500 C unislide assembly. The shaft of the unislide was attached to a Hewlett Packard HEDS-5300 shaft encoder with a resolution of 500 bits per revolution. Each complete revolution of the unislide shaft corresponded to 1/40 of an inch which, when coupled with the 500 bit per revolution resolution of the shaft encoder, produced a total resolution of the system of 1/20,000 of an inch. However, the accuracy of the measurement was only 0.01 inches because of the measurement process.

The entire leg size measurement apparatus was assembled on a *'strong'* table used *previously for instructional* structural experiments. Figure 3.15 shows the set-up of this apparatus. An aluminum I-beam was used as a support for the unislide equipment. The telescope was then attached to the unislide assembly and leveled. A digital readout box was wired to the shaft encoder such that the displacement of the unislide could be read directly in inches. A steel platform for holding the specimens was also mounted to the 'strong' table and leveled both parallel and perpendicular to the line of sight of the telescope, in the horizontal plane.

Prior to measuring the weld leg sizes, the primary test matrix specimens and the macroetch specimens were painted with oil base paint. Only a thin coat of paint was applied over the test welds. After the paint dried, a fine ball

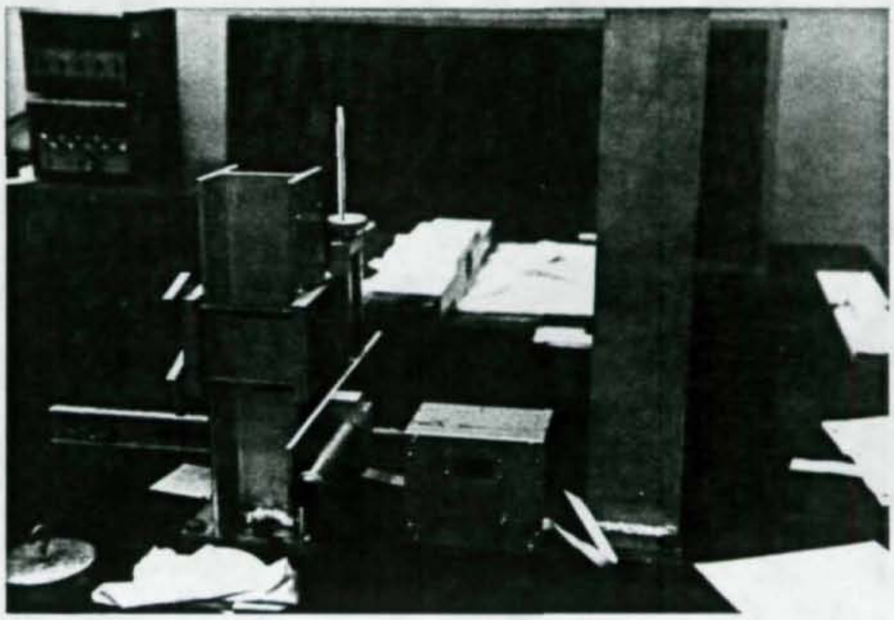


Figure 3.15 Photograph of Weld Leg Size Measurement Apparatus

point pen was used to trace along the weld-plate junction so that a continuous line at the top and bottom legs of the weld was visible. These lines were taken as the limits of the weld legs.

For all eighteen specimens in the primary test matrix, each four inch section of test weld was measured for top and bottom leg size at six different locations. Figure 3.16 shows the location of these leg size measurements on the specimens.

To measure the weld leg sizes, each specimen was placed on the steel platform and leveled in the direction of the line of sight of the telescope. The unislide was then moved until the crosshairs in the telescope lined up with the pen line for the edge of the weld. A reset button had been placed on the digital readout box for zeroing the value shown on the readout box. The crank on the unislide was then turned until the crosshairs in the telescope were lined up with the other marking for the leg size. The value indicated on the digital readout box was then recorded.

Errors were introduced in the measurement process when sighting down the edge of the steel plate at the lower leg of the weld with the telescope. Slight warpage of the plates coupled with slightly out-of-level specimens also could have caused error in the measurements. Thus, leg sizes could only be reported to the nearest 0.01 inches with confidence.

SPECIMEN LEG SIZE MEASUREMENTS

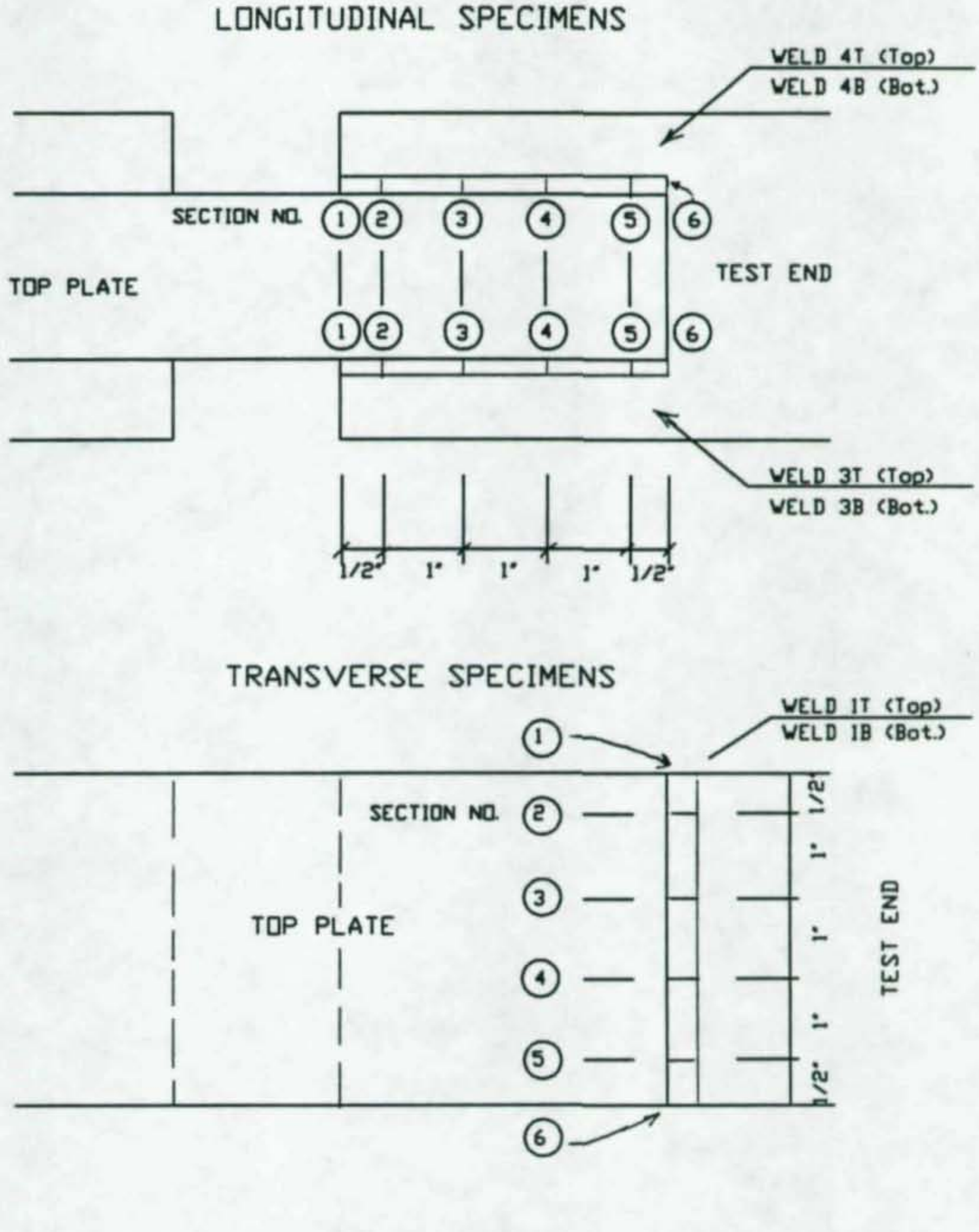


Figure 3.16 Location of Weld Leg Size Measurements

3.4.3 Exposed Weld Profile

The exposed weld profile was considered to be the cross-sectional profile of the fillet weld without the inclusion of any fusion or root penetration. Therefore, this measurement defined the convexity or concavity of the deposited weld metal. This weld profile is an important parameter in the investigation of fillet weld strength, because the weld 'reinforcement' can contribute to the strength of the weld.

An accurate measurement of weld profile is not simple to obtain because the small size and complex geometry of the weld make it difficult to evaluate. In this investigation, an impression of the weld was made from which a plaster mold was cast, in an effort to get an accurate measurement of the weld profile. This plaster mold reproduced the weld configuration along with a portion of the adjoining plates, so that cross sections of the mold could be cut and examined. Enlarged photographs of these cross-sections were taken which clearly defined the profile of the weld. The profile measurements were then taken by 'digitizing' the weld profile with the use of a computer. Details of both the mold casting procedure and the subsequent profile measurements are presented below.

3.4.3.1 Molding Process

A local dentist, Dr. Ronald Hinkel, was contacted to inquire about the process utilized in making molds of human teeth. After a brief discussion and demonstration, it was thought feasible to try a similar process on the specimens in the primary test matrix to reproduce the weld profile.

When molds are made of human teeth, an impression or 'negative' of the mouth is first made through the use of impression material in a plastic casting tray. Then labstone is cast over the impression to form a replica of the teeth, or what might be referred to as a 'positive'. The exact same procedure was used to make molds of a test weld from each specimen in the primary test matrix. One four inch long test weld from each of the eighteen specimens was molded. Unfortunately, due to monetary and time constraints, only one length of test weld could be molded. However, it was thought that this would be a representative sample and would provide some indication of the expected profiles. All of the molds were cast prior to the testing of the specimens. Therefore, the welds had not yet been stressed.

The process for molding the welds involved three stages. In the first stage, a custom impression tray for holding the impression material was made. This process involved mixing a self-curing plastic with water and placing it against the four inch section of weld to be molded. This tray set up to a hard plastic and was used for holding the impression material. In the second stage, Alginate Impression Material (Type II, Regular Set) was mixed with water and placed in the impression tray. The impression tray with the impression material was pressed up against the weld and steady pressure applied for approximately three minutes. The tray was then removed with the impression material sticking to the tray with the impression of the weld formed into it. Stage three involved mixing water with buff labstone and pouring this material over the weld impression and vibrating out the air bubbles. After approximately thirty minutes, the mold was solid enough to be removed from the custom tray. The mold was then allowed to cure for several days before it was saw cut for examination of the weld profile.

3.4.3.2 Measurement Process

After the molds hardened, four cross sections were cut from each mold with a hacksaw. The locations of these cuts corresponded with the four interior sections of the weld (2,3,4, and 5) which were measured by the telemicroscope apparatus discussed in Section 3.4.2. After cutting, these cross sections were sandpapered to a smooth finish. Based on the outline of the steel lap plate and center plate, lines were projected back on the mold by a 0.3 millimeter pencil to locate the approximate point of intersection of the two plates (root). A known dimension was then penciled on the mold by using a vernier caliper. The mold was then positioned on a platform and a photograph was taken of the cross section. A Vivitar 2x macro-focusing teleconverter lens was attached to a 28-105 mm zoom lens on a Nikon FE2 35mm camera. The camera apparatus was mounted on a tripod for better picture quality. Close up filters were also required so the camera could be positioned as near to the mold as possible. Preliminary trial photographs of grid paper showed minimal to no distortion around the edges of the photograph. The weld cross section occupied approximately a 2-3 inch by 2-3 inch portion of a 4 inch by 6 inch print. Figures 3.17 and 3.18 show sample photographs of the cross section of the molds.

A computer-aided-drawing (CAD) program with a Kurta digitizer was used to transfer the photographic image of the weld to a computer drawing. The known dimension penciled on the mold allowed the digitizing board to be directly calibrated to the correct dimensions. Tick marks were drawn on the photograph along the weld profile every 11.25° with a protractor, starting at the bottom weld leg and proceeding to the top leg. The root point, the ends of the top and bottom legs, and each point along the weld profile at 11.25° increments were digitized into the drawing. Any additional

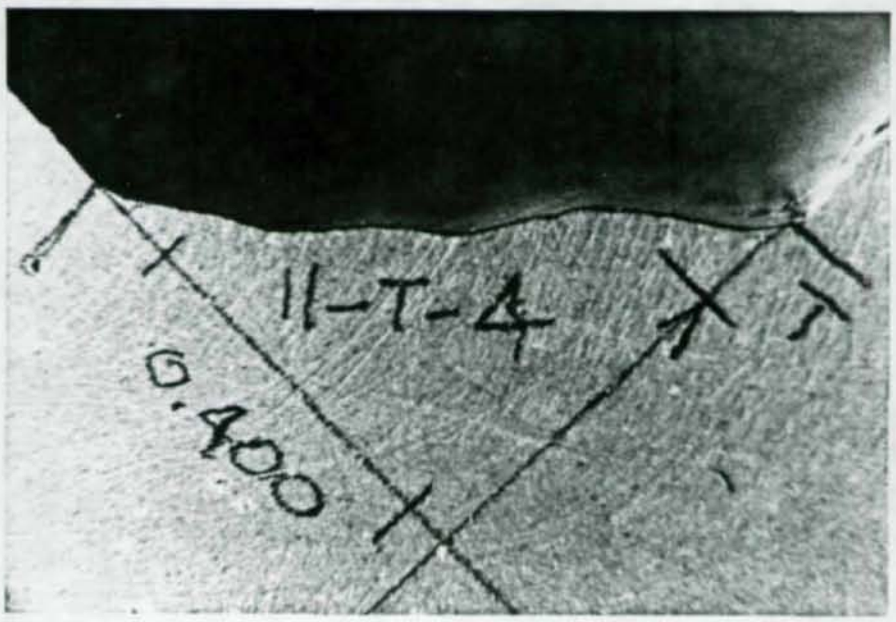


Figure 3.17 Photograph of Weld Mold; Specimen Number 11-4-T-0, Weld 1T, Cut Section Number 4

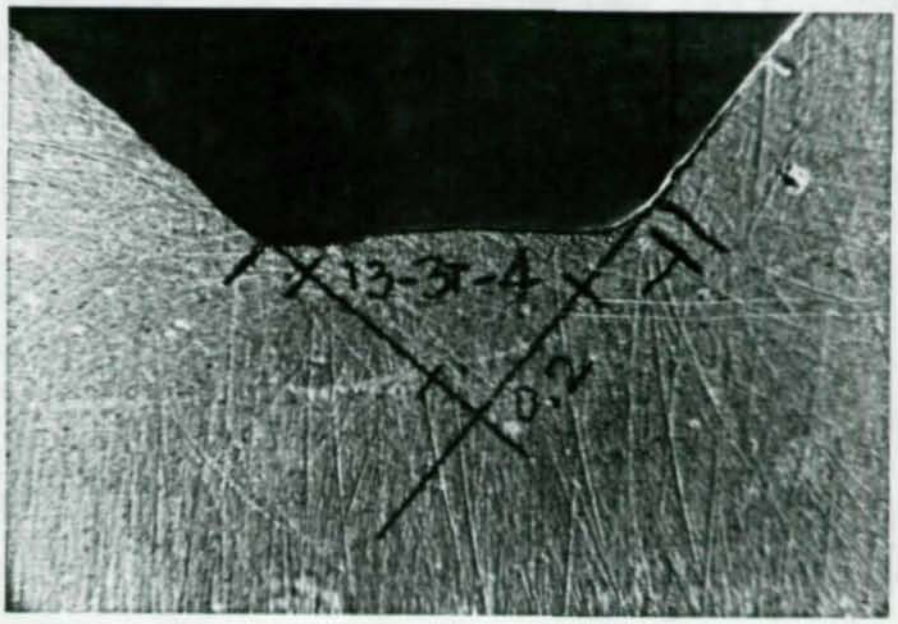


Figure 3.18 Photograph of Weld Mold; Specimen Number 13-2-L-1, Weld 3T, Cut Section Number 4

points which would help define the weld profile were digitized also. Once the profile was drawn, coordinates were established for all of the points. By knowing the coordinates, the radial distances from the root to the outside of the weld were easily computed. Therefore, for each specimen in the primary test matrix, the cross section profiles at four points along one of the test welds was measured.

3.4.4 Root Penetration

Root penetration profiles were measured from the three macroetch specimens fabricated. The three macroetch specimens had all of the weld size and fabrication gap configurations of the welds in the primary test matrix specimens.

Each macroetch specimen was saw cut at four different locations. A surface grinder was then used to bring the surface to a semi-smooth appearance. A lapper removed the lines left on the sections from the surface grinder. Finally, a polishing wheel was used to bring the sections of the specimen around the weld to a medium to high polish.

A 2% nital solution (2 ml HNO_3 concentrate mixed with 98 ml methyl alcohol) was prepared for etching the specimens. Each of the three macroetch sections had been cut into four cross sections containing four welds in each section. Thus, a total of 48 cross-sections were etched. The 2% nital solution was dabbed on the area around the weld with a cotton tip applicator and rubbed gently. The applicator was continually dipped in the nital solution for a period of approximately two minutes until the weld fusion and root penetration pattern could be clearly seen. Before the nital could dry on the surface, a close-up photograph using the 35mm camera with the 2x macro-focusing teleconverter lens, zoom lens, and close-up filters was taken. The photographic apparatus was identical to that used for the specimen molds discussed in Section 3.4.3.2. Thus, 4 x 6 inch photographs were developed and the resulting images of the weld penetration were digitized into a computer drawing as described previously. A small metal strip with a known dimension was placed on the surface near each weld before photographing so the digitizer could be calibrated. Figures 3.19 and 3.20 show typical photographs of the etched sections of weld.

3.4.5 Weld Failure Angles

After each specimen failed, the failure angles on the test welds were measured. Four separate failure angles (sections 2,3,4 and 5, as shown in Figure 3.16) for each four inch test weld were measured with a T-bevel apparatus shown in Figure 3.21. A protractor was placed against the

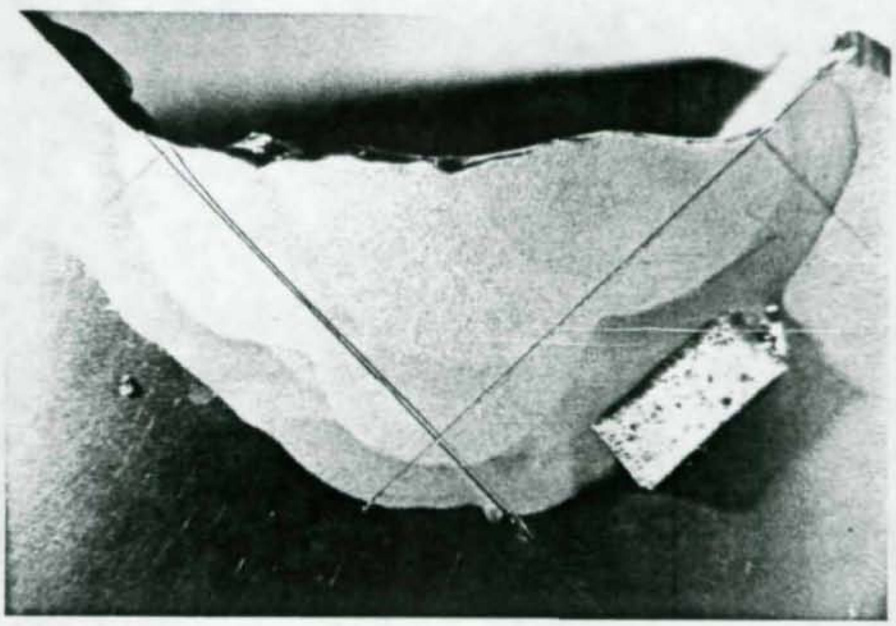


Figure 3.19 Photograph of Etched Cross Section of 1/2 Inch Weld; Specimen M2, Weld 2T, Cross Section Number 4

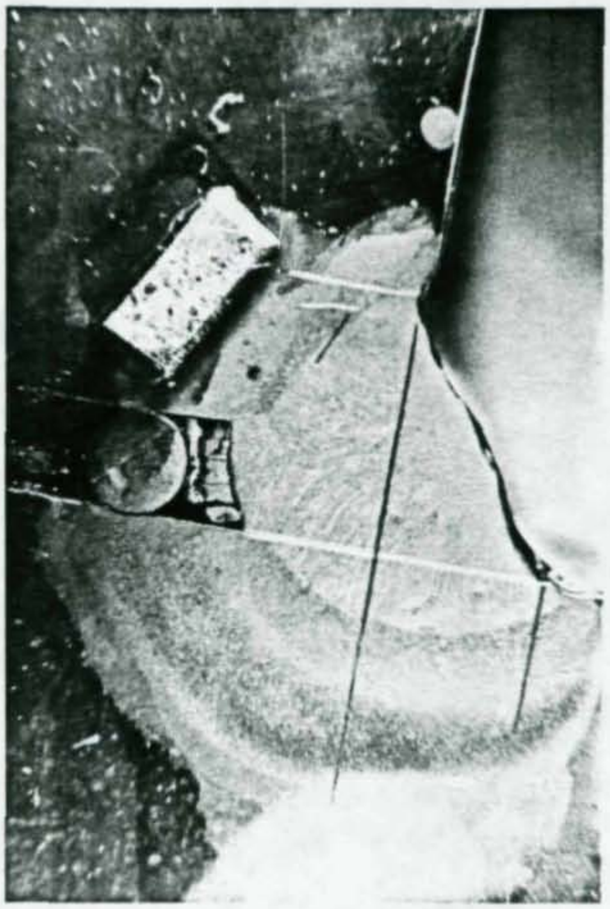


Figure 3.20 Photograph of Etched Cross Section of 1/4 Inch Weld with 1/8 Inch Gap; Specimen M3, Weld 1B, Cross Section Number 2

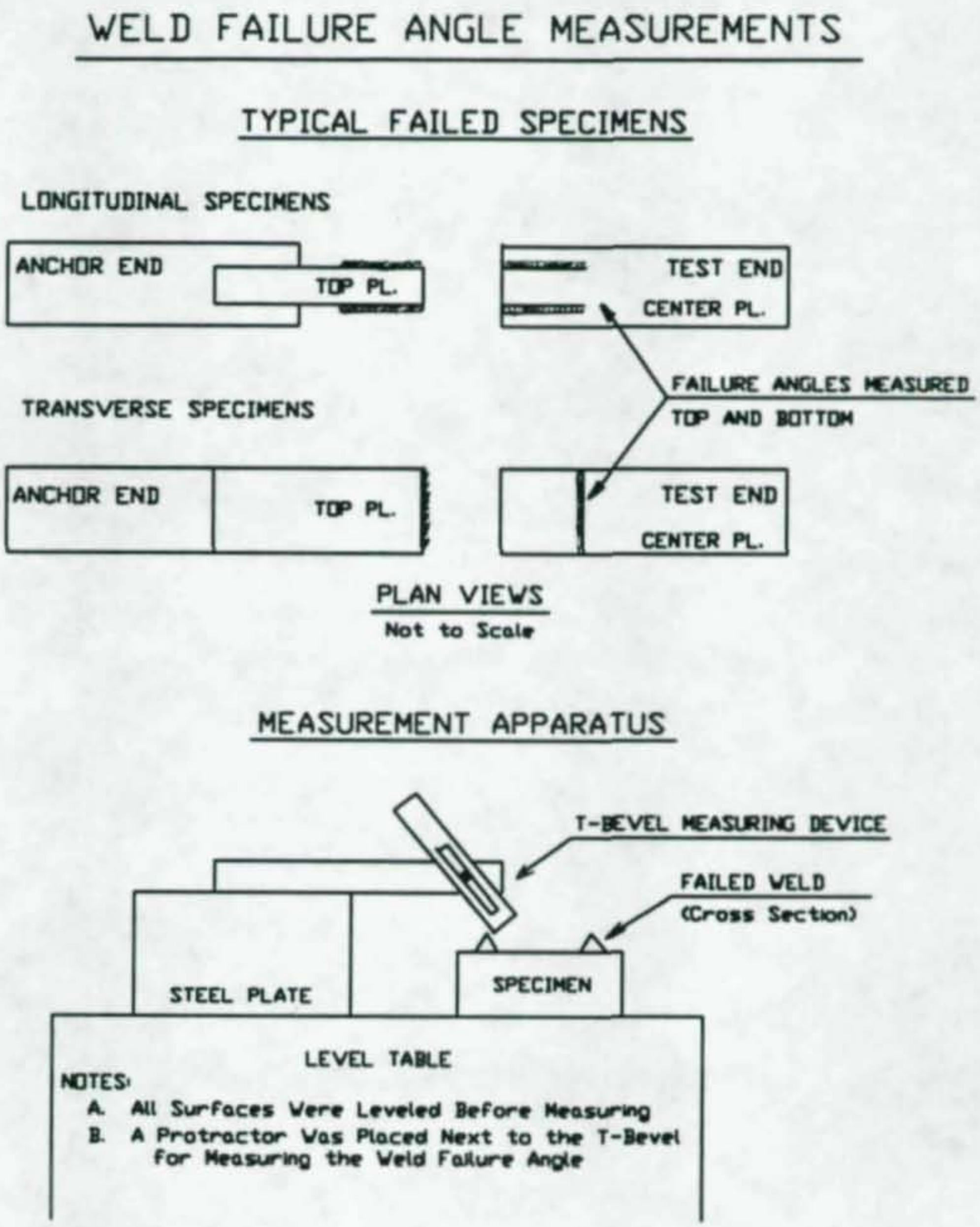


Figure 3.21 Weld Failure Angle Measurements

T-bevel to determine the angle of failure in degrees. The failure angles are reported to the nearest degree, but because of the method of measurement, are probably only accurate to +/- 3°. Furthermore, many of the failure surfaces were not planar, making it difficult to assess the actual failure angle.

3.5 Instrumentation

The instrumentation for the testing of the primary test matrix specimens and the coupon specimens is explained in this section. Since the macroetch specimens were simply cut, polished, and etched, they required no instrumentation.

All of the data from the tests requiring instrumentation were collected using an Optim Optilog 200 data acquisition and control system with OPUS 200 data acquistion software.

3.5.1 Primary Test Matrix

The instrumentation for the specimens in the primary test matrix consisted of a 600 kip Baldwin universal testing machine, strain gages, and linear variable differential transformers (LVDT's) for displacement measurements.

3.5.1.1 Testing Machine

All eighteen of the primary test matrix specimens were tested to failure using a 600 BTE Balwin universal hydraulic testing machine with a 600 kip rated capacity. The testing machine consisted of a separate load frame and control unit which is shown in Figure 3.22 along with the data acquisition center. An analog load dial located on the control unit produced continuous load readings. However, for the use with data acquisition equipment, an LVDT had been previously installed behind the load dial to correlate the load dial movement with the displacement of the LVDT core. With the use of a Schaevitz power source, the voltage output from the LVDT was recorded by the data acquisition system while the load from the analog load dial was recorded by hand. Investigation of the load-voltage data showed that the response of the LVDT-load dial system was tri-linear over the expected ranges of load for the primary test matrix specimens. Thus, the voltage was recorded for all of the tests and later converted to an equivalent load by using the tri-linear calibration equation established. This equation is provided in Appendix B.

3.5.1.2 Deformation Measurement

The weld deformation at a point along one of the test welds for each specimen was recorded by mounting two LVDTs,

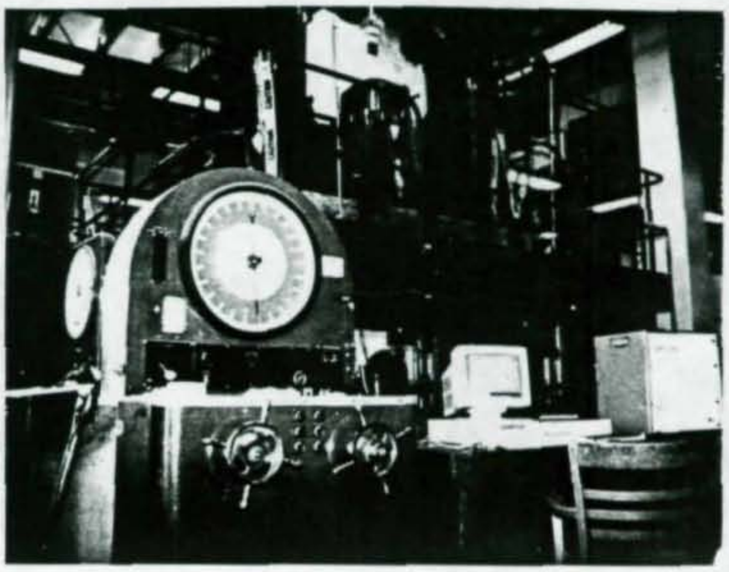
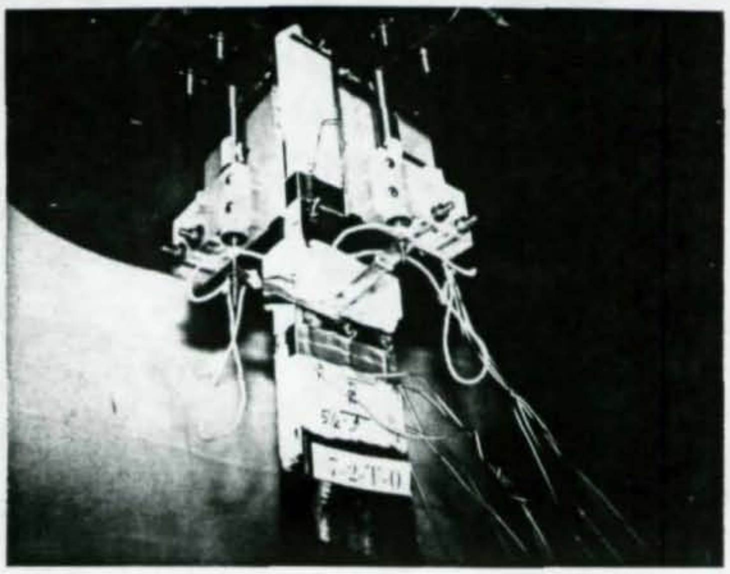


Figure 3.22 Photograph of 600 kip Baldwin Testing Machine with Data Acquisition System

one on each side of the weld, to a rigid metal frame which was bolted to the stationary upper crosshead of the testing machine. A metal tab which was approximately 1/4 inch by 1/4 inch in size was glued to the base metal directly next to both the top and bottom legs of the weld. Hard set 5-minute epoxy was used for all gluing applications. Metal 'arms' which projected out from the specimen were then glued to the metal tabs. The core of the LVDT was attached to a threaded core connecting rod, which was in turn attached to the metal arm by a series of washers and nuts. Figure 3.23 shows the apparatus for measuring the weld deformation.

Since the position of the LVDTs was fixed on the steel frame, each LVDT measured a total displacement of the point to which the tab was glued. This displacement therefore included gripping displacements, base metal deformations, and the weld deformation. However, because two LVDTs were mounted on the frame, both LVDTs measured the same gripping displacement. For the longitudinal weld specimens, the LVDT's were mounted at the center of the weld. It was assumed that the plate deformations on both the top plate and the center plate would be approximately the same at the LVDT site because the plate stresses would be similar. The stresses in the plates near the LVDT site for the transverse specimens would also be approximately equal. Thus, the plate deformations would be similar and would not be included in the deformation because the difference in the



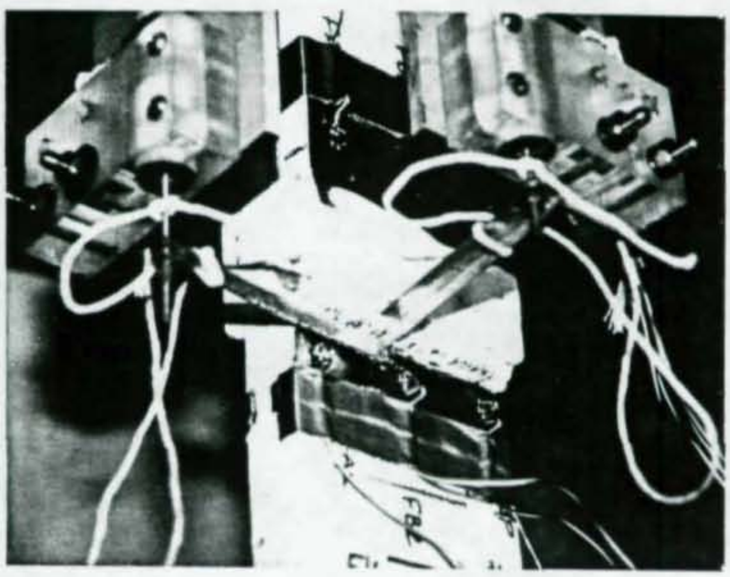


Figure 3.23 LVDT Apparatus; Specimen 7-2-T-0

two LVDT displacements was used. Thus, the difference between the displacements measured by the LVDTs was the weld deformation.

For all of the primary test matrix specimens except 1-2-L-0, two Schaevitz DC-E 500 LVDTs with a range of +/- 0.50 inches from the null output position were used. (Two Schaevitz DC-E 250 LVDTs were selected for specimen 1-2-L-0, but the total displacements went out of the LVDT range, so the larger DC-E 500 LVDTs replaced the DC-E 250 series.)

For the specimens with longitudinal welds, the LVDT apparatus was placed as shown in Figure 3.24, while the placement for the transverse specimens is shown in Figure 3.25. The brackets holding the LVDTs were modified after specimens 1-2-L-0 and 2-2-L-0 were tested so they could be moved towards the specimen or away from it. This was especially useful because it allowed the same metal 'arm' to be used for each specimen without having to fabricate a new one for each test.

3.5.1.3 Strain Gages

Strain gages were placed on all eighteen primary test matrix specimens away from the welds and the grip area on the center plate as shown in Figure 3.26. The purpose of having the gages located in this position was two-fold. First of all, it was possible to determine if there was any

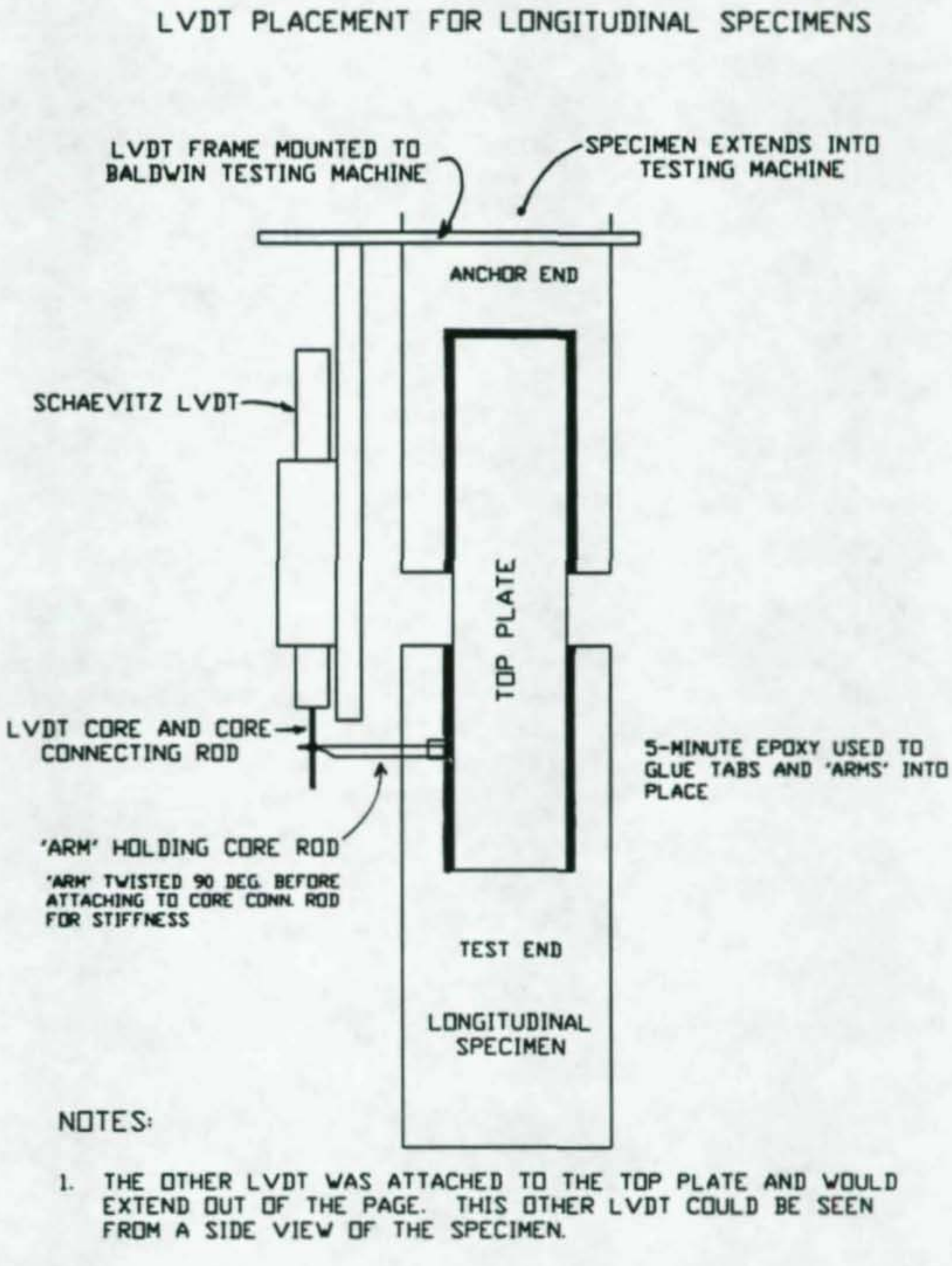


Figure 3.24 LVDT Apparatus; Longitudinal Specimens

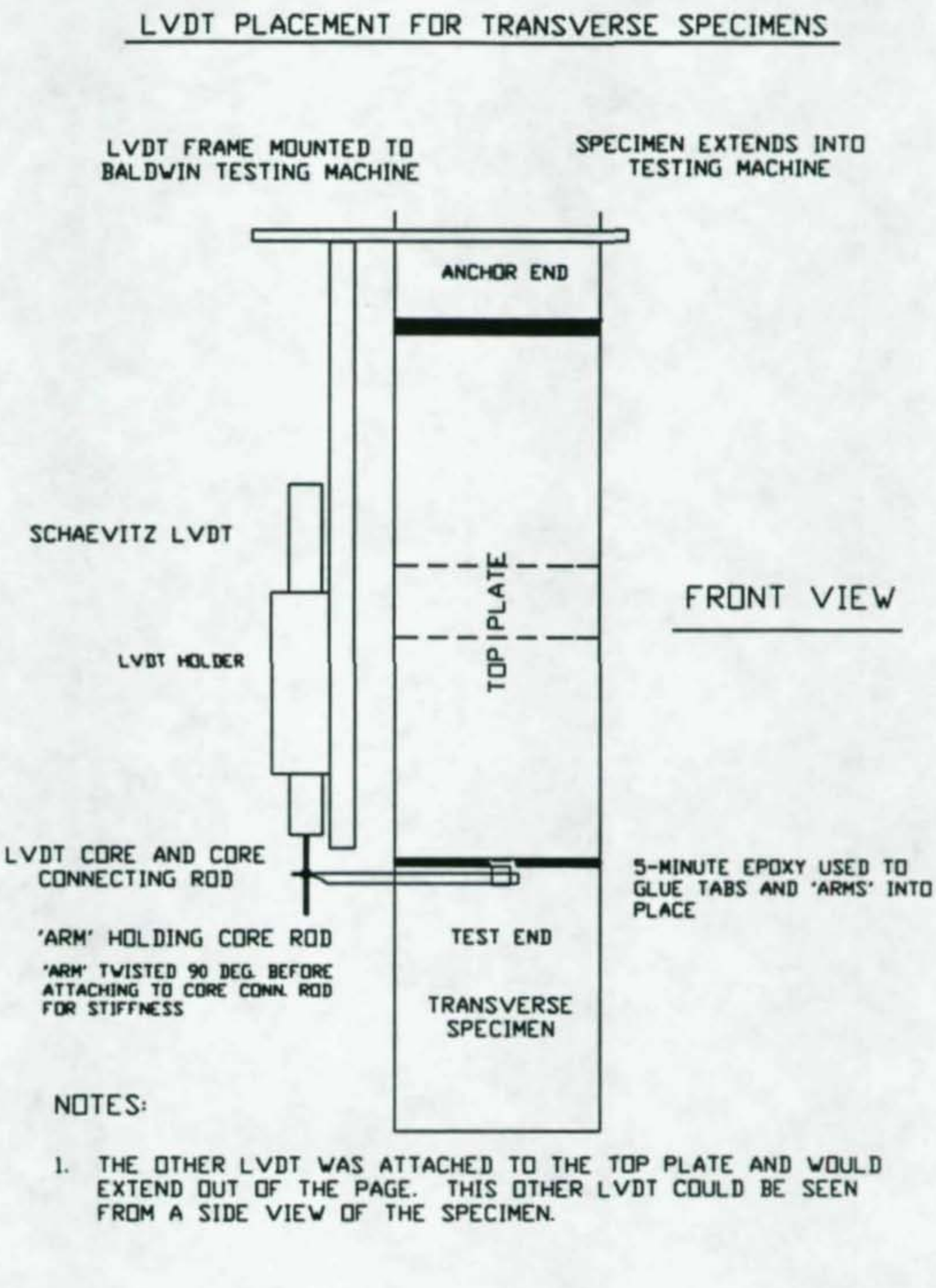


Figure 3.25 LVDT Appartus; Transverse Specimens

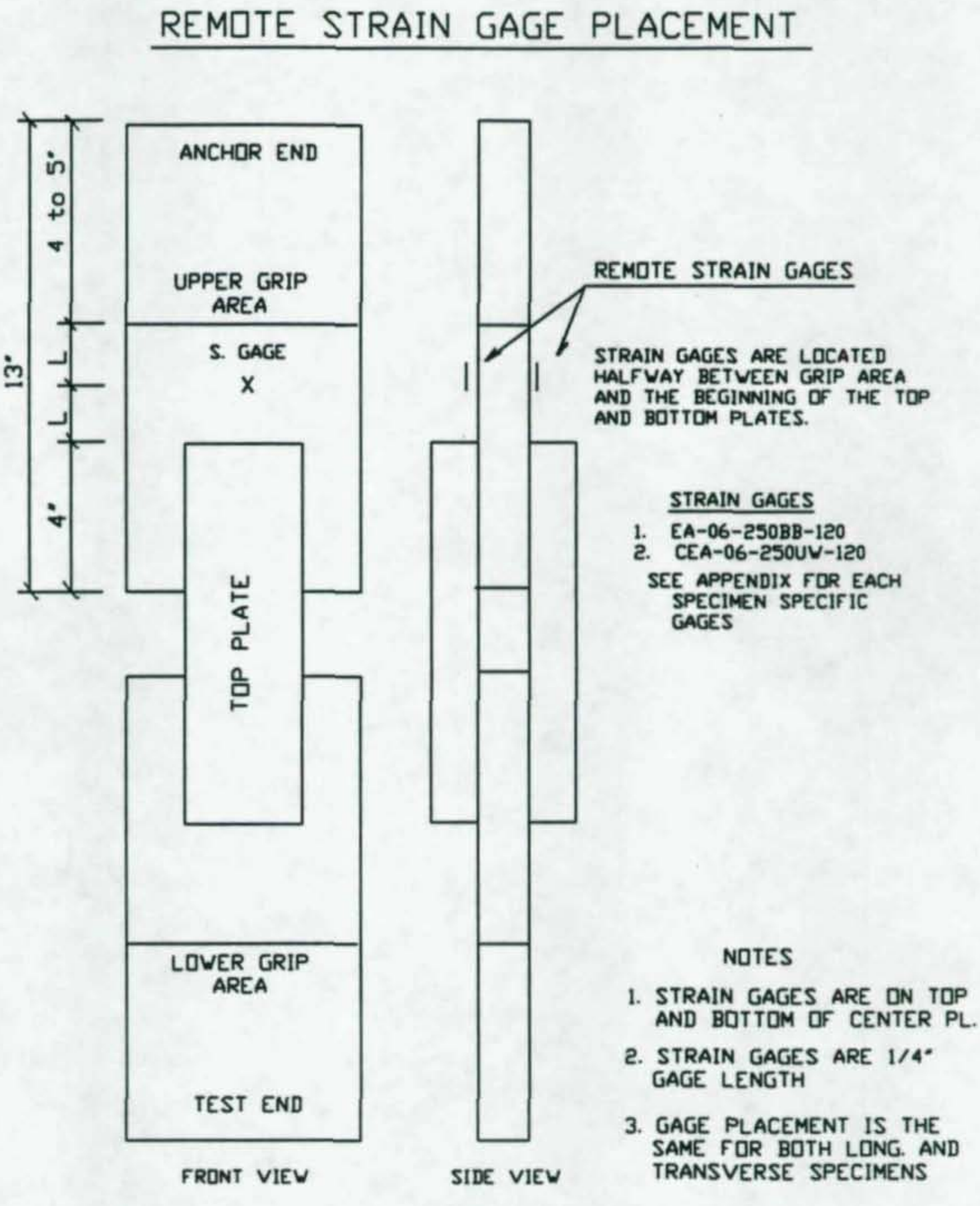


Figure 3.26 Remote Strain Gage Placement

significant bending of the specimen during the test (since wedge grips were used). Secondly, these gages would be able to sense if any yielding in the center plate had occurred during the test. All of the specimens were originally designed to inhibit yielding of the plates but yielding did occur in some of the specimens, as will be discussed in Chapter 4. For all of the specimens except 1-2-L-0, 2-2-L-0, 7-2-T-0, and 11-4-T-0, the two remote strain gages shown in Figure 3.25 were the only strain gages used. These four separate specimens had additional gages which will be discussed in Sections 3.5.1.3.1 through 3.5.1.3.3. The gage placement and the gage types are given in Appendix A for all of the specimens.

Measurements Group, Inc. electrical resistance strain gages were used for all strain gages. All gages were glued according to Micro Measurements specifications using M Bond 200 cyanoacrylate cement. Three wire, 26 gage lead wires were attached to separate terminal strips and single jumper wires were then wired to the strain gage solder tabs. Due to the long lead wire lengths required by the test apparatus, all of the gage factors were corrected to account for lead wire effects. Therefore, direct strain readings were attained. The Optilog data acquisition system used a constant current wheatstone bridge circuit with internal bridge completion to drive the strain gages. The gages were zeroed by the use of voltage injection.

3.5.1.3.1 Specimen 1-2-L-0

Sixteen short gage length strain gages, in addition to the two remote gages, were placed on Specimen 1-2-L-0 to investigate the strain distributions across the top and bottom lap plates. Figure 3.27 shows the location of these gages.

3.5.1.3.2 Specimen 2-2-L-0

Five additional strain gages were placed on Specimen 2-2-L-0 to further investigate the strain distribution across one cover plate. Furthermore, two additional strain gages were placed near the other two remote strain gages to investigate if the specimen was experiencing any two-way bending during testing. Figures 3.28 and 3.29 show the location of the additional strain gages placed on Specimen 2-2-L-0.

3.5.1.3.3 Specimens 7-2-T-0 and 11-4-T-0

Both specimens 7-2-T-0 and 11-4-T-0 had an additional ten short gage length strain gages on the top and bottom lap plates and the center plate to examine the strain

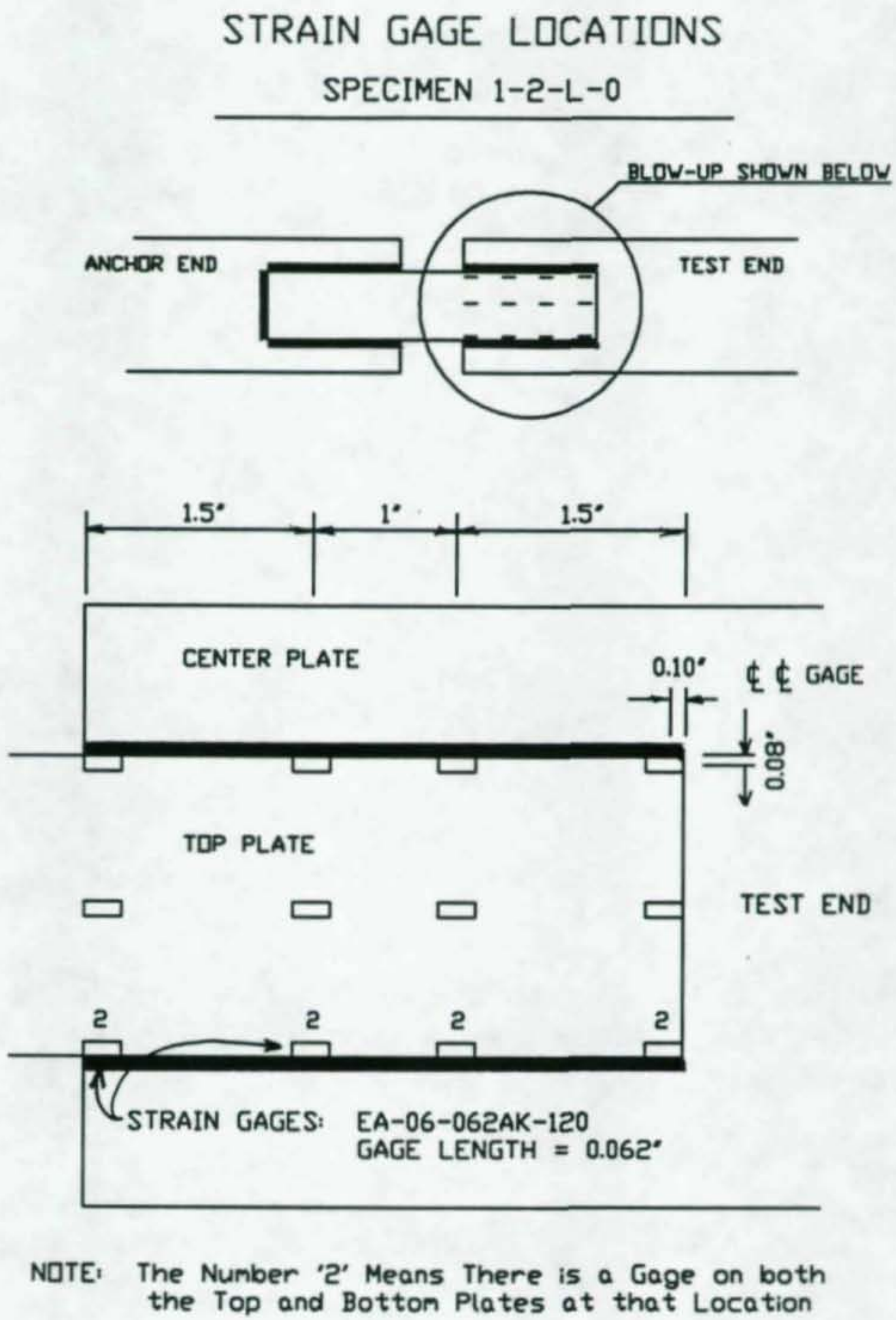


Figure 3.27 Strain Gage Locations; Specimen 1-2-L-0

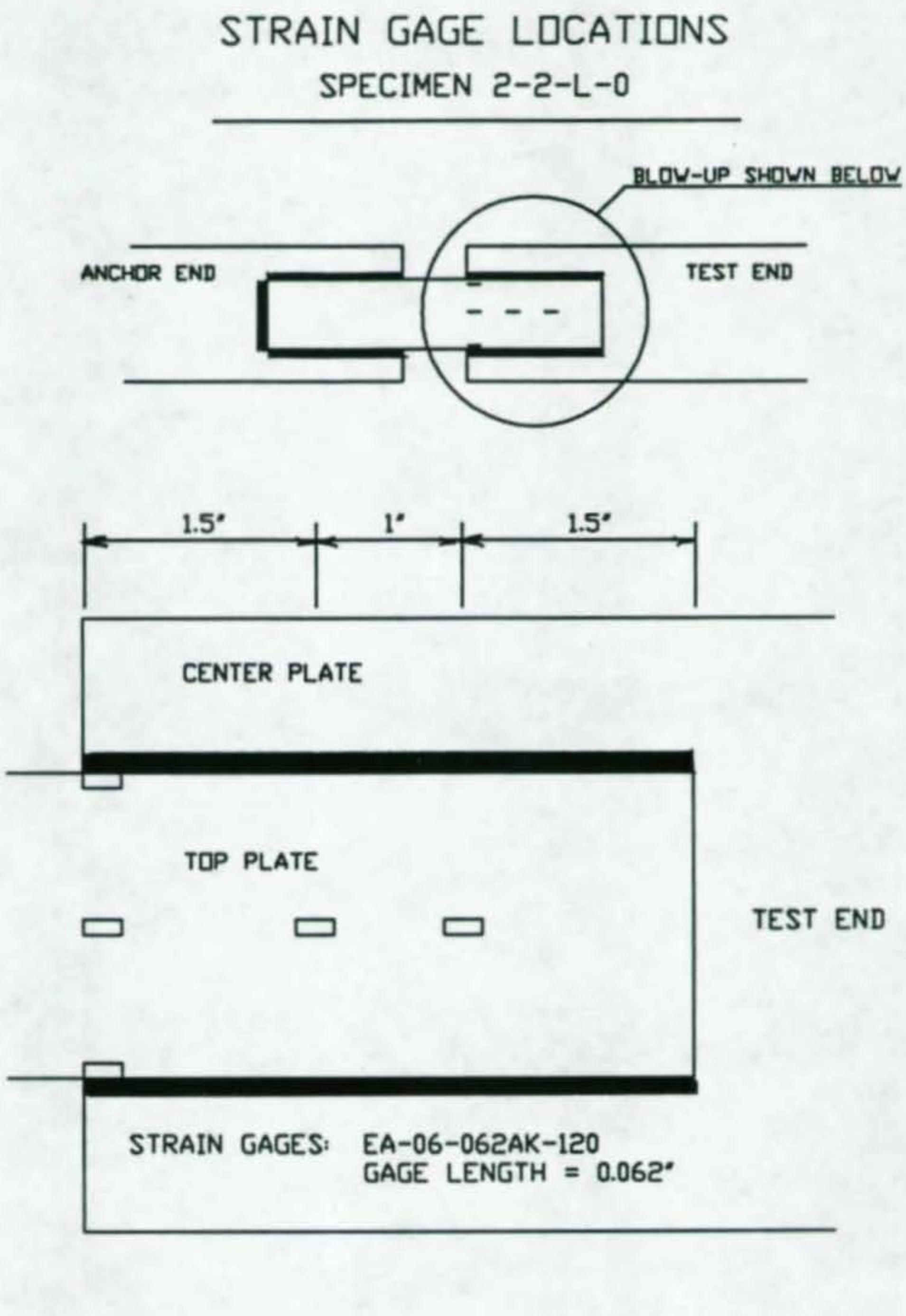


Figure 3.28 Strain Gage Locations; Specimen 2-2-L-0

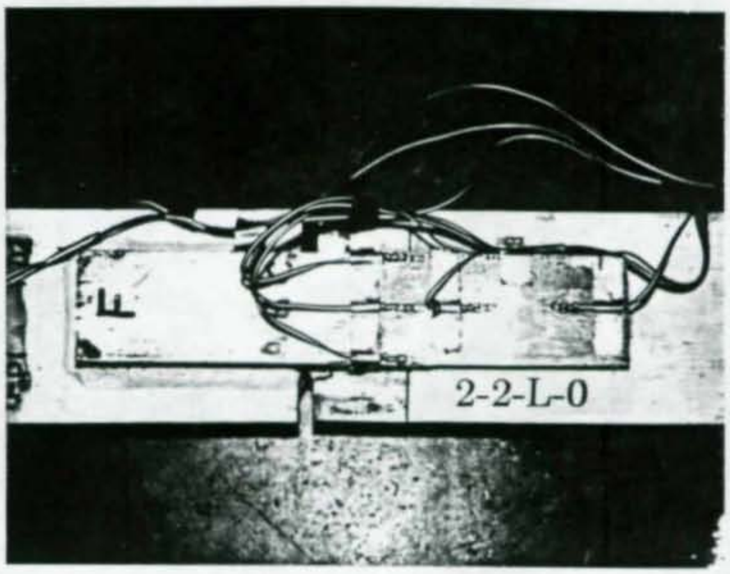


Figure 3.29 Photograph of Strain Gages; Specimen 2-2-L-0

distribution at particular load levels. Figure 3.30 shows the gage placement for these specimens.

3.5.2 Coupon Specimens

The three all-weld-metal coupon specimens (A505) and the base metal coupon specimen were tested to failure using a 220 kip servo-hydraulic MTS 810 testing machine. The machine was equipped with a 464 data display, 410 digital function generator, 445 controller, and a 436 control unit. The hydraulic grips for this testing machine applied a constant pressure to the specimen. The output voltages from the MTS load cell and the LVDT measuring crosshead stroke were fed into the data acquistion system and recorded during the test with the exception of A505 specimen number 1. The stroke voltage was not input into the computer for this test, but only the voltage from the load cell. All of the specimens had additional instrumentation which is discussed below.

3.5.2.1 All-Weld-Metal Coupon Specimens

Two high elongation Measurements Group electrical resistance strain gages were glued on the surface of all three A505 specimens using Micro-Measurements high elongation A-12 epoxy cement. Additionally, an MTS Model 632.25B-20 extensometer with a 2.053 inch gage length was

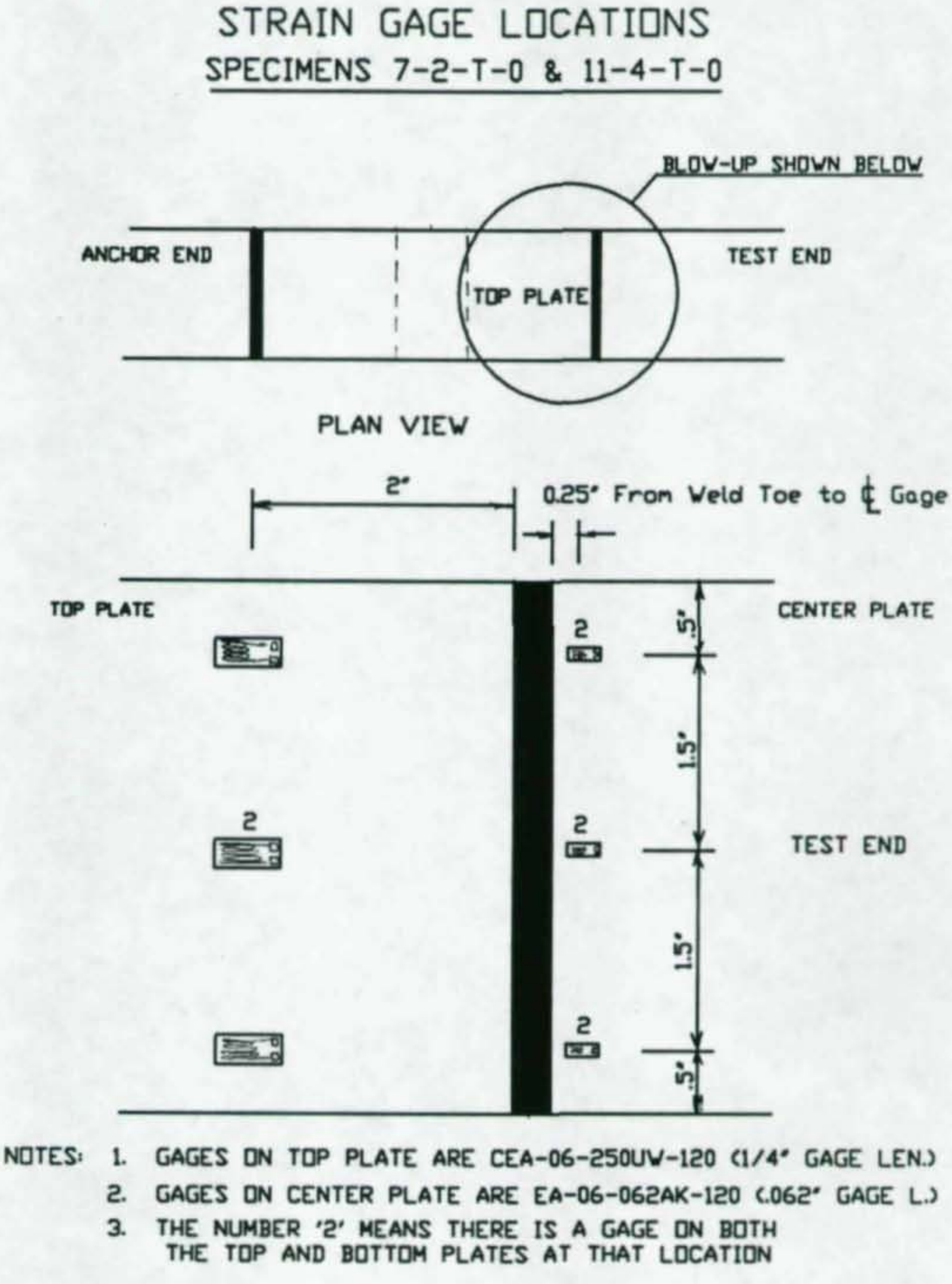


Figure 3.30 Strain Gage Locations; Specimens 7-2-T-0 and 11-4-T-0

attached to each of the three specimens to measure the specimen deformation.

The Optilog data acquisition center was again used in powering the instumentation and recording the data. Furthermore, an X-Y plotter equipped with the MTS testing machine was used to plot the load-stroke data during the tests.

3.5.2.2 Base Metal Coupon Specimen

Two Measurements Group electrical resistance strain gages were glued on the surface of the base metal coupon specimen with M-Bond 200 adhesive. These gages were used to capture the properties of the base metal until slightly past the yield point. Again, the data acquisition system was used for recording all data.

3.6 Test Procedure

The following sections describe the procedure followed for testing the primary test matrix specimens and the coupon specimens.

3.6.1 Primary Test Matrix

All of the eighteen specimens in the primary test matrix were tested to failure using the 600 kip Baldwin testing machine described in Section 3.5.1.1. Prior to testing, two tabs were glued onto the lap and center plates adjoining the weld, after the paint on the plate surface had been scraped off. These tabs were approximately 1/4 inch by 1/4 inch and were glued with 5-minute hard-set epoxy. After the glue hardened, the specimen was mounted in the test frame. The specimen was first gripped in the upper crosshead with the 'anchor end' closest to the upper crosshead. Since wedge action grips were used for holding the specimen, the self-weight of the specimen was enough to allow the specimen to hang alone from the upper crosshead. The length of the center plate in the grip differed for various specimens, ranging from four inches to five inches. The 1/4 inch weld leg size specimens had a four inch grip length, with the 3/8 inch and 1/2 inch specimens having 4-1/2 inches and 5 inches of grip length, respectively.

After hanging the specimen from the upper crosshead, the steel LVDT frame was positioned to allow the metal 'arms' to be glued correctly onto the tabs. The 5-minute epoxy was again used to attach the metal arms to the tabs. Constant thumb pressure was applied for approximately five minutes until the arm was able to remain attached without moving. String was tied around the outstanding end of the arm and secured to the LVDT frame to prevent rotation of the arm while the glue hardened. After the epoxy on the metal arm was allowed to set for a minimum of three hours, and just prior to testing, the LVDT core connecting rod and the LVDT core were fastened to the metal arm after sliding the core into the LVDT body. The core connecting rod was attached to the metal arm by a series of washers and nuts which allowed for fine adjustment of the LVDT core.

The Optilog data acquisition system was run for at least twenty minutes prior to every test to allow the circuits to warm up and stabilize.

After the LVDT attachments were properly secured, the strain gages were all balanced to read zero strain by the use of voltage injection through the data acquistion system. Each LVDT output (which was converted to inches through a calibration equation in the computer) was then 'initialized' by moving the core to a position about 0.4 inches above the null voltage output position (center) of the LVDT body. This was accomplished by adjusting the nuts on the core connecting rod. The reason for the offset initial placement of the LVDT core was that it was anticipated that the total core displacement could possibly exceed 0.50 inches during the test. Since both LVDTs had a range of +/- 0.50 inches, the cores had to be positioned above the zero output point. The two LVDTs had been previously calibrated so that one LVDT read positive for an upwards displacement while the other LVDT read negative for the same upwards displacement. Therefore, the initial starting points of the LVDTs are approximately equal in magnitude but opposite in sign.

(Note: specimen 1-2-L-0 was tested using two Schaevitz +/- 0.25 inch LVDT which were positioned at zero voltage for the start of the test. However, during the test, the core displacements exceeded 0.25 inches, so the longer LVDTs were used on all subsequent tests.)

After the initial LVDT positioning, a scan of all the channels was recorded. Then, the lower crosshead was raised up so the lower part of the specimen with the test welds could be gripped. Once the lower crosshead was in the correct position, the test end of the specimen was gripped with the wedge grips. Another scan of the data channels was recorded. The specimen was then loaded to 25 kips and released to 'seat' the specimen in the grips to ensure the specimen was properly gripped. Another scan of the channels was recorded after the load was released. At this point, if the displacements measured by the LVDTs were still within approximately 0.1 inches (but opposite in sign) the loading of the specimen was begun. If the LVDT displacement values were not within 0.1 inches, the core connecting rods were adjusted so the LVDT ouputs would be closer together. Load was applied continuously to failure at a rate of approximately 0.25-0.50 kips per second in the elastic region of the welds and plates. Data were recorded every five kips until approximately 75% of the failure load was reached. Then, the data were recorded every 2.5 kips until approximately 90% of the failure load was reached at which point the data were recorded every kip until failure. All data were recorded without any stoppage in the loading. By observing the load dial, the data storage process was manually prompted by a key on a computer keyboard. The scan corresponding to each load was recorded by hand to provide a check on the tri-linear load-voltage equation established earlier. The minimum data acquisition system scan rate was forty channels per second. Therefore, the procedure of continuous loading while recording had little impact on the data.

The design of the LVDT frame allowed the weld displacement measurements to be recorded all the way up to the failure load, since the LVDTs did not have to be removed. When failure occurred, the LVDT core and the core connecting rod simply fell out from the LVDT. String attached to the core connecting rod prevented the core from falling to the ground and being damaged. After failure, the final load was recorded and the specimen was removed from the test machine for measurement of the weld failure angles. This same procedure was followed for all eighteen specimens in the primary test matrix.

3.6.2 Coupon Specimens

Both the all-weld-metal (A505) coupon specimens and the base metal coupon specimen were tested in the 220 kip servo-hydraulic test machine discussed in Section 3.5.2 under stroke control mode. This allowed for a constant rate of crosshead movement over time. Testing in stroke control mode is especially helpful in recording the load-deformation behavior near the yield point. The test procedures for both sets of coupon specimens are presented below.

3.6.2.1 All-Weld-Metal Coupon Specimens

The three A505 specimens were tested in the MTS testing machine with the use of special threaded grips fabricated especially for these tests. The specimens were gripped under load control mode and after the specimen was properly gripped, the machine was switched to stroke control mode for the actual testing. The Optilog data acquistion system was used to collect and record the data. Two separate loading rates were used for testing each specimen. The first rate was the slower of the two rates and was used until yield occurred in the specimen. The second rate was a faster rate used after initial yielding, as a result of the large deformations experienced in the post-yield region. A505 specimen number 1 had crosshead stroke rates of 6×10^{-4} inches per second until yield and 4×10^{-3} inches per second after yield and up to failure. The test duration was approximately 25 minutes which was much longer than anticipated. This was because the special grips which were fabricated allowed some 'slop' in the threading of the specimen. This was advantageous because it allowed the specimen to somewhat align itself so the load direction was axial. However, the test duration was too long because time was required to take out the 'slop' between the specimen and the grips. To remedy the problem, the other A505 specimens were loaded in load control mode by hand to approximately two kips. The testing machine was then switched back to stroke control where the function generator was used to automatically load the specimens. The rates of loading were changed for A505 specimens 2 and 3 to 5×10^{-5} inches of crosshead movement per second up to yield and 2.2×10^{-3} inches per second from yield until failure. The test duration became considerably shorter, as was desired.

Data were recorded automatically every three seconds by the Optilog data acquistion system until the specimen failed. Because the specimens were tested under stroke control mode, the extensometer was left on each specimen until failure occurred.

3.6.2.2 Base Metal Coupon Specimen

The one inch base metal coupon specimen was tested in the MTS testing machine using flat grips which applied a constant gripping pressure of 5000 psi to the specimen. Two stroke rates were used once again with rate 1 being approximately 6.5 x 10^{-5} inches of crosshead stroke per second up to yield and 8.3 x 10^{-3} inches per second from yield until failure. The rates were switched during the test by a manually activating a break point switch which changed the rates. Data were recorded by the Optilog data acquisition system.

CHAPTER 4

RESULTS AND DISCUSSION

4.1 Introduction

This chapter presents the results of the series of tests conducted on the various fillet weld specimens. A discussion of these results is also included.

4.2 Results

4.2.1 Weld Nugget Geometry

Measurements were taken on several different cross-sections to evaluate the weld nugget geometry. These measurements include the top and bottom leg sizes at particular locations for every test weld and the weld profile geometry for one test weld of each specimen. Finally, the depth of penetration of the weld into the base metal was examined in the macroetch specimens. The following sections present the results from each of these measurements.

4.2.1.1 Leg Size

Section 3.4.2 presented the procedure for measuring the weld leg sizes using the telemicroscope apparatus. The weld profiles, which were reproduced using plaster molds as described in Section 3.4.3, also gave an indication of the weld leg size. However, the leg measurements from the weld profiles were not used for analysis for two reasons. First, only one of the test welds was molded for each specimen. On the other hand, all of the test welds were measured with the telemicroscope apparatus. Secondly, it was difficult to discern the toe of the weld on the molded specimens after the sections were cut. Therefore, only the telemicroscope values for the leg sizes were used in computing the specimen average leg sizes.

Each four inch test weld was measured at six locations for both bottom and top leg size. The location of these measurements was presented in Section 3.4.2. A weighted average based on the length of the weld segment between the measurement points was used to compute the average leg sizes for each test weld. Thus, the measurements taken at the ends of the welds were only weighted half as much as the other measurements because there was only 1/2 inch between measurement locations, whereas the interior points of measurement were spaced one inch apart. A top and bottom leg size average was computed for each test weld and each of these averages was used to compute a specimen average. The longitudinal specimens had four test welds while the transverse specimens had only two test welds. Appendix Tables E.1 through E.18 present these weld leg size averages for each specimen. Additionally, Tables 4.1 and 4.2 present the average bottom and top leg size for each specimen. An overall average leg size was also computed by simply averaging the top and bottom leg size. Tables 4.1 and 4.2 are organized by nominal specimen leg size. The weighted average leg sizes for the 1/4 inch, 3/8 inch, and 1/2 inch specimens without gaps were 0.300 inches, 0.424 inches, and 0.538 inches, respectively. As the leg size became larger, the amount of extra weld beyond the specified size decreased. This is to be expected because larger size welds require more passes and welders generally will try to get the required size in as few passes as permitted.

The average leg sizes for the gapped specimens is presented in Table 4.2. The 1/4 inch specimens had bottom leg sizes which were considerably smaller than the top leg. This might be expected because the gap introduced was in the direction of the top leg. The reverse effect occurred in the 1/2 inch gapped specimens. However, the gap size as a percentage of the weld size is much smaller for these specimens. Furthermore, because the 1/2 inch weld specimens required four weld passes, the welder probably was able to compensate for the gap.

Table 4.1 Average Leg Size - Ungapped Specimens

LEG SIZE RESULTS				
SPECIMEN NUMBER	NOMINAL LEG SIZE (inches)	AVERAGE WELD SIZES		
		BOTTOM LEG (inches)	TOP LEG (inches)	OVERALL (inches)
1-2-L-0	1/4 INCH NO GAP	0.275	0.268	0.272
2-2-L-0		0.285	0.276	0.281
7-2-T-0		0.317	0.306	0.312
8-2-T-0		0.309	0.367	0.338
AVERAGE STD. DEV.		0.297 0.017	0.304 0.039	0.300 0.026
3-3-L-0	3/8 INCH NO GAP	0.409	0.433	0.421
4-3-L-0		0.383	0.420	0.402
9-3-T-0		0.412	0.470	0.441
10-3-T-0		0.422	0.444	0.433
AVERAGE STD. DEV.		0.407 0.014	0.442 0.018	0.424 0.015
5-4-L-0	1/2 INCH NO GAP	0.538	0.532	0.535
6-4-L-0		0.571	0.555	0.563
11-4-T-0		0.553	0.498	0.526
12-4-T-0		0.541	0.518	0.530
AVERAGE STD. DEV.		0.551 0.013	0.526 0.021	0.538 0.015

Table 4.2 Average Leg Size - Gapped Specimens

LEG SIZE RESULTS -- GAPPED SPECIMENS				
SPECIMEN NUMBER	NOMINAL LEG SIZE (inches)	AVERAGE WELD SIZES BOTTOM LEG (inches)	TOP LEG (inches)	OVERALL (inches)
13-2-L-1	1/4 INCH 1/16" GAP	0.265	0.322	0.294
16-2-T-1		0.308	0.337	0.323
AVERAGE		0.287	0.330	0.308
14-2-L-2	1/4 INCH 1/8" GAP	0.231	0.326	0.279
17-2-T-2		0.251	0.354	0.303
AVERAGE		0.241	0.340	0.291
15-4-L-1	1/2 INCH 1/16" GAP	0.570	0.536	0.553
18-4-T-1		0.617	0.512	0.565
AVERAGE		0.594	0.524	0.559

For all of the specimens the overall average leg size for the entire specimen was greater than the required size specified. The amount of oversize, however, decreased with increasing leg size. For individual leg size measurements for each specimen refer to Appendix E.

4.2.1.2 Exposed Weld Profile

One four inch test weld for each specimen was reproduced using a molding technique described in Section 3.4.3. These molds were cut into four sections for measuring the profile of the weld nugget. A digitizer and a computer-aided-drafting program was used to reproduce this geometry. Appendix C contains the data collected from these measurements along with the specimen number, the weld number, and the cross section number. Coordinates are provided on the figures so dimensions can easily be calculated. All dimensions are in inches with the 'root' *coordinates of (1.00 inches, 1.00 inches) taken as the* reference location. This root location was established by projecting lines back on the molds from the outstanding plates. Therefore, there could be some error in the location of the weld root. However, the profile of the weld was quite accurately measured as described in Chapter 3, and provides a good qualitative representation of the weld profile.

4.2.1.3 Root Penetration

Root penetration for representative weld sizes was measured on the three macroetch specimens as described in Section 3.4.4. The computer-drafted profiles are given in Appendix D with coordinates so the scale of the drawing as printed out can be determined. Table 4.3 shows the average root penetrations which were measured using the CAD program. The three angles of 15, 45, and 58 degrees for which measurements were taken represent the average failure angle for the ungapped transverse specimens (15 degrees), the theoretical root angle (45 degrees), and the average failure angle for the longitudinal specimens (58 degrees).

4.2.2 Coupon Tests

4.2.2.1 All-Weld-Metal Coupon Tests

Three all-weld-metal (A505) coupon specimens were tested as described in Section 3.6.2.1. The raw data from these three tests are presented in Appendix B Tables B.19 through B.21. Table 4.4 gives a summary of the results of these three tests.

Table 4.3 Average Root Penetration

AVERAGE ROOT PENETRATION				
		AVERAGE ROOT PENETRATION BASED ON ANGLE TO HORIZONTAL (inches)		
NOMINAL LEG SIZE (inches)	GAP SIZE (inches)	ANGLE (degrees)		
		15	45	58
1/4	NONE	0.006	0.006	0.006
	1/16	0.062	0.050	0.049
	1/8	0.085	0.063	0.059
3/8	NONE	0.008	0.007	0.007
	1/16	0.061	0.046	0.045
1/2	NONE	0.034	0.029	0.028
	1/16	0.058	0.037	0.035

Table 4.4 All-Weld-Metal Coupon Test Results

ALL-WELD-METAL TENSILE COUPON TEST RESULTS (A505 SPECIMENS)				
(MTS Extensometer for Deformation Measurements)				
A505 SPECIMEN #	1	2	3	AVERAGE
DESCRIPTION				
DIAMETER (inches)	0.498	0.500	0.503	0.500
EXTENSOMETER GAGE LENGTH (inches)	2.053	2.053	2.053	2.053
YIELD STRESS (ksi)	59.0	54.2	60.1	57.8
YIELD STRAIN (%)	0.19	0.18	0.20	0.19
TENSILE STRENGTH (ksi)	70.1	66.7	70.3	69.0
MAXIMUM ELONGATION (%)	38.9	38.4	36.1	37.8

All three of the specimens were welded without controlling the interpass temperature and became very hot during the welding. Also, no stress relieving was performed for the A505 coupon weld plates.

None of the three coupon specimens achieved the minimum tensile strength of 72 ksi as prescribed by the AWS Structural Welding Code for E70xx electrodes ("Specification for Covered Carbon Steel Arc Welding Electrodes", 1981.). The specimen tensile strengths ranged from 66.7 ksi to 70.3 ksi with an average of 69 ksi. The Certified Test Report provided with the electrodes stated a tensile strength of 81 ksi without preheat and stress relieving. A summary of the Certified Test Report is provided in Appendix G. It is unclear why the difference between the A505 specimen tensile strengths and the Certified Test Report tensile strength varied so greatly.

The three A505 specimens exhibited an extremely large amount of ductility. The maximum elongation for each of the three specimens ranged from 36.1% to 38.9% as shown in Table 4.3, with an average of 37.8%. The Certified Test Report stated an elongation of 31%.

4.2.2.2 Base Metal Coupon Test

A single one inch thick base metal coupon specimen was tested as described in Section 3.5.2.2. Appendix B contains the raw data from this test. The ultimate strength and yield strength were found to be 76.3 ksi and 56.2 ksi, respectively. The modulus of elasticity was calculated from linear regression of the elastic portion of the stress-strain curve and was found to be 25,150 ksi. This value is somewhat lower than what might be normally expected for A572 Gr. 50 steel. A mill report was provided with the steel and the results are summarized in Appendix G. The mill report is helpful because only one of the specimen thicknesses was tested and the mill report provides data for all of the thicknesses.

4.2.3 Primary Test Matrix

Each of the eighteen specimens in the primary test matrix were tested to failure as described in Section 3.6.1. During each of these tests, the load and deformation were recorded up to the failure of the specimen. Appendix B contains all of the raw data from the tests. The peak load and ultimate deformation were then noted. These values are reported in Tables 4.5 and 4.6. Table 4.5 groups all of the longitudinal specimens together and the transverse specimens together and reports the actual peak load recorded. Table 4.6 presents the specimens in numerical order with the peak loads being reported per inch of weld length to eliminate weld length as a variable. As a further aid to the

Table 4.5 Primary Test Matrix Results

SUMMARY OF TEST RESULTS						
				AVERAGE WELD SIZES		
SPECIMEN NUMBER	PEAK LOAD (kips)	ULT.DEFORM. (inches)	WELD LENGTH (inches)	BOTTOM LEG (inches)	TOP LEG (inches)	OVERALL (inches)
1-2-L-0	247	N.A.	15.756	0.275	0.268	0.272
2-2-L-0	243	0.129	15.817	0.285	0.276	0.281
3-3-L-0	336	0.239	15.776	0.409	0.433	0.421
4-3-L-0	332	0.266	15.708	0.383	0.420	0.402
5-4-L-0	352	0.311	15.803	0.538	0.532	0.535
6-4-L-0	380	0.228	16.184	0.571	0.555	0.563
13-2-L-1	236	0.250	15.856	0.265	0.322	0.294
14-2-L-2	242	0.147	15.855	0.231	0.326	0.279
15-4-L-1	388	0.305	15.603	0.570	0.536	0.553
7-2-T-0	184	0.043	7.925	0.317	0.306	0.312
8-2-T-0	190	0.083	7.915	0.309	0.367	0.338
9-3-T-0	247	0.058	8.053	0.412	0.470	0.441
10-3-T-0	256	0.056	8.036	0.422	0.444	0.433
11-4-T-0	293	0.044	8.011	0.553	0.498	0.526
12-4-T-0	294	0.053	8.009	0.541	0.518	0.530
16-2-T-1	179	0.157	7.942	0.308	0.337	0.323
17-2-T-2	162	0.121	7.979	0.251	0.354	0.303
18-4-T-1	286	0.156	8.001	0.617	0.512	0.565

Table 4.6 Test Results - Based on Load per Inch of Weld

SUMMARY OF TEST RESULTS						
	PEAK LOAD Per Inch			AVERAGE WELD SIZES		
SPECIMEN NUMBER	of Weld (kips/in)	ULT. DEFORM. (inches)	WELD LENGTH (inches)	BOTTOM LEG (inches)	TOP LEG (inches)	OVERALL (inches)
1-2-L-0	15.7	N.A.	15.756	0.275	0.268	0.272
2-2-L-0	15.4	0.129	15.817	0.285	0.276	0.281
3-3-L-0	21.3	0.239	15.776	0.409	0.433	0.421
4-3-L-0	21.1	0.266	15.708	0.383	0.420	0.402
5-4-L-0	22.3	0.311	15.803	0.538	0.532	0.535
6-4-L-0	23.5	0.228	16.184	0.571	0.555	0.563
7-2-T-0	23.2	0.043	7.925	0.317	0.306	0.312
8-2-T-0	24.0	0.083	7.915	0.309	0.367	0.338
9-3-T-0	30.7	0.058	8.053	0.412	0.470	0.441
10-3-T-0	31.9	0.056	8.036	0.422	0.444	0.433
11-4-T-0	36.6	0.044	8.011	0.553	0.498	0.526
12-4-T-0	36.7	0.053	8.009	0.541	0.518	0.530
13-2-L-1	14.9	0.250	15.856	0.265	0.322	0.294
14-2-L-2	15.3	0.147	15.855	0.231	0.326	0.279
15-4-L-1	24.9	0.305	15.603	0.570	0.536	0.553
16-2-T-1	22.5	0.157	7.942	0.308	0.337	0.323
17-2-T-2	20.3	0.121	7.979	0.251	0.354	0.303
18-4-T-1	35.7	0.156	8.001	0.617	0.512	0.565

presentation of this data, Figure 4.1 graphically shows the weld strength per inch of weld based on the actual leg size. Each of specimen identification numbers is shown on this graph. The 1/2 inch longitudinal welds showed a significant reduction in strength when simply using the linear design philosophy using the 1/4 inch specimens for reference. This effect will be discussed in greater detail later in this chapter.

All eighteen of the primary test matrix specimens failed in the welds. The longitudinal specimens exhibited a two-stage failure. The initial failure occurred at the peak load. However, at this point only two of the four test welds failed, with both of the failed welds on the same side. The testing machine shed the load after the initial failure but two of the welds had not failed. The specimen was loaded again until complete failure occurred in the two unfailed welds. Because the connection was eccentric to the load axis after failure of the welds on one side only, a significant amount of bending was present in the specimens. No data were used from the second stage of loading of these longitudinal specimens.

4.2.4 Weld Failure Angles

After the specimens had failed and were removed from the testing machine, the failure angle of the weld was

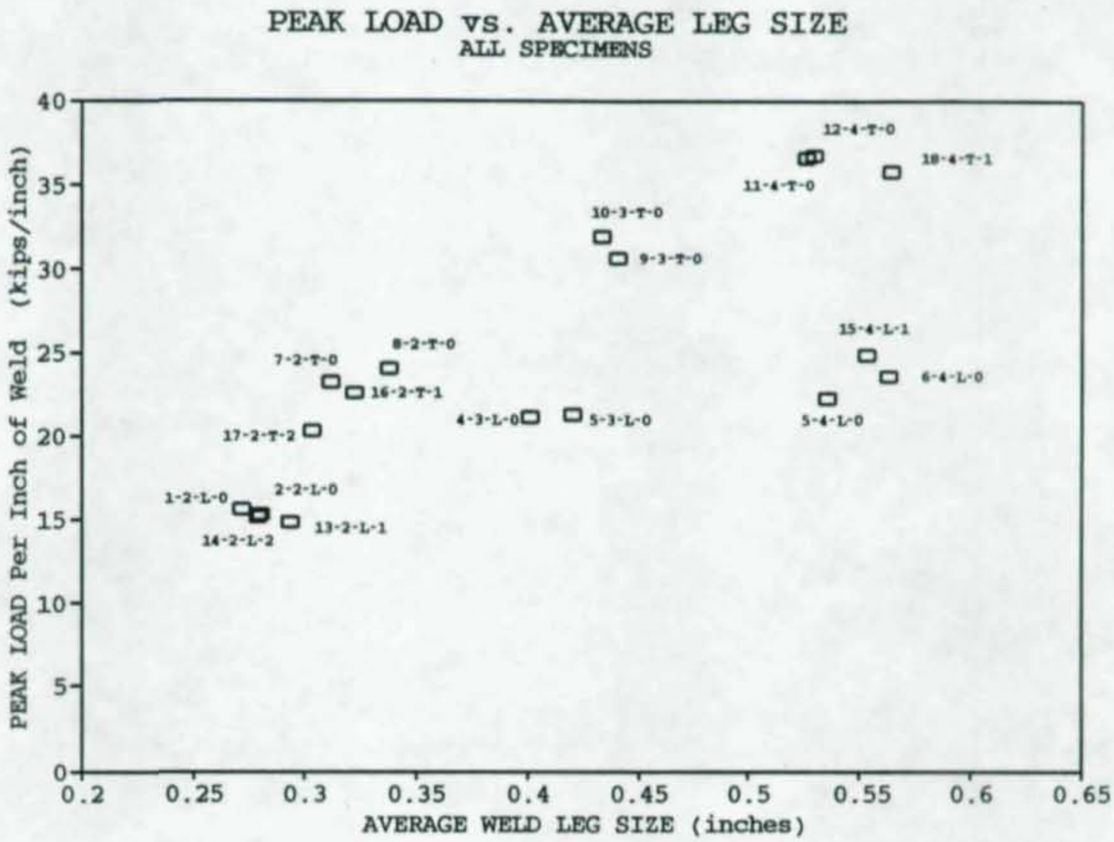


Figure 4.1 Primary Test Matrix Specimen Results

measured as described in Section 3.4.5. For the longitudinal specimens which exhibited a two-stage failure, only the test welds which failed first were used for analysis. Figure 4.2 shows the weld failure angle measurement along with the typical weld profile for the 1/4 and 3/8 inch specimens. Table 4.7 shows the average failure angle for each specimen and for groups of specimens as well. The average failure angle for the longitudinal specimens without gaps was 60 degrees while the gapped specimen failure angles averaged 55 degrees. This difference is insignificant because the measurement process introduced error which could account for the difference. The ungapped transverse specimens had an average failure angle of 15 degrees while the gapped specimen failure angles averaged 25 degrees. Overall, the failure angle averages compare within reason to commonly accepted failure angle values of 45 degrees for longitudinal specimens and 22 degrees for transverse specimens. Longitudinal and transverse welds have different failure angles because of the direction in which the welds are loaded. Longitudinal welds are primarily loaded in shear while transverse welds are loaded in combined shear and tension. This loading, therefore, results in a different failure angle of the weld.

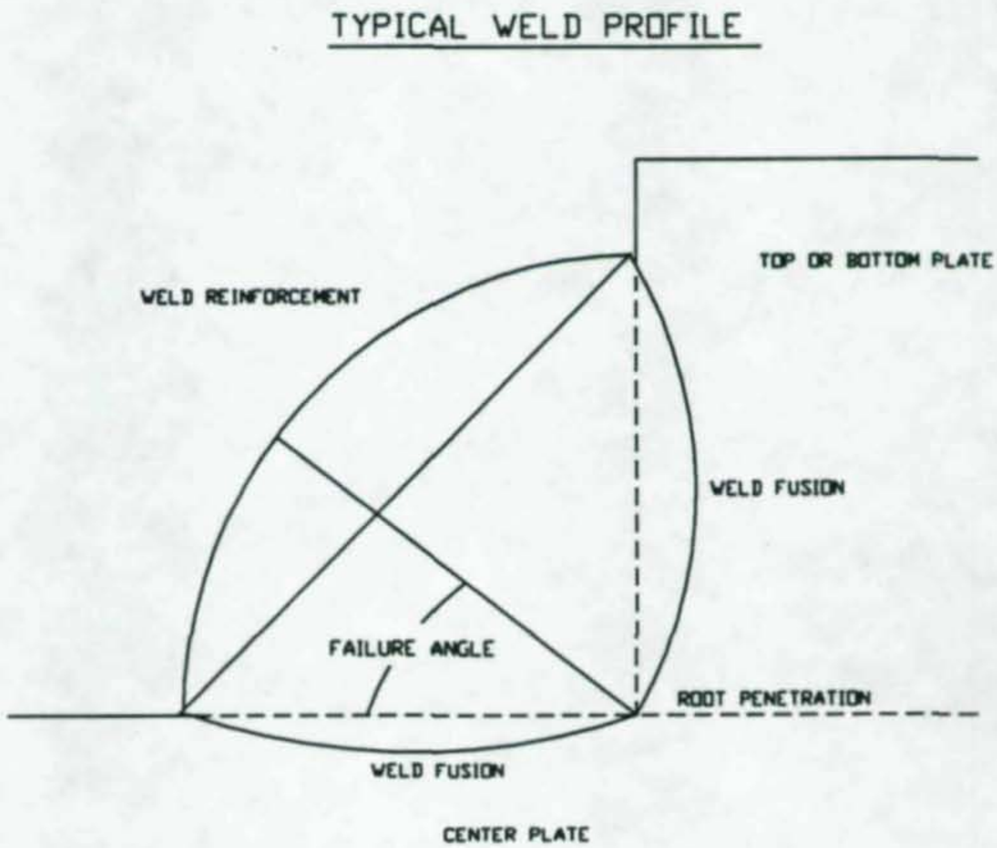


Figure 4.2 Typical Weld Profile

Table 4.7 Average Weld Failure Angles

WELD FAILURE ANGLES					
LONGITUDINAL SPECIMENS			TRANSVERSE SPECIMENS		
SPECIMEN NUMBER	WELD NUMBER	FAIL. ANG. (degrees)	SPECIMEN NUMBER	WELD NUMBER	FAIL. ANG. (degrees)
1-2-L-0	3B, 4B	64	7-2-T-0	1T, 1B	16
2-2-L-0	3B, 4B	65	8-2-T-0	1T, 1B	13
3-3-L-0	3T, 4T	57	9-3-T-0	1T, 1B	14
4-3-L-0	3T, 4T	61	10-3-T-0	1T, 1B	14
5-4-L-0	3B, 4B	57	11-4-T-0	1T, 1B	15
6-4-L-0	3T, 4T	55	12-4-T-0	1T, 1B	16
13-2-L-1	3T, 4T	61	16-2-T-1	1T, 1B	22
14-2-L-2	3T, 4T	53	17-2-T-2	1T, 1B	27
15-4-L-1	3T, 4T	50	18-4-T-1	1T, 1B	25
AVERAGE FAILURE ANG.			AVERAGE FAILURE ANG.		
	UNGAPPED	60		UNGAPPED	15
	GAPPED	55		GAPPED	25
	OVERALL	58		OVERALL	18

4.2.5 Load-Deformation Behavior

The load-deformation response of each specimen was measured as described in Section 3.5.1.2. These data have been summarized in graphical format and are shown in Figures 4.3 through 4.19. Included on these graphs are the theoretical curves given in the AISC Allowable Stress Design 9th Edition Manual (1989) and the LRFD Manual (1986). The two design manuals use different theoretical load-deformation curves. The ASD curve is the same one used in the 8th Edition Manual and was developed from tests on E60xx electrodes by Butler, Pal, and Kulak (1972). Because these equations are for E60xx electrodes, the curves presented herein have been adjusted by a factor of 70/60 to account for the use of E70xx electrodes. The 1986 LRFD manual uses a different set of equations developed by Kulak and Timler (1984) from tests on E70xx electrodes. Therefore, these equations have not been scaled because they are based on E70xx electrodes. It is unclear why AISC has not changed the equations in the 9th Edition ASD manual to account for this new data by Kulak and Timler (1984) since the LRFD manual has adopted the revised equations.

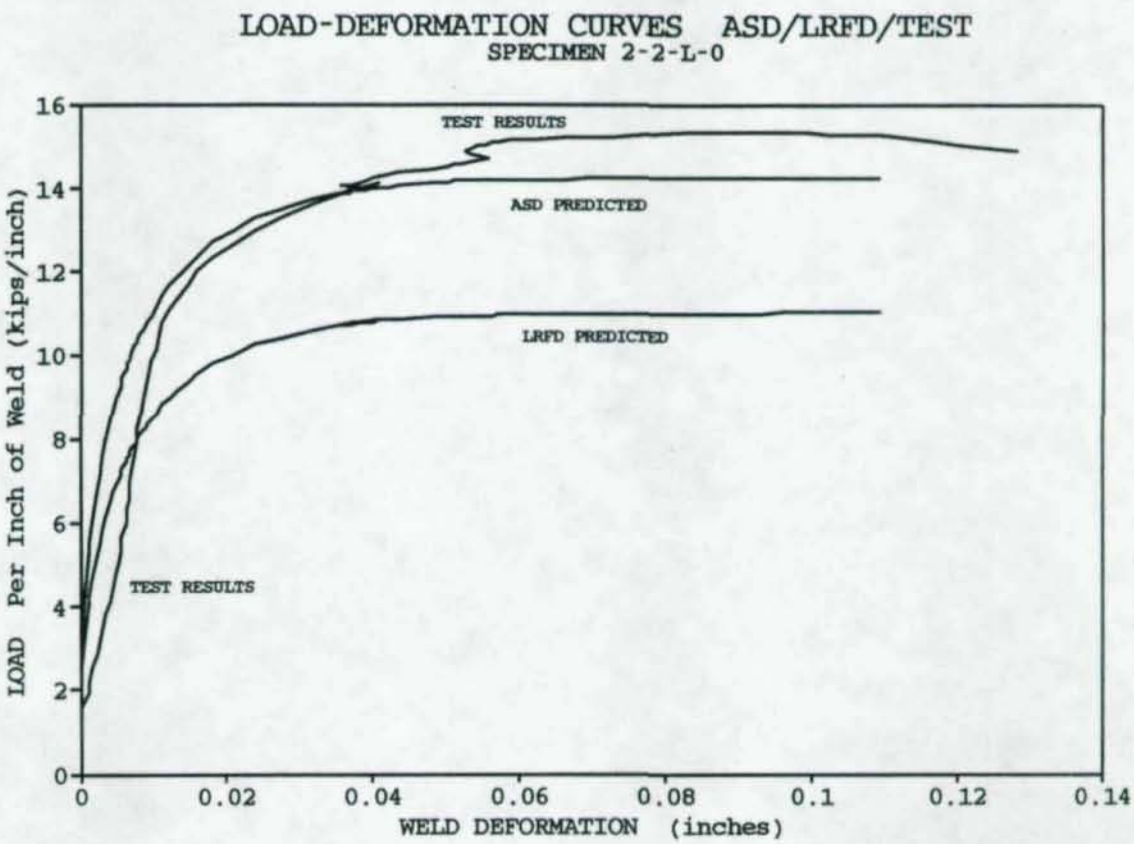


Figure 4.3 Load-Deformation Results; Specimen 2-2-L-0

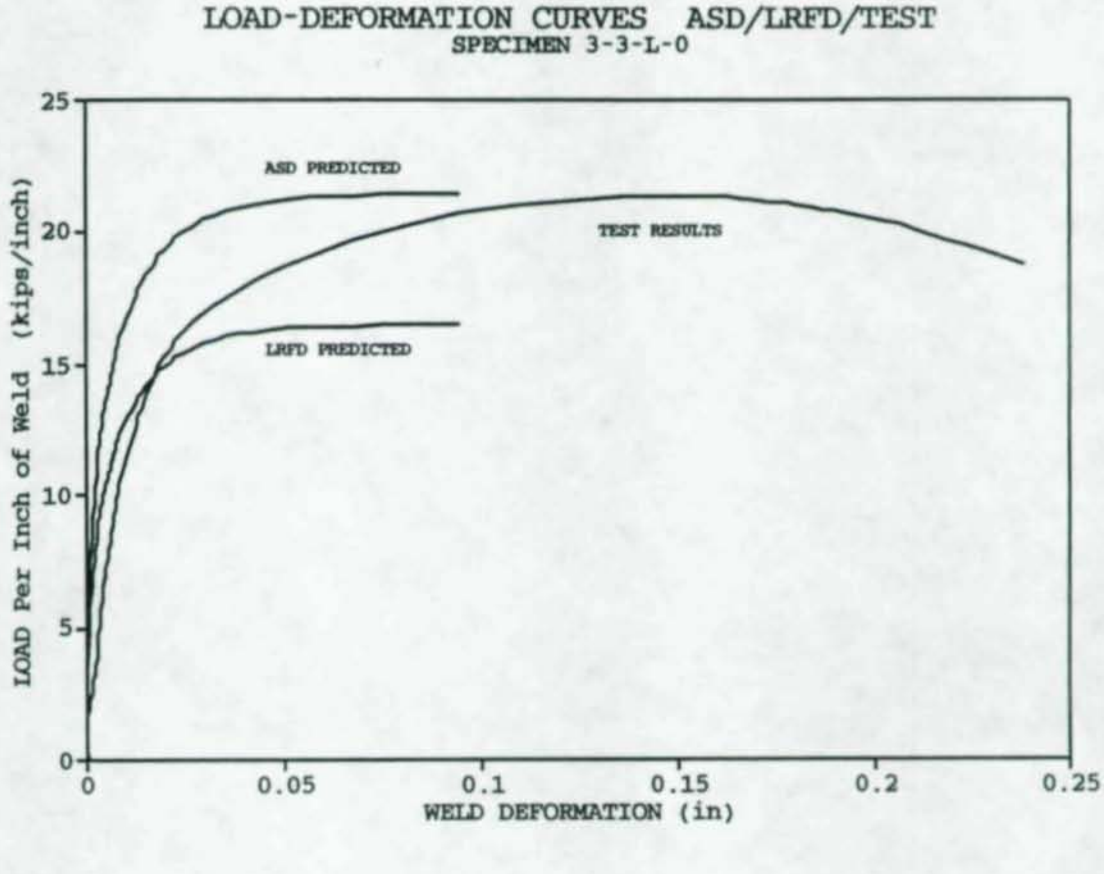


Figure 4.4 Load-Deformation Results; Specimen 3-3-L-0

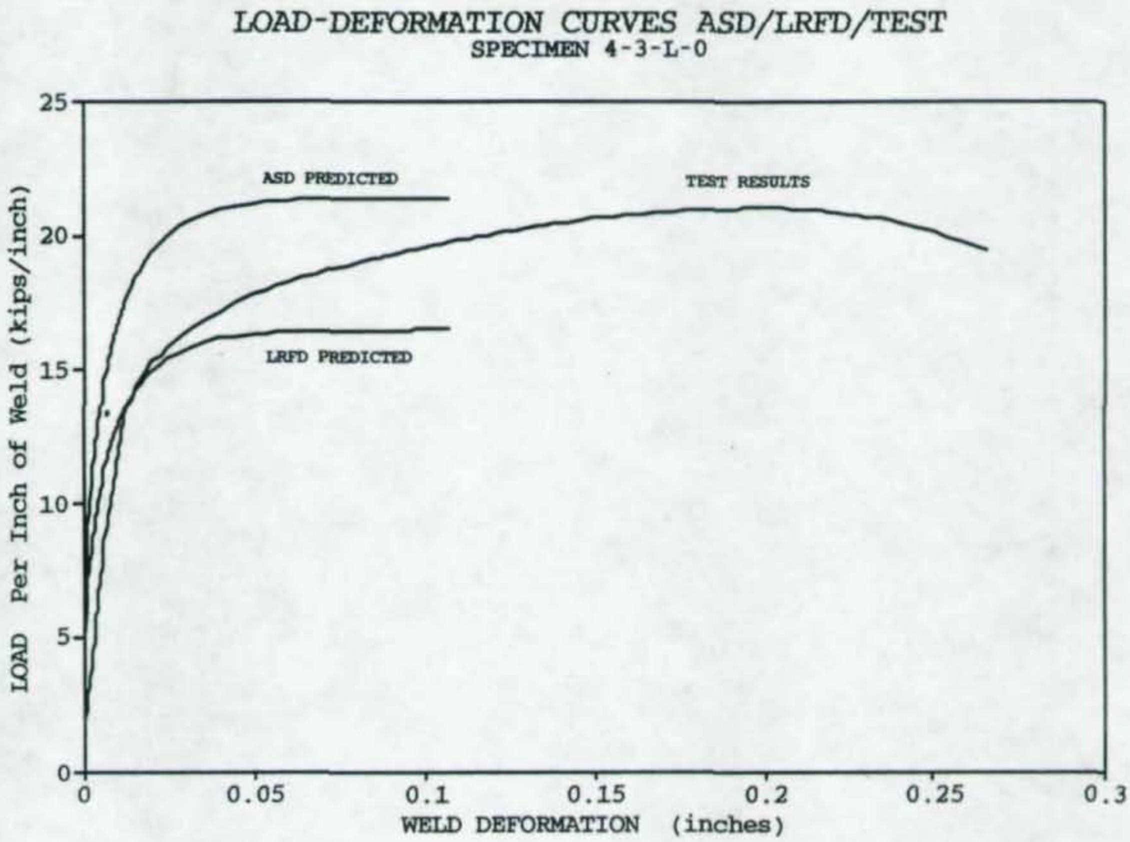


Figure 4.5 Load-Deformation Results; Specimen 4-3-L-0

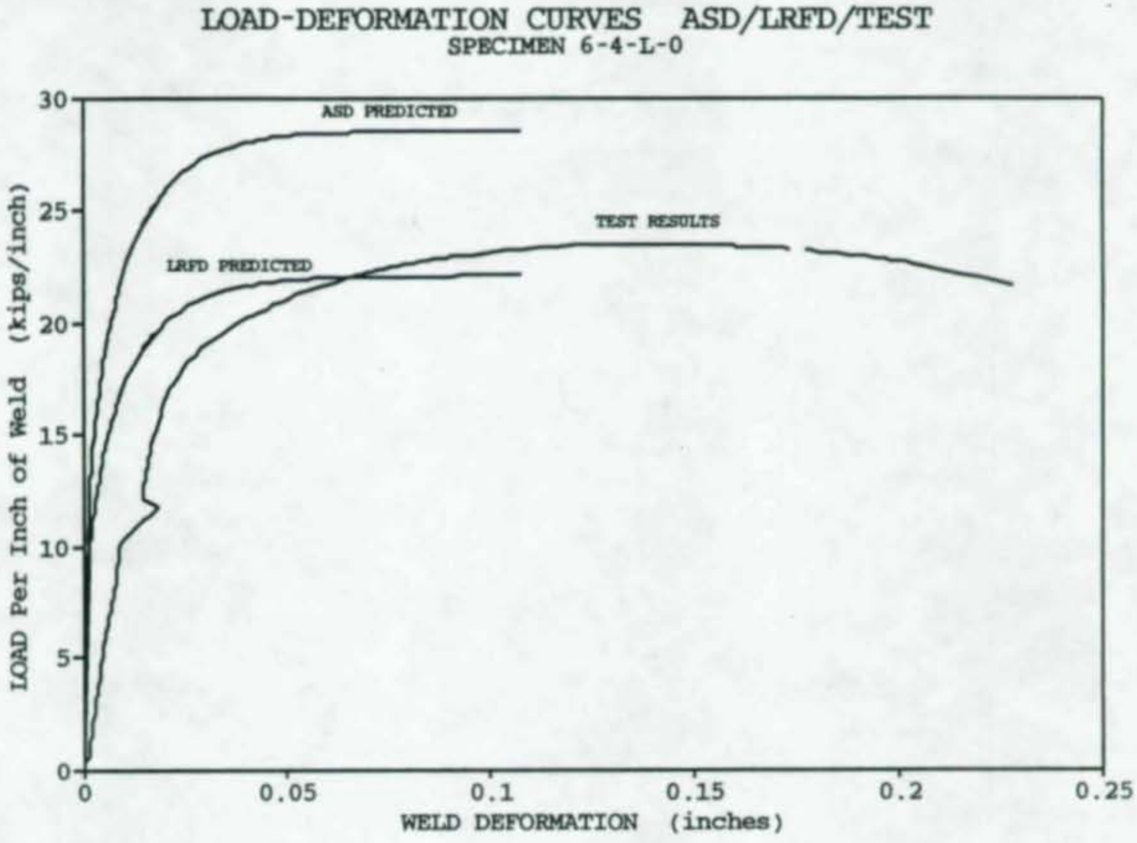


Figure 4.7 Load-Deformation Results; Specimen 6-4-L-0

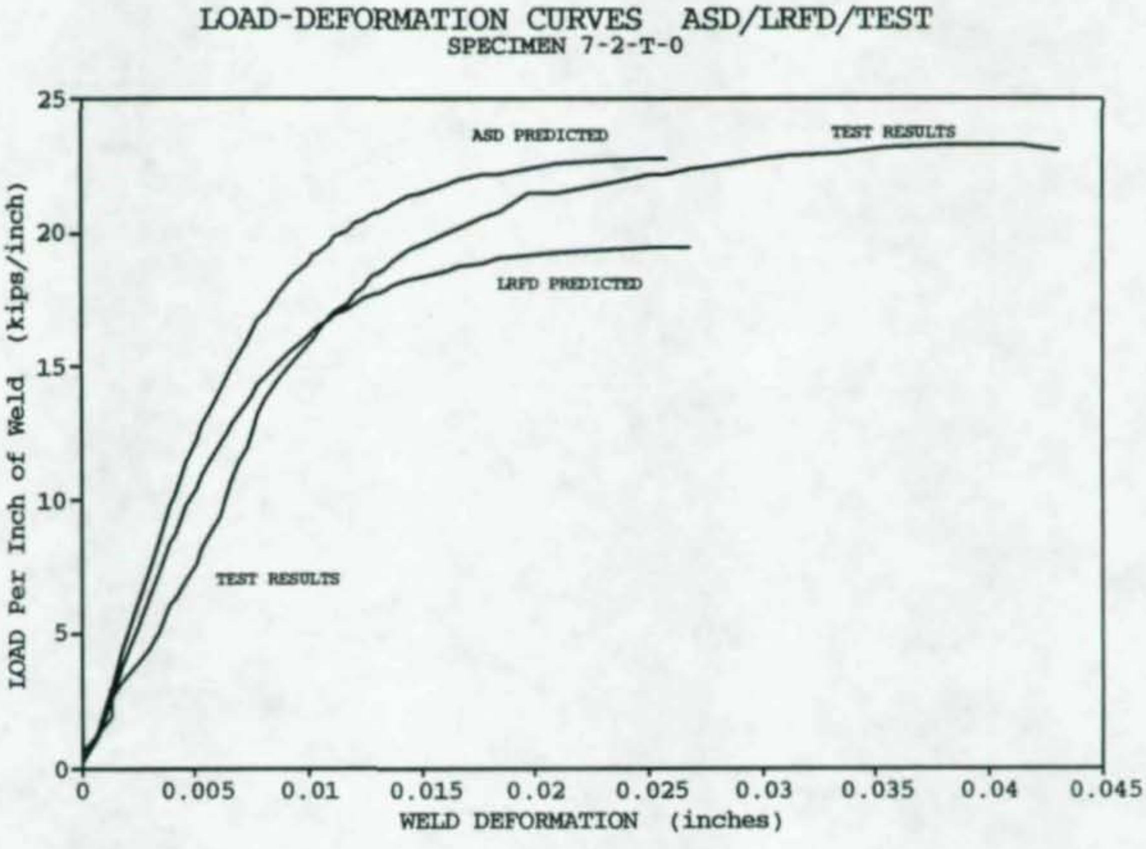


Figure 4.8 Load-Deformation Results; Specimen 7-2-T-0

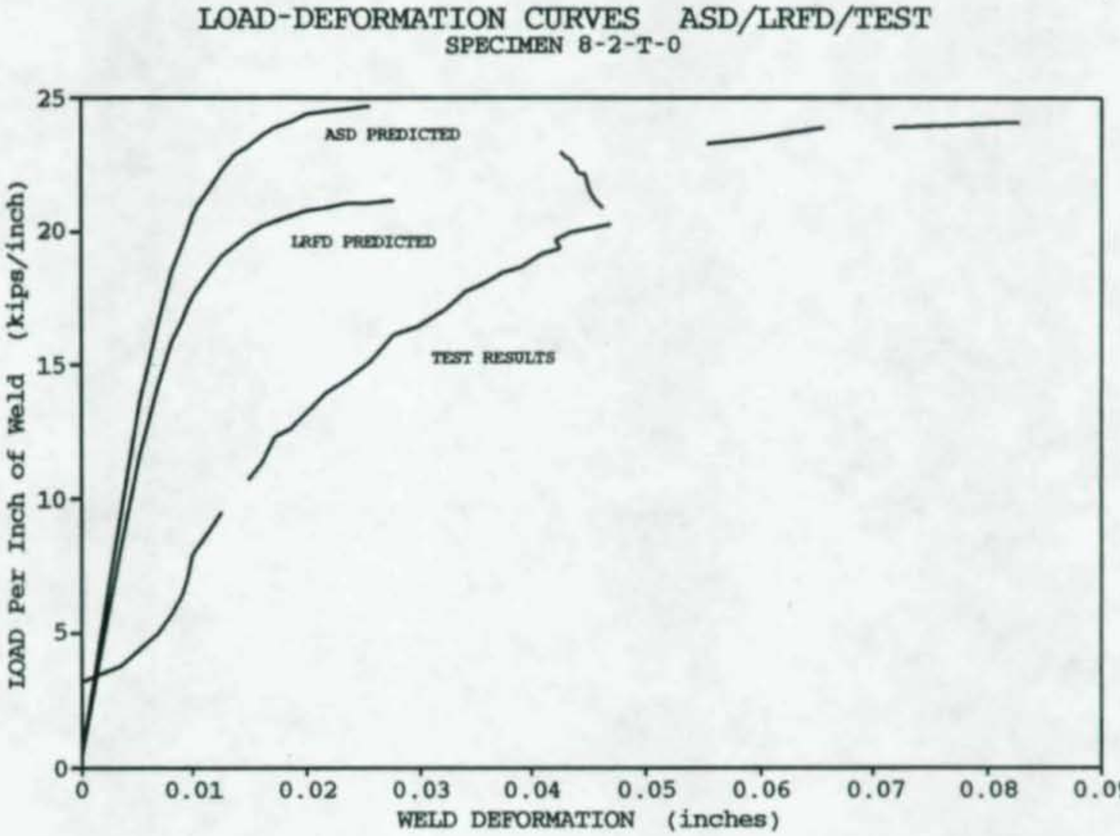


Figure 4.9 Load-Deformation Results; Specimen 8-2-T-0

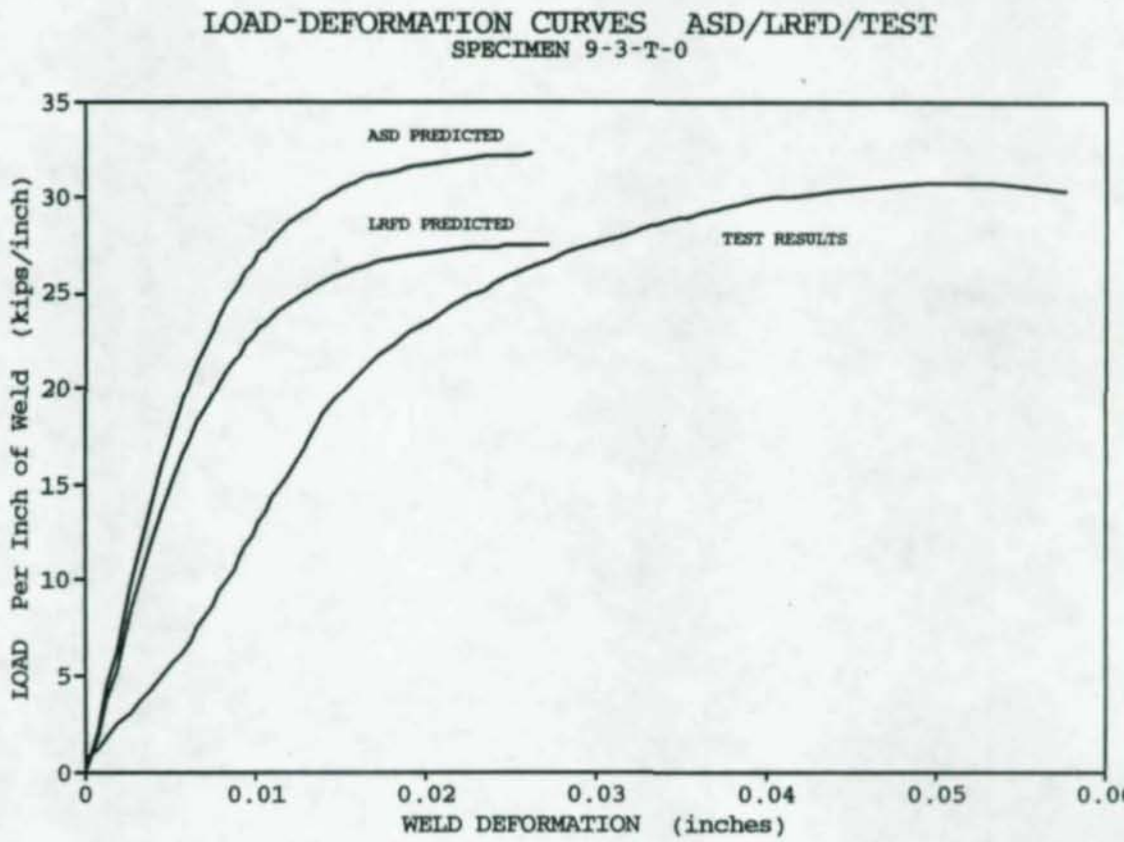


Figure 4.10 Load-Deformation Results; Specimen 9-3-T-0

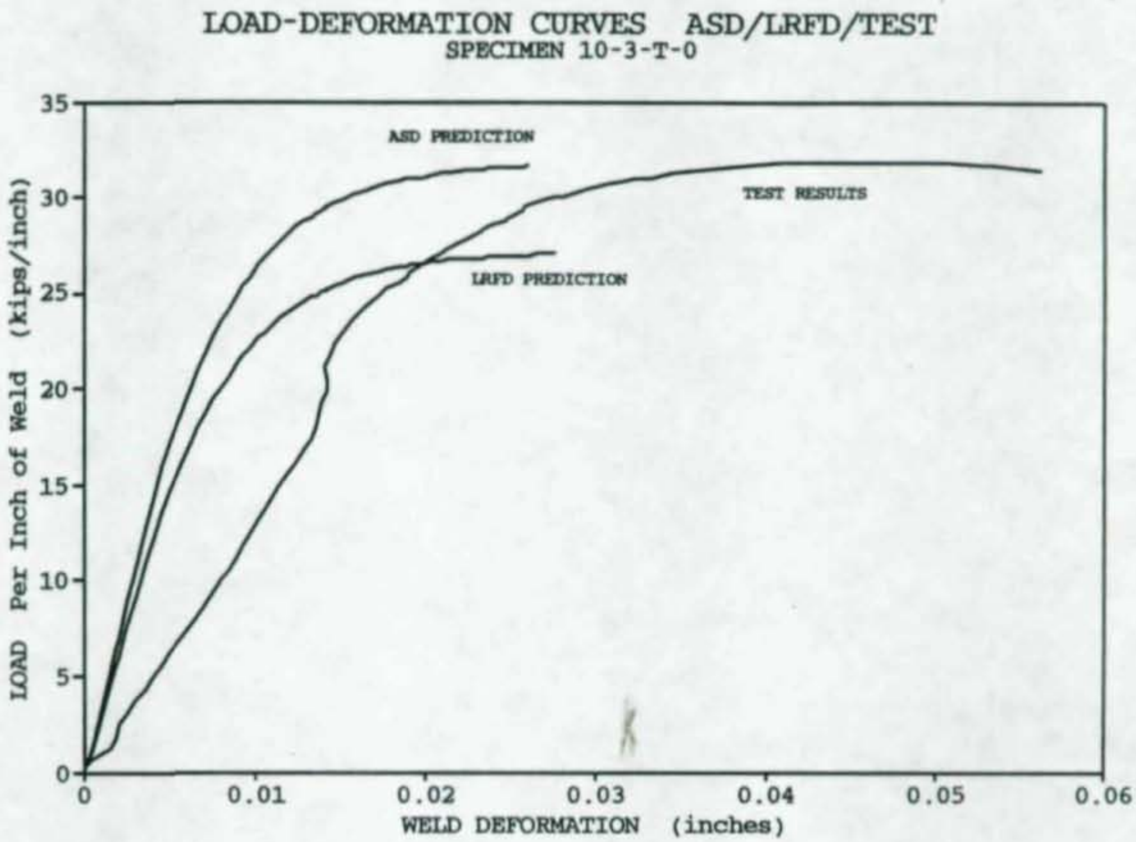


Figure 4.11 Load-Deformation Results; Specimen 10-3-T-0

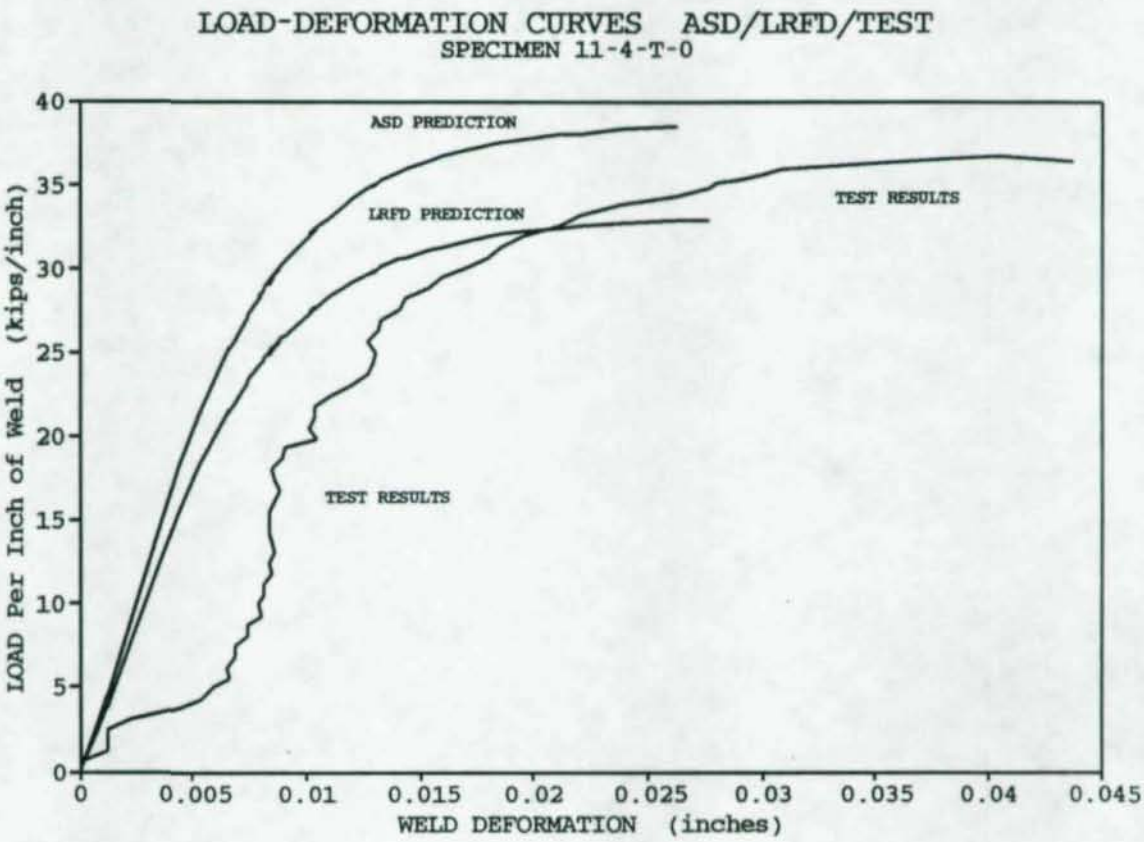


Figure 4.12 Load-Deformation Results; Specimen 11-4-T-0

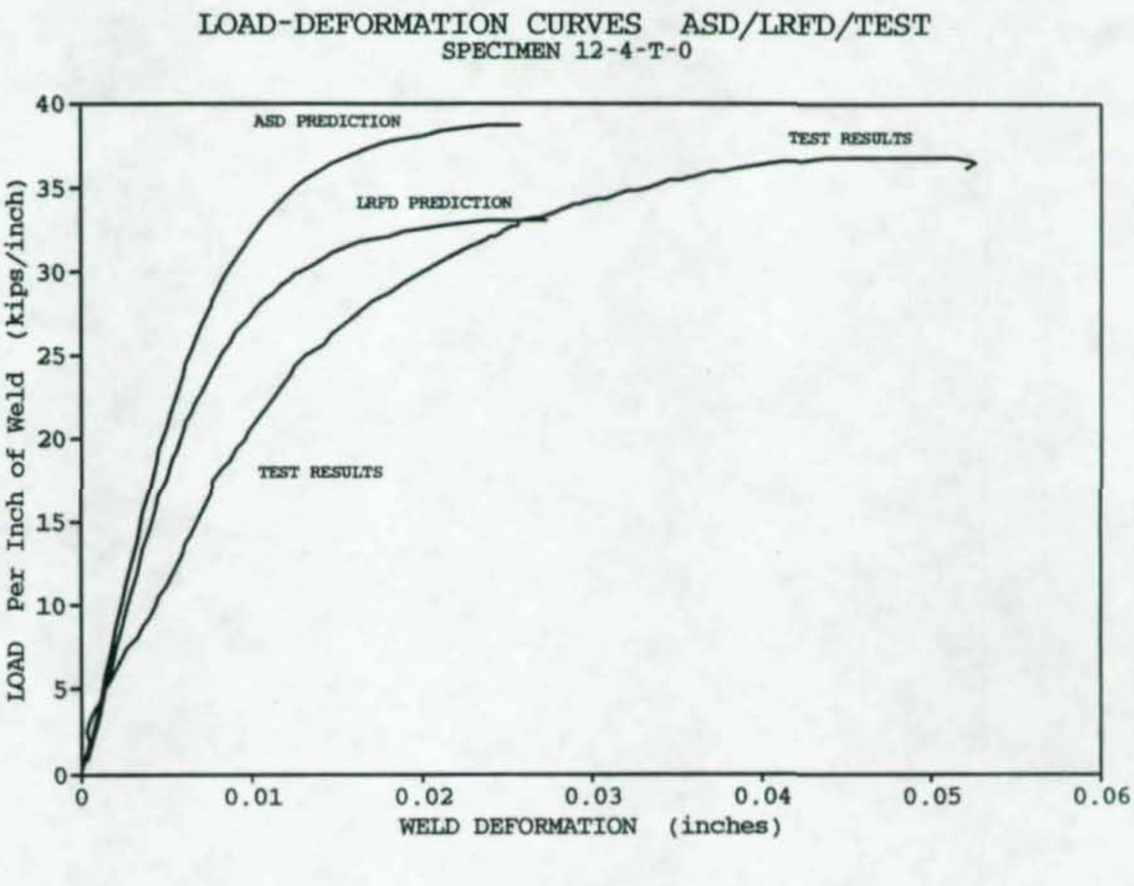


Figure 4.13 Load-Deformation Results; Specimen 12-4-T-0

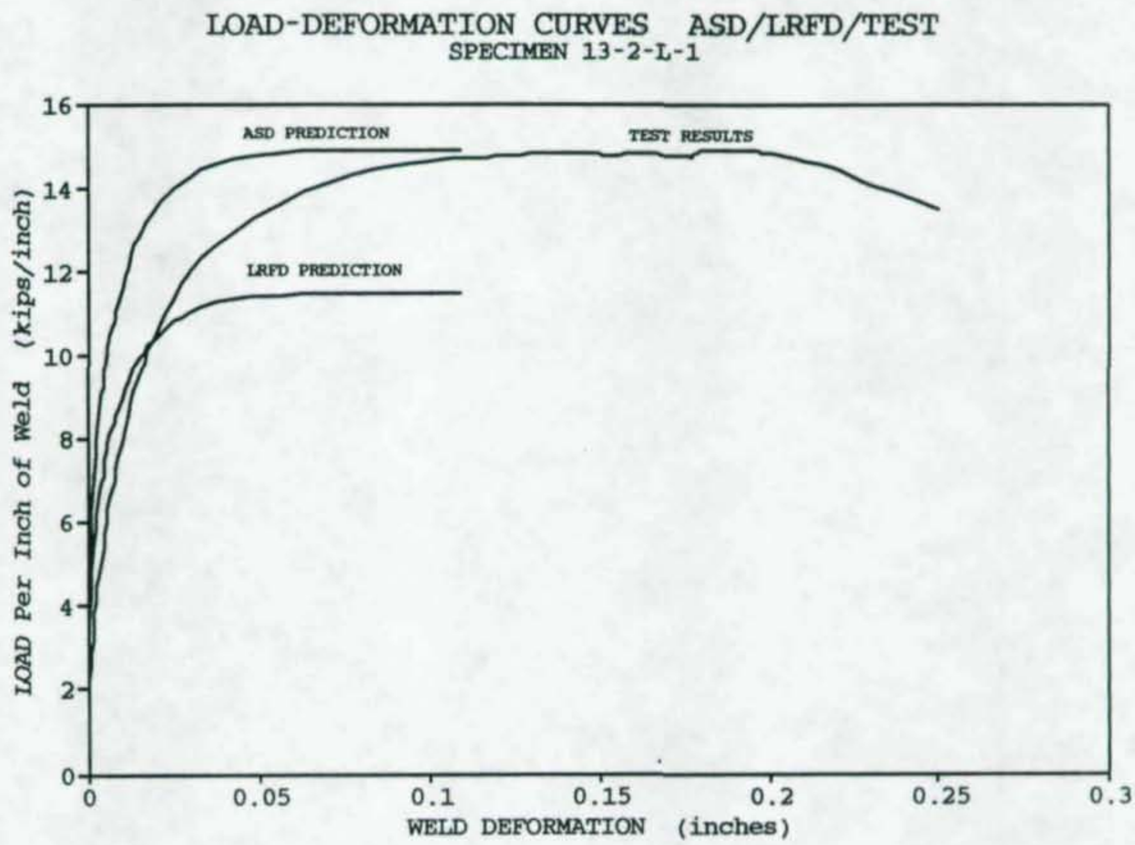


Figure 4.14 Load-Deformation Results; Specimen 13-2-L-1

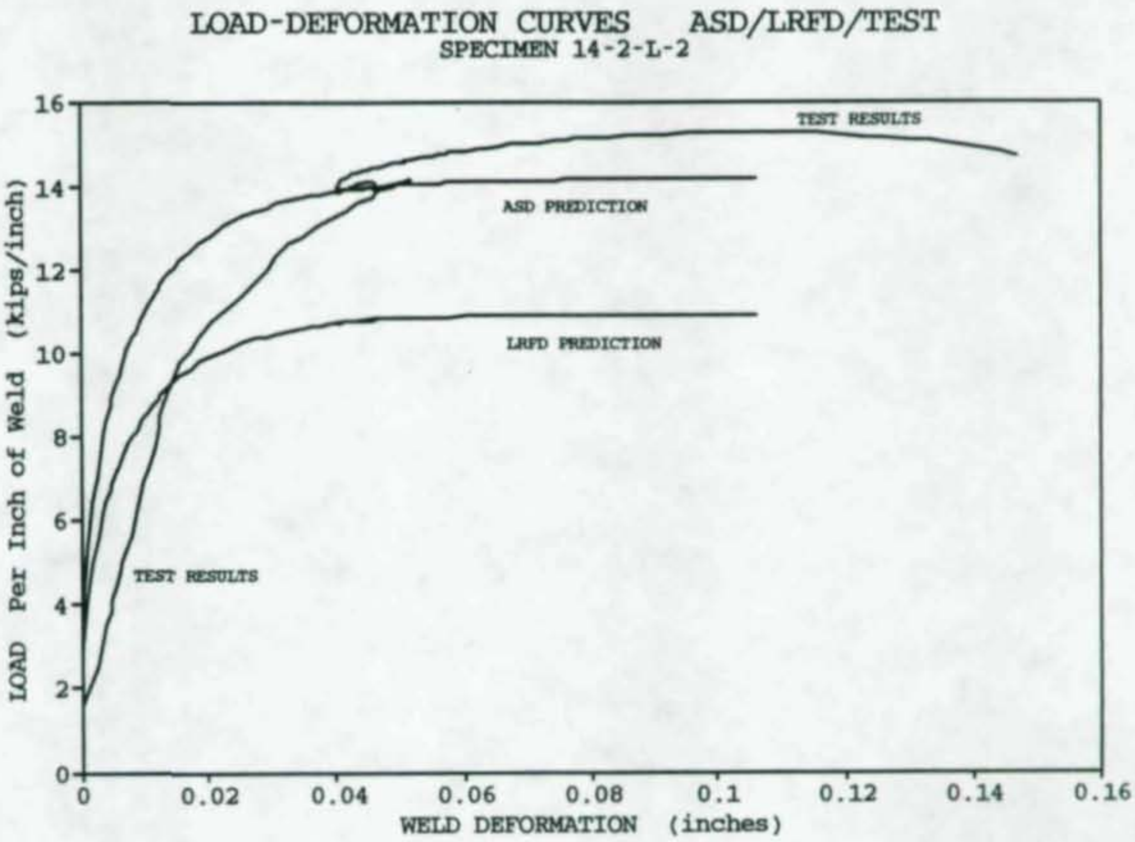


Figure 4.15 Load-Deformation Results; Specimen 14-2-L-2

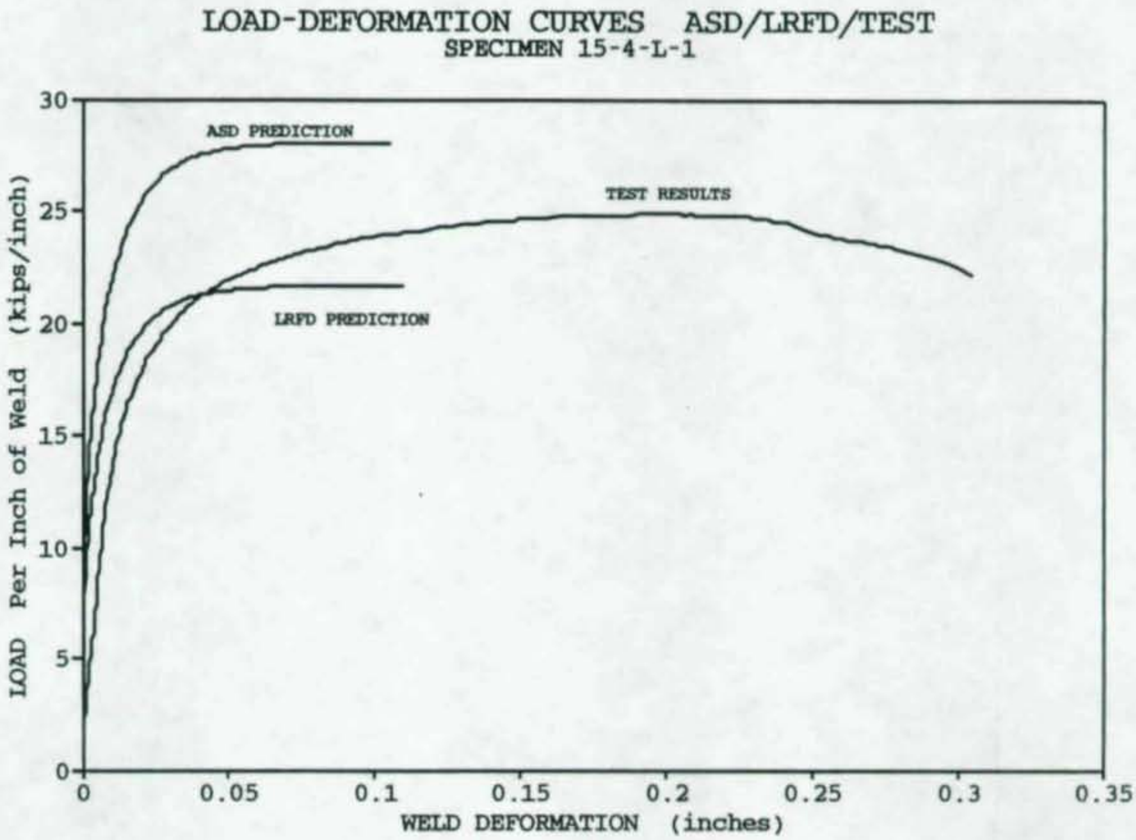


Figure 4.16 Load-Deformation Results; Specimen 15-4-L-1

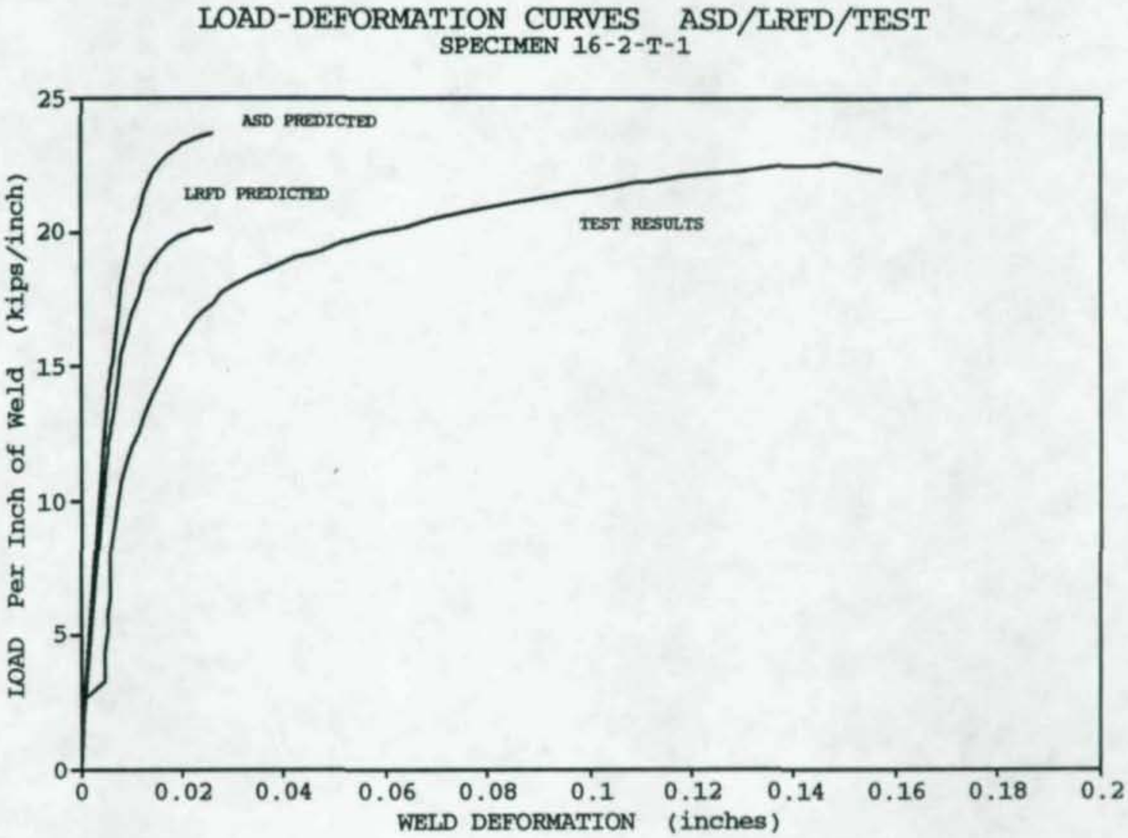


Figure 4.17 Load-Deformation Results; Specimen 16-2-T-1

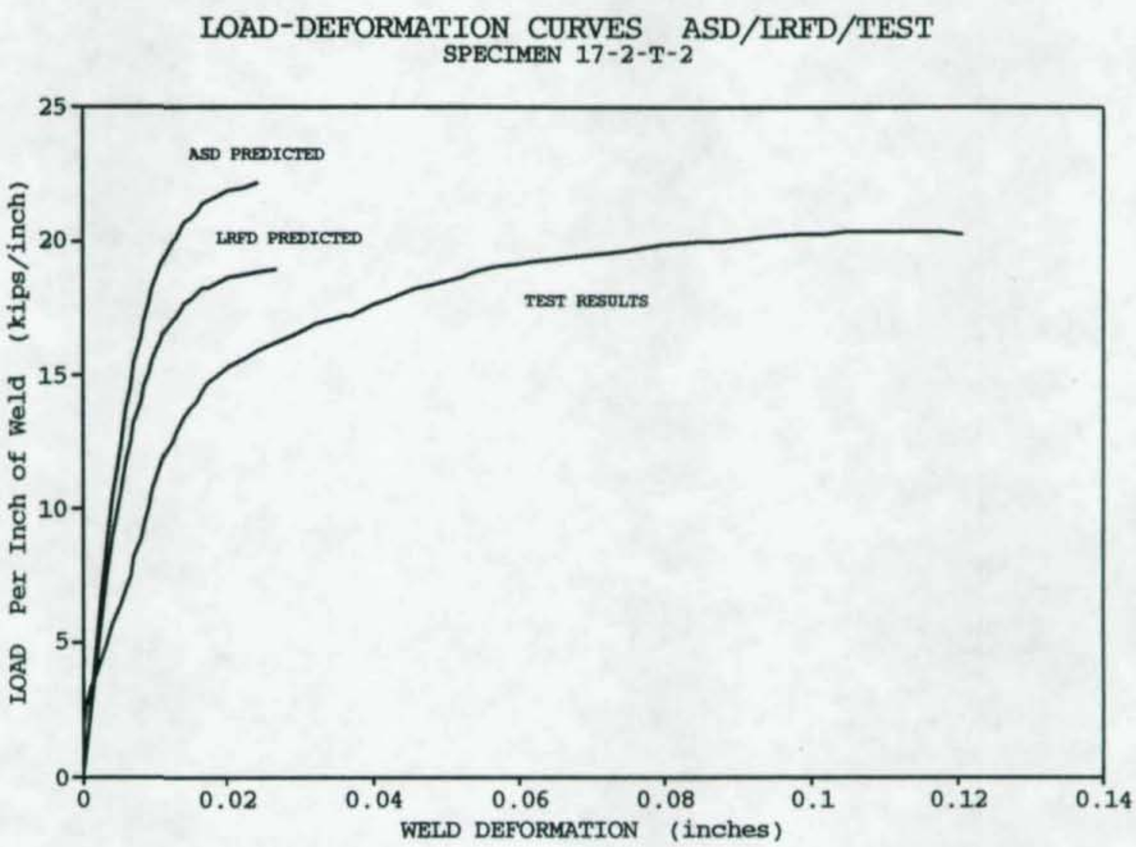


Figure 4.18 Load-Deformation Results; Specimen 17-2-T-2

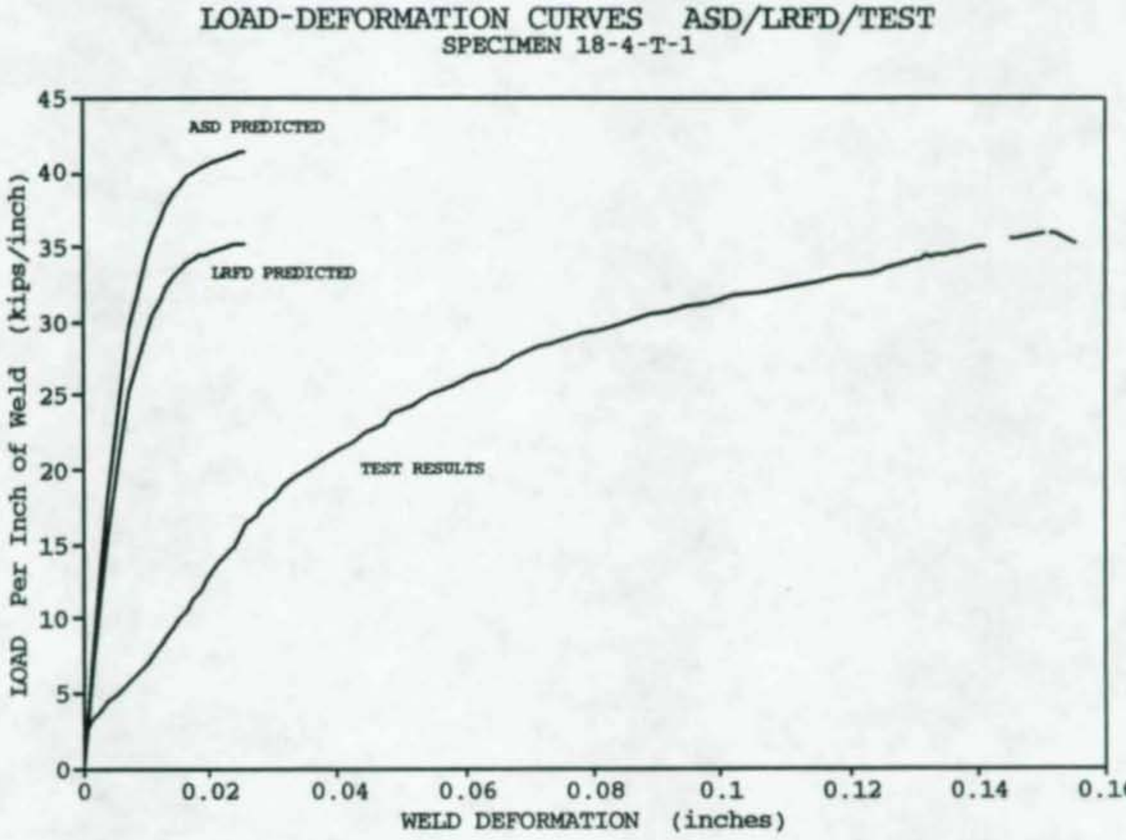


Figure 4.19 Load-Deformation Results; Specimen 18-4-T-1

All of the specimens tested demonstrated a much larger ultimate deformation than predicted by the theoretical curves, as shown in Figures 4.3 through 4.19. The ultimate strength varied, however. For the longitudinal specimens, the 1/4 inch weld strengths exceeded the ASD predicted values, which are greater than the LRFD values. However, as the weld size increased, the strength did not increase linearly. This decrease was only minimal for the 3/8 inch welds, but was much more pronounced for the 1/2 inch specimens. The 1/2 inch specimens actually came much closer to the LRFD predicted strengths, although the strengths never fell below the LRFD predicted. Section 4.3.4 provides further discussion on this topic.

The transverse specimens were, for the most part, in between the ASD and LRFD predicted ultimate strengths but still slightly closer to the ASD values. The reduction in strength for the 1/2 inch welds was minimal for the transverse specimens compared with the longitudinal specimens. It is estimated that this effect may be the result of the weld profile as will be discussed in Section 4.3.1.2.

4.2.6 Plate Stress

Remote strain gages were placed on all of the specimens as described in Section 3.5.1.3 to determine if any yielding was occurring in the specimens during testing. Appendix H presents plate stress versus average remote plate strain curves for all eighteen of the primary test matrix specimens.

There appeared to be no yielding of the plates away from the welds for the transverse weld specimens. However, all of the 1/4 inch longitudinal specimens experienced considerable yielding during the test. All of the other longitudinal specimens with the exception of 3-3-L-0 did not appear to yield. The yielding in specimen 3-3-L-0 was minimal.

4.3 Discussion

The following sections will discuss the results presented earlier in this chapter. The objectives of the report as outlined in Section 1.2 are also discussed.

4.3.1 Weld Nugget Geometry

The effects on fillet weld strength of weld leg size, exposed weld profile, and root penetration are discussed in the following sections.

4.3.1.1 Leg Size

The weld strength versus average leg size behavior was shown in Figure 4.1. There has long been discussion about the possibility that weld strength decreases with increasing leg size. Previous findings on this topic, which are summarized in Section 2.2.2, indicate that the early researchers disagreed about the influence of weld leg size on the fillet weld strength. Recent AISC code curves have been based on tests on 1/4 inch weld sizes only and thus, some investigation is warranted to determine the effect of increasing the leg size.

Specimens with different weld sizes were tested in the present study to examine the effect of weld leg size. In an effort to compare the test results of various specimens with different weld leg sizes, and to facilitate a basis of comparison with the AISC approach, all test results were compared on the basis of the strength of the 1/4 inch weldments. This was accomplished by averaging the 1/4 inch specimen strengths (without gaps) and linearly extrapolating a line which would represent the anticipated weld strength for other actual weld sizes. This was done separately for both the longitudinal and transverse specimens. Figures 4.20 and 4.21 show this extrapolated line and also where the larger weld specimens fall in relation to this line. The 'crosses' (+) in the graphs represent the expected weld

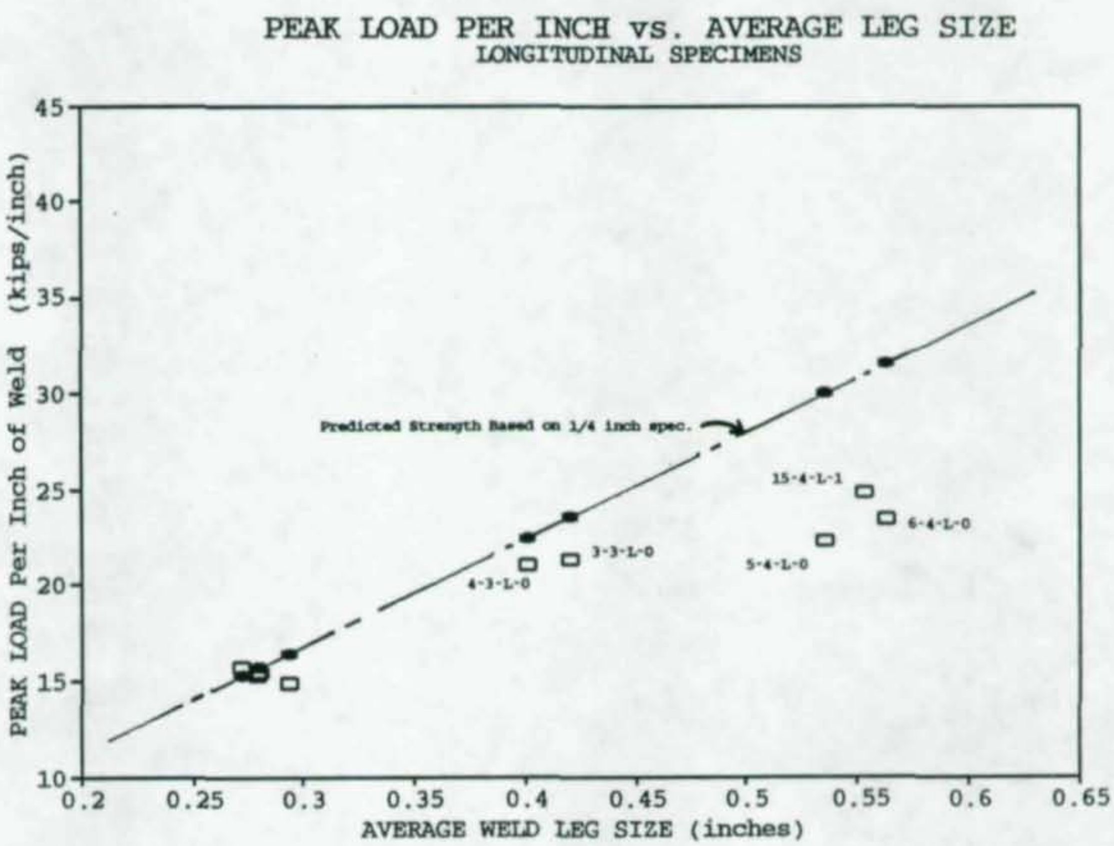


Figure 4.20 Longitudinal Specimen Test Results

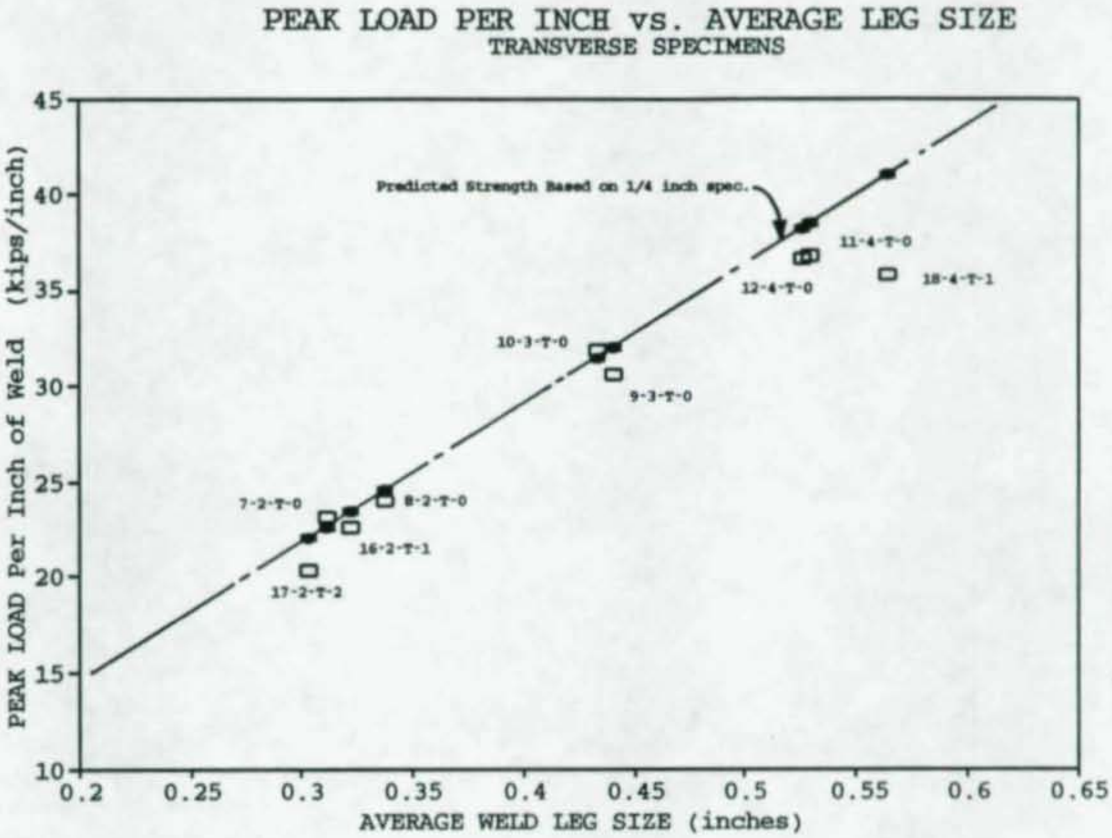


Figure 4.21 Transverse Specimen Test Results

strength which would be predicted from the 1/4 inch weld results. The greatest decrease in strength occurred in the 1/2 inch longitudinal specimens without gaps. The strength of these two specimens was 25 percent below the strength which would have been predicted using the 1/4 inch specimen results. The 3/8 inch longitudinal specimens also showed a decrease in strength from this predicted line by an average of 7.5%.

The larger transverse specimens do not demonstrate this similar significant decrease in strength. The 3/8 inch specimen strengths are quite close to the predicted values. The 1/2 inch ungapped transverse specimens do show a slight decrease in strength, but only about a 4.5% reduction. The gapped 1/2 inch transverse specimen showed a larger decrease in strength of about 13%. However, the ungapped specimen strengths were quite close to the predicted values used from the results of the 1/4 inch specimen tests.

These decreases in strength for the longitudinal specimens are significant and could lead to decreased factors of safety when linearly extrapolating 1/4 inch leg size results to larger weld sizes if only leg size is considered for the strength prediction. The reason for the decrease in strength is probably not strictly due to the leg size. The data presented here have taken into consideration the actual leg size and have used predicted strengths based on the actual leg size. It appears that the exposed weld profile which takes into the consideration the throat size may be the reason for this decrease in strength. The effect of exposed weld profile is discussed in the following section.

4.3.1.2 Exposed Weld Profile

The exposed weld profiles for one of the test welds for each of the eighteen primary test matrix specimens are shown in Appendix C. The 1/2 inch specimens have a much different profile than the 1/4 inch and 3/8 inch specimens because of the number of weld passes required to achieve the required leg size. Most of the 1/2 inch specimens required four weld passes for sufficient leg size. However, as can be seen in the Appendix figures, these specimens had a 'dimple' located at an angle between approximately 35 and 65 degrees from the bottom leg and root. Therefore, even though the leg sizes were sufficient, the failure throat may have been shorter than what would be predicted from the leg size because of this 'dimple'. The failure angles for the specimens where the failure initiated in the molded test weld are also shown in the Appendix C figures. It appears that the failure angle for the 1/2 inch longitudinal specimens did somewhat 'seek' the area where the dimple occurred. This could be a major reason why the specimen strengths shown in Figure 4.20 dropped so greatly for the 1/2 inch specimens. Since the predicted strengths were based on the actual leg size, a strength reduction would be expected because of the decrease in throat size.

The 1/2 inch transverse specimens did not experience a similar reduction in strength. The possible reason for this is the different angle of failure of the transverse welds. As was shown in Table 4.6, the average failure angle for the ungapped transverse specimens was 15 degrees. Because the 'dimple' in the 1/2 inch specimens occurred at a much greater angle, the specimen failure angle could not be forced to go through this 'dimple' where the reduced throat size was present. Therefore, the larger transverse specimens did not experience a significant decrease in strength from what would be predicted from the 1/4 inch results.

The variation in weld profile for differing weld sizes may be significant in determining the strength of the specimen. A general perusal of the 1/4 inch weld profiles from Appendix C shows a typically convex weld profile, resulting in a greater throat size than what would be predicted from the well-accepted design approach which uses a straight line approach between leg sizes. This approach is not a problem, because a convex profile results in a larger throat size. As the weld sizes become larger, such as in the 3/8 inch welds, the profile becomes less convex because the welder is putting on more weld passes, and tries to get an acceptable profile in as few passes as possible. This is still not a problem because an acceptable profile was still made, but was not as convex as the single pass 1/4 inch welds. However, the differing profile of the 1/2 inch welds could lead to an decreased factor of safety when using the actual leg size. When the specimens were fabricated, the leg and throat sizes were checked by the welder with a weld gage and appeared to be sufficient for a 1/2 inch weld. There was not a welding inspector who checked the welds, however. Thus, it is not known whether an experienced weld inspector would not have accepted the 1/2 inch welds because *of this 'dimple'. In any event, this differing weld profile* does appear to affect the weld strength and should be investigated further.

4.3.1.3 Root Penetration

The average root penetrations which were measured were reported in Table 4.3. Both the 1/4 inch and 3/8 inch macroetch specimens without gaps had minimal penetration of about 0.01 inches, with some locations having literally no penetration. Of course, there was some error in determining the root location because it was difficult to project the plate lines to the root location. However, there was still very little penetration for these specimens. The 1/2 inch macroetch specimens without gaps had more penetration, with an average of 0.03 inches. While this is three times that of the 1/4 and 3/8 inch specimens, it is still small. The root penetration for the ungapped specimens does not appear to affect the strength significantly, since the 1/2 inch specimens with the largest penetration had a lower strength than expected based on the 1/4 inch tests. Furthermore, the root penetration distance is a small percentage of the overall throat dimension.

The gapped specimens had a larger root penetration because the weld material 'flowed' into the gap, thus creating a larger root.

4.3.2 Fabrication Gap Effects

Table 4.5 and Figure 4.1 showed the weld strength of all the specimens so comparisons can easily be made. Specimens 13-18 (first number in sequence for quick reference) all had fabrication gaps. For the longitudinal specimens, the specimen with a 1/4 inch weld and 1/16 inch gap was approximately 10% weaker than the 1/4 inch welds without gaps, taking into account weld leg size. The 1/4 inch weld with a 1/8 inch gap was only 3% weaker than the 1/4 inch welds without gaps. Finally, the 1/2 inch weld specimen with a 1/16 inch gap was approximately 8% stronger than the 1/2 inch non-gapped weld specimens. The effects of fabrication gaps appear to be minimal for the longitudinal specimens. Of course, only three gapped specimens were tested, so the amount of data is limited and conclusions from these tests should be used cautiously.

The transverse specimens with gaps also showed some slight decreases in strength. The 1/4 inch specimens with a 1/16 and 1/8 inch gap showed decreases in strength from the 1/4 inch ungapped specimens of 4% and 8% respectively. The 1/2 inch specimen with a 1/16 inch gap was 9% weaker than its corresponding ungapped specimen. All of the transverse specimens with gaps did show a decrease in strength from the ungapped specimens, but the decrease was slight. Again, caution should be exercised in using this data because only three gapped specimens were tested.

When the gapped specimens were welded, the welder had to decrease the welding speed slightly because the weld material was 'flowing' into the gap. When looking at the macroetch profiles shown in Appendix D, this is evident. The specimen strengths may not have decreased significantly with the gapped specimens because of the extra weld material in the gapped area. Therefore, the required weld throat was still achieved by the presence of the extra weld material in the gap. If the weld material had not been allowed to 'flow' into the gapped area, it is quite possible that the specimen strengths would have decreased significantly.

4.3.3 Longitudinal Versus Transverse Fillet Weld Strength

It has long been known that transverse fillet welds are stronger per inch of weld than longitudinal fillet welds. This increase in strength is accompanied by a decrease in ductility, however. Various studies have been conducted to determine the strength and deformation ratios of the two types of weld configurations. Previous researchers have found the transverse fillet welds to be anywhere from 1.1 to 1.7 times stronger than longitudinal fillet welds. The ultimate deformations for transverse welds are typically in the range of 0.01 to 0.05 inches while the longitudinal deformations are approximately 0.08 to 0.15 inches. Of course, with such small deformations, it is difficult to accurately measure these deformations.

The test results reported herein generally agree with previous results, with the exception that the ultimate deformations for all of the specimens were larger than previous literature reported. The 1/4 inch ungapped transverse specimens were approximately 1.3 times as strong as the corresponding 1/4 inch longitudinal specimens, per square inch of weld (for discussion of weld stresses see Section 4.3.5). The 3/8 inch and 1/2 inch ungapped transverse specimens were approximately 1.4 and 1.7 times as strong as the corresponding longitudinal specimens. The large jump in the 1/2 inch specimens is the result of the significant reduction of weld strength recorded for the longitudinal specimens, as was discussed in Section 4.3.1.2.

The gapped transverse specimens showed similar increases in strength over their longitudinal counterparts, with the exception that the 1/2 inch specimen did not demonstrate such a large increase in strength. The strength ratios of the transverse specimens to longitudinal specimens (per square inch of weld basis) for the 1/4 inch weld 1/16 inch gap, 1/4 inch weld 1/8 inch gap, and 1/2 inch weld 1/16 inch weld, were approximately 1.4, 1.2 and 1.4, respectively.

Ultimate deformations for all of the specimens were given in Table 4.4. The average ultimate deformation was 0.23 inches for the ungapped longitudinal specimens, and 0.056 inches for the ungapped transverse specimens. These deformations are higher than what would be expected, and will be discussed in Section 4.3.4.

4.3.4 Load-Deformation Behavior

The load-deformation results for the eighteen primary test matrix specimens were given in Section 4.2.5 and Figures 4.3 through 4.19. All of the specimens had larger deformations than expected, with ultimate loads falling generally in between the ASD and LRFD predicted curves, with the exception of the 1/2 inch longitudinal ungapped specimens. Discussion of specimen strength was primarily presented in Section 4.3.1.2.

The large weld deformations experienced by the specimens could be the result of several factors. First of all, the weld metal coupon specimens (A505) had elongations of 36% to 39%. This is significantly greater than the expected elongation of 25-30%. Thus, the exceptional ductility of the weld electrode could be a major reason for the increased ultimate deformation.

Secondly, the LVDT apparatus for measuring the specimens could have possibly given erroneous results. 'Five-minute' hard set epoxy was used to glue the 'arm' holding the LVDT core onto the specimen. This procedure was described in Section 3.5.1.2. The glue was allowed to cure for at least four hours before the test was conducted, with the exception of specimen 18-4-T-1. Even though it appeared that the glue was set and the test duration was only fifteen minutes, it is remotely possible that some additional deformation was measured because of creep of the glue, or other unknown factors which were not considered. It is the author's opinion that these deformations were probably minimal.

4.3.5 Weld Failure Stresses

An examination of the failure stresses on the weld is warranted to investigate the shear strength of the welds. Current LRFD Specifications define weld strength based on the Von Mises yield criterion as well as plastic flow and limits weld strength to 0.6 times the tensile strength of the electrode (multiplied by the appropriate phi factor). Previous test results for various geometries have generally shown theoretical weld stresses ranging from 0.6 times the electrode strength to upwards of 1.5 times the electrode strength. Most of these tests did not measure the actual throat and/or leg size and, thus, could have had larger weld sizes than the nominal size.

Table 4.8 presents the weld failure stresses as computed for the eighteen primary test matrix specimens. These stresses were calculated by dividing the peak load by the weld area. The weld area was taken as the combined test end weld length times the throat dimension. The throat dimension was computed by dividing the overall average leg size (for each individual specimen) by the square root of two. Thus, a 'theoretical throat' dimension based on the actual leg size was used. This analysis assumed a 45 degree failure angle, and did not account for any weld 'reinforcement'. It was shown that the actual failure angles differed slightly from 45 degrees for the

Table 4.8 Weld Failure Stresses

SUMMARY OF TEST RESULTS						
SPECIMEN NUMBER	PEAK LOAD (kips)	WELD LENGTH (inches)	OVERALL AVG WELD SIZE (inches)	PEAK LOAD/INCH (kips/in)	WELD STRESS (THEO.THR.) (ksi)	ULT.DEFORM. (inches)
1-2-L-0	247	15.756	0.272	15.68	81.5	N.A.
2-2-L-0	243	15.817	0.281	15.36	77.3	0.129
3-3-L-0	336	15.776	0.421	21.30	71.5	0.239
4-3-L-0	332	15.708	0.402	21.14	74.4	0.266
5-4-L-0	352	15.803	0.535	22.27	58.9	0.311
6-4-L-0	380	16.184	0.563	23.48	59.0	0.228
13-2-L-1	236	15.856	0.294	14.88	71.6	0.250
14-2-L-2	242	15.855	0.279	15.26	77.4	0.147
15-4-L-1	388	15.603	0.553	24.87	63.6	0.305
7-2-T-0	184	7.925	0.312	23.22	105.2	0.043
8-2-T-0	190	7.915	0.338	24.01	100.4	0.083
9-3-T-0	247	8.053	0.441	30.67	98.4	0.058
10-3-T-0	256	8.036	0.433	31.86	104.0	0.056
11-4-T-0	293	8.011	0.526	36.57	98.3	0.044
12-4-T-0	294	8.009	0.530	36.71	98.0	0.053
16-2-T-1	179	7.942	0.323	22.54	98.7	0.157
17-2-T-2	162	7.979	0.303	20.30	94.8	0.121
18-4-T-1	286	8.001	0.565	35.75	89.5	0.156

longitudinal specimens and greatly for the transverse specimens. However, since previous researchers have reported stresses based on this throat, the same was done in this report. Table 4.8 shows that the longitudinal specimens had weld failure stresses ranging from 58.9 ksi to 81.5 ksi. The 1/2 inch specimens had the lowest failure stresses.

The transverse specimens had weld failure stresses ranging from 89.5 ksi to 105.2 ksi. The ungapped transverse specimens had much lower failure angles, so this analysis which was based on a 45 degree failure throat would produce higher stresses than actually occurred in the welds.

Table 4.9 shows a comparison between the failure stresses in the transverse and longitudinal welds. As mentioned previously, the transverse welds were notably stronger than comparable longitudinal welds.

Nevertheless, the stresses for both the longitudinal and transverse specimens were greater than the AISC LRFD Specification of 0.6 FExx. If the code equation was used for these electrodes, the resulting stress limit would be: 0.6*(69 ksi) = 41.4 ksi. All of the specimens had much greater failure stresses based on the throat size as was explained above.

Table 4.9 Transverse versus Longitudinal Weld Behavior

TRANSVERSE vs. LONGITUDINAL WELD BEHAVIOR			
WELD CONDITION	AVG. LONG. WELD STRESS (ksi)	AVG. TRANS. WELD STRESS (ksi)	(TRANSVERSE)/ (LONGITUDINAL)
1/4" WELD	79.4	102.8	1.29
3/8" WELD	72.9	101.2	1.39
1/2" WELD	58.9	98.2	1.67
1/4" WELD, 1/16" GAP	71.6	98.7	1.38
1/4" WELD, 1/8" GAP	77.4	94.8	1.22
1/2" WELD, 1/16" GAP	63.6	89.5	1.41
ALL WELDS	70.6	98.6	1.40

4.3.6 Plate Stress

Strain gages were placed on all of the primary test matrix specimens to investigate if any yielding was occurring away from the welds in the connecting plates. Many of the previous tests on fillet welds have had plate sizes proportioned to eliminate any yielding of the base metal during the test duration. Section 2.2.5 discussed the effect of plate stress as reported in the literature by previous investigators. There have been different views concerning this phenomenon, with some saying that plate stress has no effect to others saying that increased plate sizes and lower plate stresses increase the strength of connections.

All of the primary test matrix specimens were initially designed to inhibit yielding of the base metal. However, because of the unexpected high strengths of the longitudinal specimens, several of the plates in these specimens actually yielded. These specimens include all of the 1/4 inch longitudinal specimens (1-2-L-0, 2-2-0, 13-2-L-1, 14-2-L-2) as well as one of the 3/8 inch longitudinal specimens (3-3-L-0), although the yielding in the 3/8 inch specimen was minimal. As was mentioned earlier, Appendix H contains remote plate stress versus average remote plate strain curves for all eighteen of the primary test matrix specimens.

It is unclear from this investigation if the plate stress had any impact on the weld strengths. However, since the 1/4 inch longitudinal specimens were somewhat stronger than expected, it is possible that the plate stress had no effect. Section 4.3.1.2 discussed the weld profile effects on the weld strength, which probably had a greater impact on the weld strength.

Additional strain gages were placed on specimens 1-2-L-0, 2-2-L-0, 7-2-T-0, and 11-4-T-0 as was reported in Section 3.5.1.3. This data is provided in Appendix B. Additionally, figures A.1 and A.2 show the location of these strain gages.

Typical strain distributions for the two longitudinal specimens with additional gages is shown in Figure 4.22. The strain distribution along the axis of the weld on the top and bottom plates was not linear, as might be expected. There were not enough strain gages to fit a curve through the distribution, but general trends can be observed. At lower loads, the largest increase in strain occurred between gage lines F*2 and F*3, with lower increases in strain at the end gages. At higher loads before failure, the strain actually decreased between gage lines F*2 and F*1. This is probably due to yielding of the top plate and subsequent redistribution of some of the strain back along the plate.

The distribution of strain across the top and bottom plates perpendicular to the weld axis for the longitudinal

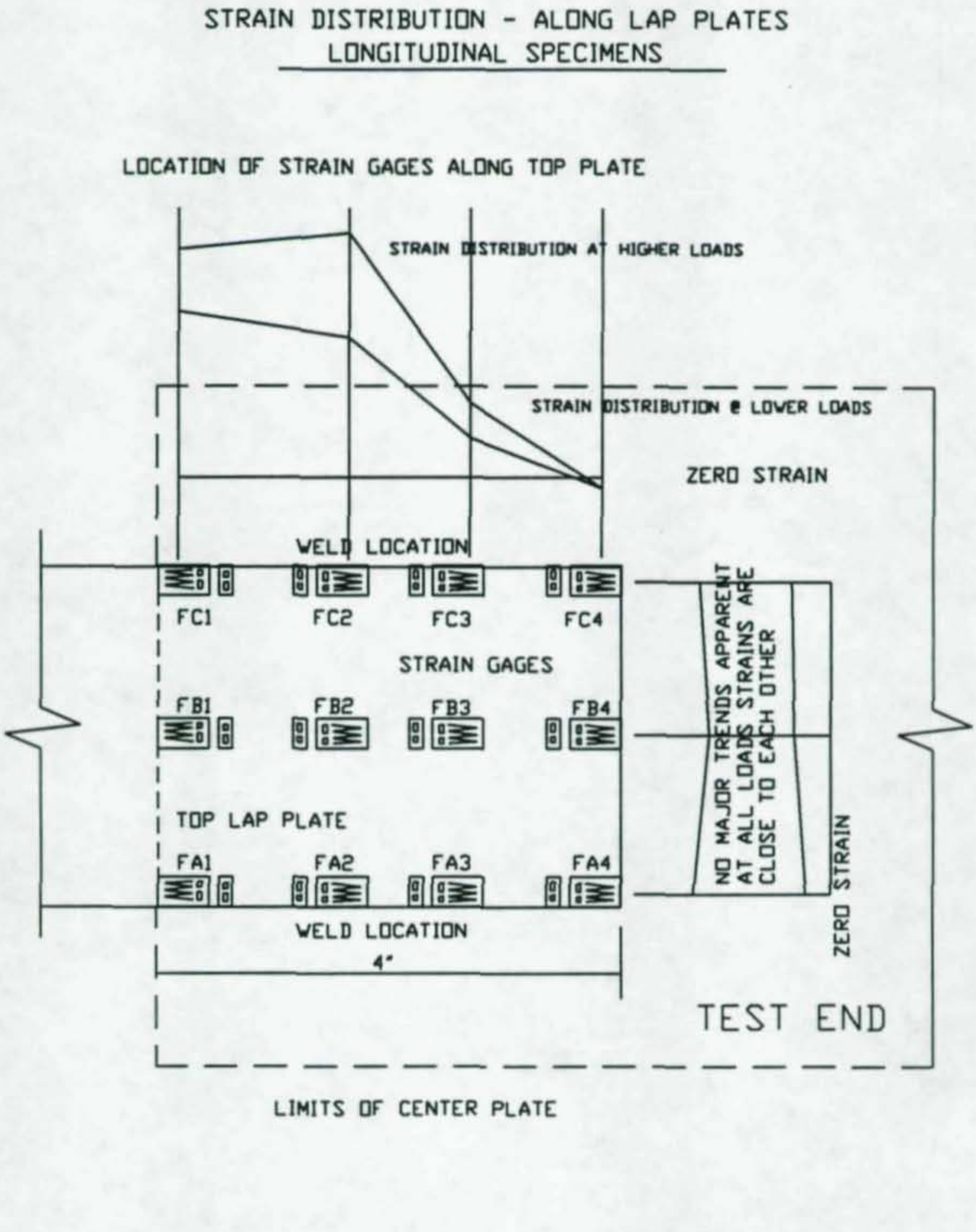


Figure 4.22 Strain Distribution - Longitudinal Specimens

specimens did not show any distinct trends. All of the strains across gage lines A, B, and C were relatively close with minor fluctuations. Thus, the strain appeared to be fairly constant perpendicular to the weld axis across the top and bottom plates.

Similarly, data from the additional gages placed on transverse weld specimens 7-2-T-0 and 11-4-T-0 did not show any significant trends in the strain distribution. Yielding in the center plate next to the welds began occurring slightly before failure, as might be expected. No yielding occurred on the top and bottom plates at gage line 1 which was 2 inches from the end of the plate.

4.3.7 Comparison with Previous Results

Chapter 2 presented a literature review of existing data and a discussion on the strength of fillet welds. For comparison purposes, this report will focus on some of the more recent research (1965-present). The primary reason for this restriction is that significant changes in welding procedures and weld electrodes occurred between the inception of welding to 1960. Of course, changes are still taking place, but these changes are not as pronounced as some of the earlier changes.

Some of the more important recent research on fillet weld strength includes; Preece (1968), Clark (1971), Butler, Pal and Kulak (1972), Kulak and Timler (1984), and Miazga and Kennedy (1989).

As a result of Preece's work, the allowable design stresses for fillet welds were changed to be a function of the weld electrode strength. The specimens tested were 1/4, 3/8 and 1/2 inch longitudinal specimens and 1/4 inch transverse specimens. Additionally, electrode strengths of 60 ksi, 70 ksi, 90 ksi, and 110 ksi were used for the welding. Figures 4.23 and 4.24 show Preece's data along with the other reports mentioned as well as the data from this series of tests discussed within this report, for both longitudinal and transverse welds. The strengths in these figures have been scaled so all tests are for an equivalent E70xx electrode. Some of the tests used E70xx electrodes, and these results were therefore not scaled. The weld strengths are given as a function of the weld leg size.

The weld strengths from the primary test matrix specimens compared quite well with the results of Preece. The weld strengths from the tests presented herein all fell within the band of results from Preece for the longitudinal specimens. The transverse welds by Preece all had smaller leg sizes but on the specimens which were close in leg size, Preece's specimens had a greater strength by approximately 2-5 kips per inch. Since Preece only used 1/4 inch transverse specimens, no other comparisons can be drawn.

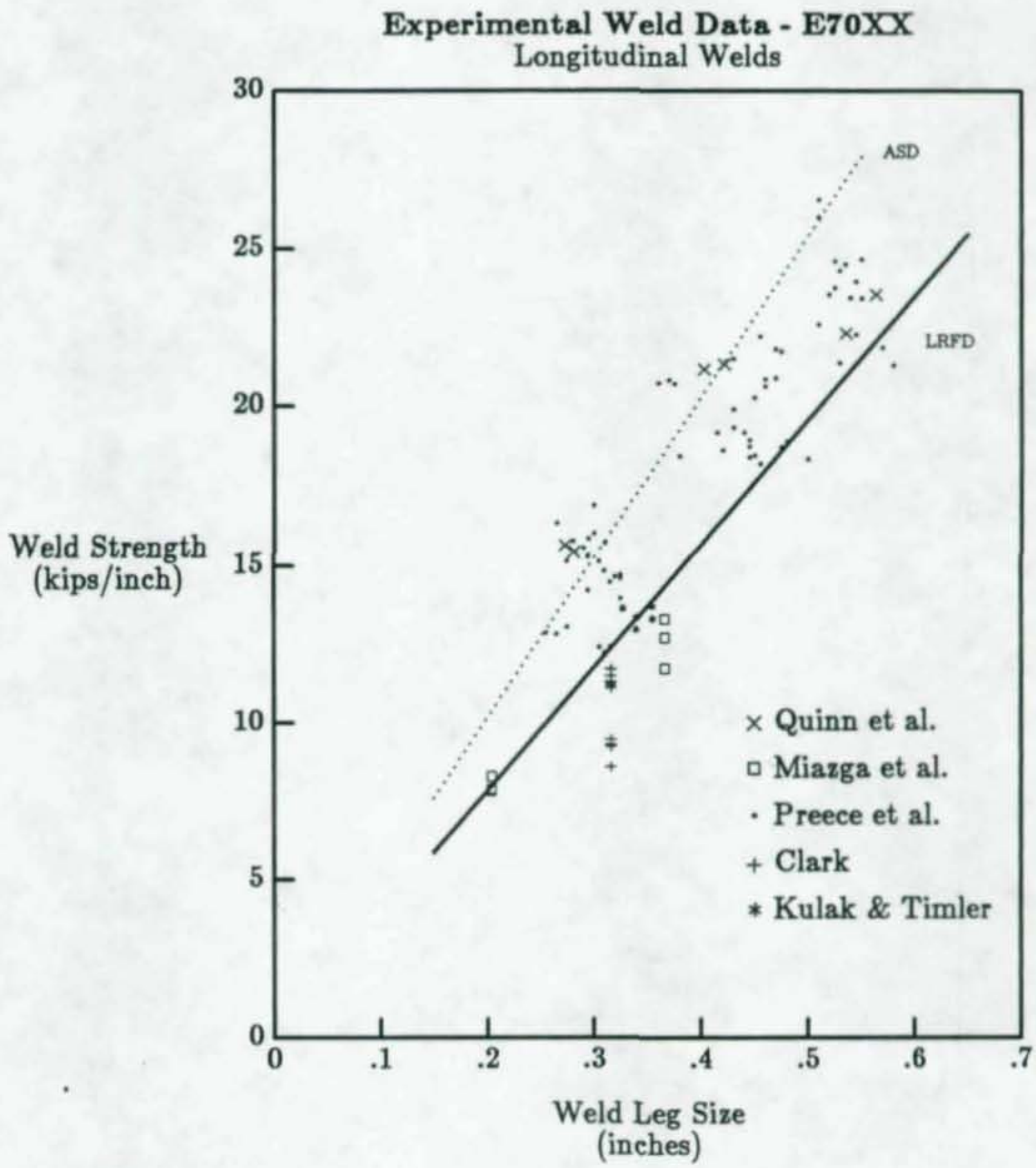


Figure 4.23 Comparison with Previous Research - Longitudinal Welds (from M.D.Bowman)

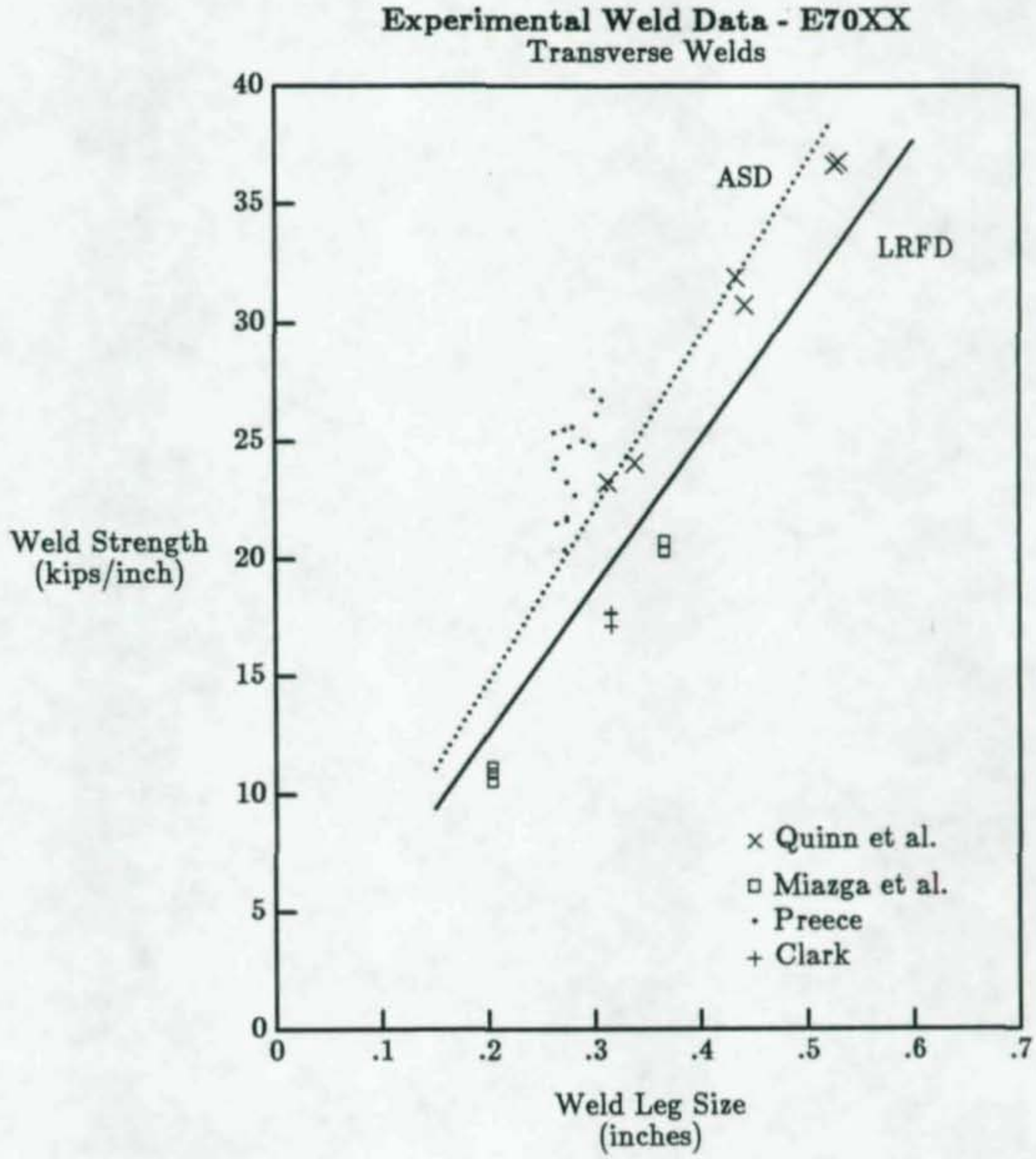


Figure 4.24 Comparison with Previous Research - Transverse Welds (from M.D.Bowman)

Overall, Preece's test results compare well with the tests conducted in this project. Preece also noted a similar reduction in weld strength for larger size fillet welds (1/2 inch) as was noticed for this series of tests.

The ASD and LRFD curves shown in Figures 4.23 and 4.24 are based on the ultimate shear load equations presented in the load-deformation curve development. The ASD curve was a result of Butler, Pal, and Kulak's research, while the LRFD curve was derived from the work of Kulak and Timler. The lines shown are from a best fit line through the data. Kulak and Timler tested 1/4 inch nominal size fillet welds only, but their best fit equation is used for all weld sizes in the LRFD code. Once again, it is unclear why the ninth edition ASD Specification has not adopted the 1984 work of Kulak and Timler which was incorporated in the 1986 LRFD Specification. The weld strengths for the 1/4 and 3/8 inch longitudinal primary test matrix specimens were slightly greater than the ASD predicted, but considerably larger than the LRFD predicted. However, the 1/2 inch longitudinal specimen strengths were much closer to the LRFD line, although none of the specimens fell below this line. Preece's results follow a similar pattern. The transverse specimen strengths in the primary test matrix compare much better with the ASD equation as shown in Figure 4.23.

Some of the test results from Clark (1971) and Miazga and Kennedy (1989) are also shown. Both Clark and Miazga's tests have given weld strengths lower than the LRFD predicted curve, and much lower than the results from the eighteen primary test matrix specimens. The cause for the lower strengths reported by Clark and Miazga is unclear to the author.

CHAPTER 5

SUMMARY AND CONCLUSIONS

5.1 Summary

The primary purpose of this research study was to investigate a few of the critical parameters which affect fillet weld strength. These parameters include: the effect of weld nugget geometry, the effect of fabrication gaps, the difference in strength of longitudinal and transverse fillet welds, and finally, the load-deformation behavior of both longitudinal and transverse fillet welds.

Eighteen primary test matrix specimens consisting of nine longitudinal and nine transverse fillet weld specimens were tested in this study. Additionally, three weld electrode coupon specimens were fabricated and tested to determine the weld electrode strength. Furthermore, three macroetch specimens were fabricated for the investigation of weld penetration into the base metal. 'Dentist' type plaster molds were also made of one of the test welds for each of the primary test matrix specimens, with the exception of the first specimen. These specimens gave an indication of the 'reinforcement' weld distance due to the convexity of the weld profile.

Peak loads, ultimate deformations, weld leg size, and weld profile data were all recorded for each of the eighteen primary test matrix specimens. Chapter 4 provided the results from this series of tests and the Appendices provide all of the raw data for possible future investigation. The following section provides tentative conclusions which can be drawn from the test results.

5.2 Conclusions

Based on the results of the limited number of tests conducted on the fillet weld specimens, several conclusions can be drawn.

1. The strengths of the fillet weld specimens were most similar to the weld strengths of the 1968 tests conducted by F.R. Preece. This was shown in Figures 4.23 and 4.24 where the test results from several recent reports were compared. This includes a significant reduction in strength per square inch of weld (based on a theoretical throat for an actual leg size) for 1/2 inch longitudinal weld specimens when compared to the results of the 1/4 inch longitudinal specimens.

"size effect"

2. It is probable that the weld strengths are closely related to the actual weld profile, given the same electrode strength. After investigation of the decreased strength for the 1/2 inch longitudinal specimens, it can be concluded that the exposed weld profile may have a significant impact on the specimen weld strength. The 1/2 inch weld specimens exhibited a 'dimple' in the profile because of the increased number of passes. This 'dimple' occurred between angles of 35 and 65 degrees from the horizontal plane. Because the longitudinal specimens had an average failure angle of 58 degrees, the failure was forced to go through a 'reduced' throat thickness where the 'dimple' was present. The transverse specimens did not exhibit a similar reduction in strength because the average weld failure angle for the transverse specimens was 15 degrees. Therefore, the profile of the weld appears to have significant effect on fillet weld strength.

3. Root penetration did not appear to affect the weld strength. Some specimens even appeared to have minimal to no root penetration. This was most prominent in the 1/4 and 3/8 inch specimens.

4. Fabrication gaps did not appear to affect the weld strength by any significant amount. The specimens with

fabrication gaps were generally on the order of 5% weaker than similar specimens without fabrication gaps. The 1/2 inch specimen with a 1/8 inch fabrication gap was actually stronger than the similar specimens without fabrication gaps.

The longitudinal specimen with a 1/8 inch gap was slightly stronger per square inch of weld than a similar specimen with only a 1/16 inch gap. The reverse effect occurred for the transverse specimens.

It is possible that because weld material 'flowed' into the gapped area, a weld with an equivalent weld strength was produced. However, if the weld material was ever prohibited from flowing into the gapped area, it is the author's opinion that a significant reduction in weld strength would occur.

5. Weld failures appear to be offset from the root of the weld, and actually go through the intersection point of the weld material and the center plate.

6. All of the transverse specimens were stronger than the corresponding longitudinal specimens (per square inch of weld, based on a theoretical throat using the acutal leg size) by a factor ranging from 1.3 to 1.7 for the ungapped specimens, and 1.2 to 1.4 for the gapped specimens.

7. The ultimate deformation of all of the specimens was greater than the ASD and LRFD Specification predictions. This could be the result of the high ductility of the weld electrodes as well as possibly the test apparatus introducing error.

There appears to be some discrepancy between the ASD and LRFD Specification curves for load-deformation behavior of fillet welds. The ASD Specification is based on Butler, Pal, and Kulak's research (1972) for specimens fabricated with E60xx electrodes. The LRFD Specification is based on the 1984 work of Kulak and Timler for E70xx electrodes.

The primary test matrix specimens had strengths (per inch of weld) closer to the ASD Specification curve (scaled to equivalent E70xx electrodes) with the exception of the 1/2 inch longitudinal specimens. These specimens were closer to the LRFD Specification curve.

8. Fillet weld strength is a function of many variables. Some of these have been mentioned above, but several others exist which have not been investigated. These variables include: weld process, the skill of the person performing the welding, the type of electrode within the same electrode class (for example, E7018 vs. E7024), and base metal stress, to name a few. This list

is by no means all-inclusive of all the variable affecting fillet weld strength.

5.3 Further Research

An experimental study which better examines the effect of weld profile on fillet weld strength is warranted. Only one test weld for each specimen was molded for the tests presented in this report. Further tests should mold all test welds and characterize the weld profile. Correlations should be made between the profiles, the failure angles, and the corresponding weld failure stresses.

Further investigation into the load-deformation behavior of fillet welds should be undertaken. The results from the tests conducted in this research study show extremely high weld deformations. Further research should investigate this phenomenon. (The author has more E7018 electrodes from the same lot which could be used to check these deformations).

A statistical investigation into weld leg size is also warranted. The amount of excess weld decreased with increasing weld size for the specimens in this report. This was probably a result of the additional passes required to attain the required leg and throat size.

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