University of Alberta
Department of Civil &
Environmental Engineering

Structural Engineering Report No. 271

Reliability Analysis of Concentrically Loaded Fillet Welded Joints

by

Chunlong Li

Gilbert Y. Grondin

and

Robert G. Driver

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ABSTRACT

Tests on joints of cruciform configuration conducted in a previous test program indicated that fillet welds in these joints may possess reduced strength and ductility compared to transverse welds in lapped joints. An experimental program consisting of 12 fillet weld cruciform specimens was conducted to investigate effect of root notch orientation on weld strength and ductility. The reliability analyses presented in the previous phases of this program were conducted using mostly test results obtained at the University of Alberta. To augment this database of test results, test data from various test programs on lapped splices with single and multiple orientation welds and on cruciform test specimens were collected. This provides a larger database of test results, which better reflect the variation present in industry. A reliability analysis was conducted to assess the current North American and proposed design equations for lapped joints with single and multiple orientation welds and for cruciform connections.

ACKNOWLEDGEMENTS

Funding for this research project was provided by the Natural Sciences and Engineering Research Council of Canada and the American Institute of Steel Construction.

Funding was also provided by Canadian Institute of Steel Construction in the form of the G. L. Kulak scholarship to the senior author.

The tests presented in this report were conducted by Mr. Logan Callele, Mr. Andre Blanchard and Mr. Derek Kramar, from the Department of Civil and Environmental Engineering of the University of Alberta.

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LIST OF SYMBOLS†

A_{throat}	Measured throat area of the weld (mm^2)
A_w	Theoretical throat area of the weld (mm^2)
C	Adjustment factor for the weld resistance factor
CPL	The central plate leg is the fillet weld leg that is on the central plate of the cruciform specimen (mm)
$CRF(\theta)$	Combination reduction factor for any fillet weld orientation, θ.
d^*	Average measured fillet weld leg dimension (mm)
LPL	The lap plate leg is the fillet weld leg that is on the lap plate of the lapped specimen (mm)
$MOFW$	Multi-orientation fillet weld
MPL	The main plate leg is the fillet weld leg that is on the main plate of the specimen (mm)
MTD	Measured throat dimension (mm), see definition in Section 4.1
Normalized P_{ST}/A_{throat}	The value of the term (P/A_{throat}) divided by the ultimate tensile strength of the filler metal
P	Applied load (kN)
P_{ST}	Maximum applied static load (kN)
P_u	Maximum applied load (kN)
P_u	Capacity of a weld with a loading angle of θ (kN)
s_1, s_2	Fillet weld leg dimensions (mm)
$SOFW$	Single orientation fillet weld
V_G	Coefficient of variation for the measured-to-nominal weld dimension

V_{M1}	Coefficient of variation for the measured-to-nominal ultimate tensile strength of the filler metal
V_{M2}	Coefficient of variation for the measured-to-predicted ultimate shear strength of the filler metal
V_P	Coefficient of variation for the test-to-predicted weld capacity
V_R	Coefficient of variation for the resistance of the weld
V_r	Capacity of a fillet weld connection
X_u	Nominal ultimate tensile strength of the filler metal (MPa)
α_R	Coefficient of separation
β	Reliability index
Δ	Fillet weld deformation (mm)
Δ_f	Fillet weld deformation at weld fracture (mm)
Δ_{ult}	Fillet weld deformation at ultimate load (mm)
ε	Strain measured by strain gauge
ε_y	Strain equal to 1750×10^{-6}
θ	Angle between the axis of the fillet weld and the direction of the applied load (degrees)
λ	Regression coefficient used to characterize fillet weld response
μ	Regression coefficient used to characterize fillet weld response
ρ_G	Bias coefficient for the theoretical weld dimension
ρ_{M1}	Bias coefficient for the ultimate tensile strength of the filler metal
ρ_{M2}	Bias coefficient for the ultimate shear strength of the filler metal

ρ_P	Mean test-to-predicted weld capacity
ρ_R	Bias coefficient for the resistance of the weld
σ_u	The tensile strength of the weld metal
τ_u	Measured ultimate shear strength for a longitudinal weld (MPa)
ϕ	Resistance factor
ϕ_{w}	Weld resistance factor

† Symbols used in Appendix E may be different from this list and were explained where they appeared in Appendix E.

CHAPTER 1

INTRODUCTION

1.1 Background

The effect of load orientation on the strength and ductility of fillet welds has been recognized for a long time (Butler and Kulak, 1971; Clark, 1971 and Miazga and Kennedy, 1989). Transverse fillet welds, loaded at a right angle to the axis of the weld, provide the most strength but least ductility, whereas longitudinal welds provide the least strength, but most ductility. Relationships between load orientation and strength and ductility have been adopted in North American design standards (CSA, 2001; AISC, 2005).

The current design equation for strength of fillet welds used in the North American design standards originated from the work of Miazga and Kennedy (1986, 1989) and Lesik and Kennedy (1990). The test specimens by Miazga and Kennedy were prepared using the shielded metal arc welding (SMAW) process and an E4814 filler metal, which has no toughness requirement. This work was recently expanded by Ng *et al.* (2002), Deng *et al.* (2003), and Callele *et al*. (2005) to include the more prevalent flux-cored arc welding (FCAW) process and filler metals both with and without a toughness requirement. The results demonstrated that the current design equation, which acknowledges a strength for transverse welds 50% higher than that for longitudinal welds, provides an adequate level of safety for connections with fillet welds loaded in the plane of the joint.

In the case of a connection that combines welds with different orientations, the ductility of each weld segment must be accounted for when the strength of the joint is evaluated. In a typical welded joint that combines weld segments of different orientations, the weld segments with the least ductility usually develop their full strength, whereas the segments with the most ductility develop only part of their strength. Kulak and Grondin (2003) observed that the only 85% of the strength of longitudinal welds is developed when combined with transverse welds in the same joint. This observation was made from tests on joints that combined transverse welds, longitudinal welds, and bolts in the same shear plane. Callele *et al.* (2005) further expanded the research work of Ng *et al*. (2002) and Deng *et al*. (2003) to include connections with multiple orientation fillet welds (MOFW). It was demonstrated that the strength of differently oriented weld segments is not fully mobilized at failure of the welded joint. They confirmed the observation of Kulak and Grondin (2003) that when longitudinal welds are combined with a transverse weld in the same joint, only 85% of the strength of the longitudinal weld is mobilized at failure of the joint. Based on their test results, Callele *et al.* (2005) proposed a reliability based procedure to account for the effect of any weld orientation on ductility and contribution to the strength of MOFW.

The weld research program at the University of Alberta has included six different electrode classifications, which represents only a small portion of the electrode classifications used in industry. It is therefore desirable to conduct an extensive review of the literature to augment the database of test results on welded concentrically loaded joints.

1.2 Objectives and Scope

This report presents results of the fourth phase of a research project initiated at the University of Alberta to investigate the behaviour of concentrically loaded fillet welded connections. Ng *et al.* (2002), Deng *et al.* (2003) and Callele *et al.* (2005) presented the results of previous three phases of the project.

The fourth phase presents additional test results from welded cruciform joints. Tests on joints of this configuration conducted in phase 1 indicated that fillet welds in these joints may possess reduced strength and ductility compared to transverse welds in lapped joints.

In order to meet the objective of this project, an experimental program consisting of 12 fillet weld cruciform specimens was conducted. All specimens were prepared using the FCAW process and two electrodes, namely, E70T-7 and E71T8-K6. The E70T-7 filler metal has no toughness requirement, while the E71T8-K6 filler metal has a toughness requirement of 20 J at -29ºC (AWS 1998).

The reliability analyses presented in the previous phases of this program were conducted using test results obtained primarily at the University of Alberta. Another main objective of this phase is to augment this database of test results to include test results from other sources. This provides a larger database of test results that better reflects the variation present in industry. Test data from various test programs on lapped splices with single and multiple orientation welds and on cruciform test specimens were collected. A reliability analysis was conducted to assess the current North American design equations.

1.3 Units Used in this Paper

SI units are generally used throughout this document, although there are exceptions. The filler metal designations use imperial units as implemented in the AWS classification. This exception was made because the AWS classification is more commonly used in industry. The weld sizes are the direct conversion from their imperial units because of the practice adopted by the fabrication workshop.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

Although both analytical and experimental investigations of the strength and ductility of fillet welds exist, this review covers only experimental research. The literature review focuses particularly on experimental work conducted from the 1960s to the present on concentrically loaded fillet weld connections, as this is the most relevant to the current research. A detailed literature review of fillet weld research is available from Ng *et al*. (2002).

The test data of some experimental programs are reproduced and analyzed in Appendix E, and the results of those tests are used in Chapter 4 for a reliability analysis.

2.2 Fillet Weld Strength as a Function of Loading Direction

Ligtenberg (1968) presented the results of an international test series on double lapped splice fillet weld joints loaded in tension. Including Canada, 11 countries participated in this study and each country performed separate tests under the direction of a common committee. The specimen configurations included longitudinal welds only, transverse welds only, and combined longitudinal and transverse welds with different proportions of weld throat size and weld length. The majority of the test series were performed on St.37 steel (minimum ultimate tensile strength 360 MPa), or material of similar quality, and a few additional test series were carried out on St.52 steel (minimum ultimate tensile strength 510 MPa) to broaden the scope of application of the test results. To diversify the electrodes and welding processes, each country selected three electrodes (acid coated, basic and rutile) in such a way that they were made and commonly used in the participating country. The weld metal tensile strength ranged from about 450 MPa to 580 MPa and the weld throat size ranged from 3 mm to 10 mm. The strength of transverse welds was found to be 1.6 times that of longitudinal fillet welds when the weld strength was defined as one half of the sum of steel plate ultimate tensile strength and the filler metal ultimate tensile strength.

Based on the test results presented by Ligtenberg (1968), Bornscheuer and Feder (1966) designed a test program to investigate further the effect on fillet weld strength of weld length, weld throat dimension, and the ratio of the area of the plate to the cross-sectional area of the fillet weld. The specimen configurations were the same as those reported by Ligtenberg (1968) and a rutile-type electrode was used. The throat dimensions of specimens were 4 mm, 8 mm and 12 mm. The ratio of the strength of transverse welds to that of longitudinal welds was found to be similar to the results presented by Ligtenberg (1968).

After the international test series presented by Ligtenberg (1968), Kato and Morita (1969) reported tests that were designed to further investigate the effects of weld metal mechanical properties, the amount of weld penetration, and weld leg sizes on fillet weld strength. Basic and rutile electrodes were used. The weld leg size ranged from 5 mm to 40 mm for transverse welds and from 5 mm to 22 mm for longitudinal welds. Kato and Morita proposed that the strength of transverse fillet welds was statistically 1.46 times that of longitudinal fillet welds. The test results reported by Ligtenberg (1968) were also used to substantiate their strength prediction formulae.

Higgins and Preece (1969) reported a series of 168 tests on double lapped splice specimens with all longitudinal or all transverse fillet welds. A variety of shielded metal arc welding electrodes (E60XX, E70XX, E90XX and E110XX), base metals (ASTM A36, A441 and A514), fillet weld sizes (6.35 mm, 9.53 mm and 12.7 mm), and weld lengths (from 38.1 mm to 101.6 mm) were used. Another important factor considered in the design of the test specimens was the matching of base metal and the weld metal. For fillet welds made with E70XX electrodes and deposited on matching base metals of grade A441 steel, the strength of transverse welds was found to be 1.57 times that of longitudinal welds. For fillet welds made with E110X electrodes and deposited on matching base metals of grade A514 steel, the average strength of transverse welds was 1.44 times that of longitudinal welds.

Clark (1971) reported a series of 18 tests conducted to investigate the variation of strength and ductility with the loading direction. The specimens included 0º (longitudinal), 30º, 60º and 90º (transverse) fillet weld orientations. The results showed an increase in strength of approximately 70% as the loading angle changed from 0º to 90º.

Butler and Kulak (1969, 1971) reported a series of 23 concentrically loaded double lapped connections with 6.35 mm (¼ in.) fillet welds of different angles, namely 0º (longitudinal), 30º, 60º and 90º (transverse). The objective of the tests was to establish load–deformation relations for elemental lengths of fillet weld. The results showed that both weld strength and deformation capacity vary with the loading direction. The specimens were prepared using E60XX electrodes and CSA G40.12 steel plates, which have a specified yield strength of 300 MPa and a minimum tensile strength of 450 MPa. The test results showed that the increase in strength of the fillet welds was approximately 44% as the angle of loading changed from 0º to 90º.

Swannell and Skews (1979a, b) reported the results of a series of tests designed to obtain load–deformation relationships for different loading angles. The main specimens were loaded in compression, which differs from most of other test programs. The major tests consisted of six specimens loaded in compression for every loading angle of 0º (longitudinal), 30º, 60º and 90º (transverse). The specimens were prepared using E6013 electrodes and steel plates with a minimum yield strength of 210 MPa and a minimum tensile strength of 410 MPa. The leg size was 6.35 mm. The test results showed an increase in strength of approximately 19% as the angle of loading changed from 0º to 90º.

Miazga and Kennedy (1986, 1989) reported the results of tests on 42 fillet weld double lapped splice specimens loaded in tension. The loading angle varied from 0º to 90º in 15º intervals. Two weld sizes were tested, namely, 5 mm and 9 mm, deposited using the SMAW process with E7014 electrodes. The ratio of the transverse weld strength to the longitudinal weld strength was 1.28 for the 5 mm welds and 1.6 for the 9 mm welds, with an average of 1.43 for all specimens. Based on the measured strength data and the analysis of a free body diagram of a fractured weld, they developed an expression that related weld strength to the loading angle. Later, Lesik and Kennedy (1990) formulated a simplified version of the strength expression proposed by Miazga and Kennedy (1989). The expression of Lesik and Kennedy (1990) takes the following form:

$$P_\theta = P_0 \ (1.00 + 0.50 \sin^{1.5}\theta) \qquad (2.1)$$

where P_θ is the load capacity of the fillet weld subjected to any direction of loading, P_0 is the load capacity of a longitudinal fillet weld of same size, and θ is the angle between the line of action of the load and the axis of the fillet weld. Equation 2.1 is commonly used in North American design standards to account for the effect of the angle of loading on fillet weld capacity.

Bowman and Quinn (1994) conducted an experimental investigation of geometrical factors that influence the behaviour of fillet welds. The experimental program had 18 specimens, including longitudinal and transverse weld specimens with three leg sizes, namely, 6.35 mm (1/4 in.), 9.53 mm (3/8 in.), and 12.7 mm (1/2 in.), and three different root gap configurations. The welds were prepared using E7018 electrodes. The ratio of the strength of transverse welds to that of longitudinal welds ranged from 1.3 to 1.7 for the un-gapped specimens and 1.2 to 1.4 for the gapped specimens.

Ng *et al*. (2002) conducted tests on 102 transverse fillet weld connection specimens prepared primarily using the flux core arc welding (FCAW) process, although nine specimens were prepared using the shielded metal arc welding (SMAW) process to provide a direct comparison with the test results from Miazga and Kennedy (1989). Of 102 specimens, 96 were double lapped joints and six were cruciform connections. All specimens were concentrically loaded in tension and deformations were measured across the weld leg using LVDTs. The tests were designed to investigate the effect of the following parameters: (1) filler metal classification, both with and without a toughness requirement; (2) welding process, flux cored vs. shielded metal arc melding; (3) weld size and number of passes; (4) welding electrode manufacturers; (5) steel fabricators; (6) low temperature; and (7) root notch orientation of fillet weld, i.e. lapped vs. cruciform splice. The capacity was predicted using Equation (2.1), since it has been adopted by both CSA-S16-01 (CSA 2001) and the AISC Specification (AISC 2005), and the measured weld material strength and fillet weld size. The ratio of tested to predicted strength ranged from 1.14 to 2.30. A reliability analysis was performed for different groups of connections and the safety index, β, was found to be at least equal to 4.5, which is the traditional target value for connections in the Canadian design standard.

Deng *et al*. (2003) presented the results of 18 tests on joints with longitudinal and 45° fillet welds that were tested to complement the test program reported by Ng et al. (2002). The test specimens were prepared with 12.7 mm fillet welds and three different FCAW electrode classifications. It was reported that the strength of fillet welds increased with increasing loading angle. It was found that the design equation currently used in North America provides an adequate level of safety for joints with single orientation fillet welds.

2.3 Strength of Cruciform Fillet Weld Specimens

Pham (1983a) reported results of 36 tests on cruciform specimens, of which 18 were made with the FCAW process and 18 were made with the SAW process. The nominal leg sizes were 6 mm, 10 mm and 16 mm. The primary objectives of the tests were to assess the effects of leg size on the strength of fillet welds and to obtain a corresponding load–deformation relationship. Pham (1983a) did not provide results of transverse welds in lapped joints. The results of his test program, presented in Table E9.5 of Appendix E, show that the ratio of measured strength to predicted strength using Equation (2.1) is 1.05 for both FCAW and SAW specimens.

It is postulated by Miazga and Kennedy that the prediction models proposed by Miazga and Kennedy (1986, 1989) might apply to double fillet T-joints in tension. The predicted fracture for such joints is 22.5º to the axis of the stem of the Tee and the weld strength would be at least 1.34 times the longitudinal value.

Ng *et al*. (2002) tested six cruciform specimens made with E70T-4 and E70T7-K2 electrodes. The test results showed that transverse fillet welds in a cruciform configuration tend to provide both lower weld strength and lower ductility than transverse welds in a lapped splice connection.

2.4 Load Capacity of Joints with Multiple Orientation Fillet Welds (MOFW)

Ligtenberg (1968) reported 223 MOFW connections loaded concentrically and 54 specimens loaded with out-of-plane eccentricity. The results showed that the ratio of the area of transverse welds to that of longitudinal welds was the most critical factor that affected the strength of an MOFW connection. A statistical analysis of the test results indicated that less than 100 percent of the capacity of the transverse and longitudinal welds was developed in a MOFW.

Based on the observation that longitudinal welds have more ductility than transverse welds, Kato and Morita (1969) proposed a participation factor for the contribution of the longitudinal welds to the capacity of a MOFW joint. The contribution factor, μ, which represents the fraction of the longitudinal weld strength that is developed in a MOFW joint, is given as:

$$\mu = 0.788 + 0.065/z, \quad 0.28 \le z \le 3.6 \tag{2.2}$$

where z is the ratio of leg size of longitudinal welds to that of transverse welds in the MOFW joint. Equation (2.2) was used to predict the strength of the test specimens from the international test series of Ligtenberg (1968). The ratio of the tested to predicted capacity was 1.007 for St.37 steel specimens and 1.023 for St.52 steel specimens.

Callele *et al.* (2005) expanded the research program of Ng *et al.* (2002) and Deng *et al.* (2003) to include MOFW joints to investigate whether the least ductile segment in a concentrically loaded MOFW connection can deform sufficiently to develop the full strength of the more ductile segments. A total of 31 double lapped joints that combined transverse welds with either longitudinal or 45º welds were tested. Complementary tests, including nine longitudinal and three transverse fillet welds, were conducted to define the load–deformation curves for fillet welds. The parameters considered in the MOFW specimen design were: (1) fillet weld leg size, (2) number of weld passes, (3) weld continuity at the corners, (4) weld length, and (5) stress state of the connection plates, which is characterized by the plates remaining elastic throughout the test or the plates yielding. Callele *et al.* (2005) proposed the following equation to calculate the capacity of the various segments of a MOFW:

$$\text{Segment Capacity} = P_\theta \; CRF(\theta) \tag{2.3}$$

where P_θ is the capacity of the weld segment predicted by equation (2.1), CRF(θ) is the reduction factor, which accounts for the fact that the segment strength may not be fully mobilized. For a MOFW joint with combined longitudinal (θ=0º) and transverse (θ=90º) fillet welds, CRF(0º) = 0.85 and CRF(90º) = 1.0. The capacities of tested MOFW specimens were predicted using equation (2.3) and the test-to-predicted ratio was 0.89. However, a reliability analysis showed the safety index is acceptable for a resistance factor of 0.67, as specified in CSA-S16-01.

2.5 Effects of Weld Size and Length on Fillet Weld Strength

Ligtenberg (1968) examined the effect of weld size on the strength of connections with transverse welds only and longitudinal welds only. Within the limits of the weld throat dimensions tested, i.e., for weld throats between 3 and 10 mm, with a rather small weld length, the throat size had no significant effect on the strength. However, similar tests by Bornscheuer and Feder (1966) on 35 specimens welded with rutile electrodes showed that the weld size effect on weld strength was significant. The unit strength of 12 mm longitudinal fillet welds was about 35% smaller than that of 4 mm welds. The strength of 12 mm transverse fillet welds was about 20% lower than that of 4 mm welds. Results of Bornscheuer and Feder (1966) also demonstrated that the length of longitudinal fillet welds (length-to-size ratio of 25, 50, 75, and lengths varying from 100 mm to 300 mm) had no influence on the strength.

Kato and Morita (1969) performed tests similar to those presented by Ligtenberg (1968). In their tests, the weld leg size ranged from 5 mm to 40 mm for transverse welds and from 5 mm to 22 mm for longitudinal welds. The strength was calculated on the measured failure area. Kato and Morita concluded that the average maximum strength of fillet welds was not affected by the size of weld within the large range of leg sizes examined.

Higgins and Preece (1969) investigated the effect of weld length upon weld strength. The weld leg size was 6.35 mm (1/4 in.) and the length varied from 6 to 16 times the weld size. Test results showed the strength increased slightly with the increasing length.

Pham (1981) investigated the effect of weld size upon the weld strength by testing welds with in-plane load eccentricity. The nominal weld leg sizes were 5 mm, 10 mm and 16 mm. The other factors considered in specimen design were the weld length and magnitude of eccentricity. Pham (1981) found that the unit strength of small welds was larger than that of large welds.

Pham (1983a) investigated the effect of weld size on the strength of fillet welds using IIW-recommended cruciform specimens for FCAW and SAW processes. The results showed that the size effect was most dominant in FCAW for welds up to 8 mm measured at the throat. For larger welds there was no further reduction. For SAW specimens the size effect was more gradual but covered the whole range of weld sizes investigated in the test series. In a separate investigation, Pham (1983b) confirmed the observations of the earlier investigation using Werner specimens in which the welds are loaded longitudinally.

Bowman and Quinn (1994) tested specimens with longitudinal and transverse welds with leg sizes of 6.35 mm (1/4 in.), 9.53 mm (3/8 in.) and 12.7 mm (1/2 in.) to investigate the effect of weld size on weld strength. The strength was calculated on the measured rupture areas. For longitudinal specimens, the average strength of 12.7 mm welds was 25% lower than that of 6.35 mm welds. For transverse specimens, the average strength of 12.7 mm specimens was only 4% lower than that of 6.35 mm specimens. It was concluded that a dimple in the exposed weld profile of the 12.7 mm welds due to multiple passes was responsible for the reduced strength.

Ng *et al.* (2002) reported tests of transverse welds prepared with four different FCAW electrodes. The average ratio of the unit strength of the 6.35 mm welds to 12.7 mm welds was 1.26.

Callele *et al.* (2005) analyzed the effect of weld size and number of passes on weld strength using data from Ng *et al.* (2002), Miazga and Kennedy (1989) and their own tests. Generally, the small size welds were found to have higher unit strength with larger scatter. The number of weld passes seemed to have no effect on strength.

Callele *et al.* (2005) also analyzed the effect of longitudinal weld length on weld strength using data from Deng *et al.* (2003), Miazga and Kennedy (1989) and their own tests. The lengths of fillet welds examined were 50, 80, 100 and 150 mm. The 50 mm welds had the highest average strength and the 100 mm welds had lowest strength, which showed the decrease in strength with an increase of length. However, the 150 mm welds showed higher strength than the 80 mm and 100 mm welds, which made the investigation inconclusive.

2.6 Summary

Considerable experimental research has been performed on lapped splice connections with fillet welds loaded at various angles to the weld axis. Researchers generally agree that the weld strength increases as the weld orientation changes from longitudinal to transverse. A reliability analysis of test data from the University of Alberta has shown that the current North American design equations provide an acceptable safety index.

The strength of fillet welds in cruciform joints has not been given much attention yet. The results from a limited number of tests have shown that the strength of cruciform connections tends to be lower than that of transverse welds in lapped splice joints. It is questionable whether the current design equation for weld strength yields an acceptable level of safety when used with cruciform joints.

When fillet welds of different orientations are used in a MOFW connection, the capacity of the more ductile segment cannot be developed fully because of the limited ductility of the least ductile segment. Callele *et al.* (2005) have proposed an equation to consider both the reduction of strength of more ductile weld segments and the increase of strength of the less ductile weld segments compared with that of longitudinal welds. A reliability analysis demonstrated an acceptable level of safety based on limited test results. The applicability of the formula needs to be examined further with a larger number of test results.

Some test results have shown that smaller size fillet welds tend to provide higher unit strengths, no matter whether the strength is calculated on the nominal throat area or on the measured fracture area. Therefore, reliability analysis results based on data from tests on small weld sizes (such as 1/4 in.) should be used with caution. No effect of weld length on weld strength was generally observed.

It is therefore concluded that further experimental research on the strength of cruciform connections is required and a reliability analysis on SOFW and MOFW joints based on a larger data pool is desirable.

CHAPTER 3

EXPERIMENTAL PROGRAM AND RESULTS

3.1 Introduction

A review of the literature on fillet weld research showed that most experimental programs have used double lap joints, with limited tests on cruciform connections. Because of the more severe root notch orientation in cruciform specimens, it is possible that the strength and ductility of fillet welds in joints of that configuration might be significantly lower than the strength and ductility of double lapped joints. Therefore, an experimental program was designed to investigate the strength and ductility of fillet welds in cruciform connections in order to expand the database of test results on concentrically loaded fillet weld connections. This represents the fourth phase of an ongoing research program on welded joints conducted at the University of Alberta. Phase 1 included tests on transverse welds conducted by Ng *et al.* (2002), phase 2 refers to the test program by Deng *et al*. (2003) and phase 3 refers to the work of Callele *et al.* (2005). The tests presented in this chapter were conducted by Mr. Andre Blanchard and Mr. Derek Kramar, under the supervision of Mr. Logan Callele.

3.2 Test Parameters

The factors considered in the design of the test matrix are: connection configuration (*i.e.* cruciform connection vs. lapped splice specimens from previous phases of the research program), welding electrode classification, fillet weld size, main plate stress condition, and test temperature. The phase 4 test matrix, including four different test cases, is presented in Table 3.1. The test specimens are designated by the letters CNY, indicating a cruciform joint configuration with "non-yielding" plates, i.e., plates designed to remain elastic throughout the tests. The specimens are numbered sequentially from 1 to 12. Each test was repeated three times to assess variability of the test results within one treatment.

The specimens were prepared using the flux-cored arc welding (FCAW) process. Two FCAW filler metals were selected, namely, an E70T-7 filler metal, which has no toughness requirement (AWS, 1995), and an E71T8-K6 filler metal, which has a toughness requirement of 20 J at –29 ºC (AWS, 1998). The nominal tensile strength for both electrodes is 480 MPa (70 ksi) and the actual tensile strength was established using tests on all-weld-metal tension coupons. Three such coupons, with a 50 mm gauge length, were prepared in accordance with the appropriate AWS specification (AWS, 1995, 1998) from each wire spool. The results of six coupon tests are presented in Table 3.2 and the stress versus strain curves from each tension coupon are presented in Appendix A.

The steel plates used for the fabrication of the test specimens conformed to the requirements of ASTM A572 Grade 50 and CSA G40.21 350W. This grade of steel is suitable for welding but has no toughness requirement. All specimens were fabricated with plates from the same heat.

The test results from phases 1 to 3 indicated that weld size has a significant effect on the unit strength of fillet welds. Test specimens with a weld size of 6.4 mm showed a higher unit strength than 12.7 mm welds. Since the six pilot cruciform specimens in phase 1 had a leg size of 6.4 mm, all the test specimens from the current phase were made with (nominally) 12.7 mm welds.

Another factor considered in specimen design is the average stress level in the plates during testing. Test results from Ligtenberg (1968) indicated that stress level in the plates did not have a significant effect on fillet weld strength. Callele *et al.* (2005) examined the test results from phases 1 and 3 and those of Miazga and Kennedy (1989) and found that plate yielding before weld fracture may increase the weld ductility, but has negligible effect on weld strength. The plates used in this phase of the test program were therefore designed to remain elastic.

The effect of low temperature on fillet weld behaviour was also one of the test parameters for this phase of the test program. Six cruciform specimens were tested at -50°C. Unfortunately the specimens did not fail as expected. All the specimens tested at low temperature fractured in the plates. Therefore, the low temperature test results are not included in the analysis presented in Chapters 3 and 4. A discussion of the low temperature tests can be found in Appendix D.

3. 3 Specimens Description

The dimensions of the test specimens are shown in Figure 3.1. As depicted in the figure, three 76 mm cruciform test specimens were obtained from each assembly. The assemblies were fabricated so that both sides of the connections were nominally identical. Once the assemblies were fabricated they were inspected visually for weld quality and conformance to the design specifications. Whichever side of the central plate was determined to have better weld quality was taken as the test welds and the other side was reinforced by adding additional weld passes in order to force the failure in the test welds, thus reducing the number of welds that had to be instrumented during testing. The test specimens were prepared from the weld assemblies by water jet cutting, followed by milling.

3.4 Pre-Test Measurements

Four types of measurements were made to characterize the fillet weld before testing: main plate leg size (MPL), central plate leg size (CPL), throat dimension (measured at 45º), and length of the two test fillet welds. A description of the weld dimensions measured is shown in Figure 3.2. The MPL and CPL dimensions and the 45º throat dimension were measured at eight locations spaced equally along the two test welds for each test specimen. The devices used for measurement of weld size were described in detail in Callele *et al.* (2005).

A summary of the measured weld sizes is presented in Table 3.3, where the values shown represent the average of eight measurements. The complete set of measurements is reported in Appendix B.

For cruciform specimens, any misalignment of the main plates results in load eccentricity during testing. The eccentricities of the main plates were measured as depicted in Figure 3.3 and the results are presented in Table 3.4. The results show that the maximum eccentricity was only 2.05% of the thickness of main plate.

3.5 Instrumentation and Test Procedure

The cruciform specimens were tested in a MTS 6000 universal testing machine and loaded in concentric tension until rupture of the fillet welds or plates occurred. The specimens were oriented so that the weld axis was horizontal and the test welds were positioned below the reinforced welds. This orientation facilitated the instrumentation of the specimens with linear variable differential transformers (LVDTs). The overall test setup and instrumentation for the specimens are depicted in Figure 3.4.

Special LVDT brackets were designed in phase 1 to measure the deformation of the test welds during loading. The LVDTs were mounted on the test specimens as shown in Figure 3.4. Two hardened steel anchors used to support one end of the mounting bracket were set in two light punch marks made on the base plates at the toe of the welds. These punch marks ensured that the anchors of the brackets remained in place during the test. The rear of each bracket was fitted with two rollers to stabilize the assembly while at the same time eliminating longitudinal restraint. The brackets were kept anchored to the punch marks during the test using rubber bands wrapped around the specimens. The gauge length over which the weld deformations were measured was the distance between the punch marks and the face of the central plate. The punch marks were placed as close as possible to the toe of the weld so that the amount of plate deformation captured within the gauge length was kept to a minimum. The gauge length used for strain calculations was taken as the average weld leg size within the instrumented weld segment.

For specimens CNY-6, 7, 8, 10, 11, 12, electrical resistance strain gauges were used to measure the strains at the edges of the test specimens, near the weld toe. The strain gauge arrangement is depicted in Figure 3.5. These strain gauges were used to assess the amount of load eccentricity both in the in-plane and in the out-of-plane directions.

The specimens were loaded quasi-statically under displacement control. The load and displacements were recorded in real time during the tests. Static load values were acquired by maintaining a constant deformation for about five minutes. The tests were terminated when one of the test welds ruptured. The instrumentation was then removed and the specimen was loaded until both test welds had ruptured so that the weld fracture surfaces could be inspected.

3.6 Main Plates Misalignment Second Order Effects

Although precautions were taken, fabrication imperfections in the test specimens were unavoidable. Both an angular misalignment and an offset of the axis of the main plates (see measurement 1 and 2 in Figure 3.3 for example) cause bending of the main plates and affect the stresses in the welds during the test. Neglecting the small offsets, the relationship between the maximum bending stress in the plate, σ_b, resulting from the second order effects, and the tensile stress, σ_t, caused by the axial force can be estimated by the following equation if the plates are known to remain elastic and the test machine grips are considered pinned:

$$\sigma_b / \sigma_t = \frac{6e}{h} \tag{3.1}$$

where e is the eccentricity of the applied load at the section of interest and h is the dimension of the cross-section perpendicular to the bending axis, as shown in Figure 3.6. The value of σ_b / σ_t for the six specimens tested at room temperature was analyzed and the results are summarized in Table 3.5. The load eccentricity used in the calculations is the maximum of the four measurements for each specimen as presented in Table 3.4 (i.e., the maximum of L1, L2, L5, and L6). A positive eccentricity causes an increase in tensile stress on the front face of the test specimen as shown in Figure 3.6. The section height (main plate thickness), h, was 50.8 mm.

Table 3.5 indicates that the bending stress on the surface of main plates could be as high as 11% of the tensile stress during the tests. This means that one of the two welds would potentially carry more load than the other weld. However, this observation is based on the assumption that the material remains elastic throughout the test, which was not the case. Yielding of a weld segment would cause a redistribution of the load carried by each weld segment, thus reducing the eccentricity effect. In fact, the fractured welds were not always at the face with higher tensile strains, but were always at the face having the least weld throat area. This result indicates that in reality the bending effect caused by the eccentricities was not as large as is implied by Table 3.5.

The strain measurements from the six specimens tested at room temperature are presented in Appendix C. Figures C14 to C19 show plots of the normalized load, P/P_u, as a function of the normalized strain, $\varepsilon/\varepsilon_y$.

Figures C20 to C25 present plots of the strain ratio, $\varepsilon_b/\varepsilon_t$ as a function of the load ratio, P/P_u. Generally, the bending strains reached a peak at about less than 10% of the ultimate load and then decreased sharply to a value close to zero. The stress concentration caused by the abrupt change in geometry made the strains measured with strain gauges very different from the average strain in the plates and it is likely that localized yielding near the weld toe occurred early causing the forces in the welds to redistribute. Overall, the fabrication imperfections are not considered to have had a significant effect on the behaviour of the specimens.

3.7 Cruciform Specimen Capacities

The ultimate static capacity of each specimen tested at room temperature is presented in Table 3.6. The strength of the fillet weld was obtained by dividing the static ultimate load P_{ST} by the throat area of the specimens as measured before testing.

The minimum throat area A_{throat} of each segment is a function of the measured weld leg size on the main plate, MPL, and on the central plate, CPL, and the weld length. The definition of MPL, CPL and minimum throat dimension (MTD) for a typical fillet weld cross-section is illustrated in Figure 3.2. The minimum throat dimension (MTD) is the shortest distance from the root of the fillet weld to the hypotenuse of the triangle defined by the two legs of the weld. The minimum throat dimension is obtained from:

$$\text{MTD} = \frac{\text{MPL} \times \text{CPL}}{\sqrt{\text{MPL}^2 + \text{CPL}^2}} \tag{3.2}$$

The minimum throat area, A_{throat}, is therefore equal to the product of the minimum throat dimension, MTD, and the weld length. The throat area thus obtained ignores the weld root penetration and the weld face reinforcement, if any. The total throat area is calculated differently depending on the number of fractured welds. If only one weld fractured, the total throat area is taken as twice the minimum throat area of the fractured weld. This, in effect, assumes that half of the applied load was carried by the fractured weld. If both welds fractured simultaneously, the throat area is taken as the sum of the minimum throat areas of the two welds.

The specimens were loaded quasi-statically under displacement control. The load and displacements were recorded in real time during the tests. Static load values were acquired by maintaining a constant deformation for about five minutes and the upper load is the extreme large value and the lower load is the extreme small value within the five minute maintenance of the deformation. The static drop is the difference between the upper and lower load. The ultimate load is the extreme large value of load during the entire loading process. The ultimate load may occur within the last five minute maintenance of deformation or after. The static load reported in Table 3.6 is the one recorded near the ultimate load.

3.8 Weld Strains Calculated from Deformations Measured with LVDTs

The weld segment deformations and the calculated strains at the ultimate load and at fracture of specimens tested at room temperature are presented in Table 3.7. The weld strains in the direction of applied load are obtained by dividing the measured weld deformation, Δ, by the average main plate leg (MPL) dimension, d^*.

The measured deformation Δ is reported differently depending on the number of fractured welds. If only one weld fractured, the deformation is taken as the average deformation from the two LVDTs mounted on the fractured weld. Otherwise, the deformation is taken as the average of the four LVDT measurements on the two test welds. The response curves for the specimens tested at room temperature are presented in Appendix C.

3.9 Effect of Root Notch Orientation on Weld Strength

The normalized P_{ST}/A_{throat} values presented in Table 3.8 were obtained by dividing P_{ST}/A_{throat} by the measured weld metal tensile strength for the corresponding spool of filler metal. The normalized strength of cruciform specimens is compared with that of lapped splice specimens with transverse welds from phases 1 and 3. These results are tabulated in Tables 3.8a through 3.8d and presented graphically in Figures 3.7a to 3.7d. Each of the figures indicates both the range of values and the mean for a particular set of variables.

Table 3.8a compares the normalized strengths for the lapped splice joint configuration to those obtained from cruciform specimens with a leg size of 12.7 mm and fabricated using E70T-7 welding electrodes. The normalized strengths are plotted in Figure 3.7a. The ratio of the mean normalized strength for cruciform joints to that of lapped splice specimens is 0.81. Table 3.8b and Figure 3.7b present a similar comparison for test specimens with a leg size of 12.7 mm and E71T8-K6 filler metal. The ratio of the mean normalized strength for cruciform joints to that of lapped splice specimens is 0.70. The results indicate that the strength of cruciform joints is significantly lower than that of equivalent lapped splice joints.

Table 3.8c presents a comparison between the normalized strength for lapped splice joints and cruciform joints for 6.4 mm welds and E70T-4 welding electrode classification from phase 1 of the University of Alberta weld test program. The range of the normalized strength is depicted in Figure 3.7c. The ratio of the mean normalized strength for cruciform joints to that of lapped splice joint specimens is 1.01. A similar comparison between cruciform joints and lapped splice joints made with 6.4 mm welds of E70T7-K2 filler metal is presented in Table 3.8d and Figure 3.7d. In this case, the ratio of the mean normalized strength of cruciform joints to that of lapped splice joints is 0.87. The results indicate that the strength of cruciform joints is equal to or lower than that of lapped splice joints with 6.4 mm weld size.

The strength ratios presented in Tables 3.8a to 3.8d are summarized in Table 3.9. The comparisons indicate that the root notch orientation in the cruciform specimen results in lower fillet weld strength and the magnitude of the strength reduction is affected by the leg size and the toughness requirement of the electrodes. A larger strength reduction is observed with larger weld size and electrodes with toughness requirement. The most severe situation is the fillet weld with a leg size of 12.7 mm and a welding electrode with toughness requirements, for which a strength reduction of almost 30% was observed.

3.10 Effect of Root Notch Orientation on Ductility

The weld strains of cruciform specimens are compared with those of lapped splice specimens tested in phase 1 and phase 4. These results are tabulated in Tables 3.10a through 3.10d.

The weld strains measured in specimens prepared with E70T-7 electrodes and 12.7 mm welds are compared in Table 3.10a. When the steel plates remained elastic during the test for both cruciform and lapped splice specimens, the average strain at ultimate load for cruciform joints was found to be 100% of that of lapped splice specimens and the average strain at fracture of cruciform specimens is 70% of that of lapped splice specimens. However, when the comparison is made between cruciform specimens with elastic plates during the test and lapped splice specimens with yielding plates, the average strain at ultimate load for the cruciform specimens was found to be 22% of that of the lapped splice specimens and the average strain at fracture of the cruciform specimens is 13% of that of the lapped splice specimens.

Table 3.10b indicates that specimens prepared with E71T8-K6 electrodes and 12.7 mm welds have an average strain at ultimate load for the cruciform joints 12% of that of the lapped splice specimens. The average strain at fracture of the cruciform specimens is 35% of that of the lapped splice specimens when the steel plates of lapped specimens yielded during the tests but the steel plates of cruciform specimens remained elastic.

In Table 3.10c, the weld strains measured in specimens prepared with E70T-4 electrode and 6.4 mm welds are compared. The average strain at ultimate load for the cruciform joints was found to be 21% of that of the lapped splice specimens. The average strain at fracture of the cruciform specimens is 35% of that of the lapped splice specimens when the steel plates yielded during the tests.

A comparison of cruciform and lapped splice specimens prepared with E70T7-K2 electrode and 6.4 mm welds is presented in Table 3.10d. The average strain at ultimate load for the cruciform joints was found to be 8% of that of the lapped splice specimens and the average strain at fracture of the cruciform specimens is 8% of that of the lapped splice specimens when the steel plates yielded during the tests.

The results show that cruciform fillet weld specimens have lower ductility compared with lapped splice specimens. It should be noted that in phase 1 the steel plates of the test specimens yielded before the welds fractured and in phases 3 and 4 the steel plates remained elastic throughout the tests. This difference is another reason for the extent of the reduction in weld ductility of cruciform specimens compared to that of lapped splice specimens.

Table 3.1 – Test Matrix – Cruciform Specimens

Weld Metal Classification	E70T–7	E71T8–K6	E70T–7	E71T8–K6
Test Temperature	20 ºC		- 50 ºC	
Specimen Designation†	CNY–7,8,10	CNY–6,11,12	CNY–1,5,9	CNY–2,3,4

† All specimens were fabricated using three passes.

Table 3.2 – Mechanical Properties of Weld Metal †

Electrode	Test ID	Static Yield Strength		Static Tensile Strength		Modulus of Elasticity		Rupture Strain	
		Test	Mean	Test	Mean	Test	Mean	Test	Mean
		(MPa)	(MPa)	(MPa)	(MPa)	(MPa)	(MPa)	(%)	(%)
E71T8–K6	203–1	393	383	495	489	195000	197000	29.8	30.2
	203–2	367		484		196000		31.6	
	203–3	389		488		200000		29.3	
E70T–7‡	103–1	418	420	568	569	197000	195000	8.3	11.0
	103–2	431		566		196000		9.0	
	103–3	410		573		193000		15.6	

† The strength and strain are expressed as engineering stress and stain.

‡ The test results for this electrode were also reported by Callele *et al*. (2005).

Table 3.3 – Summary of Pre-Test Weld Measurements

Specimen	Front Face						Back Face					
	MPL (mm)	CPL (mm)	45° Meas. (mm)	Weld Length (mm)	MTD (mm)	A_{throat} (mm^2)	MPL (mm)	CPL (mm)	45° Meas. (mm)	Weld Length (mm)	MTD (mm)	A_{throat} (mm^2)
CNY–1	12.87	10.31	9.72	72.4	8.05	582.5	11.85	9.85	9.84	72.4	7.58	548.6
CNY–2	11.89	12.67	10.85	76.3	8.67	661.8	11.50	11.42	11.01	76.3	8.10	618.2
CNY–3	12.90	11.98	12.12	76.3	8.77	669.8	13.49	10.71	11.61	76.3	8.39	640.2
CNY–4	14.97	11.63	12.28	76.3	9.18	700.8	13.51	10.79	11.27	76.3	8.43	643.5
CNY–5	11.46	11.60	9.39	72.4	8.15	590.6	12.64	9.06	9.62	72.4	7.36	533.4
CNY–6	13.15	10.71	11.51	76.3	8.30	633.6	11.98	12.64	11.83	76.3	8.69	663.5
CNY–7	12.81	9.54	8.95	72.5	7.65	554.6	12.13	9.76	9.41	72.4	7.60	550.7
CNY–8	13.50	10.15	10.36	72.4	8.11	587.5	13.10	10.23	9.76	72.4	8.06	584.1
CNY–9	13.48	10.40	10.76	72.4	8.23	596.4	11.91	11.65	9.94	72.4	8.33	603.1
CNY–10	11.91	11.55	9.82	72.4	8.29	600.1	11.47	9.63	9.39	72.3	7.37	533.4
CNY–11	12.25	11.76	10.78	76.3	8.48	647.1	11.90	12.17	10.83	76.3	8.51	649.0
CNY–12	11.82	11.86	10.87	76.3	8.37	638.7	11.06	12.49	10.26	76.3	8.28	631.8

Table 3.4 – Measured Eccentricities in the Cruciform Specimens

specimen	L1* (mm)	L2 (mm)	L3 (mm)	L4 (mm)	(L1/h†)×100 (%)	(L2/h)×100 (%)	L5 (mm)	L6 (mm)	L7 (mm)	L8 (mm)	(L5/h)×100 (%)	(L6/h)×100 (%)
CNY–1	0.533	0.178	343	342	1.05	0.35	0.457	0.254	341	344	0.90	0.50
CNY–2	0.432	0.000	347	338	0.85	0.00	0.406	0.076	342	343	0.80	0.15
CNY–3	-0.788	-0.914	337	349	-1.55	-1.80	-0.686	-0.838	340	343	-1.35	-1.65
CNY–4	-0.813	-0.889	336	349	-1.60	-1.75	0.940	1.041	333	352	1.85	2.05
CNY–5	0.483	0.686	343	341	0.95	1.35	0.483	0.635	335	350	0.95	1.25
CNY–6	0.787	0.889	338	346	1.55	1.75	0.737	0.838	339	346	1.45	1.65
CNY–7	0.584	0.089	342	343	1.15	0.18	0.533	0.152	347	338	1.05	0.30
CNY–-8	-0.635	-0.178	337	347	-1.25	-0.35	-0.673	0.000	348	335	-1.32	0.00
CNY–9	-0.559	-0.559	337	348	-1.10	-1.10	-0.533	-0.686	344	341	-1.05	-1.35
CNY–10	0.559	0.813	348	337	1.10	1.60	0.635	0.813	337	348	1.25	1.60
CNY–11	0.508	0.102	337	348	1.00	0.20	0.533	0.178	340	344	1.05	0.35
CNY–12	-0.406	-0.102	335	349	-0.80	-0.20	-0.508	-0.152	346	338	-1.00	-0.30
maximum	-0.813	-0.914	348	349	-1.60	-1.80	0.940	1.041	348	352	1.85	2.05

* See Figure 3.3 for a definition of the measured eccentricities.

† h = 50.8 mm (thickness of main plate).

Table 3.5 – Bending Effect on Cruciform Specimens

Specimen	Maximum Eccentricity (mm)	Bending Effect σ_b / σ_t †	Face Fractured	A_{throat} (mm^2)	
				Front Face	Back Face
CNY–6	0.889	0.11	Front	634	663
CNY–7	0.584	0.07	Back	555	551
CNY–8	-0.673	-0.08	Back	587	584
CNY–10	0.813	0.10	Back	600	533
CNY–11	0.533	0.06	Back	647	649
CNY–12	-0.508	-0.06	Back	639	632

† A positive effect implies high tension on the front face.

Table 3.6 – Summary of Test Capacities Obtained at Room Temperature

Specimen	Electrode	P_u Ultimate Load (kN)	Static Drop (kN)			$P_{ST} = P_u - \Delta P$ (kN)	Total Area A_{throat} (mm^2)	P_{ST} / A_{throat} (MPa)	Average P_{ST} / A_{throat}	Weld Failed
			upper	lower	ΔP					
CNY–7	E70T–7	606	586	577	8	597	1109	539	588	Front
CNY–8		723	713	702	11	712	1168	609		Back
CNY–10		667	658	647	11	656	1067	615		Back
CNY–6	E71T8–K6	770	762	750	12	759	1327	572	576	Back
CNY–11		760	754	743	11	749	1298	577		Back
CNY–12		744	741	727	13	731	1264	578		Back

Table 3.7 – Ultimate and Fracture Weld Deformations and Strains

Specimen	Deformation (mm)		Strain (mm/mm)			
	Ultimate Δ_{ult}	Fracture Δ_f	Δ_{ult} / d^*	Mean of Δ_{ult} / d^*	Δ_f / d^*	Mean of Δ_f / d^*
CNY–7	0.30	2.04	0.0234	0.025	0.0797	0.062
CNY–8	0.48	0.70	0.0363		0.0535	
CNY–10	0.17	0.62	0.0145		0.0538	
CNY–6	0.27	1.19	0.0224	0.034	0.0990	0.091
CNY–11	0.45	0.94	0.0379		0.0789	
CNY–12	0.47	1.04	0.0422		0.0938	

Table 3.8a – Comparison of Fillet Weld Strength (12.7 mm, E70T–7)

Specimen	Joint Configuration	Phase	Electrode	Plate Stress	P_{ST} / A_{throat} (MPa)	Normalized ‡ P_{ST} / A_{throat}	Mean	Strength Ratio†
T25–1	lapped	1	E70T–7	yield	780	1.29	1.28	0.81
T25–2					771	1.27		
T25–3					795	1.31		
T26–1	lapped	1		yield	822	1.36		
T26–2					836	1.38		
T26–3					807	1.33		
T27–1	lapped	1		yield	647	1.11		
T27–2					736	1.26		
T27–3					748	1.28		
T28–1	lapped	1		yield	775	1.19		
T28–2					810	1.24		
T28–3					781	1.20		
TNY–1	lapped	3		elastic	752	1.32		
TNY–2					740	1.30		
TNY–3					774	1.36		
CNY–7	cruciform	4		elastic	539	0.95	1.03	
CNY–8					609	1.07		
CNY–10					615	1.08		

† The strength ratio is the mean normalized strength of cruciform to that of lapped splice connections.

‡ P_{ST} / A_{throat} is normalized against the measured weld metal tensile strength.

Table 3.8b – Comparison of Fillet Weld Strength (12.7 mm, E71T8–K6)

Specimen	Joint Configuration	Phase	Electrode	Plate Stress	P_{ST} / A_{throat} (MPa)	Normalized P_{ST} / A_{throat}	Mean	Strength Ratio
T31–1	lapped	1	E71T8–K6	yield	847	1.73	1.67	0.70
T31–2					822	1.68		
T31–3					870	1.78		
T32–1	lapped	1		yield	779	1.58		
T32–2					789	1.60		
T32–3					828	1.68		
CNY–6	cruciform	4		elastic	572	1.17	1.18	
CNY–11					577	1.18		
CNY–12					578	1.18		

Table 3.8c – Comparison of Fillet Weld Strength (6.4 mm, E70T–4)

Specimen	Joint Configuration	Phase	Electrode	Plate Stress	P_{ST} / A_{throat} (MPa)	Normalized P_{ST} / A_{throat}	Mean	Strength Ratio
T4–1					982	1.84		
T4–2	lapped	1		yield	973	1.82		
T4–3					972	1.82		
T5–1					998	1.87		
T5–2	lapped	1		yield	943	1.76		
T5–3					993	1.86		
T6–1					1175	2.20		
T6–2	lapped	1		yield	1073	2.01		
T6–3					1172	2.19	1.87	
T8–2	lapped	1	E70T–4	yield	930	1.66		1.01
T8–3					934	1.66		
T9–1					1098	1.95		
T9–2	lapped	1		yield	1084	1.93		
T9–3					1111	1.98		
T10–1					970	1.73		
T10–2	lapped	1		yield	1049	1.87		
T10–3					952	1.69		
C1–1					1067	1.99		
C1–2	cruciform	1		yield	1028	1.92	1.89	
C1–3					943	1.76		

Table 3.8d – Comparison of Fillet Weld Strength (6.4 mm, E70T7–K2)

Specimen	Joint Configuration	Phase	Electrode	Plate Stress	P_{ST} / A_{throat} [t] (MPa)	Normalized P_{ST} / A_{throat}	Mean	Strength Ratio
T16–1	lapped	1	E70T7-K2	yield	936	1.58	1.84	0.87
T16–3					952	1.61		
T17–1	lapped	1		yield	1158	1.96		
T17–2					1222	2.06		
T17–3					1180	1.99		
C2–1	cruciform	1		yield	997	1.68	1.59	
C2–2					954	1.61		
C2–3					877	1.48		

Table 3.9 – Summary of Strength Ratio (strength of cruciform joint/strength of lapped splice joint)

		Electrode			
		With toughness requirement		Without toughness requirement	
		E71T8–K6	E70T7–K2	E70T–7	E70T–4
Leg size (mm)	12.7	0.70	—	0.81	—
	6.4	—	0.87	—	1.01

Table 3.10a – Comparison of Fillet Weld Strains (12.7 mm, E70T–7)

Specimen	Joint Configuration	Phase	Electrode Classification	Plate Stress	Mean of Δ_{ult} / d^*	Mean of Δ_f / d^*	Strain Ratio† (Ultimate Load)	Strain Ratio† (Fracture)
T25–1	lapped	1	E70T–7	yield	0.12	0.13	0.22	0.13
T25–2								
T25–3								
T26–1	lapped	1		yield	0.20	0.20		
T26–2								
T26–3								
T27–1	lapped	1		yield	0.10	0.10		
T27–2								
T27–3								
T28–1	lapped	1		yield	0.12	0.12		
T28–2								
T28–3								
TNY–1	lapped	3	E70T–7	elastic	0.03	0.10	1.0	0.7
TNY–2								
TNY–3								
CNY–7	cruciform	4		elastic	0.03	0.07	—	—
CNY–8								
CNY–10								

† The strain ratio is the mean strain of cruciform to that of lapped splice connections.

Table 3.10b – Comparison of Fillet Weld Strains (12.7 mm, E71T8–K6)

Specimen	Joint Configuration	Phase	Electrode Classification	Plate Stress	Mean of Δ_{ult} / d^*	Mean of Δ_f / d^*	Strain Ratio† (Ultimate Load)	Strain Ratio† (Fracture)
T31–1								
T31–2	lapped	1		yield	0.24	0.26		
T31–3							0.12	0.35
T32–1								
T32–2	lapped	1	E71T8–K6	yield	0.27	0.26		
T32–3								
CNY–6								
CNY–11	cruciform	4		elastic	0.03	0.09	—	—
CNY–12								

† The strain ratio is the mean strain of cruciform to that of lapped splice connections.

Table 3.10c – Comparison of Fillet Weld Strains (6.4 mm, E70T–4)

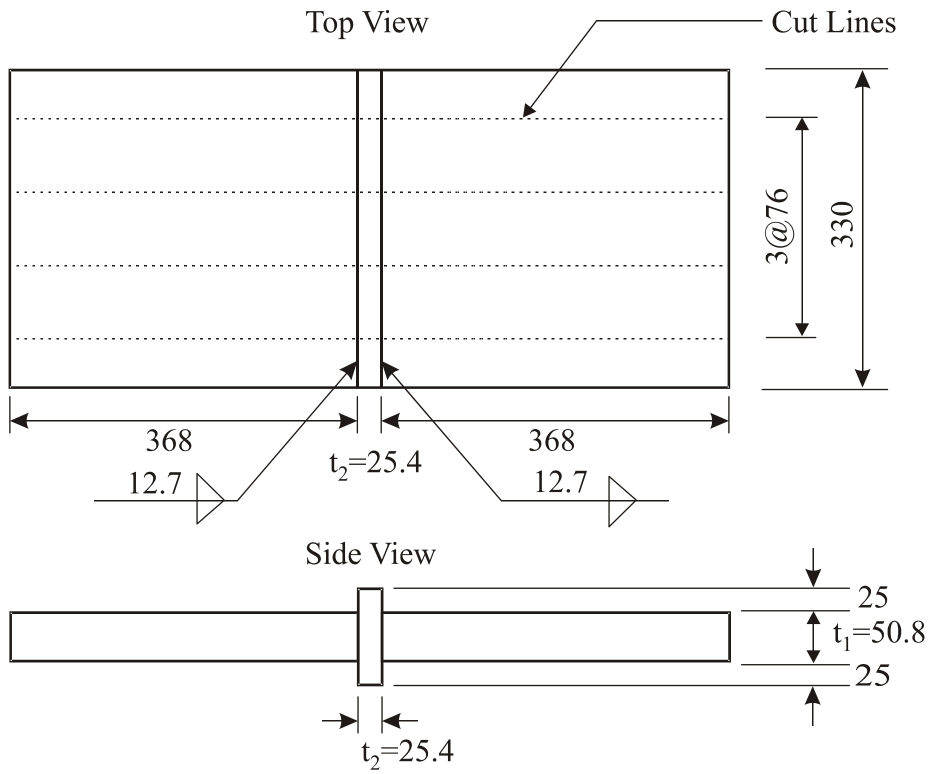
Specimen	Joint Configuration	Phase	Electrode Classification	Plate Stress	Mean of Δ_{ult} / d^*	Mean of Δ_f / d^*	Strain Ratio† (Ultimate Load)	Strain Ratio† (Fracture)
T4–1	lapped	1	E70T–4	yield	0.08	0.08	0.21	0.35
T4–2								
T4–3								
T5–1	lapped	1		yield	0.09	0.09		
T5–2								
T5–3								
T6–1	lapped	1		yield	0.16	0.16		
T6–2								
T6–3								
T8–2	lapped	1		yield	0.21	0.23		
T8–3								
T9–1	lapped	1		yield	0.19	0.19		
T9–2								
T9–3								
T10–1	lapped	1		yield	0.11	0.12		
T10–2								
T10–3								
C1–1	cruciform	1		yield	0.03	0.03	—	—
C1–2								
C1–3								

† The strain ratio is the mean strain of cruciform to that of lapped splice connections.

Table 3.10d – Comparison of Fillet Weld Strains (6.4 mm, E70T7–K2)

Specimen	Joint Configuration	Phase	Electrode Classification	Plate Stress	Mean of Δ_{ult} / d^*	Mean of Δ_f / d^*	Strain Ratio† (Ultimate Load)	Strain Ratio† (Fracture)
T16–1	lapped	1	E70T7–K2	yield	0.27	0.29	0.08	0.08
T16–2								
T16–3								
T17–1	lapped	1		yield	0.09	0.09		
T17–2								
T17–3								
C2–1	cruciform	1		yield	0.03	0.03	—	—
C2–2								
C2–3								

† The strain ratio is the mean strain of cruciform to that of lapped splice connections.



All dimensions are in mm

Figure 3.1 – Dimensions of Cruciform Test Specimens

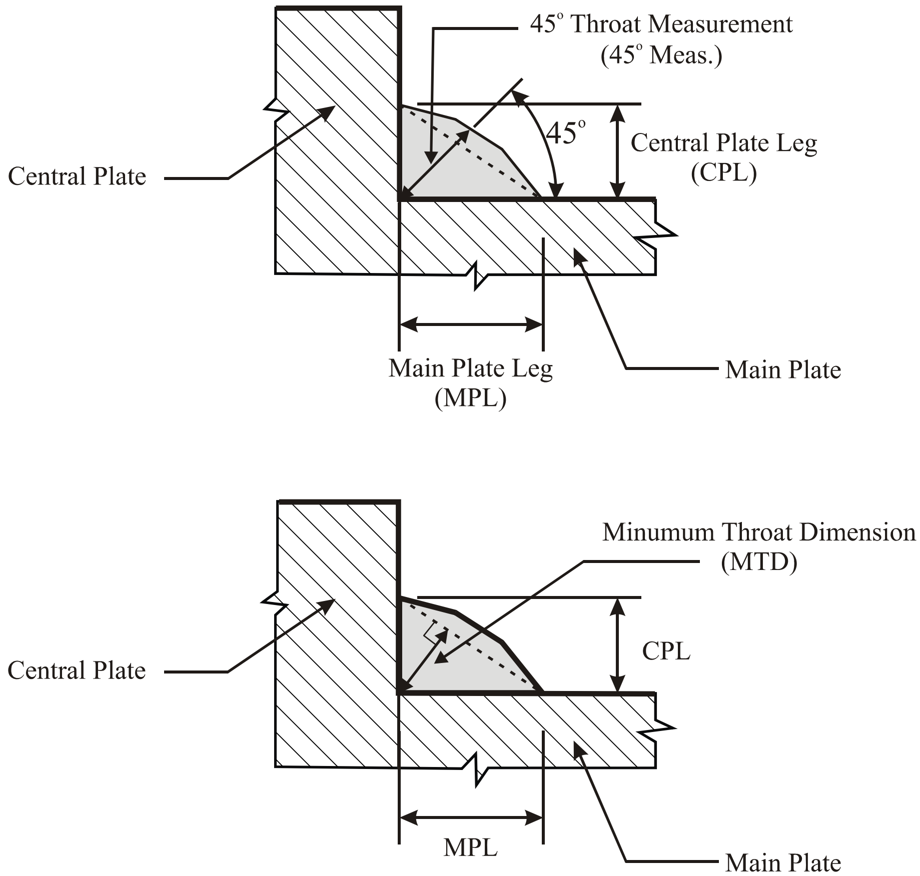
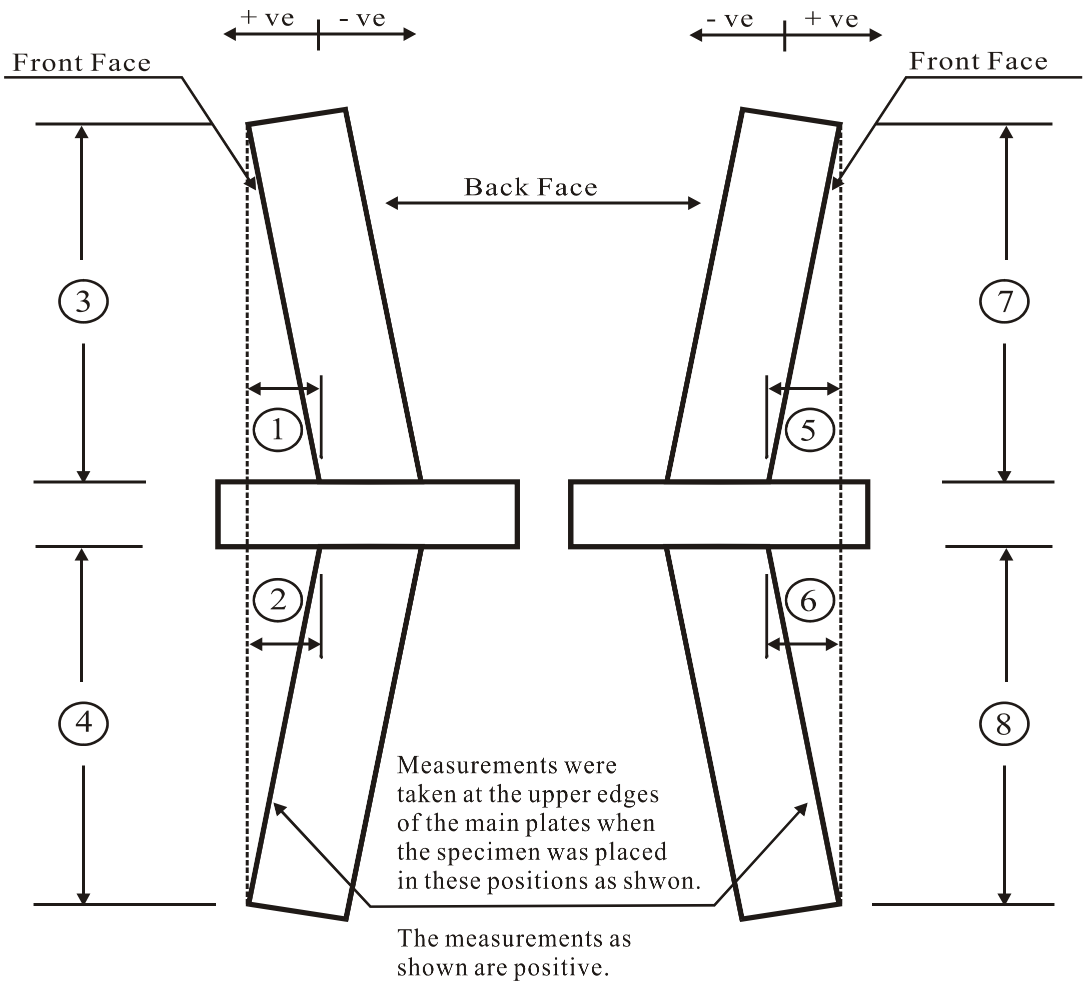
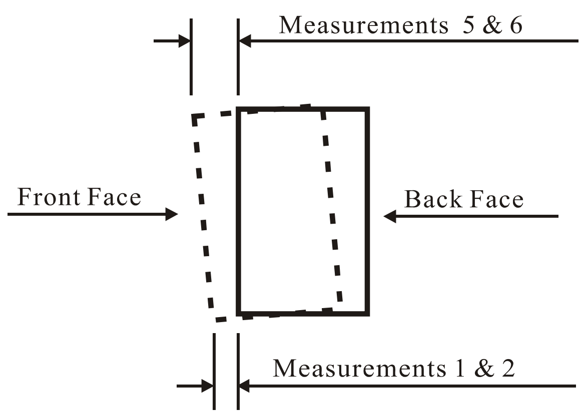


Figure 3.2 – Definition of Fillet Weld Pre-Test Measurements



Side View



Top View

Figure 3.3 – Eccentricity Measurements

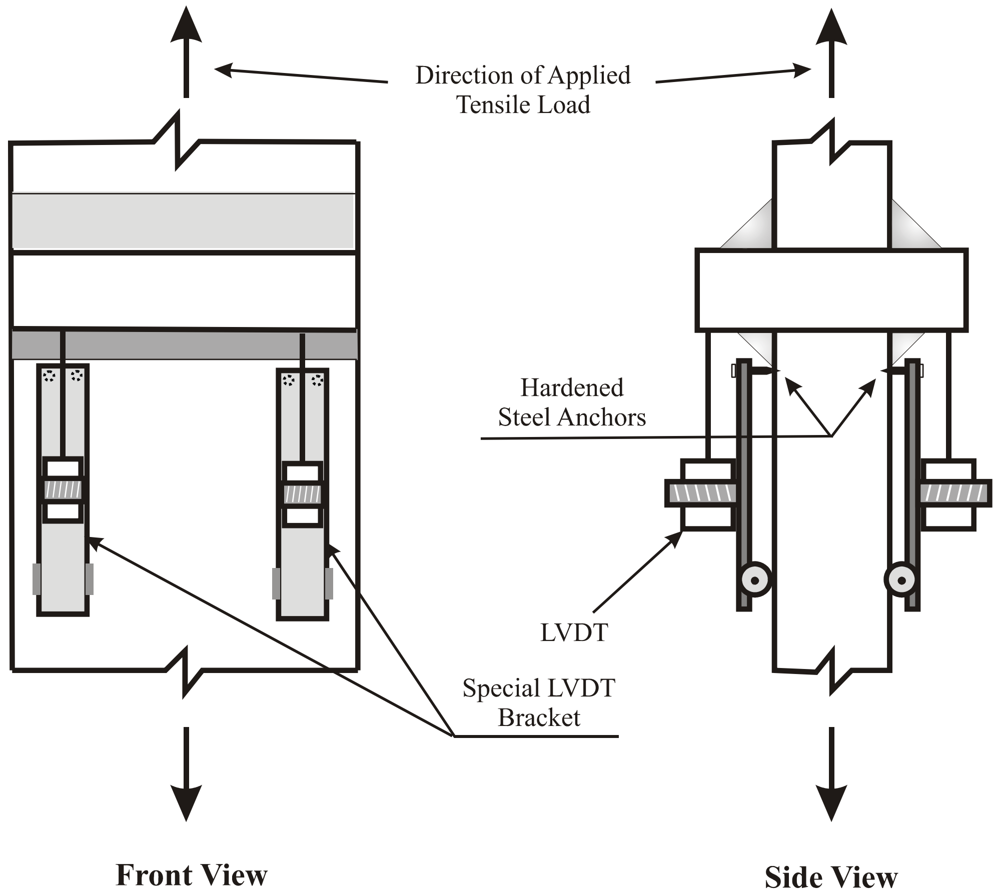
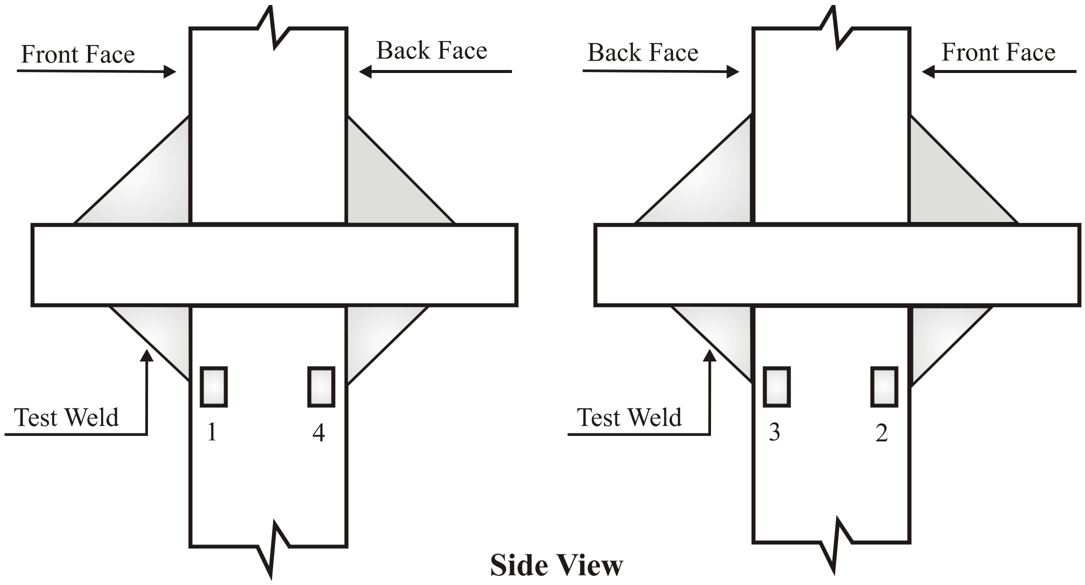
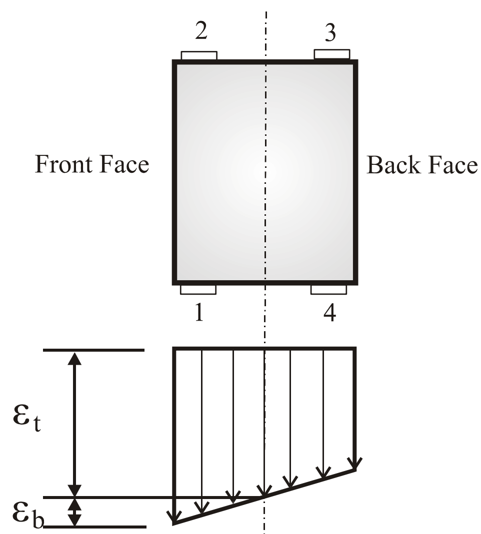


Figure 3.4 – Weld Deformation Measurements



Side View



Top View and Strains

Figure 3.5 – Arrangement of Strain Gauges

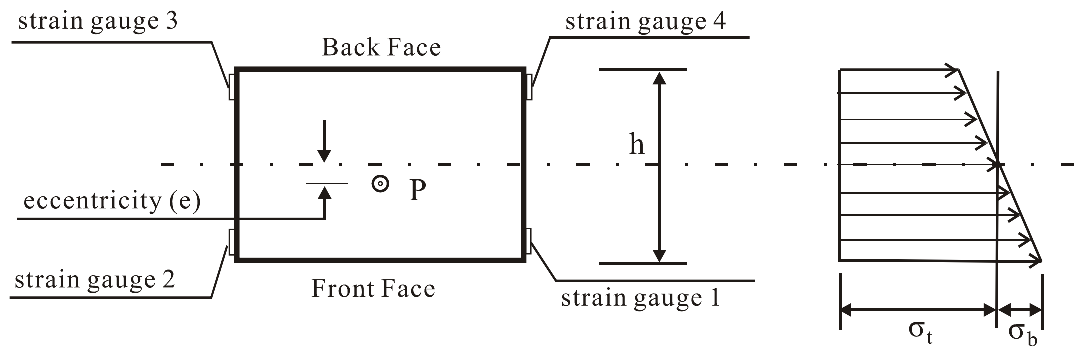
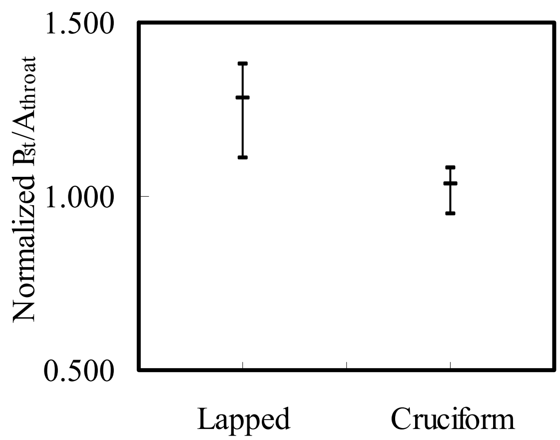
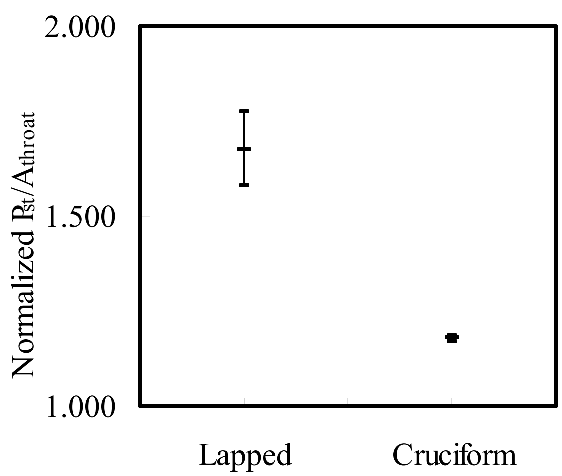


Figure 3.6 – Load Eccentricity and Bending Effect

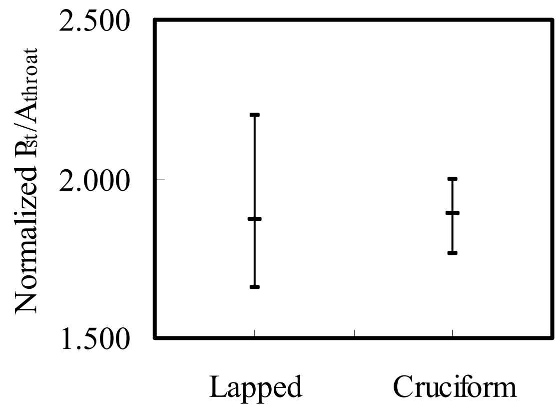


(a) Leg size 12.7mm, E70T-7

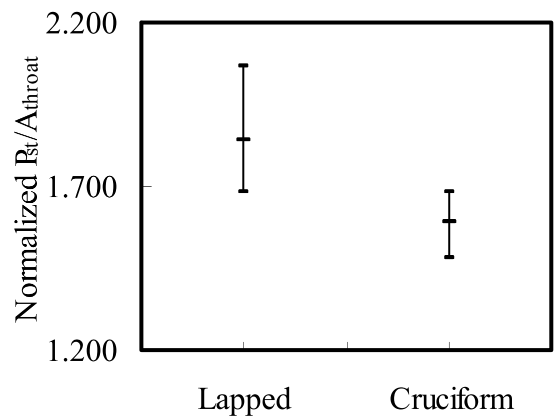


(b) Leg size 12.7mm, E71T8-K6

Figure 3.7 – Effect of Root Notch Orientation on Weld Strength



(c) Leg size 6.4mm, E70T-4



(d) Leg size 6.4mm, E70T7-K2

Figure 3.7 (cont.)

CHAPTER 4

ANALYSIS OF TEST RESULTS

4. 1 Introduction

To get a better representation of the scatter present in industry, test data from different sources were pooled. About 1160 specimens from 16 test programs were examined. The detailed information about the data sources is given in Appendix E.

The strength equation used for the design of fillet welds in the Canadian design standard, CSA S16.1–01 (CSA 2001), is given as:

$$V_r = 0.67\phi_w A_w X_u (1.00 + 0.50\sin^{1.5}\theta) \tag{4.1a}$$

where the resistance factor ϕ_w is taken as 0.67, A_w is the effective throat area of the weld, X_u is the minimum specified tensile strength of the weld metal, and θ is the angle between the weld axis and the line of action of the applied load. The numerical modifier 0.67 relates the shear strength of the fillet weld to the tensile strength, X_u, of the weld metal.

Similarly, the equation in the ANSI/AISC 360-05 (AISC 2005) is given as:

$$V_r = 0.60\phi A_w F_{EXX} (1.00 + 0.50\sin^{1.5}\theta) \tag{4.1b}$$

where the resistance factor ϕ is taken as 0.75, A_w is the effective throat area of the weld, and F_{EXX} is the tensile strength of the weld metal. The numerical modifier 0.60 relates the shear strength of the weld metal to its tensile strength.

The difference between the observed and the nominal strength of fillet welds results from the variation in the geometric and material properties of the weld segments, as well as from the equation used to predict the fillet weld strength. To assess the safety index associated with Equation 4.1, the bias coefficient for resistance, ρ_R, and its coefficient of variation, V_R, can be obtained using the following equations:

$$\rho_R = \rho_G \rho_{M1} \rho_{M2} \rho_P \tag{4.2}$$

$$V_R^2 = V_G^2 + V_{M1}^2 + V_{M2}^2 + V_P^2 \tag{4.3}$$

The geometric bias coefficient, ρ_G, which reflects the difference between the nominal and actual fillet weld throat area, can be calculated as the mean value of the ratio of the measured throat dimension (MTD) to 0.707 times of nominal weld leg size, namely,

$$\rho_G = \text{Mean}\left(\frac{\text{MTD}}{0.707 \times (\text{nominal weld leg size})}\right) \tag{4.4a}$$

In addition, the geometric bias coefficient can be calculated as the mean value of the ratio of MTD to the nominal throat dimension, namely,

$$\rho_G = \text{Mean}\left(\frac{\text{MTD}}{\text{nominal throat dimension}}\right) \tag{4.4b}$$

In Equations 4.4a and 4.4b, MTD is taken differently as described in the following three cases, depending on the data available (measured leg or measured throat).

Case 1: when two leg sizes were measured and reported from a test program, MTD is taken as the minimum throat dimension:

$$\text{MTD} = \frac{s_1 \times s_2}{\sqrt{s_1^2 + s_2^2}} \tag{4.4c}$$

where, s_1 and s_2 are two measured leg sizes.

Case 2: when two leg sizes were measured but only the average of the two leg sizes was reported, MTD is taken as in the following equation:

$$\text{MTD} = 0.707 \times (\text{average of two leg sizes}) \tag{4.4d}$$

Case 3: when only the throat dimension at 45º was measured and reported from a test program, MTD is taken as the measured throat dimension:

$$\text{MTD} = \text{measured throat dimension} \tag{4.4e}$$

Then the measured throat area, A_{throat}, can hereafter be calculated as follows:

$$A_{throat} = \text{MTD} \times (\text{weld length}) \tag{4.4f}$$

where MTD is the measured throat dimension as described in the three cases above.

Equations 4.4c and 4.4d neglect the variability of the reinforcement at the weld face and Equations 4.4c, 4.4d and 4.4e all neglect the variability of weld penetration at the root.

The variability of the reinforcement of test specimens from phase 1 through 4 is presented in Section 4.2.1 and Table 4.3. Although Equation 4.4b might on this basis appear to be the more representative quantity, "nominal" throat dimensions are rarely specified now. In all cases, the variability of the weld length is neglected, in part due to a lack of suitable data, and also since this is likely to lead to conservative conclusions due to the tendency of welds to be longer than specified.

The first material bias coefficient, ρ_{M1}, is the mean value of the measured to nominal weld metal tensile strength, expressed as:

$$\rho_{M1} = \text{Mean}\left(\frac{\text{Measured Tensile Strength, } \sigma_u}{\text{Specified Tensile Strength, } X_u \text{ or } F_{EXX}}\right) \tag{4.5}$$

where σ_u is determined from all-weld-metal tension coupons.

Another source of variation in material strength is related to the relationship between the tensile strength and the shear strength. Equation 4.1a uses a factor 0.67 and Equation 4.1b uses a factor 0.60to convert the tensile strength into shear strength. The measured shear strength to tensile strength ratio can be obtained from longitudinal weld test specimens. The shear strength, τ_u, from test specimens is calculated using the measured throat area, A_{throat}. The second material bias coefficient, ρ_{M2}, is expressed as:

$$\rho_{M2} = \text{Mean}\left(\frac{\text{Measured Shear Strength, } \tau_u \,/\, \text{Measured tensile strength, } \sigma_u}{0.67}\right) \tag{4.6a}$$

for Equation 4.1a, or

$$\rho_{M2} = \text{Mean}\left(\frac{\text{Measured Shear Strength, } \tau_u \,/\, \text{Measured tensile strength, } \sigma_u}{0.60}\right) \tag{4.6b}$$

for Equation 4.1b.

The professional factor, ρ_P, is the mean value of the test-to-predicted capacity ratio for test specimens with various fillet weld orientations:

$$\rho_p = \text{Mean}\left(\frac{\text{Test Capacity}}{\text{Predicted Capacity}}\right) = \text{Mean}\left(\frac{\text{Test Capacity}}{\tau_u \; A_{throat}(1.00 + \sin^{1.5}\theta)}\right) \tag{4.7}$$

The area A_{throat} used in Equation 4.7 is defined in Equation 4.4f. The term τ_u is the measured shear strength from tests on longitudinal weld specimens prepared using the same filler metal as the test specimens used for other weld orientations within the same program. It is based on the measured throat area, A_{throat}.

The variables in Equation 4.3 are the coefficients of variation corresponding to the four bias coefficients described above.

The above discussion is applied to connections with single orientation fillet welds (SOFW). For connections with multiple orientations fillet welds (MOFW), 3 models are used to calculate the capacity of such connections.

Model 1: Callele *et al.* (2005) recommended the following equation to calculate the capacity of weld segments for design:

$$\text{Segment Capacity} = 0.67\phi_w A_w X_u (1.00 + 0.50 \sin^{1.5}\theta)\ CRF(\theta) \tag{4.8}$$

where $CRF(\theta)$ is the reduction factor that accounts for the fact that the strength of the most ductile segment of the MOFW connection may not be reached by the time the least ductile segment fractures. For a connection with combined longitudinal $(\theta = 0°)$ and transverse $(\theta = 90°)$ fillet welds, $CRF(0°) = 0.85$ and $CRF(90°) = 1.0$. The capacity of the connection with longitudinal and transverse welds is the summation of all segment capacities:

$$V_r = c_1\ \phi\ X_u (0.85 A_{wl} + 1.5 A_{wt}) \tag{4.9}$$

where c_1 is equal to 0.67 in CSA S16.1–01 (2001) and 0.60 in ANSI/AISC 360-05 (AISC 2005), A_{wl} is the total throat area of longitudinal welds and A_{wt} is the total throat area of transverse welds.

Model 2: when CSA S16.1–01 (CSA 2001) design Equation 4.1a is used to calculate the capacity of a weld segment, the total capacity of a MOFW connection with both longitudinal and transverse welds can be intuitively calculated as:

$$V_r = c_1\ \phi\ X_u (A_{wl} + 1.5 A_{wt}) \tag{4.10}$$

Since no guidelines currently exist in S16.1–01 for the calculation of the strength of MOFW joints, this model ignores the difference in ductility between segments loaded in different directions.

Model 3: when the ANSI/AISC 360-05 (AISC 2005) is applied, the capacity of a MOFW connection with both longitudinal and transverse welds is determined as the greater of:

$$V_r = c_1 \phi F_{EXX} (A_{wl} + A_{wt}) \quad (4.11a)$$

or

$$V_r = c_1 \phi F_{EXX} (0.85 A_{wl} + 1.5 A_{wt}) \quad (4.11b)$$

The professional factor, ρ_P, can be calculated for the above three models with the resistance factor, ϕ_W or ϕ, set to 1.0.

Once the bias coefficient for resistance, ρ_R, and the associated coefficient of variation, V_R, are obtained, the safety index β can be determined from the following equation for the resistance factor, ϕ, which was originally proposed by Ravindra and Galambos (1978):

$$\phi_w = C \rho_R \exp\left(-\beta \alpha_R V_R\right) \quad (4.12)$$

The separation variable, α_R, was set to 0.55 as suggested by Ravindra and Galambos (1978). The factor C is an adjustment factor that modifies ϕ when β is not equal to the safety index used for the evaluation of load factors, which is normally 3.0. The following equation, developed using a procedure proposed by Fisher *et al*. (1978), was used to calculate this factor for a live to dead load ratio of 3.0:

$$C = 0.0078\beta^2 - 0.156\beta + 1.400 \quad (4.13)$$

It should be noted that the above equation is applicable for a range of safety index from 1.5 to 6.0.

4.2 Summary of Test Data from Different Sources

4.2.1 Geometric Factor, ρ_G

The bias coefficient, ρ_G, and the coefficient of variation, V_G, for the measured-to-nominal throat dimension collected from literature (see Appendix E) are summarized in Table 4.1. First, the specimens are separated into two groups according to the weld dimension measurement method, namely, specimens with measured throat dimension and specimens with measured leg size. For each group, the geometric factor, ρ_G, and the associated coefficient of variation, V_G, are calculated. Then, all data are pooled to obtain the mean ratio ρ_G and associated V_G. The mean values for the two groups are nearly identical, but the dispersion, as expected, is somewhat greater when the throat measurements are used.

The variations of ρ_G and V_G as a function of the nominal weld leg size are illustrated graphically in Figures 4.1a and 4.1b. The general trend is that the small size welds are more likely to be oversized than large welds and the size of large welds is slightly less variable than the size of small welds. These observations reflect the difficulty of producing small size welds.

It is noted that the data presented in Table 4.1 were all collected from experimental programs. It is also noted that in some test programs, for example those of Ng *et al*. (2002), Deng *et al*. (2003), Callele *et al.* (2005), and the current test program, strict tolerances were set on the weld sizes during fabrication of the test specimens so that fracture of the welds would be most likely to occur rather than fracture of the plates. It is therefore possible that the ratio ρ_G obtained from such data would be smaller than what would be expected in practice, thus making the results of a reliability analysis based on this data conservative. It should also be noted that the value of V_G might be slightly underestimated for the same reason.

For the current test specimens and those from Ng *et al*. (2002), Deng *et al*. (2003), and Callele *et al.* (2005), the geometric factor ρ_G was calculated using Equation 4.4a and MTD was calculated using Equation 4.4c, which accounts for the unequal leg sizes.

Of all the research compiled in this report from the literature, only that of Ng *et al*. (2002), Deng *et al.* (2003), and Callele *et al.* (2005) reported both measured leg and throat dimensions (see Section E.12), thereby giving an opportunity to assess directly the degree of face reinforcement in the fillet weld as deposited. To this end, two ratios based on these measurements are defined as follows:

$$\alpha_1 = \text{Mean}\left(\frac{45^\circ \text{ Meas}}{\text{MTD}}\right) \tag{4.14a}$$

$$\alpha_2 = \text{Mean}\left(\frac{45^\circ \text{ Meas}}{0.707 \times (\text{average of MPL and LPL})}\right) \tag{4.14b}$$

The measurements of MPL, LPL, and 45º Meas, the calculated MTD, and the ratios α_1 , α_2, and ρ_G for the specimens of Ng *et al*. (2002), Deng *et al.* (2003) and Callele *et al.* (2005) (Phases 1 to 3 of this research program) are presented in Tables E12.1 through E12.5. The same analysis for specimens from the current test program (Phase 4) is presented in Table 4.2. The results are summarized in Table 4.3.

The overall mean values for α_1 and α_2 from Phases 1 to 4 are 1.12 and 1.11, respectively, with corresponding coefficients of variation of 0.088 and 0.090, indicating that the throat dimension from the weld root to the weld face is about 10% greater than the theoretical throat for these groups of specimens.

4.2.2 Material Factor, ρ_{M1}

The material factor ρ_{M1} and the corresponding coefficient of variation, V_{M1}, collected from the literature are summarized in Table 4.4. The variation of ρ_{M1} as a function of the nominal tensile strength of the electrode is shown in Figure 4.2. For the data available, there seems to be no correlation between ρ_{M1} and the nominal filler metal tensile strength.

The variation in ρ_{M1}, expressed as a range of two standard deviations about the mean value for each test program presented in Table 4.4 is plotted in Figure 4.3 to show the variability of the ratio ρ_{M1} of those tests that span from as early as 1970s to the most recent as the year of 2005.

4.2.3 Material Factor, ρ_{M2}

The material factor ρ_{M2} and the associated coefficient of variation V_{M2} are associated with the shear strength, τ_u, of the filler metal. The data collected from the literature are summarized in Table 4.5, in which the ratio ρ_{M2} was calculated according to Equation 4.6a. To obtain the ratio ρ_{M2} for Equation 4.6b, the ratio ρ_{M2} for Equation 4.6a is multiplied by 1.12. The associated coefficient V_{M2} is same for both Equations 4.6a and 4.6b.

Similar to the treatment to the geometric factor, the specimens are separated into two groups, namely, specimens with measured throat dimension and specimens with measured leg size. For each group, the material factor, ρ_{M2}, and the coefficient of variation, V_{M2}, are calculated. Then, all data are pooled to obtain additional values of ρ_{M2} and V_{M2}.

Pham (1983b) tested longitudinal fillet welds on specimens of the Werner type, illustrated in Figure 4.4, while other test programs used lapped splice specimens. The Werner specimen has the advantage of eliminating both in-plane and out-of-plane eccentricity in single lapped joints.

The size effect on the longitudinal weld strength was investigated by plotting the bias coefficient ρ_{M2} against the measured weld leg size in Figure 4.5, in which the leg size was determined from the measured throat size if the leg size was not reported (leg size equal to 1.414 times measured throat size without considering face reinforcement). The figure shows no significant effect of the leg size on the bias coefficient ρ_{M2}.

The bias coefficient ρ_{M2} may also be affected by the tensile strength of the weld metal. The ratio ρ_{M2} is plotted as a function of the measured tensile strength of the weld metal in Figure 4.6. The figure shows no particular effect of the tensile strength on the bias coefficient ρ_{M2}.

4.2.4 Professional Factor, ρ_P, for Joints with Only One Weld Orientation

The professional factor, ρ_P, and the associated coefficient of variation, V_P, for connections with a single orientation fillet weld are summarized in Table 4.6. The samples do not include the longitudinal welds because the longitudinal weld test results were used to evaluate the value of τ_u in Equation 4.7. Most (85%) specimens with single orientation fillet welds presented in Table 4.6 were with transverse welds and a few specimens with other weld orientations. Similar to the treatment of the geometric factor, ρ_G, and material factor, ρ_{M2}, the specimens were separated into two groups and then pooled to get the professional factor, ρ_P, and associated coefficient of variation, V_P.

The professional factor for SOFW joints with transverse welds, ρ_P, is plotted as a function of the measured weld size in Figure 4.7. It can be seen that the leg size has no significant effect on the professional factor, ρ_P. Similarly, a plot of the professional factor for transverse welds versus measured filler metal tensile strength, presented in Figure 4.8, shows no correlation between the professional factor and the tensile strength of the filler metal.

4.2.5 Professional Factor, ρ_P, for Joints with Multiple Weld Orientations

As discussed in Section 4.1, three models are used to predict the capacity of MOFW connections with transverse and longitudinal welds. The professional factor, ρ_P, and the associated coefficient of variation, V_P, for MOFW connections, except the specimens with out-of-plane eccentricity from Ligtenberg (1968) (see Figure 4.9), are summarized in Tables 4.7a, 4.7b, and 4.7c. All the test specimens presented in the tables combined transverse and longitudinal welds.

Figure 4.10 presents a plot of the professional factor for the test specimens presented in Table 4.7a, ρ_P , versus the measured tensile strength of the filler metal. The tensile strength of the filler metal has no significant effect on the professional factor, ρ_P. The same trend is applicable to the professional factors calculated by Equations 4.10 and Equation 4.11a and 4.11b.

4.2.6 Professional Factor, ρ_P, for Cruciform Connections

The strengths of 12 cruciform specimens from phases 1 and 4 were predicted using Equation 4.1a. The resulting professional factor, ρ_P , and associated coefficient of variation, V_P are presented in Table 4.8.

The professional factor, ρ_P, and the associated coefficient of variation, V_P, for cruciform specimens from phases 1 and 4 and from Pham (1983a) are summarized in Table 4.9. For specimens from Pham (1983a), the longitudinal welds of Werner specimens from Pham (1983b) were used to calculate the shear strength, τ_u , in Equation 4.7 to obtain the professional factor, ρ_P.

4.3 Safety Level of Lapped Splice Connections

4.3.1 Connections with Single Orientation Fillet Welds

The test programs presented in Table 4.6 were used to conduct a reliability analysis to determine the level of safety provided by the current North American design equations for design of fillet welds with a single orientation. The weld dimension measurement method is also treated as a factor for the reliability analysis. The results of this analysis and the resistance factors for various levels of safety index are presented in Table 4.10.

The results in Table 4.10 indicate that the weld measurement method has a very small effect on the safety indices. The general trend is the group of specimens with measured throat dimension yields a safety index about 3% larger than does the group of specimens with measured leg size.

The analysis results for all pooled data in Table 4.10 indicate the following observations. For CSA S16.1-01 (CSA 2001) design Equation 4.1a, the analysis indicates that a safety index of 4.5 is obtained with a resistance factor of 0.68 (0.67 is currently used in the design standard). A value of 4.0 is obtained for a resistance factor of 0.77. For the AISC design specification (AISC 2005), defined by Equation 4.1b, the analysis indicates that a safety index of 4.5 is obtained with a resistance factor of 0.76 (0.75 is currently used in the design specification). A value of 4.0 is obtained for a resistance factor of 0.86.

4.3.2 Connections with Fillet Welds Oriented in Multiple Directions

A reliability analysis was performed to assess the level of safety provided by three different models to calculate the strength of welded joints combining fillet welds with transverse and longitudinal orientations. The data presented in Tables 4.7a, 4.7b and 4.7c served as the primary data for this evaluation.

The safety indices obtained based on all pooled data are presented in Table 4.11 for weld strength equations presented in both S16.1-01 (CSA 2001) and ANSI/AISC 360-05 (AISC 2005). The result for weld strength equation of S16.1-01 (CSA 2001) has indicated that for design Equation 4.9 (Model 1) and design Equation 4.11a, b (Model 3), safety indices are slightly larger than 4.5. However, for design Equation 4.10 (Model 2), the safety index is less than the traditional target value for connections of 4.5. To reach a safety index of 4.5 when the S16-01 design equation is considered, a resistance factor of 0.63 for design Equation 4.10 may be used. To reach a safety index of 4.0, a resistance factor of 0.77 for design Equation 4.9, 0.71 for design Equation 4.10, and 0.77 for design Equation 4.11a, b may be used. A similar result is obtained for weld strength equations of ANSI/AISC 360-05 (AISC 2005).

A reliability analysis conducted on the specimens with out-of-plane eccentricity from Ligtenberg (1968), as shown in Figure 4.9, is summarized in Table 4.12. The reliability analysis was conducted for only one model, namely, Equation 4.9 (Model 1). The reliability analysis based on 33 such MOFW specimens has indicated that for S16.1-01 (CSA 2001) a safety index of 4.5 is reached for a resistance factor of 0.51 and a value of 4.0 is obtained for a resistance factor of 0.58. For ANSI/AISC 360-05 (AISC 2005) a safety index of 4.5 is reached for a resistance factor of 0.57 and a value of 4.0 is obtained for a resistance factor of 0.65. The significantly lower resistance factors required for these specimens compared to the resistance factor required for the concentrically loaded test specimens illustrates the significant impact of the out-of-plane eccentricity on joint strength.

4.4 Safety Level of Cruciform Connections

A reliability analysis was performed for the test specimens presented in Table 4.9. The results of this analysis are presented in Table 4.13.

The reliability analysis indicates that a safety index of 4.3 is obtained with a resistance factor of 0.67 for design Equation 4.1a and a safety index of 4.3 is also obtained with a resistance factor of 0.75 for design Equation 4.1b. To achieve a safety index of 4.5, the resistance factor for Equation 4.1a needs to be decreased to 0.64 and the resistance factor for Equation 4.1b to 0.72. To reach a safety index of 4.0, a resistance factor of 0.73 is required for design Equation 4.1a and a resistance factor of 0.82 for design Equation 4.1b.

Table 4.1 – Summary of Geometric Factor ρ_G from Various Sources

Weld Dimension Measurement Method	Source of Data	Nominal Leg Size (mm)	Sample Size n	Ratio of Measured to Nominal ρ_G	Coefficient of Variation V_G
Measured Throat Dimension	Bornscheuer and Feder (1966)	5.7	18	0.957	0.090
		11.3	6	0.938	0.048
		17.0	5	0.921	0.020
	Ligtenberg (1968)	4.2	97	1.230	0.168
		5.0	67	1.121	0.163
		5.7	91	1.109	0.171
		6.4	13	1.071	0.096
		7.1	302	1.056	0.155
		8.5	145	1.039	0.147
		10.6	41	0.986	0.098
		11.3	87	0.997	0.100
		14.1	31	0.996	0.124
	Kato and Morita (1969)	5.0	8	1.057	0.065
		7.0	1	1.041	—
		10.0	3	1.009	0.021
		12.0	1	0.953	—
		15.0	6	1.014	0.005
		20.0	3	0.96	0.079
		22.0	1	0.929	—
		30.0	1	1.000	—
		40.0	2	0.940	0.09
	Clark (1971)	7.9	18	0.985	0.065
	Pham (1981)	5.0	17	1.072	0.102
		10.0	6	1.058	0.051
		16.0	3	1.030	0.054
	All Specimens with Measured Throat Dimension	N.A.	973	1.065	0.148

Table 4.1 (cont.)

Weld Dimension Measurement Method	Source of Data	Nominal Leg Size (mm)	Sample Size n	Ratio of Measured to Nominal ρ_G	Coefficient of Variation V_G
Measured Leg Size	Butler and Kulak (1969)	6.4	31	1.138	0.069
	Dawe and Kulak (1972)	6.4	43	1.158	0.075
	Swannell (1979b)	6.4	21	1.070	0.031
	Pham (1983a, b)	6.0	22	1.346	0.060
		10.0	23	1.118	0.106
		16.0	23	1.072	0.081
	Miazga and Kennedy (1986)	5.0	21	1.040	0.026
		9.0	21	1.030	0.027
	Bowman and Quinn (1994)	6.4	8	1.182	0.082
		9.5	4	1.128	0.040
		12.7	6	1.087	0.030
	Phase 1 through 4	6.4	126	1.026	0.102
		7.9	48	1.118	0.061
		12.7	336	1.078	0.161
	All Specimens with Measured Leg Size	N.A.	733	1.087	0.126
All Sources		N.A.	1706	1.074	0.142

Table 4.2 – Geometric Factor ρ_G for Specimens from Current Test Program

Specimen	Nominal Leg Size (mm)	Weld	MPL (mm)	CPL (mm)	45° Meas. (mm)	MTD (mm)	Ratio α_1	Ratio α_2	Ratio ρ_G
CNY-1	12.7	Front	12.9	10.3	9.7	8.0	1.205	1.184	0.896
		Back	11.9	9.9	9.8	7.6	1.294	1.278	0.844
CNY-2	12.7	Front	11.9	12.7	10.9	8.7	1.257	1.255	0.966
		Back	11.5	11.4	11.0	8.1	1.357	1.358	0.902
CNY-3	12.7	Front	12.9	12.0	12.1	8.8	1.378	1.376	0.978
		Back	13.5	10.7	11.6	8.4	1.383	1.356	0.934
CNY-4	12.7	Front	15.0	11.6	12.3	9.2	1.339	1.308	1.023
		Back	13.5	10.8	11.3	8.4	1.340	1.315	0.939
CNY-5	12.7	Front	11.5	11.6	9.4	8.2	1.153	1.153	0.908
		Back	12.6	9.1	9.6	7.4	1.304	1.251	0.820
CNY-6	12.7	Front	13.2	10.7	11.5	8.3	1.385	1.363	0.925
		Back	12.0	12.6	11.8	8.7	1.357	1.356	0.968
CNY-7	12.7	Front	12.8	9.5	8.9	7.7	1.163	1.126	0.852
		Back	12.1	9.8	9.4	7.6	1.236	1.215	0.847
CNY-8	12.7	Front	13.5	10.2	10.4	8.1	1.280	1.243	0.905
		Back	13.1	10.2	9.8	8.1	1.215	1.188	0.898
CNY-9	12.7	Front	13.5	10.4	10.8	8.2	1.312	1.279	0.917
		Back	11.9	11.7	9.9	8.3	1.189	1.189	0.928
CNY-10	12.7	Front	11.9	11.6	9.8	8.3	1.182	1.182	0.923
		Back	11.1	9.6	9.4	7.3	1.290	1.280	0.812
CNY-11	12.7	Front	12.3	11.8	10.8	8.5	1.273	1.272	0.945
		Back	11.9	12.2	10.8	8.5	1.269	1.269	0.948
CNY-12	12.7	Front	11.8	11.9	10.9	8.4	1.302	1.302	0.932
		Back	11.1	12.5	10.3	8.3	1.244	1.237	0.922
All Specimens			Mean of Ratios				1.280	1.264	0.914
			Coefficient of Variation, V				0.055	0.055	0.055

Table 4.3 – Summary of Geometric Factor ρ_G from Phases 1 through 4

Source of Data	Nominal Leg Size	Sample Size †	Ratio α_1		Ratio α_2		Ratio ρ_G	
	(mm)	n	Mean α_1	V_1	Mean α_2	V_2	Mean ρ_G	V_G
Ng *et al.* (2002)	6.4	126	1.165	0.070	1.145	0.077	1.026	0.102
	12.7	78	1.108	0.076	1.076	0.077	0.954	0.073
Deng *et al.* (2003)	12.7	54	1.049	0.085	1.043	0.086	0.836	0.053
Callele *et al.* (2005)	7.9	48	1.102	0.061	1.091	0.065	1.118	0.061
	12.7	180	1.106	0.085	1.090	0.088	0.981	0.082
Current Test Program	12.7	24	1.280	0.055	1.264	0.056	0.914	0.055
All Specimens from Phase 1 through 4	N.A.	510	1.119	0.088	1.105	0.090	0.983	0.108

† A weld segment measured is treated as a sample.

Table 4.4 – Summary of Material Factor ρ_{M1}

Source of Data	Sample Size	Nominal Tensile Strength (MPa)	Mean Tensile Strength (MPa)	Ratio of Measured to Nominal	Coefficient of Variation	Data Set
	n	X_u	σ_u	ρ_{M1}	V_{M1}	
Miazga and Kennedy (1986)	3	480	537.7	1.120	0.014	1
Gagnon and Kennedy (1987)	10	480	579.9	1.208	0.035	2
Swannell and Skewes (1979)	2	410	538.8	1.314	0.020	3
Fisher et al. (1978)	127	414	455.1	1.100	0.038	4
	138	483	516.4	1.070	0.035	5
	136	552	606.1	1.099	0.049	6
	16	621	690.9	1.113	0.043	7
	72	758	806.0	1.063	0.040	8
	128	483	588.8	1.220	0.056	9
	40	483	598.5	1.240	0.113	10
Pham (1981)	3	480	500	1.042	0.044	11
Mansell and Yadav (1982)	6	410	558	1.361	0.027	12
Bowman and Quinn (1994)	3	483	475.8	0.986	0.029	13
Callele *et al.* (2005)†	32	480	552.3	1.151	0.084	14
All Sources	716	N.A.	N.A.	1.127	0.080	15

† Including all weld metal tension coupon tests from phases 1 through 4.

Table 4.5 – Summary of Material Factor ρ_{M2} per Equation 4.6a

Weld Dimension Measurement Method	Source of Data		Sample Size n	Ratio of Measured to Nominal ρ_{M2}	Coefficient of Variation V_{M2}
Measured Throat Dimension	Ligtenberg (1968)	England (St.37 steel)	18	1.077	0.096
		Japan (St.37 steel)	18	1.103	0.152
		USA (St.37 steel)	18	1.234	0.125
		France (St.37 steel)	18	1.087	0.124
		Germany (St.37 steel)	18	1.087	0.085
		Belgium (St.37steel)	18	1.108	0.121
		Netherlands (St.37 steel)	17	1.210	0.077
		Canada (St.37 steel)	18	1.236	0.129
		Sweden (St.37 steel)	18	1.149	0.145
		Yugoslavia (St.37 steel)	18	1.195	0.091
		Netherlands (St.52 steel)	10	1.186	0.093
		Germany (St.52 steel)	10	1.238	0.117
		Italy (St.52 Steel)	10	1.230	0.060
		Sweden (St.52 steel)	14	1.306	0.138
	Kato and Morita (1969)		11	1.116	0.068
	All Specimens with Measured Throat Dimension		234	1.165	0.112
Measured Leg Size	Swannell and Skewes (1979b)		7	1.045	0.041
	Pham (1983b)		33	1.022	0.159
	Miazga and Kennedy (1986)		6	1.141	0.081
	Bowman and Quinn (1994)		6	1.526	0.135
	Deng *et al.* (2003)		9	1.344	0.113
	Callele *et al* (2005)		9	1.187	0.086
	All Specimens with Measured Leg Size		70	1.140	0.180
All Sources			304	1.159	0.130

Table 4.6 – Summary of Professional Factor ρ_P for SOFW Joints

Weld Dimension Measurement Method	Source of Data		Orientation of Weld Segments	Sample Size	Ratio of Measured to Predicted	Coefficient of Variation
				n	ρ_P	V_P
Measured Throat Dimension	Ligtenberg (1968)	England (St.37 steel)	90º	9	1.044	0.115
		Japan (St.37 steel)	90º	9	1.100	0.092
		USA (St.37 steel)	90º	9	0.991	0.129
		France (St.37 steel)	90º	9	1.047	0.074
		Germany (St.37 steel)	90º	9	1.132	0.137
		Belgium (St.37steel)	90º	9	1.128	0.123
		Netherlands (St.37 steel)	90º	9	1.043	0.093
		Canada (St.37 steel)	90º	9	1.156	0.090
		Sweden (St.37 steel)	90º	9	1.066	0.145
		Yugoslavia (St.37 steel)	90º	18	0.954	0.142
		Netherlands (St.52 steel)	90º	5	0.916	0.129
		Germany (St.52 steel)	90º	5	1.154	0.112
		Italy (St.52 Steel)	90º	5	0.873	0.060
		Sweden (St.52 steel)	90º	7	1.009	0.087
	Bornscheuer and Feder (1966)		90º	8	1.197	0.120
	Kato and Morita (1969)		90º	9	0.933	0.104
	All Specimens with Measured Throat Dimension		N.A.	138	1.046	0.138

Table 4.6 (cont.)

Weld Dimension Measurement Method	Source of Data	Orientation of Weld Segments	Sample Size	Ratio of Measured to Predicted	Coefficient of Variation
			n	ρ_P	V_P
Measured Leg Size	Butler and Kulak (1969)	30º	6	1.225	0.002
		60º	6	0.845	0.036
		90º	6	0.914	0.061
	Clark (1971)	30º	2	1.352	0.054
		60º	2	1.067	0.233
		90º	4	1.139	0.034
	Miazga and Kennedy (1986)	15º	6	0.953	0.051
		30º	6	1.079	0.056
		45º	6	0.990	0.129
		60º	6	1.105	0.112
		75º	6	0.996	0.018
		90º	6	0.954	0.056
	Bowman and Quinn (1994)	90º	6	0.956	0.030
	Ng *et al.* (2002)†	90º	86	1.169	0.157
	Deng *et al.* (2003)†	45º	8	1.403	0.088
	All Specimens with Measured Leg Sizes	N.A.	162	1.119	0.168
All Sources		N.A.	300	1.085	0.159

† Data were directly from literature.

Table 4.7a – Summary of Professional Factor ρ_P for MOFW Joints for Equation 4.9

Source of Data		Sample Size n	Ratio of Measured to Predicted ρ_P	Coefficient of Variation V_P
Ligtenberg (1968)	England (St.37 steel)	16	1.085	0.095
	Japan (St.37 steel)	17	1.053	0.048
	USA (St.37 steel)	18	1.054	0.090
	France (St.37 steel)	18	1.091	0.106
	Germany (St.37 steel)	16	1.040	0.098
	Belgium (St.37steel)	16	1.136	0.107
	Netherlands (St.37 steel)	17	0.962	0.071
	Canada (St.37 steel)	15	1.121	0.111
	Sweden (St.37 steel)	18	1.036	0.118
	Yugoslavia (St.37 steel)	18	1.011	0.110
	Netherlands (St.52 steel)	13	1.029	0.090
	Germany (St.52 steel)	13	1.132	0.055
	Italy (St.52 Steel)	13	1.025	0.067
	Sweden (St.52 steel)	14	1.011	0.061
Bornscheuer and Feder (1966)		5	0.913	0.042
Kato and Morita (1969)		3	1.090	0.089
Callele *et al.* (2005)†		20	0.848	0.075
All Sources		262	1.033	0.114

† Only test program for which the throat area is calculated from measured leg dimensions. All others used the measured throat dimension.

Table 4.7b – Summary of Professional Factor ρ_P for MOFW Joints for Equation 4.10

Source of Data		Sample Size n	Ratio of Measured to Predicted ρ_P	Coefficient of Variation V_P
Ligtenberg (1968)	England (St.37 steel)	16	0.992	0.101
	Japan (St.37 steel)	17	0.969	0.045
	USA (St.37 steel)	18	0.967	0.086
	France (St.37 steel)	18	1.001	0.103
	Germany (St.37 steel)	16	0.940	0.103
	Belgium (St.37steel)	16	1.025	0.108
	Netherlands (St.37 steel)	17	0.875	0.080
	Canada (St.37 steel)	15	1.024	0.102
	Sweden (St.37 steel)	18	0.946	0.114
	Yugoslavia (St.37 steel)	18	0.922	0.120
	Netherlands (St.52 steel)	13	0.943	0.085
	Germany (St.52 steel)	13	1.035	0.048
	Italy (St.52 Steel)	13	0.935	0.066
	Sweden (St.52 steel)	14	0.948	0.067
Bornscheuer and Feder (1966)		5	0.785	0.033
Kato and Morita (1969)		3	1.024	0.117
Callele *et al.* (2005) †		20	0.779	0.073
All Sources		262	0.944	0.114

† Only test program for which the throat area is calculated from measured leg dimensions. All others used the measured throat dimension.

Table 4.7c – Summary of Professional Factor ρ_P for MOFW Joints for Equation 4.11a and b

Source of Data		Sample Size n	Ratio of Measured to Predicted ρ_P	Coefficient of Variation V_P
Ligtenberg (1968)	England (St.37 steel)	16	1.082	0.100
	Japan (St.37 steel)	17	1.050	0.057
	USA (St.37 steel)	18	1.052	0.091
	France (St.37 steel)	18	1.088	0.104
	Germany (St.37 steel)	16	1.026	0.111
	Belgium (St.37steel)	16	1.117	0.115
	Netherlands (St.37 steel)	17	0.952	0.076
	Canada (St.37 steel)	15	1.117	0.111
	Sweden (St.37 steel)	18	1.031	0.120
	Yugoslavia (St.37 steel)	18	1.003	0.117
	Netherlands (St.52 steel)	13	1.028	0.090
	Germany (St.52 steel)	13	1.129	0.051
	Italy (St.52 Steel)	13	1.023	0.068
	Sweden (St.52 steel)	14	1.011	0.061
Bornscheuer and Feder (1966)		5	0.913	0.042
Kato and Morita (1969)		3	1.090	0.089
Callele *et al.* (2005) †		20	0.848	0.075
All Sources		262	1.028	0.115

† Only test program for which the throat area is calculated from measured leg dimensions. All others used the measured throat dimension.

Table 4.8 – Professional Factor ρ_P for Cruciform Specimens from Phases 1 and 4

Specimen	Phase	Weld Metal Spec.	Nominal Leg Size (mm)	P_{ST} / A_{throat} (MPa)	τ_u (MPa)	Ratio ρ_P	Mean ρ_P	V_P
C1-1	1	E70T-4	6.4	1067	496	1.433	1.204	0.154
C1-2				1028		1.381		
C1-3				943		1.267		
C2-1		E70T7-K2		997	600	1.107		
C2-2				954		1.059		
C2-3				877		0.974		
CNY-7	4	E70T-7	12.7	539	453	0.794	0.817	0.082
CNY-8				609		0.897		
CNY-10				615		0.906		
CNY-6		E71T8-K6		572	500	0.762		
CNY-11				577		0.769		
CNY-12				578		0.771		

Table 4.9 – Summary of Professional Factor ρ_P for Cruciform Connections

Source of Data		Sample Size	Ratio of Measured to Predicted	Coefficient of Variation
		n	ρ_P	V_P
Ng *et al*. (2002)	FCAW, 6.4 mm	6	1.204	0.154
Current Test	FCAW, 12.7 mm	6	0.817	0.082
Pham (1983a)	FCAW, 6 mm	6	1.206	0.042
	FCAW, 10 mm	6	0.888	0.072
	FCAW, 16 mm	6	0.906	0.099
	SAW, 6 mm	6	1.091	0.033
	SAW, 10 mm	6	1.251	0.030
	SAW, 16 mm	6	0.981	0.054
All specimens		48	1.043	0.170

Table 4.10 – Summary of Safety Indices for SOFW Joints

		Equation 4.1a CSA S16.1-01			Equation 4.1b AISC 2005		
Weld Dimension Measurement Method		Measured Throat Dimension	Measured Leg Size	All Sources	Measured Throat Dimension	Measured Leg Size	All Sources
ρ_G		1.065	1.087	1.074	1.065	1.087	1.074
V_G		0.148	0.126	0.142	0.148	0.126	0.142
ρ_{M1}		1.127	1.127	1.127	1.127	1.127	1.127
V_{M1}		0.080	0.080	0.080	0.080	0.080	0.080
ρ_{M2}		1.165	1.140	1.159	1.301	1.273	1.294
V_{M2}		0.112	0.180	0.130	0.112	0.180	0.130
ρ_P		1.046	1.119	1.085	1.046	1.119	1.085
V_P		0.138	0.168	0.159	0.138	0.168	0.159
ρ_R		1.463	1.563	1.522	1.633	1.745	1.699
V_R		0.245	0.288	0.262	0.245	0.288	0.262
β	$\phi_w = 0.67$	4.59	4.42	4.57	—	—	—
	$\phi = 0.75$	—	—	—	4.51	4.41	4.55
ϕ_w	$\beta = 4.5$	0.68	0.66	0.68	—	—	—
ϕ		—	—	—	0.76	0.73	0.76
ϕ_w	$\beta = 4.0$	0.77	0.75	0.77	—	—	—
ϕ		—	—	—	0.86	0.83	0.86

Table 4.11 – Summary of Safety Indices for MOFW Joints

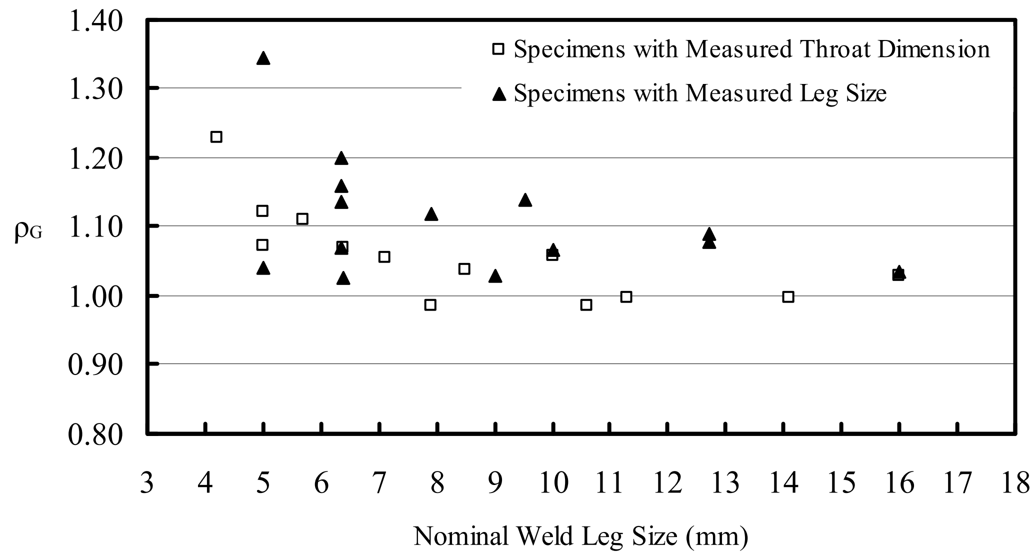
Model		Model 1 Equation 4.9		Model 2 Equation 4.10		Model 3 Equations 4.11a and b	
Design Code		S16.1-01	AISC 2005	S16.1-01	AISC 2005	S16.1-01	AISC 2005
ρ_G		1.074	1.074	1.074	1.074	1.074	1.074
V_G		0.142	0.142	0.142	0.142	0.142	0.142
ρ_{M1}		1.127	1.127	1.127	1.127	1.127	1.127
V_{M1}		0.080	0.080	0.080	0.080	0.080	0.080
ρ_{M2}		1.159	1.294	1.159	1.294	1.159	1.294
V_{M2}		0.130	0.130	0.130	0.130	0.130	0.130
ρ_P		1.033	1.033	0.944	0.944	1.028	1.028
V_P		0.114	0.114	0.114	0.114	0.115	0.115
ρ_R		1.449	1.618	1.324	1.479	1.442	1.610
V_R		0.238	0.238	0.238	0.238	0.238	0.238
β	$\phi_w = 0.67$	4.63	—	4.23	—	4.60	—
	$\phi = 0.75$	—	4.61	—	4.22	—	4.60
ϕ_w	$\beta = 4.5$	0.69	—	0.63	—	0.69	—
ϕ		—	0.77	—	0.70	—	0.77
ϕ_w	$\beta = 4.0$	0.77	—	0.71	—	0.77	—
ϕ		—	0.86	—	0.79	—	0.86

Table 4.12 – Summary of Safety Indices for MOFW Specimens with Out-of-plane Eccentricity from Ligtenberg (1968)

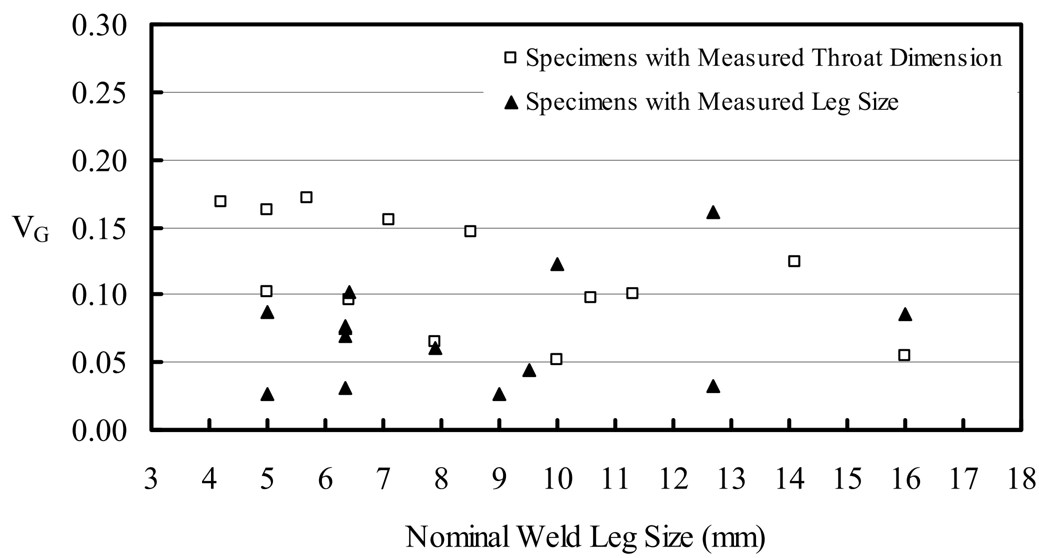
<table>
<tr><td colspan="2"></td><td colspan="2">Model 1
Equation 4.9</td></tr>
<tr><td colspan="2">Design Code</td><td>S16.1-01</td><td>AISC 2005</td></tr>
<tr><td colspan="2">ρ_G</td><td>1.074</td><td>1.074</td></tr>
<tr><td colspan="2">V_G</td><td>0.142</td><td>0.142</td></tr>
<tr><td colspan="2">ρ_{M1}</td><td>1.127</td><td>1.127</td></tr>
<tr><td colspan="2">V_{M1}</td><td>0.080</td><td>0.080</td></tr>
<tr><td colspan="2">ρ_{M2}</td><td>1.159</td><td>1.294</td></tr>
<tr><td colspan="2">V_{M2}</td><td>0.130</td><td>0.130</td></tr>
<tr><td colspan="2">ρ_P</td><td>0.878</td><td>0.878</td></tr>
<tr><td colspan="2">V_P</td><td>0.211</td><td>0.211</td></tr>
<tr><td colspan="2">ρ_R</td><td>1.232</td><td>1.377</td></tr>
<tr><td colspan="2">V_R</td><td>0.297</td><td>0.302</td></tr>
<tr><td rowspan="2">β</td><td>$\phi_w = 0.67$</td><td>3.45</td><td>—</td></tr>
<tr><td>$\phi = 0.75$</td><td>—</td><td>3.44</td></tr>
<tr><td>ϕ_w</td><td rowspan="2">$\beta = 4.5$</td><td>0.51</td><td>—</td></tr>
<tr><td>ϕ</td><td>—</td><td>0.57</td></tr>
<tr><td>ϕ_w</td><td rowspan="2">$\beta = 4.0$</td><td>0.58</td><td>—</td></tr>
<tr><td>ϕ</td><td>—</td><td>0.65</td></tr>
</table>

Table 4.13 – Summary of Safety Indices for Cruciform Joints

		CSA S16.1-01 Equation 4.1a	AISC 2005 Equation 4.1b
ρ_G		1.074	1.074
V_G		0.142	0.142
ρ_{M1}		1.127	1.127
V_{M1}		0.080	0.080
ρ_{M2}		1.159	1.294
V_{M2}		0.130	0.130
ρ_P		1.043	1.043
V_P		0.170	0.170
ρ_R		1.463	1.634
V_R		0.269	0.269
β	$\phi_w = 0.67$	4.34	—
	$\phi = 0.75$	—	4.33
ϕ_w	$\beta = 4.5$	0.64	—
ϕ		—	0.72
ϕ_w	$\beta = 4.0$	0.73	—
ϕ		—	0.81



a) Variation of ρ_G with Weld Size



b) Variation of V_G with Weld Size

Figure 4.1 – Variation of ρ_G and V_G with Weld Size

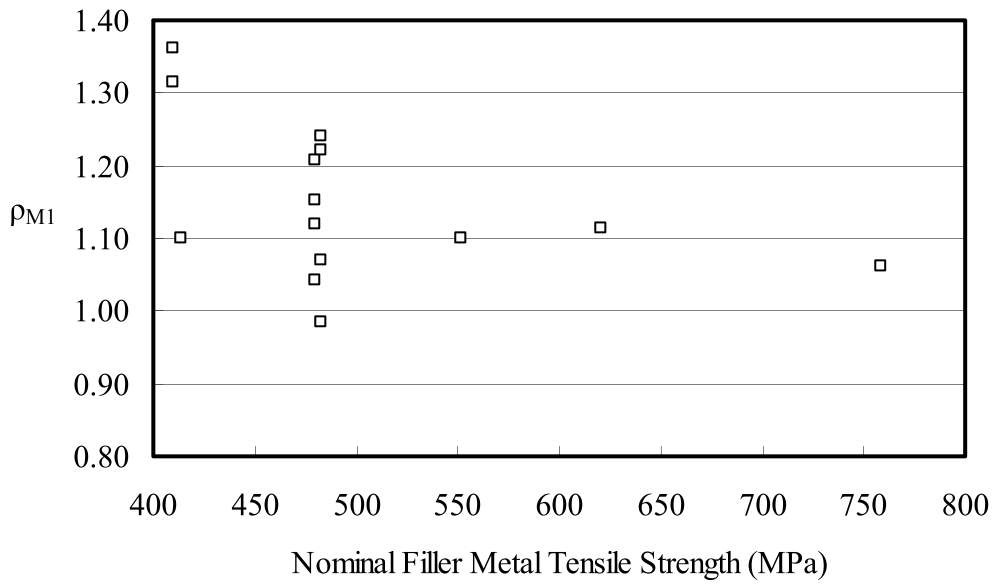


Figure 4.2 – Value of ρ_{M1} as a Function of the Nominal Tensile Strength from Various Sources

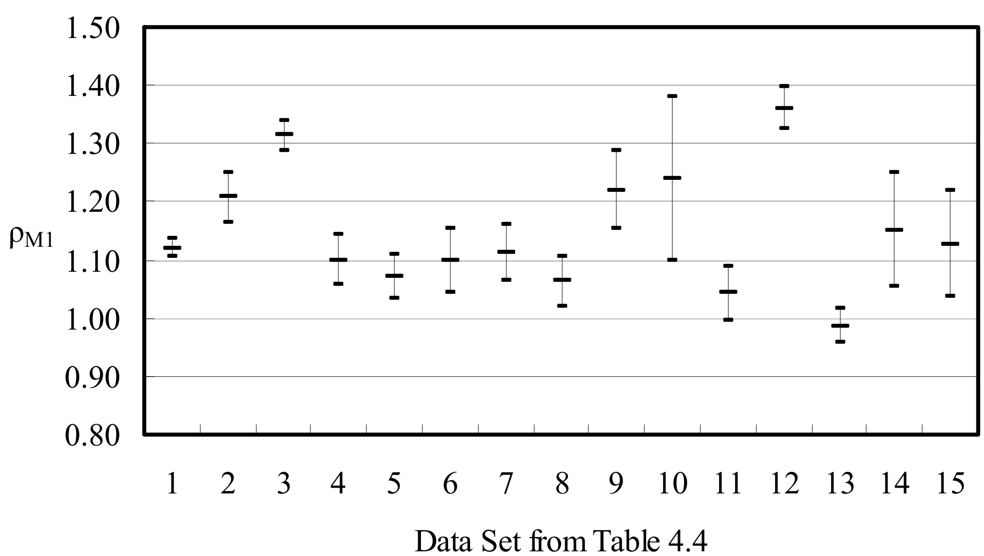


Figure 4.3 – Variation of ρ_{M1} in Various Data Sets

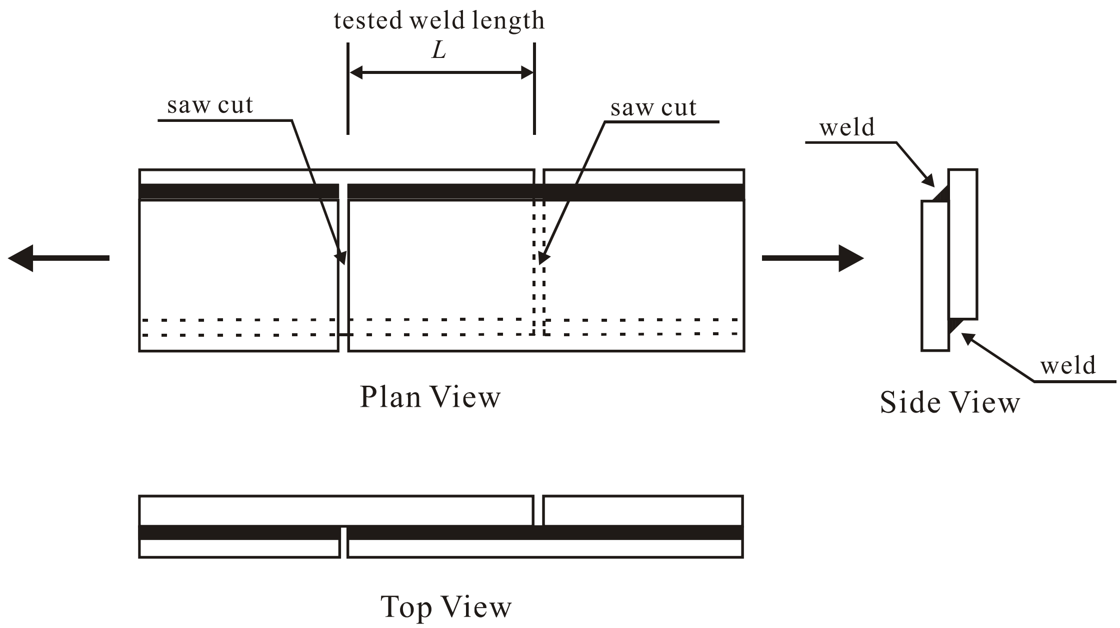


Figure 4.4 – Werner Specimen

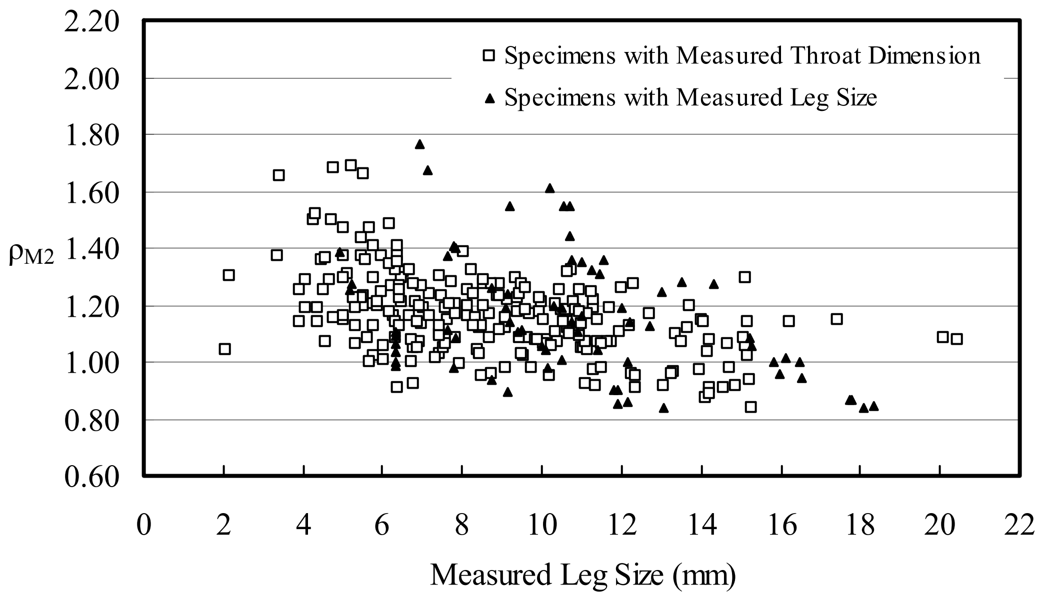


Figure 4.5 – Bias Coefficient ρ_{M2} as a Function of Weld Size

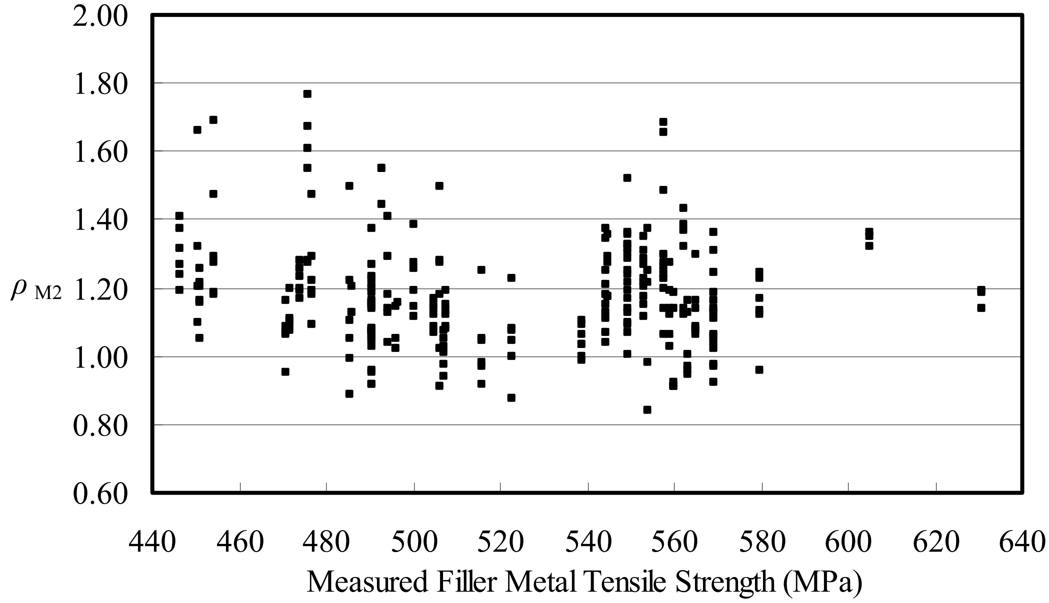


Figure 4.6 – Effect of Tensile Strength on the Bias Coefficient ρ_{M2} for All Test Specimens in Table 4.5

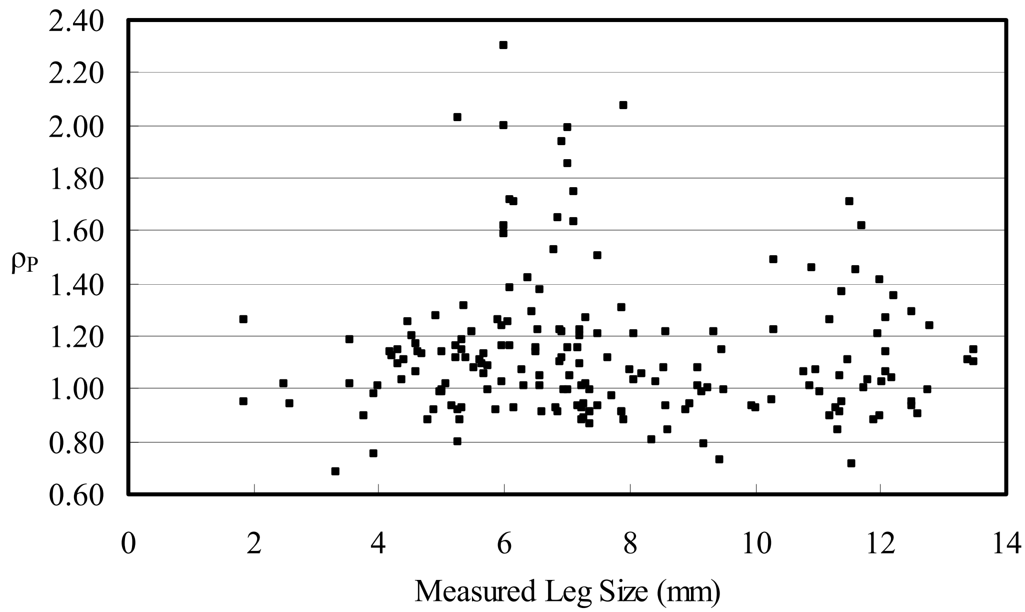


Figure 4.7 – Professional Factor, ρ_P, for Transverse Weld versus Measured Weld Size

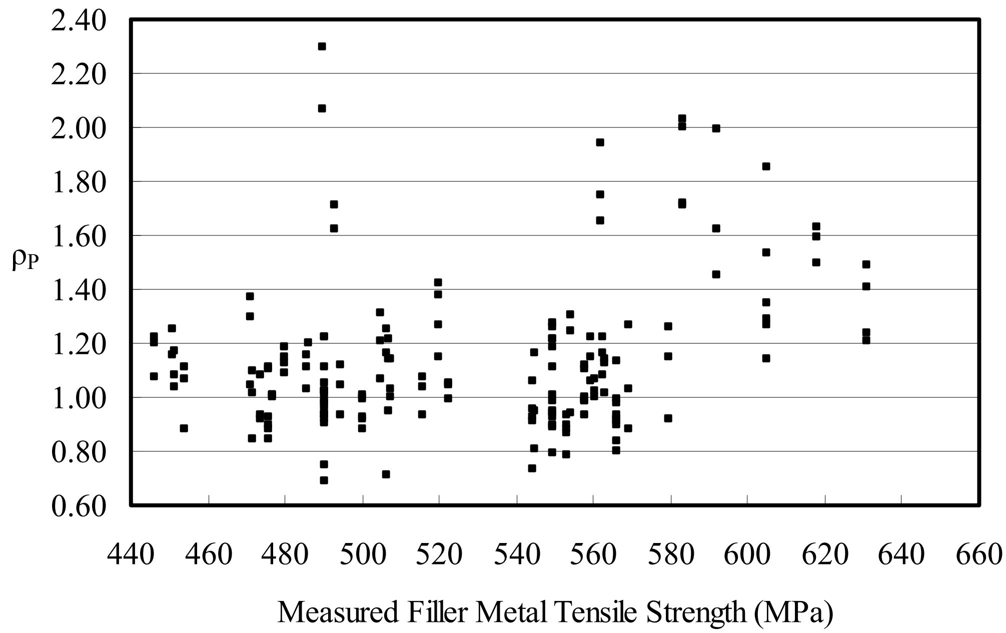


Figure 4.8 – Professional Factor, ρ_P, for Transverse Weld versus Measured Filler Metal Tensile Strength

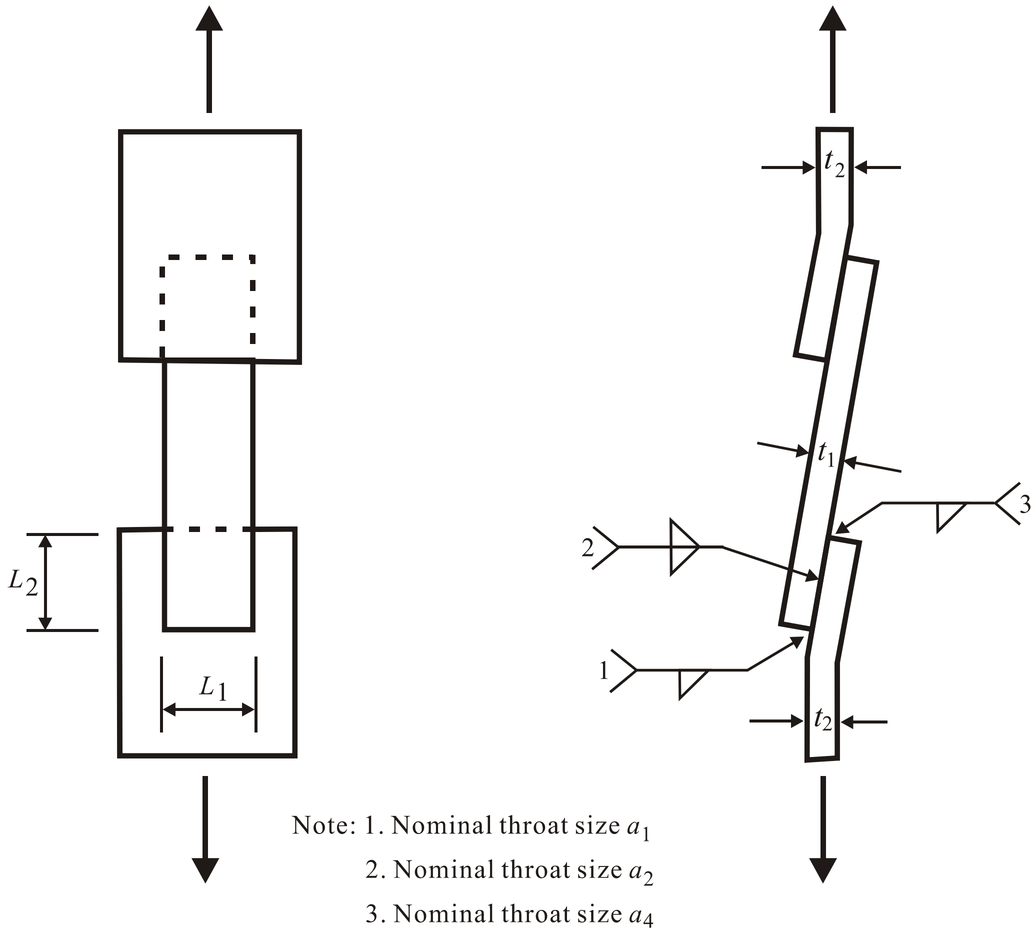


Figure 4.9 – MOFW Specimen with Out-of-plane Eccentricity from Ligtenberg (1968)

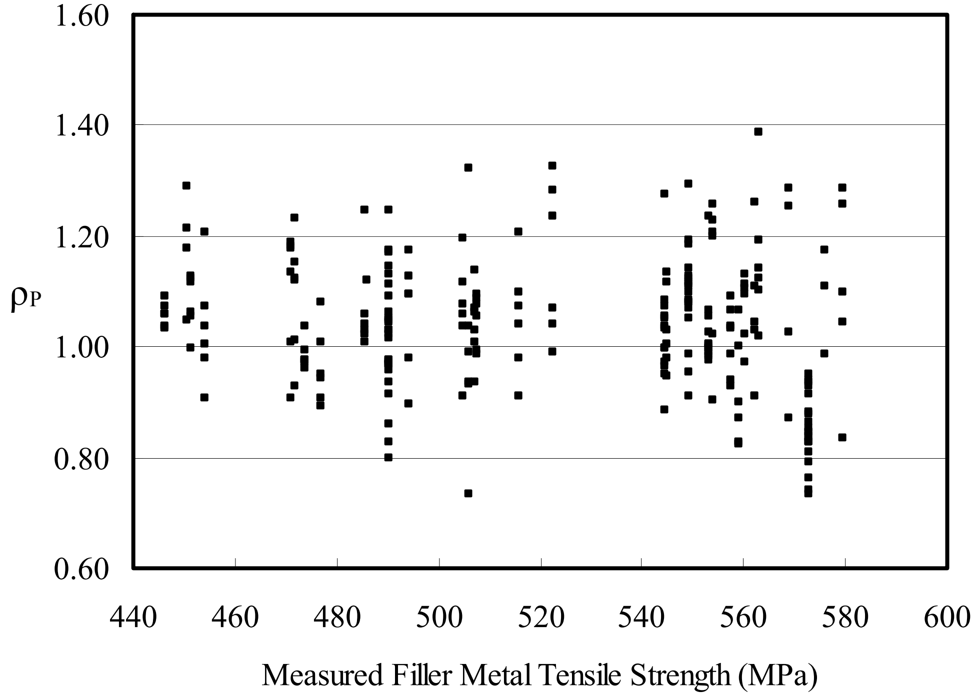


Figure 4.10 – Professional Factor, ρ_P, for Combined Transverse and Longitudinal Welds versus Measured Filler Metal Tensile Strength

CHAPTER 5

SUMMARY, CONCLUSIONS AND RECOMMENDATIONS

5. 1 Summary

An extensive research program on the strength and ductility of fillet welds in concentrically loaded joints has been conducted at the University of Alberta. Although the test program included five different filler metal classifications, this represents only a small fraction of the filler metals used in industry. The primary objective of this investigation was to augment the database of test results from the University of Alberta to include test results from other sources to increase the variety of filler metal classifications included in the database. This database of test results was then used to conduct a reliability analysis of the current North American design equation for design of fillet welds in concentrically loaded joints.

A review of the literature showed that most experimental programs have used double lap joints, with limited tests on cruciform connections. Therefore, a series of 12 cruciform specimens were tested. All specimens consisted of 12.7 mm welds prepared using two FCAW filler metals, namely, E70T-7 filler metal (AWS, 1995) and E71T8-K6 filler metal, with a toughness requirement of 20J at -29ºC (AWS, 1998). The steel plates conformed to the requirements of ASTM A572 Grade 50 and were designed to remain elastic throughout the tests. Six cruciform specimens were tested at -50°C. The specimens were concentrically loaded under displacement control.

The data pool collected from various sources includes 1706 measurements of fillet weld size, 716 all-weld-metal coupon test specimens, 304 test specimens with longitudinal fillet welds, 300 test specimens with single orientation fillet welds (SOFW) other than longitudinal welds, 262 test specimens with multiple orientation fillet welds (MOFW) and 48 cruciform test specimens. The specimens were welded with filler metals from at least 10 different classifications. The test specimens included in the database were prepared using SMAW, FCAW or SAW welding processes.

5. 2 Conclusions

The following conclusions can be drawn from the test program on cruciform specimens:

1. A comparison of the strength of cruciform joints and lapped joints with transverse welds of the same classification indicated that 12.7 mm welds in cruciform joints reached only 81% of the strength of transverse fillet welds in lapped joints for E70T-7 electrodes and 70% for E71T8-K6 electrodes. A similar comparison in phase 1 of the research program indicated that 6.4 mm welds made with E70T-4 electrodes were not affected by the joint configuration, whereas 6.4 mm fillet welds from E70T7-K2 electrodes showed that cruciform joints had only 87% of the strength of lapped joints with transverse welds.

2. A comparison of weld ductility for E70T-7 electrodes on plates that remained elastic during testing indicated an average strain at ultimate load of cruciform specimens of 100% of that of lapped specimens and an average strain at fracture of cruciform specimens of 70% of that of lapped specimens. Ng *et al.* (2002) indicated that the mean ductility of lapped joints is about 3.8 times that of cruciform joints. It is noted that in phase 1 the plates yielded before fracture of the welds.

3. The importance of second order effects from main plate misalignment on the behaviour of cruciform test specimens was investigated. For the test specimens included in the database of test results (all from phase 4 of this research program), the fabrication imperfections were not considered to have had a significant effect on the behaviour of the specimens.

The following conclusions are drawn from an analysis of the database of test results:

4. The bias coefficient for the geometric factor, ρ_G, is larger for small weld sizes than for larger weld sizes. The coefficient of variation for the geometric factor, V_G, was found to be smaller for large welds than for small welds. This reflects the difficulty of producing small size welds. The bias coefficient, ρ_G, and the

coefficient of variation, V_G, for the pooled data are 1.074 and 0.142, respectively. The geometric factor, ρ_G, and the coefficient of variation, V_G, from phases 1 through 4, in which the strict tolerances were set on the weld size, were 0.983 and 0.108, respectively.

5. For the data available, there seems to be no correlation between the ratio of measured weld metal tensile strength to the nominal tensile strength, ρ_{M1}, and the nominal strength. The bias coefficient for the material strength factor, ρ_{M1}, from phases 1 through 4 fell within one standard deviation of the mean from all the pooled data. The values of ρ_{M1} and V_{M1} were therefore obtained from the whole data pool. The bias coefficient, ρ_{M1}, and the coefficient of variation, V_{M1}, are taken as 1.127 and 0.08, respectively.

6. The material factor, ρ_{M2}, is defined as the ratio of measured weld shear strength, which is obtained from longitudinal test specimens, to 0.67 (for CSA S16–01) or 0.60 (for ANSI/AISC 360-05) times the measured tensile strength. The material factor, ρ_{M2}, therefore represents a normalized capacity of the longitudinal test specimens. The size effect on the longitudinal weld strength was investigated by examining the bias coefficient ρ_{M2} against the measured weld leg size. This investigation indicated no significant effect of the leg size on the material factor, ρ_{M2}. The effect of the measured tensile strength of the electrode on the longitudinal weld strength was also investigated. No significant effect of the tensile strength on the bias coefficient, ρ_{M2}, was observed. The bias coefficient, ρ_{M2}, and the coefficient of variation, V_{M2}, are taken as 1.159 and 0.130 for CSA S16.1-01 and 1.294 and 0.130 for ANSI/AISC 360-05, respectively.

7. About 85% of the specimens with single orientation fillet welds had transverse welds. The professional factor, ρ_P, for joints with transverse welds only was analyzed as the function of the measured leg size. No correlation between the professional factor and the measured weld size was observed. Similarly, no

correlation was found between the professional factor and the measured tensile strength of the filler metal.

8. The professional factor for MOFW joints with combined transverse and longitudinal welds for the design equation proposed by Callele *et al.* (2005) was analyzed as the function of the measured tensile strength of the filler metal. It was observed that the tensile strength of the filler metal has no significant effect on the professional factor.

9. The effect of the fillet weld characteristic dimension, namely, measurement of leg dimension or measurement of throat dimension, on the bias coefficient was investigated. Overall, the weld size has only a small effect on the values of ρ_G, ρ_{M2} and ρ_P.

10. The test data from Ng *et al.* (2002), Deng *et al*. (2003), and Callele *et al*. (2005) and the current test program, which included nominal leg sizes of 6.4 mm, 7.9 mm and 12.7 mm, show that the throat dimension measured before testing is about 10% larger than the throat dimension calculated from the measured leg sizes.

The following conclusions are drawn from the reliability analysis:

11. A reliability analysis of SOFW joints from various sources has indicated that a safety index of 4.5 is obtained with a resistance factor of 0.68 for the CSA S16.1-01 design equation and a resistance factor of 0.76 for the ANSI/AISC 360-05 design equation. A safety index of 4.0 is obtained for a resistance factor of 0.77 with the weld strength equation presented in CSA S16.1-01 and a resistance factor of 0.86 with the weld strength equation presented in ANSI/AISC 360-05.

12. A reliability analysis of MOFW joints from four different sources has indicated that the weld strength equation proposed by Callele *et al*. (2005) yields safety indices of 4.5 and 4.0 for resistance factors of 0.69 and 0.77, respectively. The

addition of the full strength of all the welds in the MOFW joint, as deduced from CSA S16.1-01, results in safety indices of 4.5 and 4.0 for resistance factors of 0.63 and 0.71, respectively. The equation adopted by AISC (2005) for joints with transverse and longitudinal welds results in safety indices of 4.5 and 4.0 for resistance factors of 0.69 and 0.77, respectively. The results have confirmed that the design equation proposed by Callele *et al.* (2005) and that used in AISC (2005), adopted from the work of Manuel and Kulak (2000) provide a sufficient level of safety.

13. A reliability analysis conducted on 33 MOFW specimens with out-of-plane eccentricity from Ligtenberg (1968) was performed for the design equation proposed by Callele *et al.* (2005) only. The analysis indicated that safety indices of 4.5 and 4.0 are obtained with resistance factors of 0.50 and 0.57, respectively. The weld strength design equation proposed by Callele *et al*. is not suitable for MOFW joints with out-of-plane eccentricity.

14. A reliability analysis of cruciform joints was performed for the CSA S16.1-01 design equation (Equation 4.1a) and the ANSI/AISC 360-05 design equation (Equation 4.1b). The analysis indicated that for the CSA S16.1-01 design equation, safety indices of 4.5 and 4.0 are obtained with resistance factors of 0.64 and 0.72, respectively. For the ANSI/AISC 360-05 design equation, safety indices of 4.5 and 4.0 are obtained with resistance factors of 0.71 and 0.81, respectively.

5. 3 Recommendations for Future Research

Although the research on concentrically loaded fillet welded joints presented in this report has helped expand our knowledge regarding fillet weld behaviour, other issues still need to be addressed.

1. A comparison between the strength of lapped and cruciform joints has indicated that both weld size and weld metal toughness have an effect on the strength reduction of cruciform specimens. In phases 1 and 4, only two leg sizes and two FCAW electrodes were used for cruciform specimens. Other leg sizes and a wider

variety of welding electrodes with and without a toughness requirement are recommended to investigate their effects on the strength of cruciform specimens.

2. The size of the root notch present in cruciform joints may be a significant factor on the strength and ductility of these joints since the root notch represents a notch oriented perpendicular to the applied stress field. Further testing is recommended to investigate the effect of root notch size on the strength and ductility of cruciform joints.

3. The specimens tested at low temperature in phases 3 and 4 fractured in the plates rather than in the weld. Therefore, the low temperature effect on the behaviour of fillet welds remains inconclusive. Further testing is recommended to investigate the effect of low temperature on fillet welds.

4. Canadian practice (CSA, 2003) for longitudinal welds requires a weld return to terminate the weld. The length of the return must be at lease twice the nominal size of the weld. The weld returns for longitudinal welds are essentially short transverse welds. It is possible that the presence of the short transverse welds will prevent the longitudinal welds from reaching their full capacity due to the difference in ductilities. Further testing is recommended to investigate the effect of weld returns on the strength of longitudinal welds.

5. Based on the above recommendations, new specimens were designed and their drawings and general requirements for fabrication are presented in Appendix F.

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APPENDIX A

ALL-WELD-METAL TENSION COUPON TESTS

APPENDIX A

ALL-WELD-METAL TENSION COUPON TESTS

This appendix contains information for the three all-weld-metal tension coupon tests on E71T8-K6 filler metal. Test results for the E70T-7 filler metal used in this investigation were reported in Appendix C of Callele *et al*. (2005) (coupons 103-1, 2, 3) and repeated here for completeness.

The stresses shown in the following figures are calculated as engineering stress, i.e., the applied load divided by the initial area. Table A1 gives the initial areas and the post-fracture areas. The initial cross-sectional areas were calculated from nine measurements of the diameter in the test region of the coupons. The post-fracture areas were calculated from six diameter measurements taken on both of the two fracture areas from each coupon. All of the diameter measurements were made with a calliper. A summary of the key stress and strain values is provided in Table 3.2.

Table A1 – Coupon Cross-Sectional Areas

Electrode	Coupon	Cross-Sectional Area		
		Initial (mm^2)	Post-Fracture (mm^2)	Reduction (%)
E70T–7	103–1	126	109	13.7
	103–2	127	111	12.4
	103–3	128	103	19.1
E71T8–K6	203–1	127	40	68.5
	203–2	127	42	66.9
	203–3	127	41	67.7

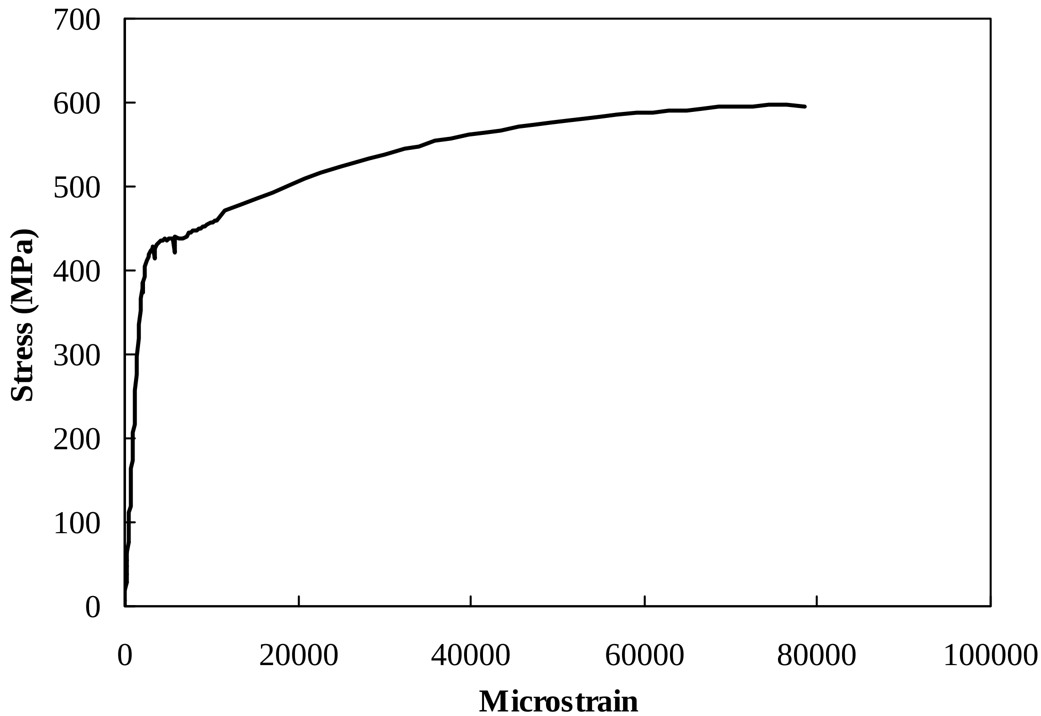


Figure A1 – Test Coupon 103–1

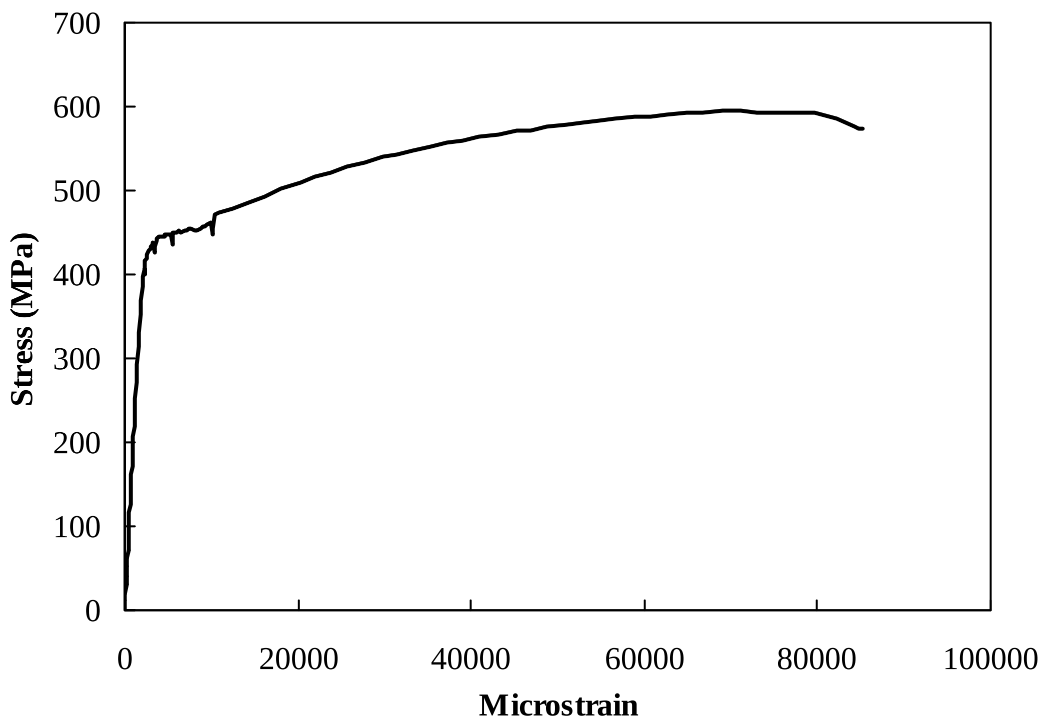


Figure A2 – Test Coupon 103–2

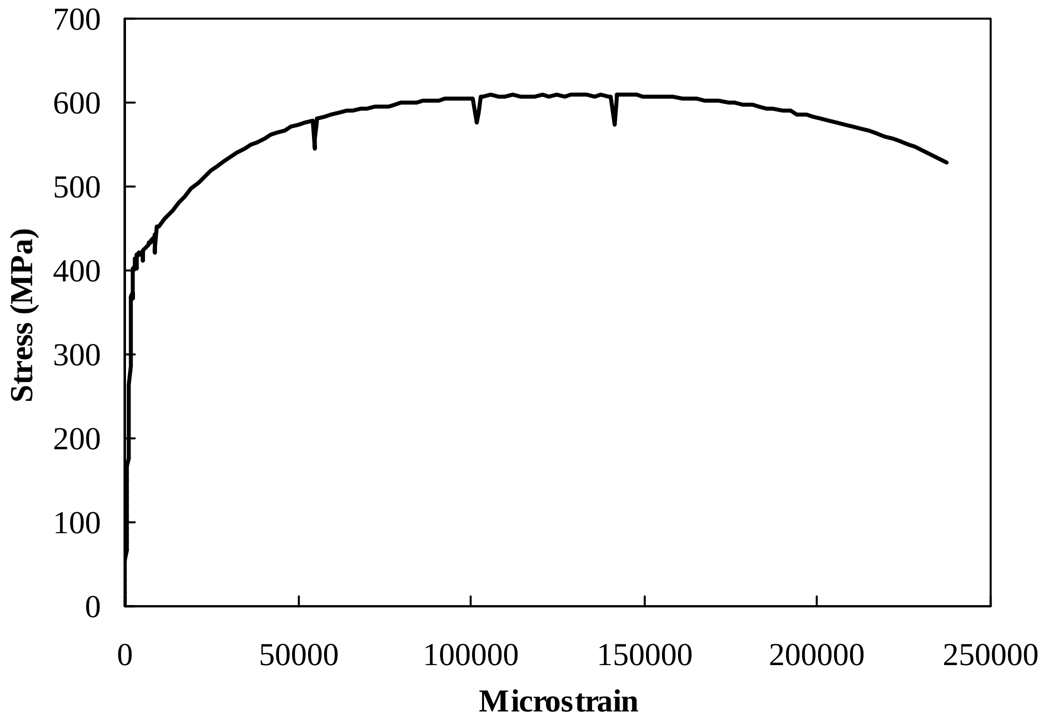


Figure A3 – Test Coupon 103–3

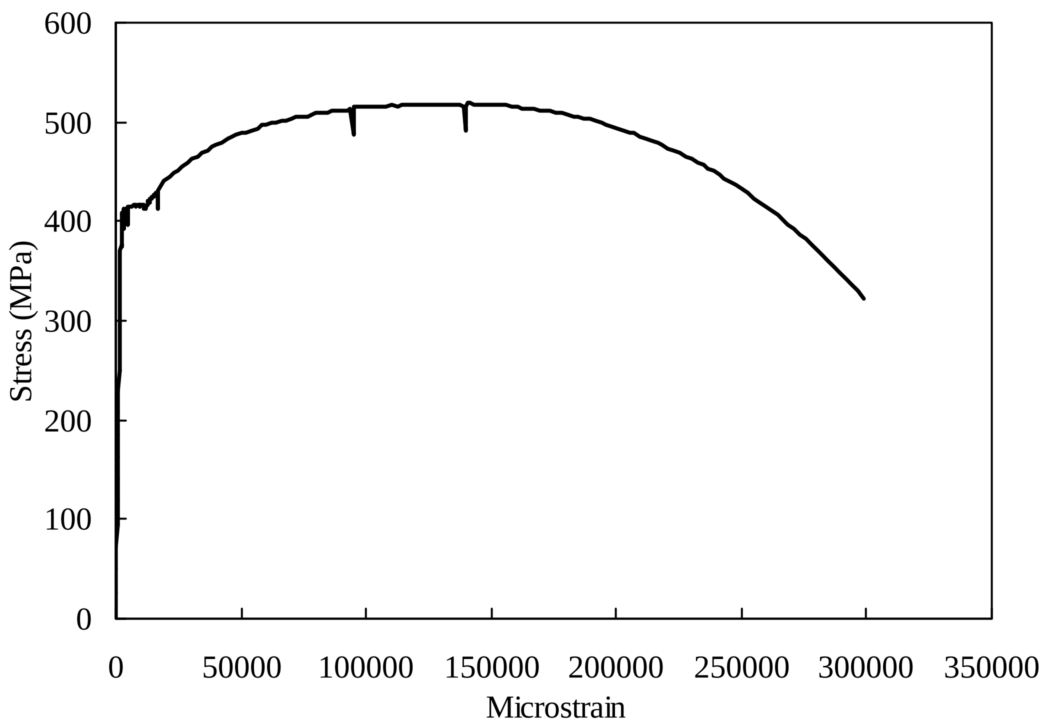


Figure A4 – Test Coupon 203–1

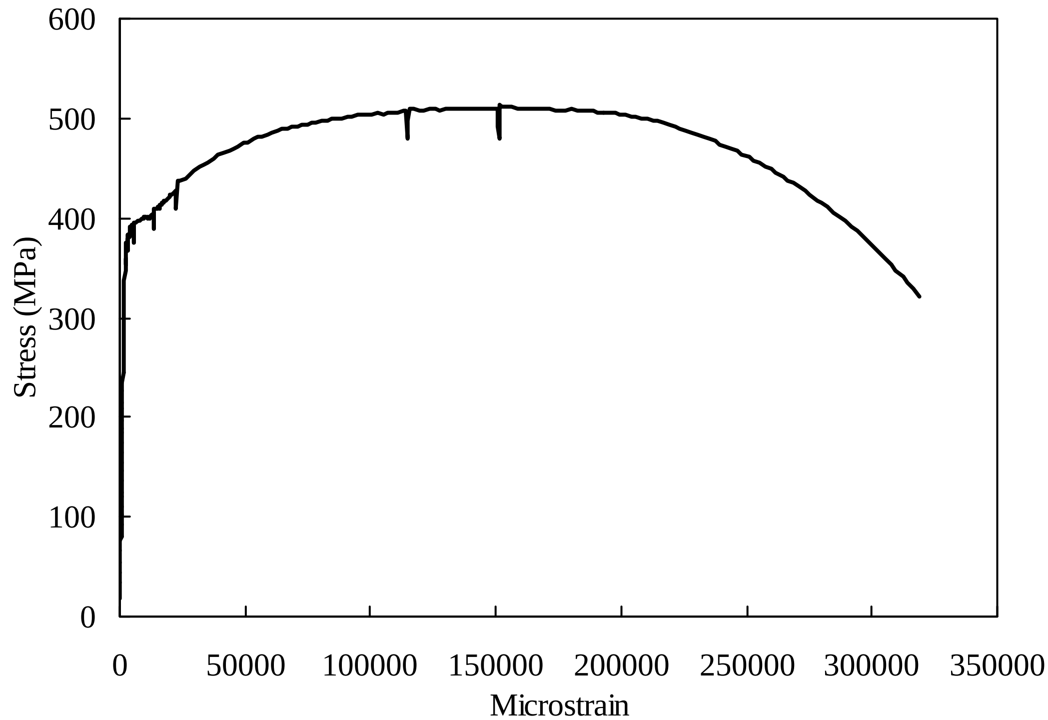


Figure A5 – Test Coupon 203–2

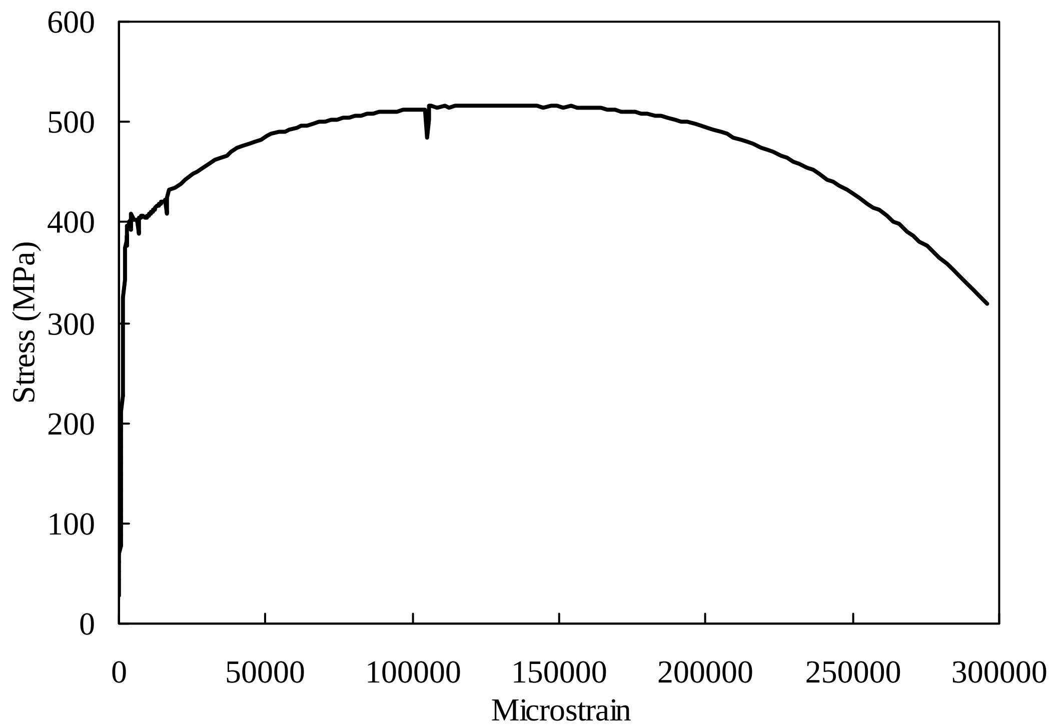


Figure A6 – Test Coupon 203–3

APPENDIX B

FILLET WELD SPECIMEN MEASUREMENTS

APPENDIX B

MEASUREMENTS OF FILLET WELD SPECIMENS

Refer to Section 3.4 and Figure 3.2 for definitions and measurement method.

Table B1 – Weld Measurements for Specimen CNY–1 (E70T-7, 12.7 mm)

Meas. Number	Pre-Test Measurement							
	Front Face				Back Face			
	MPL (mm)	CPL (mm)	45º Meas. (mm)	Weld Length (mm)	MPL (mm)	CPL (mm)	45º Meas. (mm)	Weld Length (mm)
1	12.8	10.4	10.0	72.4	11.3	9.3	9.2	72.4
2	14.0	10.8	9.7	72.4	12.1	9.4	9.4	72.4
3	14.0	11.4	10.5	72.4	12.1	9.8	9.8	72.4
4	12.0	10.7	9.8		12.2	9.8	10.3	
5	12.1	10.3	9.8		12.0	10.2	10.5	
6	12.5	9.8	9.4		12.0	10.5	10.5	
7	12.6	9.6	9.2		11.6	10.2	9.8	
8	13.0	9.5	9.4		11.4	9.7	9.2	
Mean	12.9	10.3	9.7	72.4	11.8	9.9	9.8	72.4
Gauge Length (mm)	LVDT1 = 14.4				LVDT3 = 15.7			
	LVDT2 = 14.4				LVDT4 = 13.6			

Table B2 – Weld Measurements for Specimen CNY–2 (E71T8-K6, 12.7 mm)

Meas. Number	Pre-Test Measurement							
	Front Face				Back Face			
	MPL (mm)	CPL (mm)	45º Meas. (mm)	Weld Length (mm)	MPL (mm)	CPL (mm)	45º Meas. (mm)	Weld Length (mm)
1	11.0	12.8	9.8	76.3	11.8	11.5	11.1	76.3
2	11.4	12.2	10.5	76.3	11.2	11.2	11.0	76.3
3	11.5	12.3	11.0	76.3	11.5	11.6	11.0	76.3
4	10.9	13.0	11.0		11.3	11.8	11.0	
5	12.6	12.7	11.3		11.0	12.3	11.3	
6	13.2	12.7	11.1		11.1	11.7	10.8	
7	12.6	12.7	11.3		11.1	11.4	10.5	
8	12.0	13.0	11.0		11.8	11.8	11.3	
Mean	11.9	12.7	10.9	76.3	11.3	11.7	11.0	76.3
Gauge Length (mm)	LVDT1 = 16.1				LVDT3 = 14.9			
	LVDT2 = 12.3				LVDT4 = 14.0			

Table B3 – Weld Measurements for Specimen CNY–3 (E71T8-K6, 12.7 mm)

Meas. Number	Pre-Test Measurement							
	Front Face				Back Face			
	MPL (mm)	CPL (mm)	45º Meas. (mm)	Weld Length (mm)	MPL (mm)	CPL (mm)	45º Meas. (mm)	Weld Length (mm)
1	12.6	11.3	12.4	76.3	14.5	10.4	12.2	76.3
2	12.0	12.1	11.9	76.4	13.3	10.3	11.9	76.3
3	12.9	12.3	11.3	76.3	12.6	10.1	11.3	76.3
4	12.5	12.2	12.5		12.8	11.6	11.3	
5	13.0	11.4	12.2		13.3	11.1	11.4	
6	13.6	11.4	12.4		14.1	10.8	11.7	
7	13.5	12.9	12.5		13.7	10.9	11.6	
8	13.1	12.1	11.7		13.7	10.6	11.4	
Mean	12.9	12.0	12.1	76.3	13.5	10.7	11.6	76.3
Gauge Length (mm)	LVDT1 = 16.8				LVDT3 = 17.3			
	LVDT2 = 13.8				LVDT4 = 15.8			

Table B4 – Weld Measurements for Specimen CNY–4 (E71T8-K6, 12.7 mm)

Meas. Number	Pre-Test Measurement							
	Front Face				Back Face			
	MPL (mm)	CPL (mm)	45º Meas. (mm)	Weld Length (mm)	MPL (mm)	CPL (mm)	45º Meas. (mm)	Weld Length (mm)
1	14.0	12.0	12.2	76.3	13.5	10.9	11.3	76.3
2	13.9	11.9	12.4	76.3	13.2	10.3	11.1	76.3
3	14.8	12.0	12.5	76.3	13.3	10.5	10.6	76.3
4	15.6	12.0	12.2		13.3	11.0	11.3	
5	14.0	10.6	12.2		13.5	10.8	11.1	
6	15.9	11.2	12.1		13.1	10.5	11.4	
7	17.3	11.9	12.4		14.0	11.1	11.7	
8	14.3	11.5	12.2		14.1	11.3	11.6	
Mean	15.0	11.6	12.3	76.3	13.5	10.8	11.3	76.3
Gauge Length (mm)	LVDT1 = 19.6				LVDT3 = 17.1			
	LVDT2 = 14.9				LVDT4 = 15.6			

Table B5 – Weld Measurements for Specimen CNY–5 (E70T-7, 12.7 mm)

Meas. Number	Pre-Test Measurement							
	Front Face				Back Face			
	MPL (mm)	CPL (mm)	45º Meas. (mm)	Weld Length (mm)	MPL (mm)	CPL (mm)	45º Meas. (mm)	Weld Length (mm)
1	12.5	10.8	9.2	72.5	12.5	8.4	9.7	72.4
2	12.2	11.1	9.4	72.5	12.3	9.0	9.7	72.5
3	11.1	11.2	9.5	72.4	12.8	9.2	9.5	72.5
4	11.3	11.3	9.5		12.8	8.6	9.4	
5	11.3	11.9	9.5		12.7	8.9	9.7	
6	11.3	12.2	9.5		12.9	9.7	9.7	
7	11.2	12.4	9.4		12.3	9.1	9.8	
8	10.8	12.0	9.0		12.9	9.7	9.5	
Mean	11.5	11.6	9.4	72.5	12.6	9.1	9.6	72.4
Gauge Length (mm)	LVDT1 = 13.6				LVDT3 = 16.2			
	LVDT2 = 13.6				LVDT4 = 14.8			

Table B6 – Weld Measurements for Specimen CNY–6 (E71T8-K6, 12.7 mm)

Meas. Number	Pre-Test Measurement							
	Front Face				Back Face			
	MPL (mm)	CPL (mm)	45º Meas. (mm)	Weld Length (mm)	MPL (mm)	CPL (mm)	45º Meas. (mm)	Weld Length (mm)
1	13.7	11.0	11.6	76.3	12.1	12.6	12.5	76.3
2	13.6	11.0	12.2	76.3	11.9	13.1	12.5	76.3
3	13.6	11.2	11.0	76.3	11.8	13.4	11.9	76.3
4	12.5	11.1	11.4		12.8	12.2	11.9	
5	12.5	9.7	11.3		11.6	12.2	11.1	
6	12.4	10.1	11.9		11.4	12.1	11.7	
7	13.5	10.6	11.4		12.1	13.0	11.3	
8	13.5	10.9	11.3		12.2	12.4	11.6	
Mean	13.2	10.7	11.5	76.3	12.0	12.6	11.8	76.3
Gauge Length (mm)	LVDT1 = 16.1				LVDT3 = 17.6			
	LVDT2 = 15.6				LVDT4 = 15.8			

Table B7 – Weld Measurements for Specimen CNY–7 (E70T-7, 12.7 mm)

Meas. Number	Pre-Test Measurement							
	Front Face				Back Face			
	MPL (mm)	CPL (mm)	45º Meas. (mm)	Weld Length (mm)	MPL (mm)	CPL (mm)	45º Meas. (mm)	Weld Length (mm)
1	12.8	9.8	9.0	72.5	13.2	9.3	9.2	72.4
2	11.8	9.6	9.2	72.5	12.5	9.7	9.7	72.4
3	12.1	9.8	8.3	72.4	12.1	10.1	9.4	72.4
4	12.5	10.0	8.7		11.9	10.0	9.5	
5	12.6	9.3	8.9		11.4	9.9	9.2	
6	13.5	9.7	8.7		11.6	9.2	9.5	
7	13.7	9.2	9.4		12.2	10.0	9.2	
8	13.5	9.1	9.4		12.2	9.8	9.5	
Mean	12.8	9.5	8.9	72.5	12.1	9.8	9.4	72.4
Gauge Length (mm)	LVDT1 = 15.4				LVDT3 = 14.7			
	LVDT2 = 13.0				LVDT4 = 13.8			

Table B8 – Weld Measurements for Specimen CNY–8 (E70T-7, 12.7 mm)

Meas. Number	Pre-Test Measurement							
	Front Face				Back Face			
	MPL (mm)	CPL (mm)	45º Meas. (mm)	Weld Length (mm)	MPL (mm)	CPL (mm)	45º Meas. (mm)	Weld Length (mm)
1	13.9	10.4	11.0	72.4	12.9	9.7	9.8	72.5
2	14.4	10.4	10.3	72.5	13.2	9.8	9.8	72.4
3	13.5	10.4	10.3	72.4	13.0	10.9	10.2	72.4
4	13.6	9.6	10.5		13.6	11.2	9.8	
5	13.3	10.7	10.6		13.3	10.4	10.2	
6	13.5	10.1	10.3		12.9	10.2	9.8	
7	13.2	9.9	10.0		13.0	9.9	9.2	
8	12.6	9.7	9.8		12.8	9.8	9.2	
Mean	13.5	10.1	10.4	72.4	13.1	10.2	9.8	72.4
Gauge Length (mm)	LVDT1 = 14.1				LVDT3 = 16.2			
	LVDT2 = 14.5				LVDT4 = 15.4			

Table B9 – Weld Measurements for Specimen CNY–9 (E70T-7, 12.7 mm)

Meas. Number	Pre-Test Measurement							
	Front Face				Back Face			
	MPL (mm)	CPL (mm)	45o Meas. (mm)	Weld Length (mm)	MPL (mm)	CPL (mm)	45o Meas. (mm)	Weld Length (mm)
1	12.8	9.9	10.6	72.5	12.7	11.5	9.7	72.4
2	12.7	10.0	10.8	72.4	13.5	11.9	10.5	72.4
3	13.5	10.5	10.6	72.4	11.3	12.4	11.0	72.4
4	14.0	10.5	11.0		12.7	12.4	10.3	
5	14.2	10.0	11.0		12.0	11.8	9.8	
6	14.0	10.7	10.8		11.3	11.5	9.7	
7	13.3	10.8	10.6		11.5	10.8	9.4	
8	13.2	10.7	10.6		10.3	11.0	9.2	
Mean	13.5	10.4	10.8	72.4	11.9	11.7	9.9	72.4
Gauge Length (mm)	LVDT1 = 16.2				LVDT3 = 14.8			
	LVDT2 = 15.7				LVDT4 = 15.0			

Table B10 – Weld Measurements for Specimen CNY–10 (E70T-7, 12.7 mm)

Meas. Number	Pre-Test Measurement							
	Front Face				Back Face			
	MPL (mm)	CPL (mm)	45º Meas. (mm)	Weld Length (mm)	MPL (mm)	CPL (mm)	45º Meas. (mm)	Weld Length (mm)
1	11.1	12.0	9.2	72.4	11.8	9.4	9.4	72.3
2	12.0	12.1	9.4	72.4	11.9	9.6	9.4	72.3
3	12.2	11.4	9.4	72.4	11.0	9.5	9.2	72.3
4	11.9	11.5	9.7		11.2	9.7	9.5	
5	11.2	11.4	9.7		11.4	10.0	9.4	
6	11.8	11.3	10.3		11.5	9.6	9.4	
7	12.4	11.6	11.0		11.1	9.7	9.4	
8	12.7	11.2	10.0		11.8	9.6	9.5	
Mean	11.9	11.6	9.8	72.4	11.5	9.6	9.4	72.3
Gauge Length (mm)	LVDT1 = 14.2				LVDT3 = 15.0			
	LVDT2 = 12.0				LVDT4 = 13.7			

Table B11 – Weld Measurements for Specimen CNY–11 (E71T8-K6, 12.7 mm)

Meas. Number	Pre-Test Measurement							
	Front Face				Back Face			
	MPL (mm)	CPL (mm)	45º Meas. (mm)	Weld Length (mm)	MPL (mm)	CPL (mm)	45º Meas. (mm)	Weld Length (mm)
1	12.9	12.4	11.0	76.3	10.8	12.0	11.0	76.3
2	12.7	12.0	10.8	76.3	11.1	12.2	10.5	76.3
3	11.9	11.7	10.6	76.3	11.5	12.2	11.4	76.3
4	12.4	11.2	10.6		11.6	12.0	10.8	
5	11.6	12.0	11.0		10.9	12.3	11.0	
6	12.6	11.3	10.8		12.2	12.1	10.3	
7	11.5	11.5	10.6		14.0	12.2	11.4	
8	12.5	12.2	10.8		13.1	12.3	10.3	
Mean	12.3	11.8	10.8	76.3	11.9	12.2	10.8	76.3
Gauge Length (mm)	LVDT1 = 16.6				LVDT3 = 17.0			
	LVDT2 = 14.7				LVDT4 = 12.8			

Table B12 – Weld Measurements for Specimen CNY–12 (E71T8-K6, 12.7 mm)

Meas. Number	Pre-Test Measurement							
	Front Face				Back Face			
	MPL (mm)	CPL (mm)	45º Meas. (mm)	Weld Length (mm)	MPL (mm)	CPL (mm)	45º Meas. (mm)	Weld Length (mm)
1	11.7	11.1	10.8	76.3	12.9	12.0	10.3	76.3
2	10.7	11.4	11.3	76.3	12.2	12.9	10.2	76.3
3	11.2	11.9	10.6	76.3	10.7	13.1	9.5	76.3
4	10.4	12.2	10.8		10.3	12.7	10.3	
5	12.8	12.6	11.0		10.4	12.3	10.2	
6	12.8	11.3	11.1		10.0	12.6	9.8	
7	12.3	12.1	10.8		10.5	12.1	10.8	
8	12.8	12.2	10.6		11.5	12.2	11.0	
Mean	11.8	11.9	10.9	76.3	11.1	12.5	10.3	76.3
Gauge Length (mm)	LVDT1 = 14.8				LVDT3 = 15.9			
	LVDT2 = 14.2				LVDT4 = 14.2			

APPENDIX C

SPECIMEN RESPONSE CURVES (ROOM TEMPERATURE TESTS)

APPENDIX C

SPECIMEN RESPONSE CURVES (ROOM TEMPERATURE TESTS)

C.1 Response Curves Measured by LVDTs

The response curves from specimens tested at room temperature are presented in this appendix and those for specimens tested at -50ºC are presented in Appendix D. The response curves measured by LVDTs are presented in Figures C1 to C6 in the format illustrated generically in Figure C0**,** explained as follows:

1. The vertical axis presents the value of **P/A_{throat}**, which is defined in Chapter 3.
2. The horizontal axis presents the weld strain expressed in microstrain and calculated as **$\Delta/d^* x10^6$**. The definition of **Δ/d^*** is also presented in Chapter 3.
3. Stress versus strain curves are presented for each of the four LVDTs used to monitor the fillet welds.
4. The inserted illustration shows the location and number of LVDTs used in the tests.

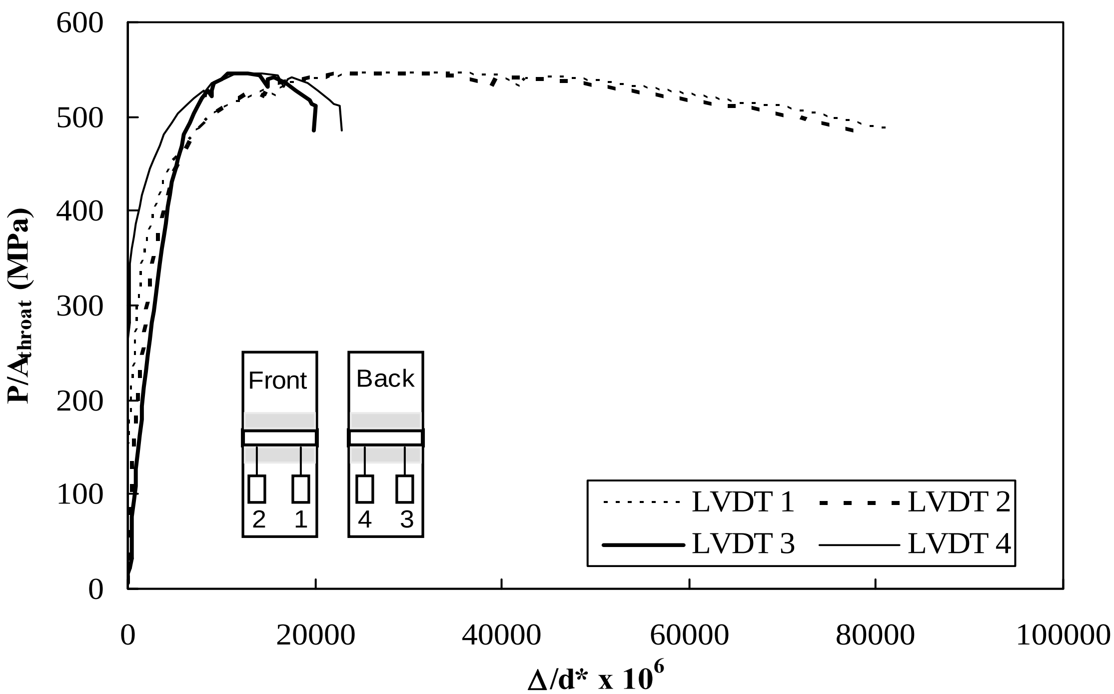


Figure C0 – Sample Response Curve

C.2 Response Curves Measured by Strain Gauges

Four strain gauges were applied to each of the six specimens tested at room temperature. The strain gauge locations are shown in Figure C7, which is a duplicate of Figure 3.5. The response curves measured by strain gauges are presented in Figures C8 to C13. In these figures, the applied load is plotted on the vertical axis and the strains recorded by the strain gauges are plotted on the horizontal axis.

Based on an assumed yield strength of the plates of 350 MPa (no material tests were carried out on the base metal) and an elastic modulus of 200 000 MPa, the yield strain of the plates was estimated to be ε_y =1750 microstrain. In Figures C14 to C19, the ratio P/P_u *vs*. the ratio $\varepsilon/\varepsilon_y$ is plotted for the six specimens to show the relationship between the load level and the strain level in the main plates.

Since the strains measured by strain gauges were only affected by the applied tension force and the eccentricity of this force, the average tensile strains were calculated as the average of strain gauges 1 and 4 and the average of strain gauges 2 and 3 (see Figure C7). The average tensile strain, ε_t , is caused by the tensile load. Half of the difference between gauges 1 and 4 and gauges 2 and 3 was treated as the bending strain, ε_b , caused by the eccentricity of the tensile load about the axis parallel to the longitudinal axis of the welds. Figures C20 to C25 present plots of P/P_u *vs*. the ratio $\varepsilon_b/\varepsilon_t$ to show the bending effect caused by main plate misalignment.

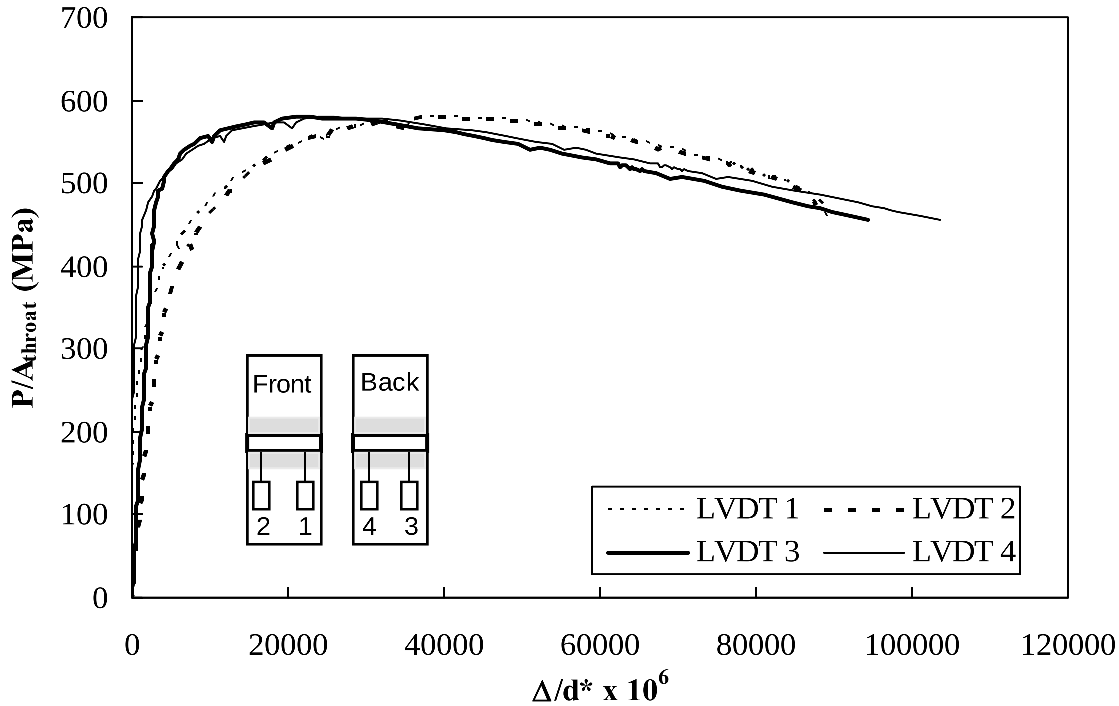


Figure C1 – Specimen CNY–6 Response Curve

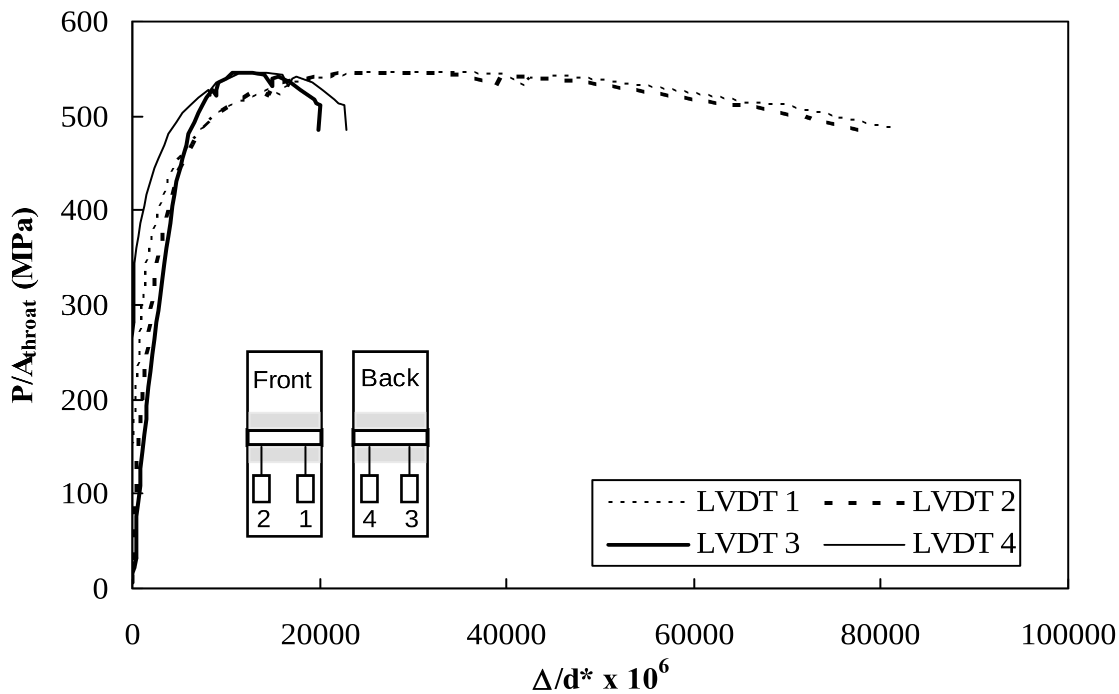


Figure C2 – Specimen CNY–7 Response Curve

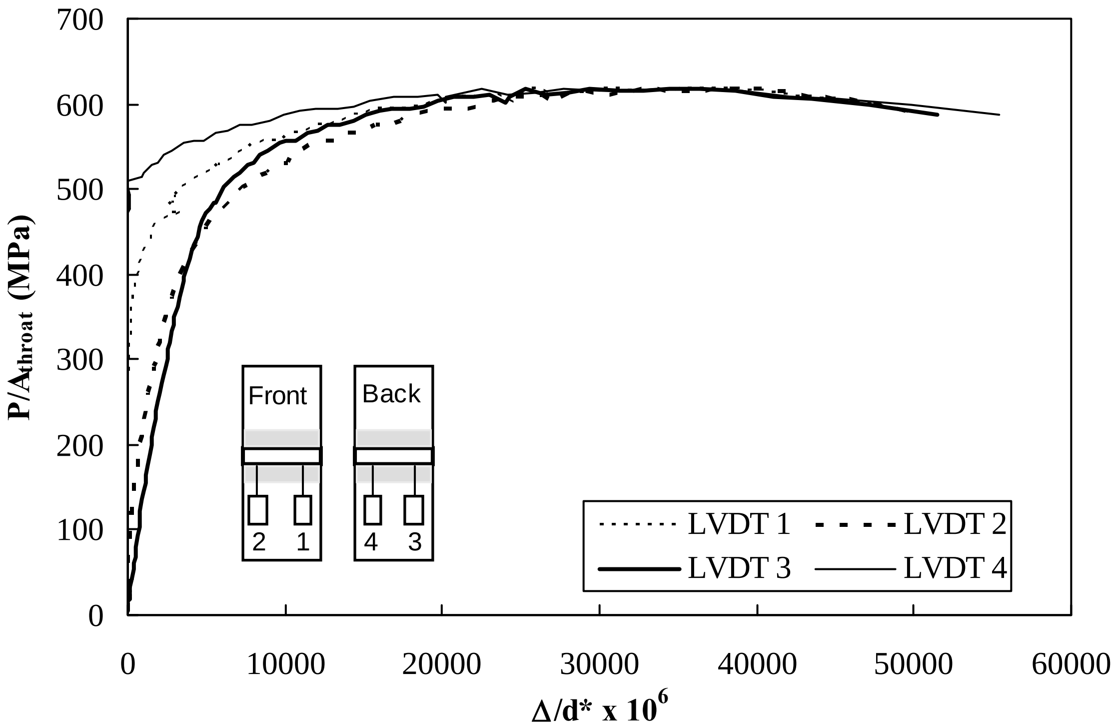


Figure C3 – Specimen CNY–8 Response Curve

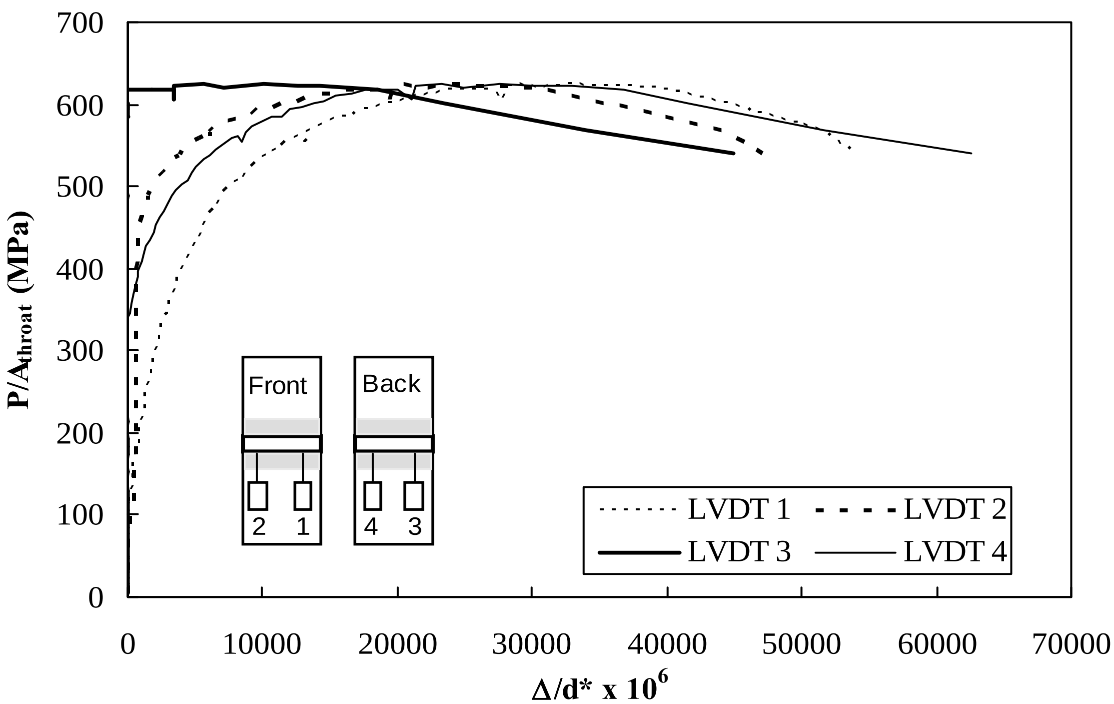


Figure C4 – Specimen CNY–10 Response Curve

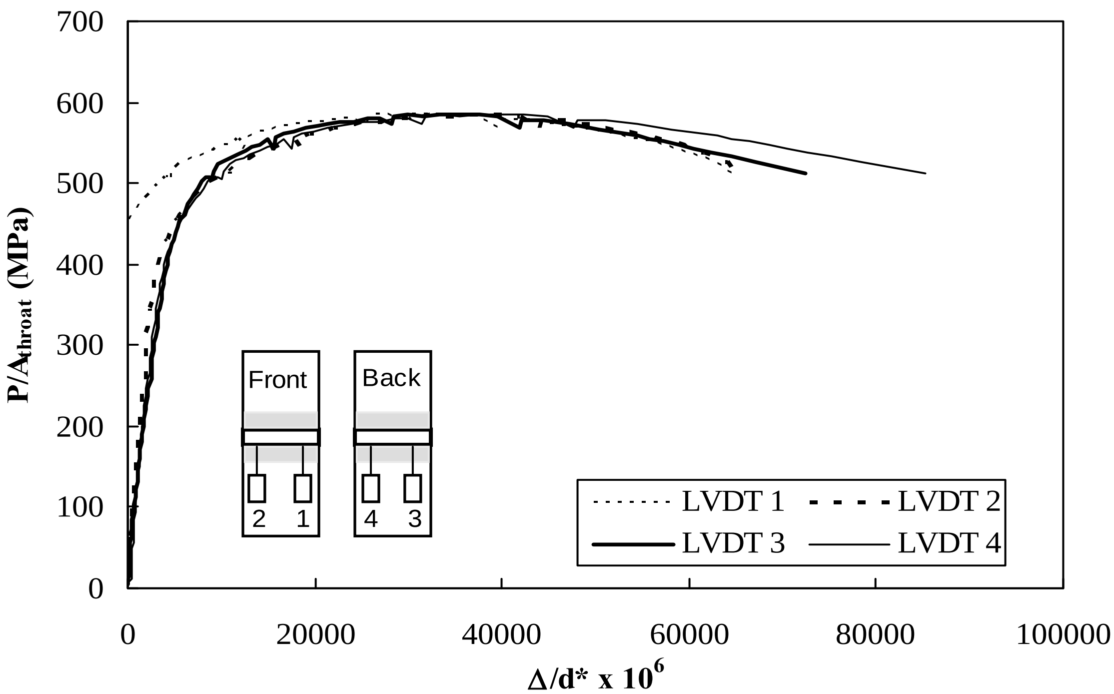


Figure C5 – Specimen CNY–11 Response Curve

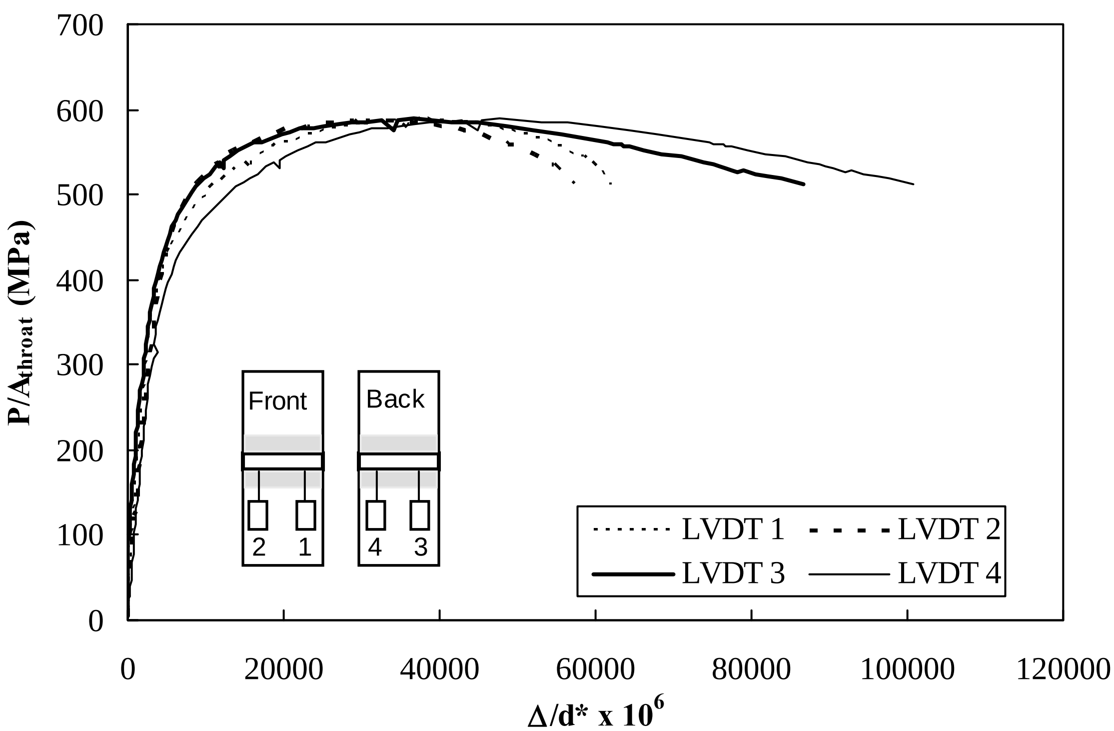


Figure C6 – Specimen CNY–12 Response Curve

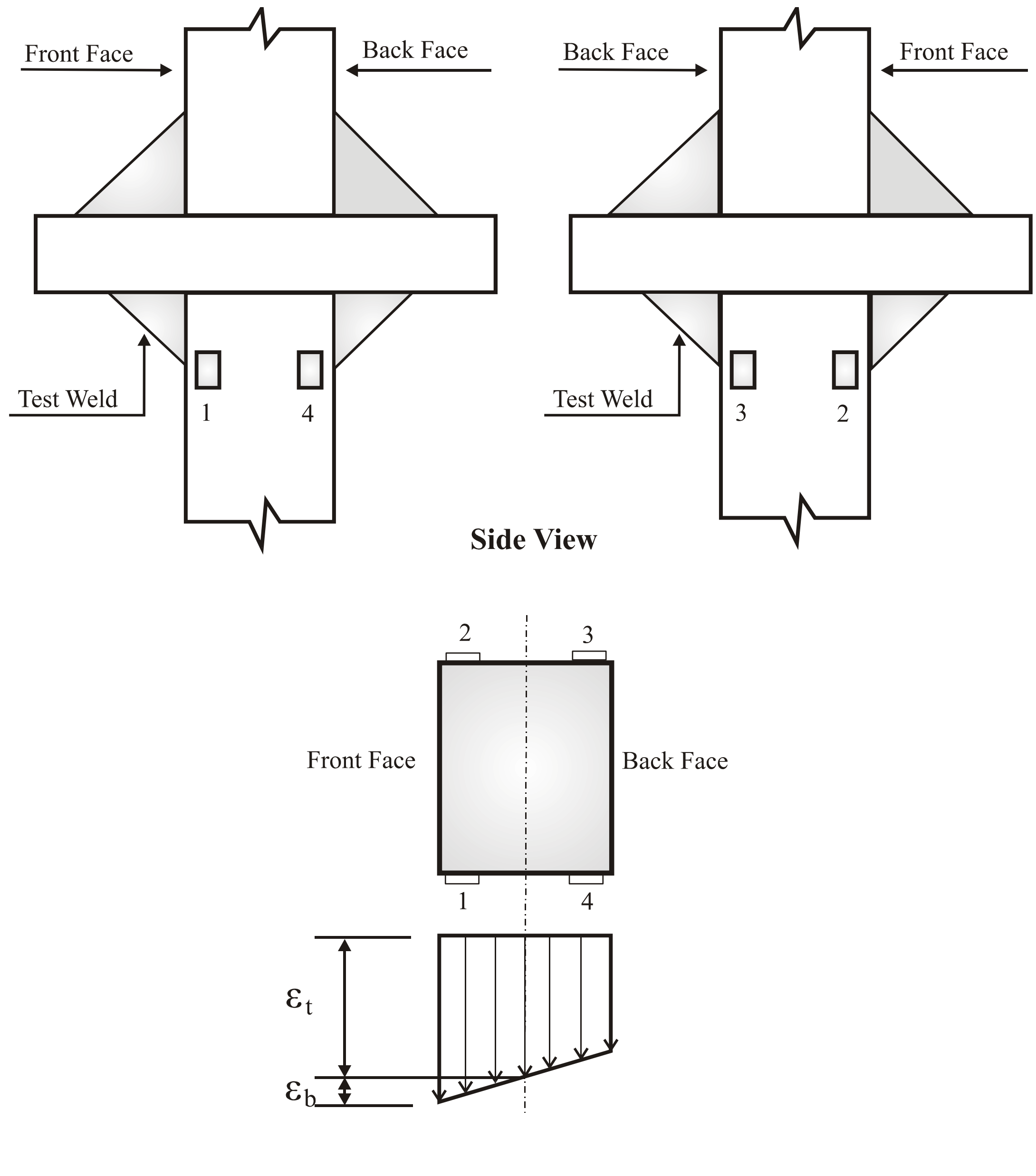


Figure C7 – Strain Gauges Arrangement

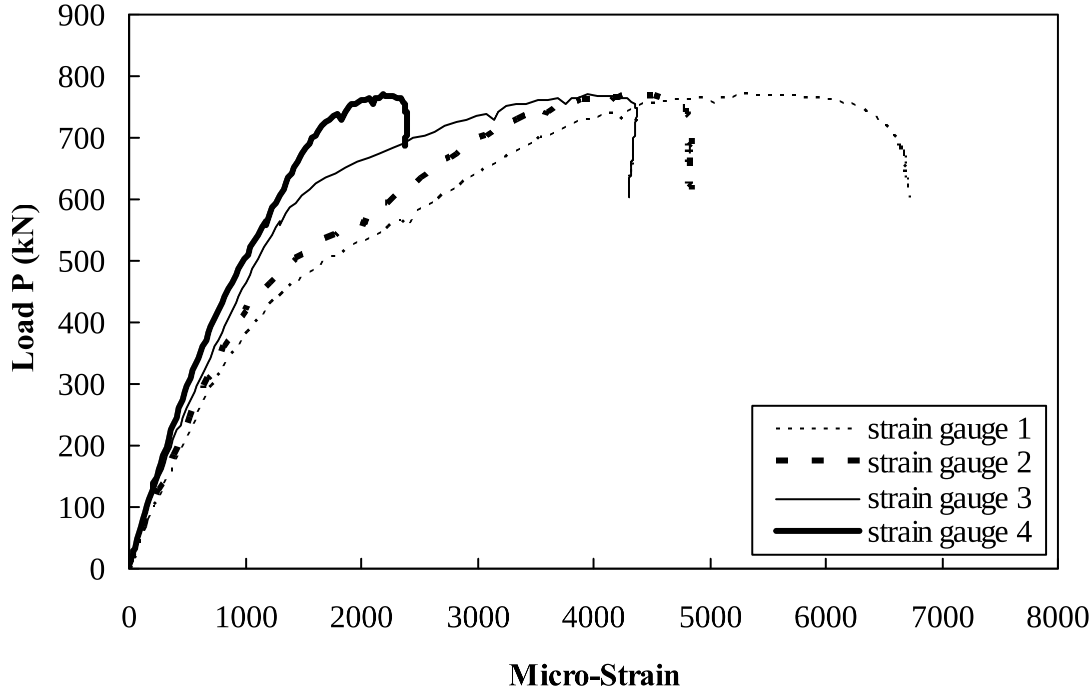


Figure C8 – Specimen CNY–6 Strain Gauge Measurement

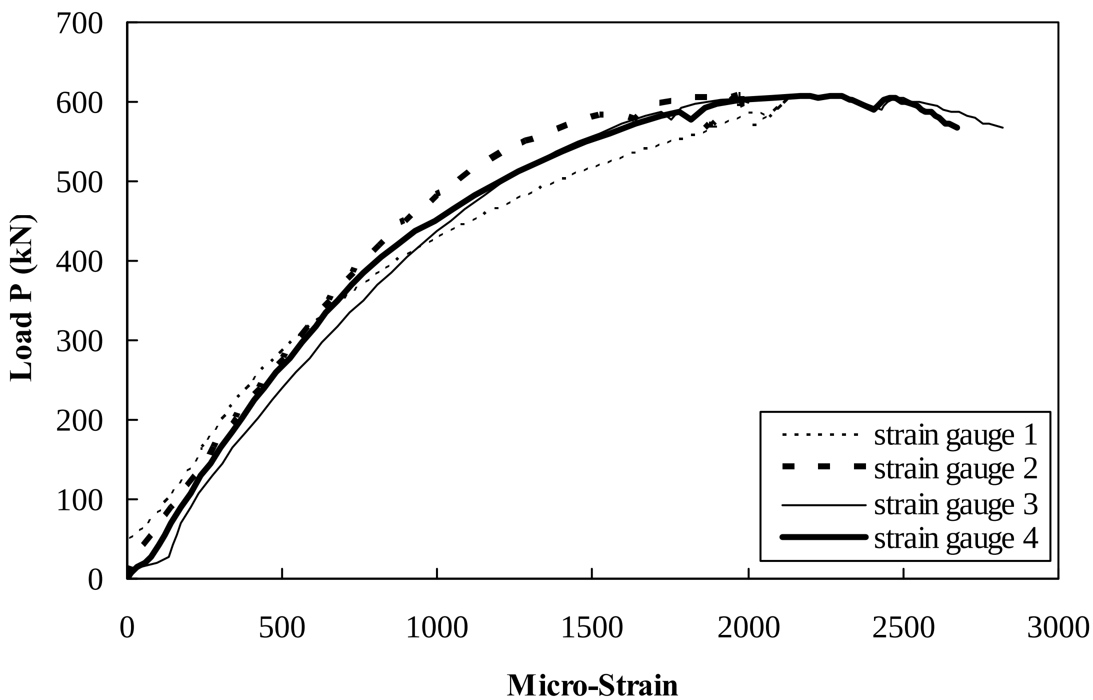


Figure C9 – Specimen CNY–7 Strain Gauge Measurement

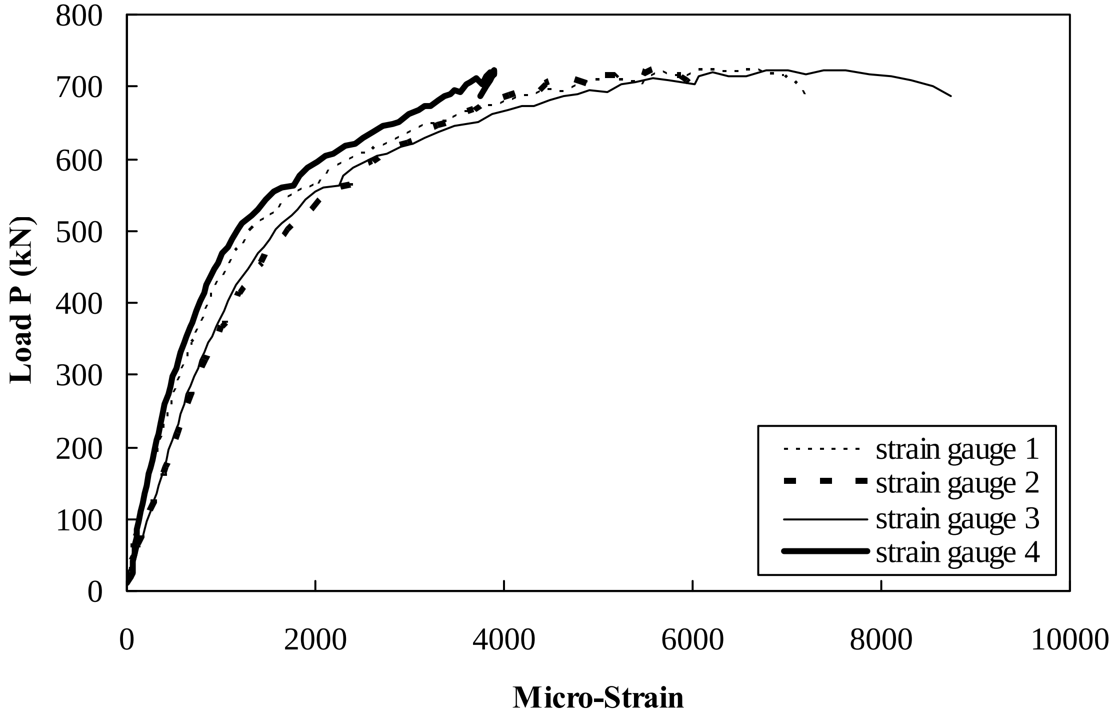


Figure C10 – Specimen CNY–8 Strain Gauge Measurement

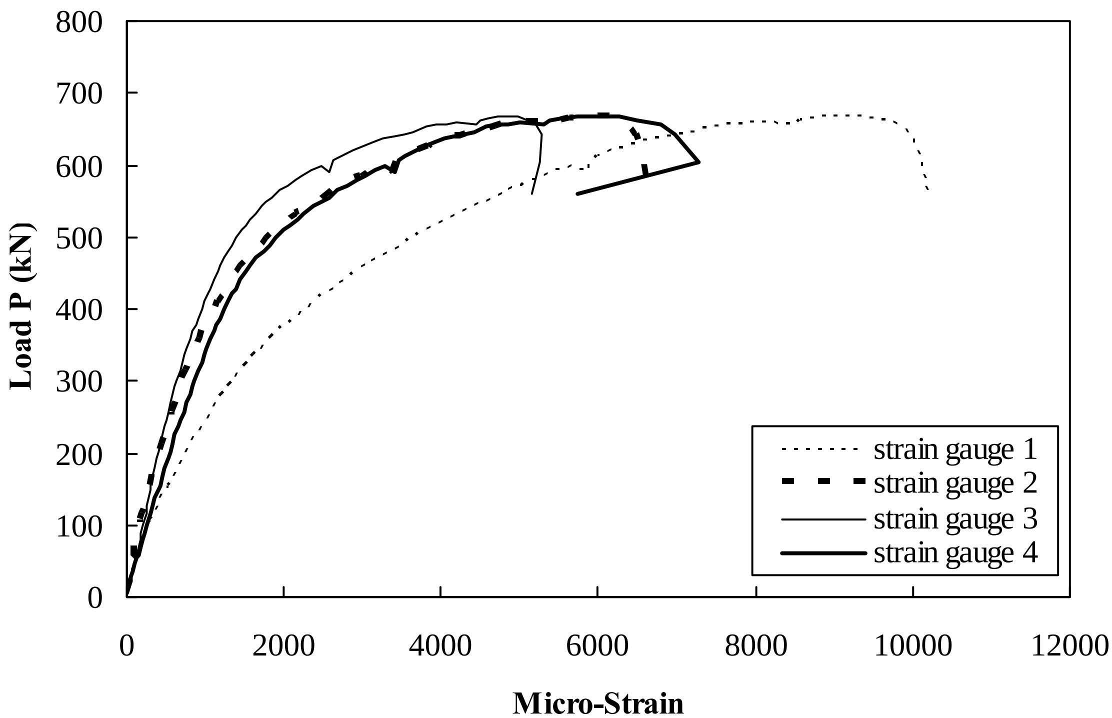


Figure C11 – Specimen CNY–10 Strain Gauge Measurement

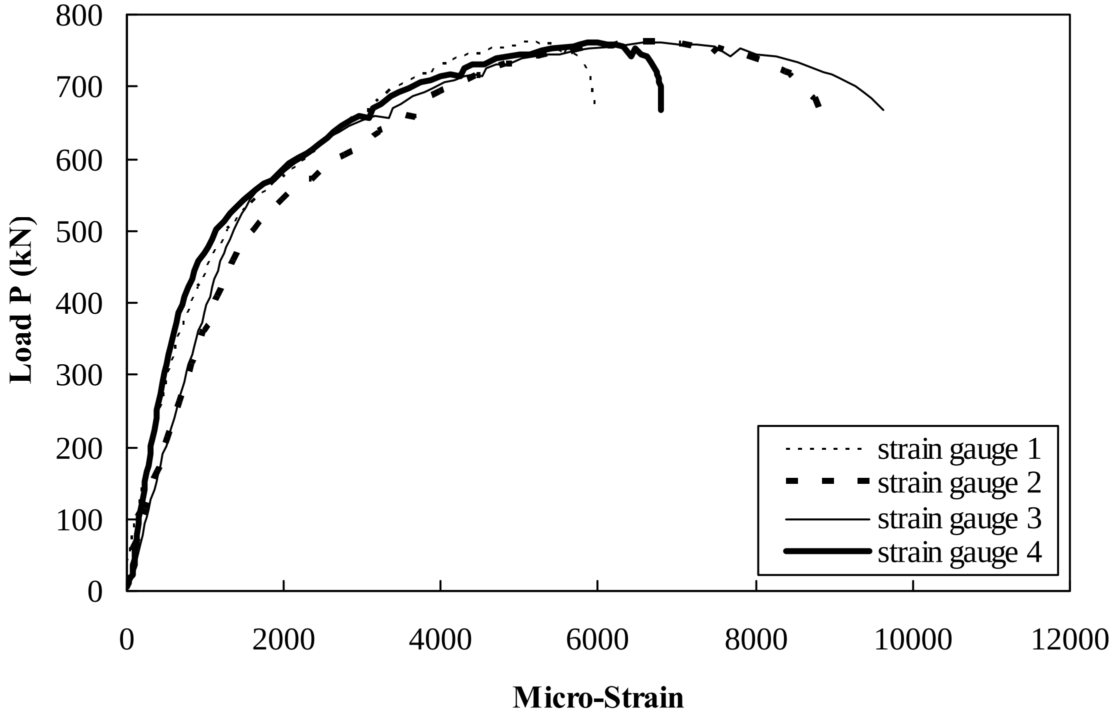


Figure C12 – Specimen CNY–11 Strain Gauge Measurement

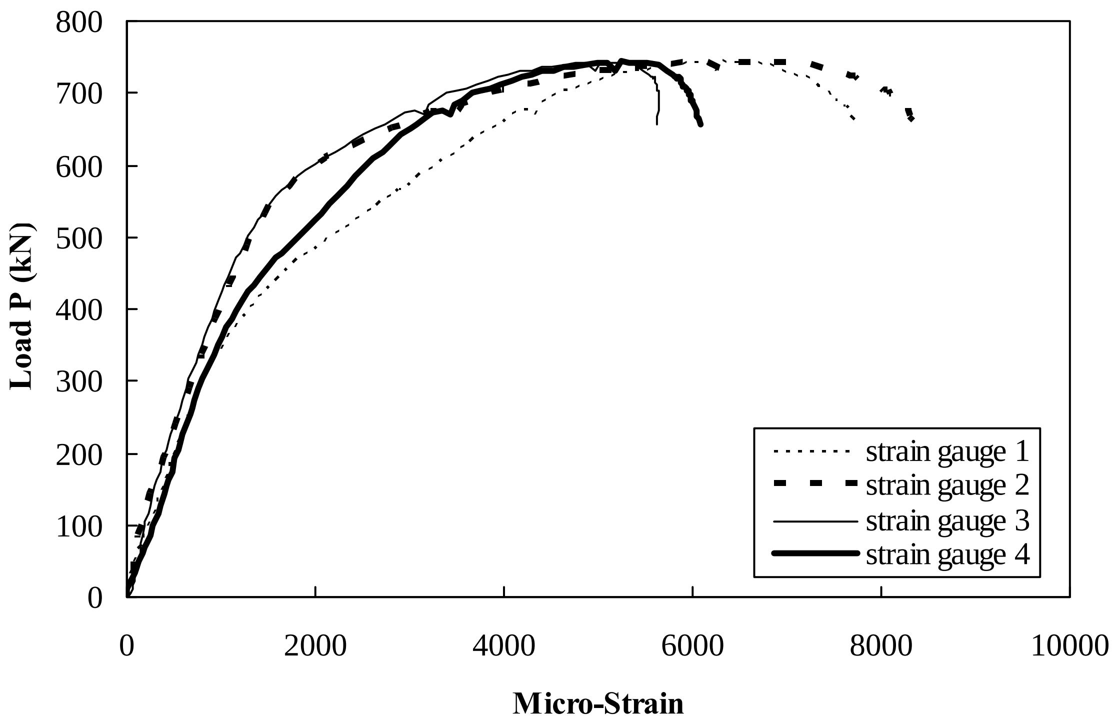


Figure C13 – Specimen CNY–12 Strain Gauge Measurement

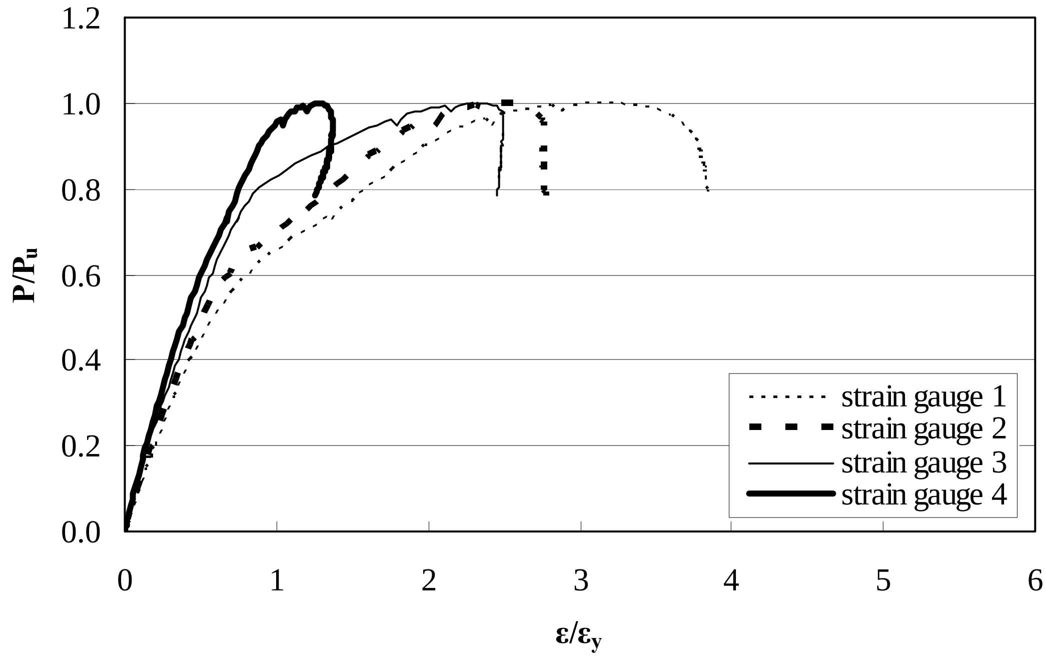


Figure C14 – P/P_u *vs.* $\varepsilon/\varepsilon_y$ of Specimen CNY–6

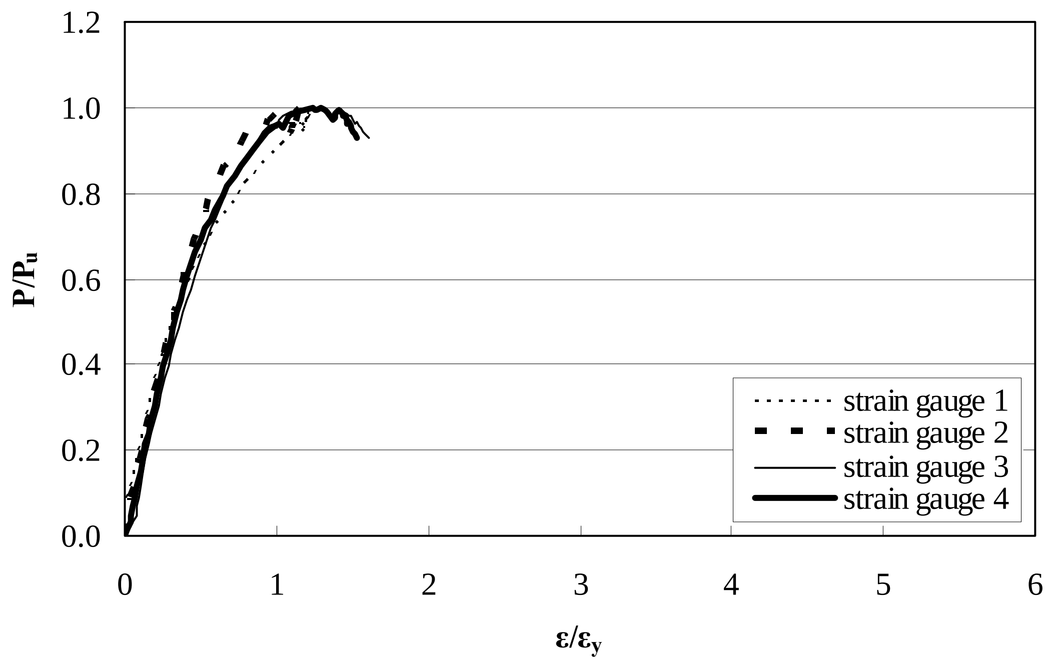


Figure C15 – P/P_u *vs.* $\varepsilon/\varepsilon_y$ of Specimen CNY–7

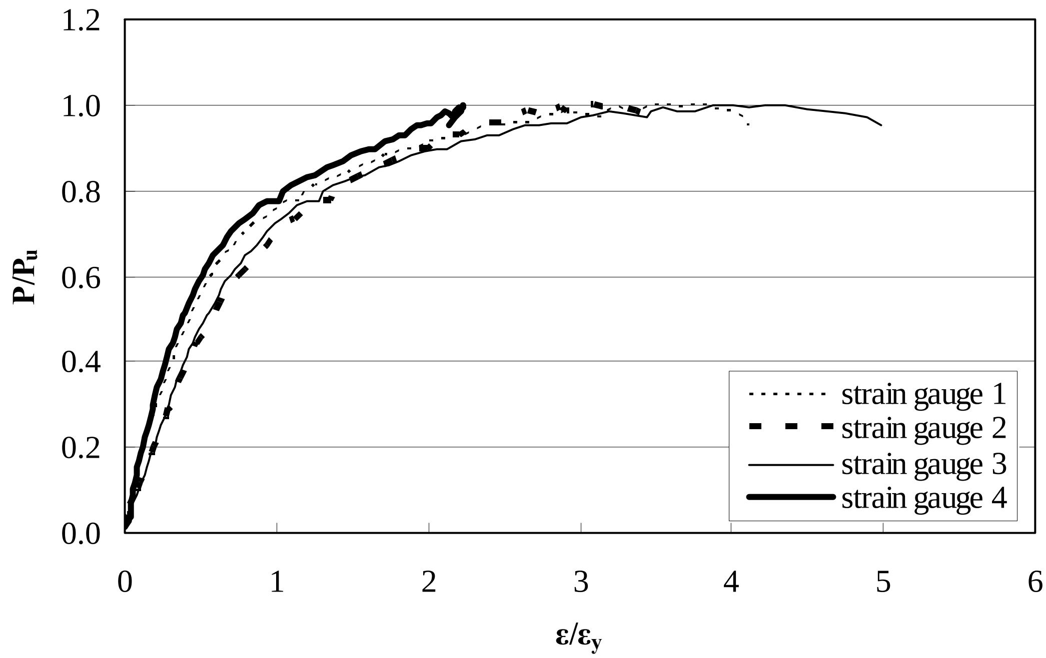


Figure C16 – P/P_u *vs.* $\varepsilon/\varepsilon_y$ of Specimen CNY–8

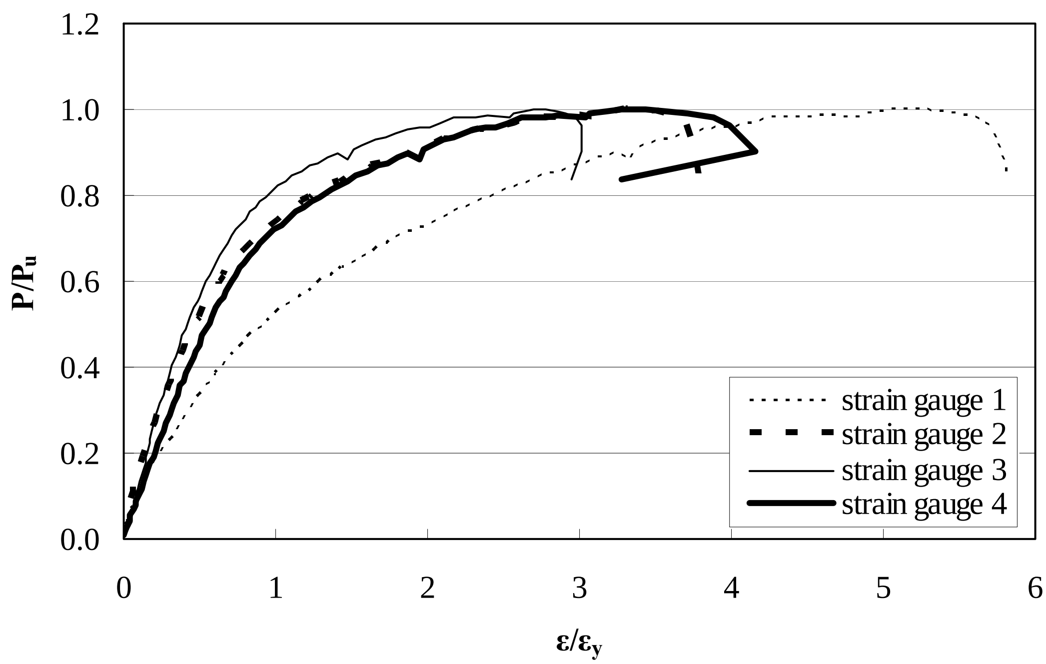


Figure C17 – P/P_u *vs.* $\varepsilon/\varepsilon_y$ of Specimen CNY–10

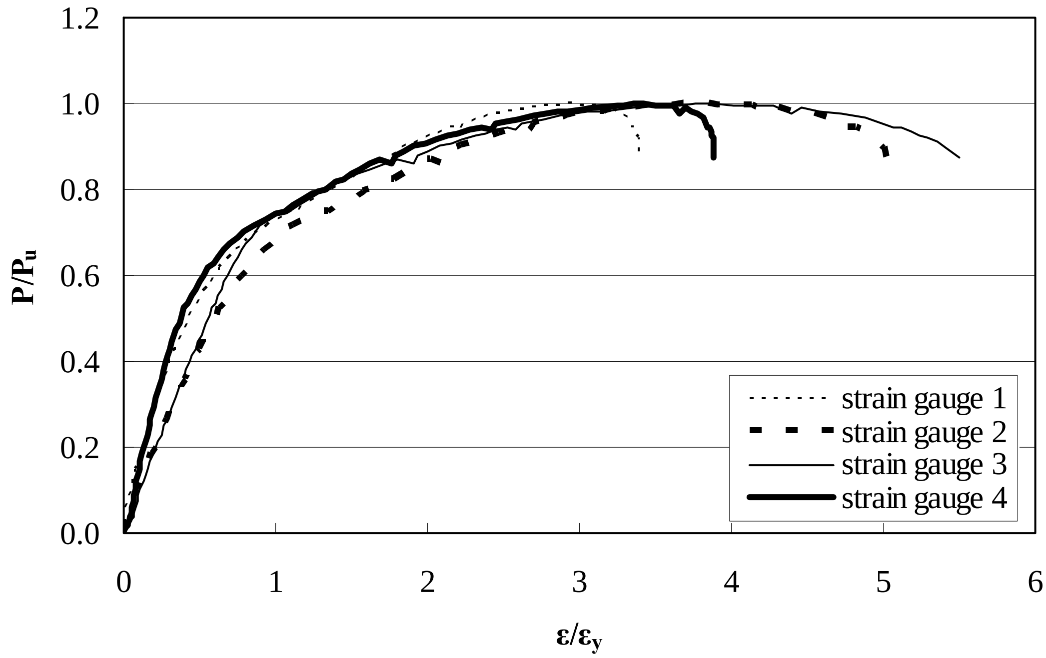


Figure C18 – P/P_u *vs.* $\varepsilon/\varepsilon_y$ of Specimen CNY–11

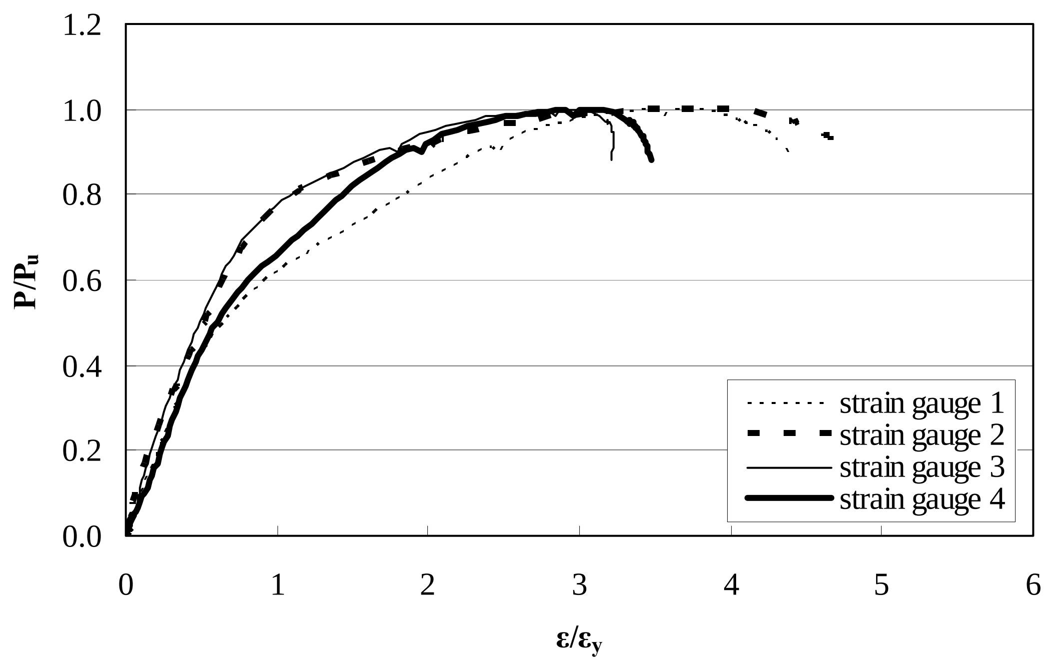


Figure C19 – P/P_u *vs.* $\varepsilon/\varepsilon_y$ of Specimen CNY–12

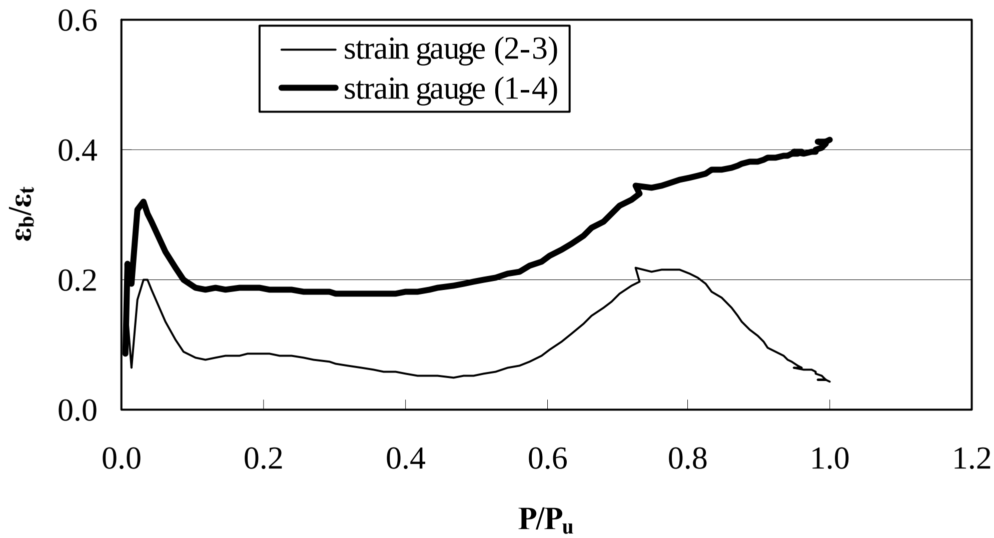


Figure C20 – $\varepsilon_b/\varepsilon_t$ *vs.* P/P_u of Specimen CNY–6

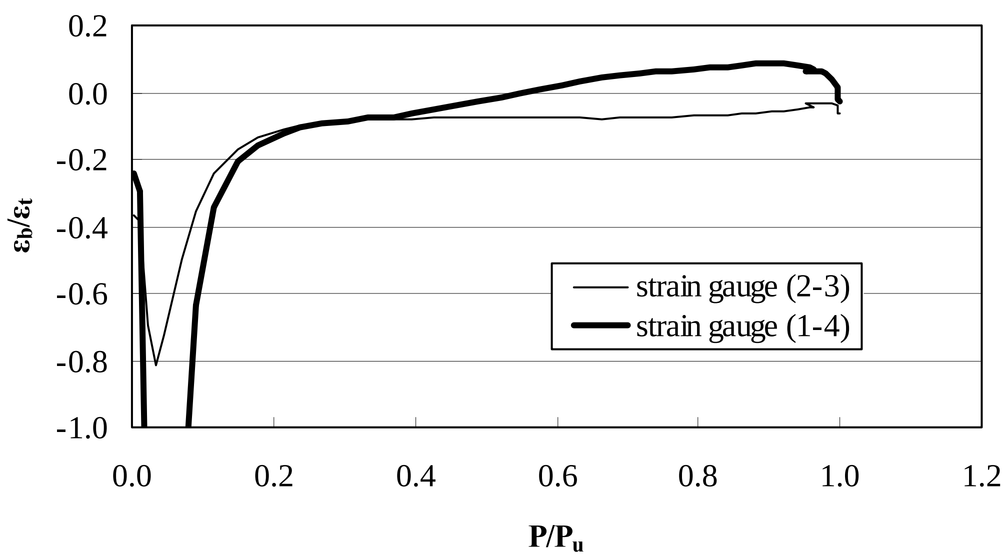


Figure C21 – $\varepsilon_b/\varepsilon_t$ *vs.* P/P_u of Specimen CNY–7

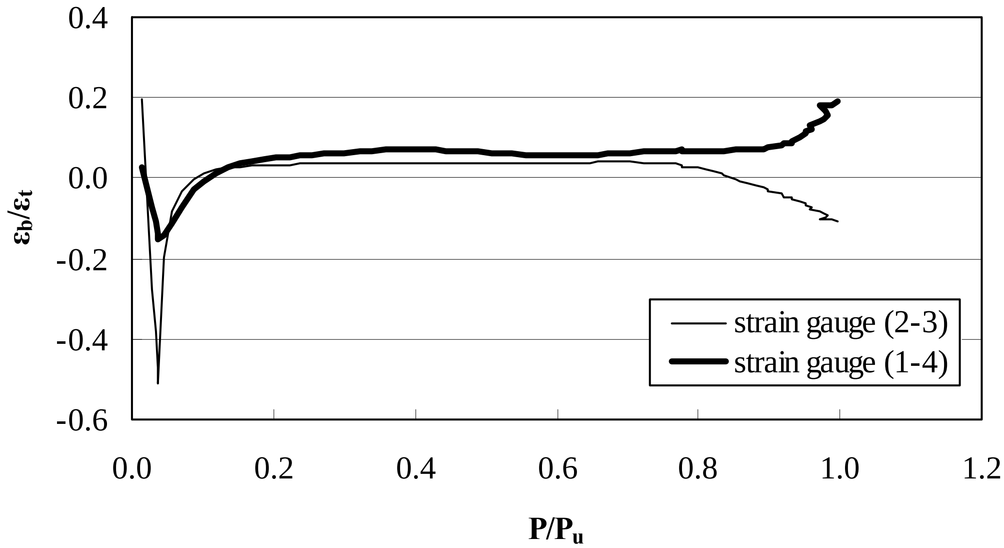


Figure C22 – $\varepsilon_b/\varepsilon_t$ *vs.* P/P_u of Specimen CNY–8

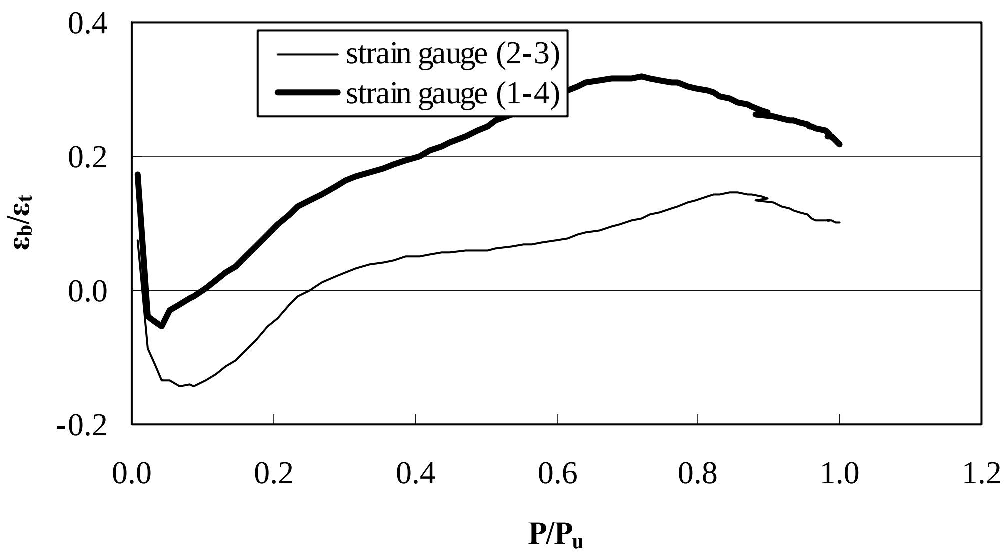


Figure C23 – $\varepsilon_b/\varepsilon_t$ *vs.* P/P_u of Specimen CNY–10

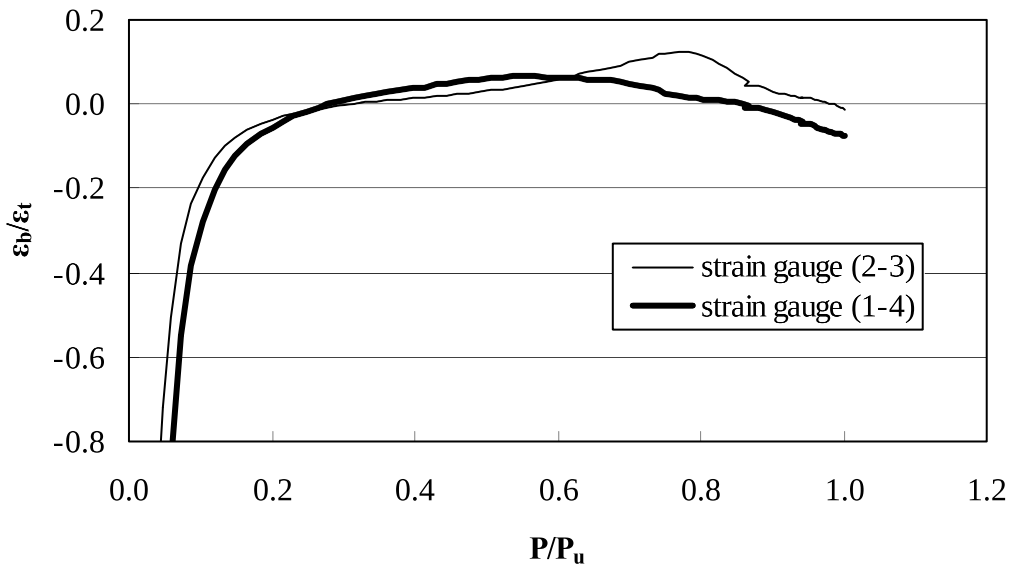


Figure C24 – $\varepsilon_b/\varepsilon_t$ *vs.* P/P_u of Specimen CNY–11

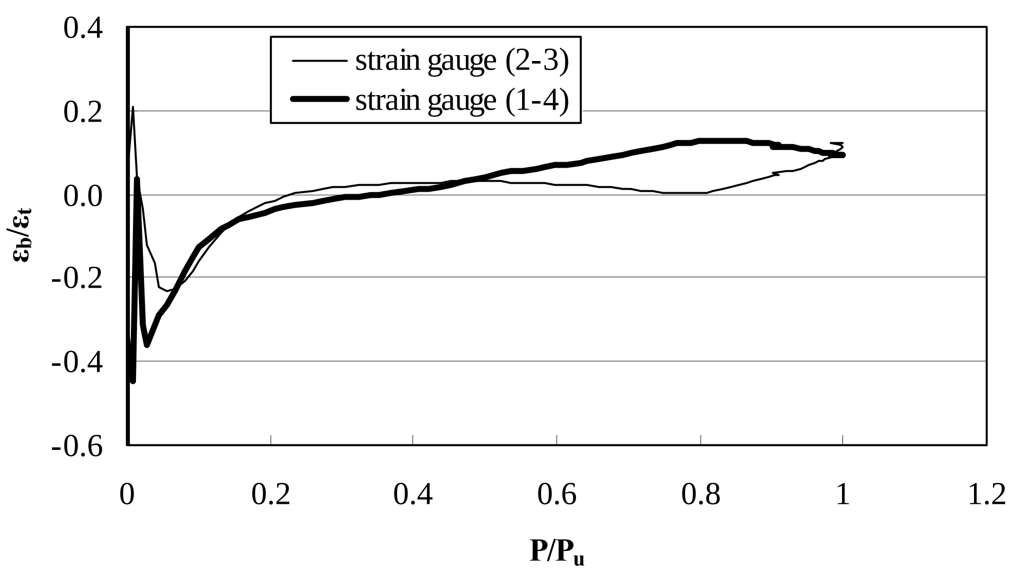


Figure C25 – $\varepsilon_b/\varepsilon_t$ *vs.* P/P_u of Specimen CNY–12

APPENDIX D

RESULTS OF WELD TESTS AT LOW TEMPERATURE

APPENDIX D

RESULTS OF WELD TESTS AT LOW TEMPERATURE

D.1 Introduction

In order to investigate the effect of low temperature on the strength and ductility of cruciform connections, six specimens were tested at -50 °C. The description of those specimens was presented in Chapter 3 and Table 3.1. The specimens tested at low temperature were designed and fabricated in the same way as the specimens tested at room temperature. Unfortunately, all six cruciform specimens failed in main plates. Nevertheless, the test results still provide valuable information about the behaviour of cruciform joints at low temperature.

Low temperature is known to affect the ductility of fillet welds in double lapped fillet weld connections. Ng *et al.* (2002) tested three transverse fillet weld joints at -50 ºC made with filler metal without a toughness requirement. The results showed that the ductility of transverse fillet welds was significantly lowered when the welds were tested at low temperature. These three connections had a mean ductility that was only 58% of that of the specimens tested at room temperature. Callele *et al.* (2005) tested three specimens with combined transverse and longitudinal welds at -50 ºC. All three specimens failed in the lap plates. Fracture of the lap plates resulted from a combination of a stress concentration, low toughness of the lap plates at low temperature, and shear lag.

From a fracture mechanics point of view, fracture of welds in cruciform joints can be affected by the root notch since the applied load is perpendicular to the root notch. Since fracture toughness decreases with temperature, the behaviour of cruciform joints at low temperature needs to be investigated.

D.2 Testing Procedure

The test set-up and instrumentation were the same as for other specimens except that a customized environmental chamber, described in detail by Callele *et al.* (2005), was used to control the test temperature. The specimens and instruments were enclosed in the chamber, in which the temperature was maintained -50 ± 5 ºC.

The specimens were loaded quasi-statically under displacement control. The load and displacements were recorded in real time during the tests. Static load values were acquired by maintaining a constant deformation for about five minutes and the upper load is the extreme large value and the lower load is the extreme small value within the five minute maintenance of the deformation. The static drop is the difference between the upper and lower load. The ultimate load is the extreme large value of load during the entire loading process. The ultimate load may occur within the last five minute maintenance of deformation or after. The upper and lower loads are reported in Table D1.

D.3 Test Results and Discussion

All six test specimens failed in the main plates. The measured strengths of the specimens are presented in Table D1. Although fracture took place in the plates, the tabulated strength of the test specimens was calculated as P_{ST} / A_{throat}, which is identical to the procedure used in Chapter 3. The measured load versus deformation response curves are shown in Figures D1 to D6. The format of these figures is explained in Appendix C. Although the test specimens failed unexpectedly in the plates rather than in the welds, the load versus deformation curves indicates that the welds might be deforming plastically before rupture of the plates. This indicates that the weld capacity could be reached before the plates fractured. It is inconclusive because the deformation measured by LVDTs included components from both fillet welds and steel plates.

A comparison of the test specimens' strengths recorded at low temperature with those of tests at room temperature is presented in Table D2. The strength of specimens tested at low temperature is approximately the same as that of specimens tested at room temperature.

The root openings of cruciform specimens cause a significant shear lag effect and stress concentration, so the stress in the plates around the fillet weld toe was much higher than the average stress in the plates. The strain gauge measurements for specimens tested at room temperature demonstrated this phenomenon. The low toughness of the plates at low temperature induced the fracture. For further tests at low temperature, the plates should have sufficient toughness.

Table D1 – Summary of Capacity of Specimens Tested at Low Temperature

Specimen	Electrode	Ultimate Load. P_u (kN)	Static Drop (kN)			$P_{ST} = P_u - \Delta P$ (kN)	Throat Area A_{throat} (mm^2)	P_{ST} / A_{throat} (MPa)	Average P_{ST} / A_{throat} (MPa)	Initiation of Plate Failure
			upper	lower	ΔP					
CNY–1	E70T–7	711	706	694	13	698	1131	617	587	Both Faces
CNY–5		636	624	597	27	609	1124	542		Back Face
CNY–9		725	652	648	4	721	1199	601		Back Face
CNY–2	E71T8–K6	770	697	691	6	765	1280	597	583	Back Face
CNY–3		737	725	718	7	765	1310	584		Back Face
CNY–4		800	778	763	15	765	1344	569		Both Faces

Table D2 – Comparison of Test Results at Room and Low Temperature

Specimen	Electrode	Test Temp.	Ultimate Load P_u (kN)	P_{ST} / A_{throat} (MPa)	Average P_{ST} / A_{throat} (MPa)	Strength Ratio -50ºC/20ºC
CNY–1	E70T–7	-50 ºC	711	617	587	0.999
CNY–5			636	542		
CNY–9			725	601		
CNY–7		20 ºC	606	539	588	
CNY–8			723	609		
CNY–10			667	615		
CNY–2	E71T8–K6	-50 ºC	770	597	583	1.013
CNY–3			737	584		
CNY–4			800	569		
CNY–6		20 ºC	770	572	576	
CNY–11			760	577		
CNY–12			744	578		

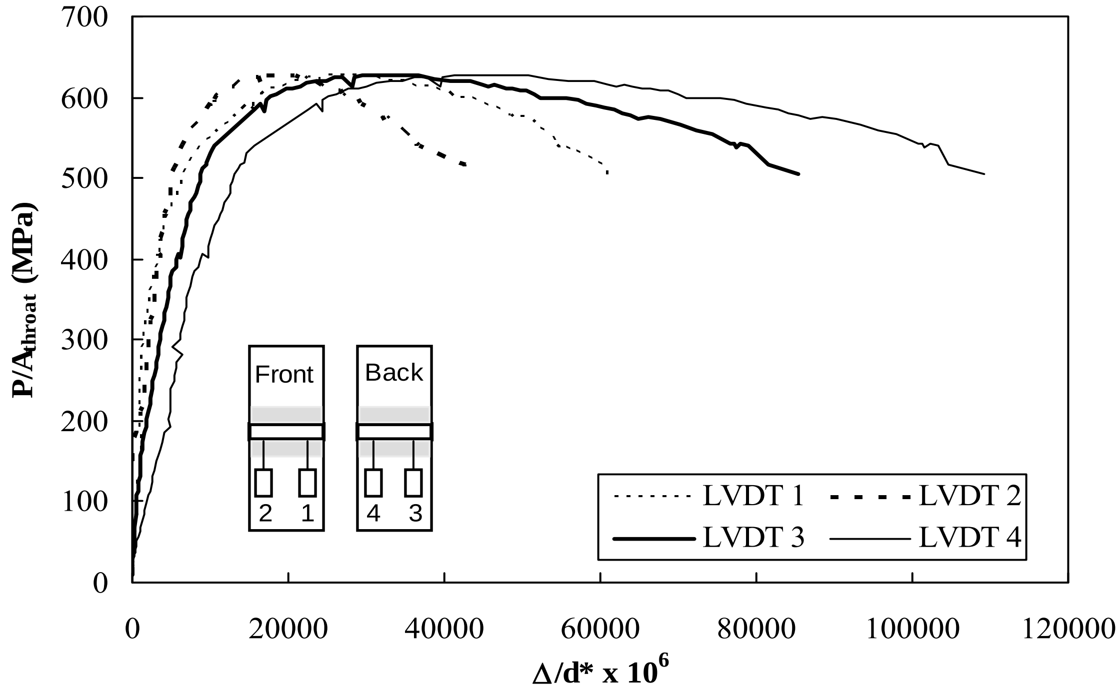


Figure D1 – Specimen CNY–1 Response Curve

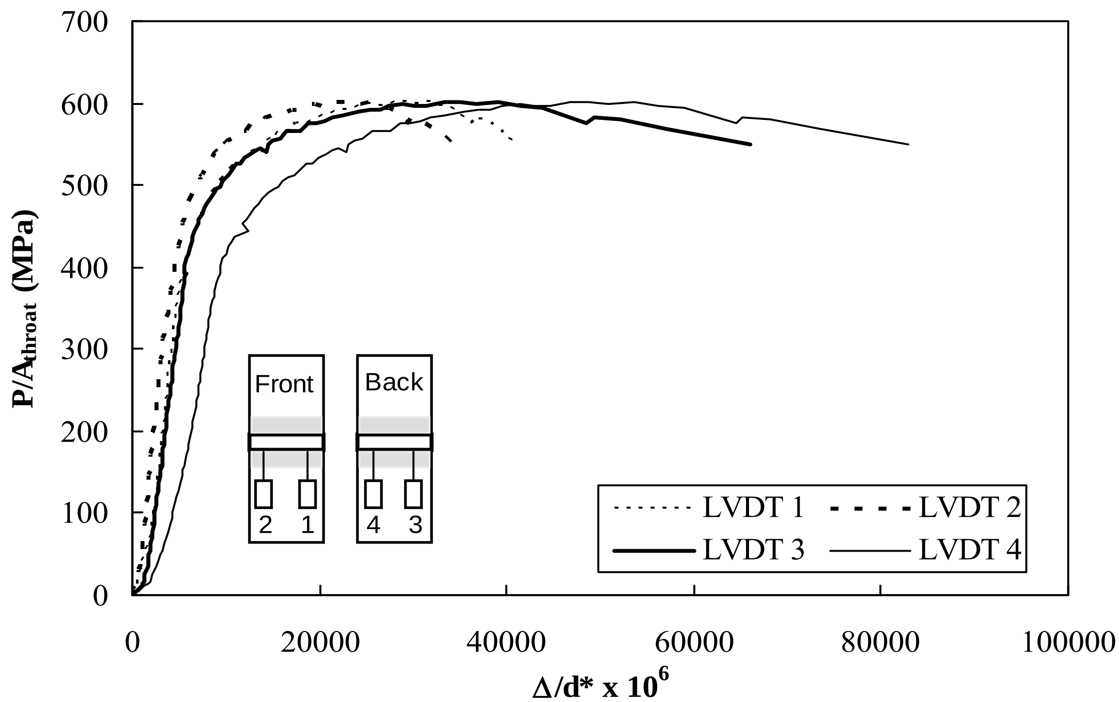


Figure D2 – Specimen CNY–2 Response Curve

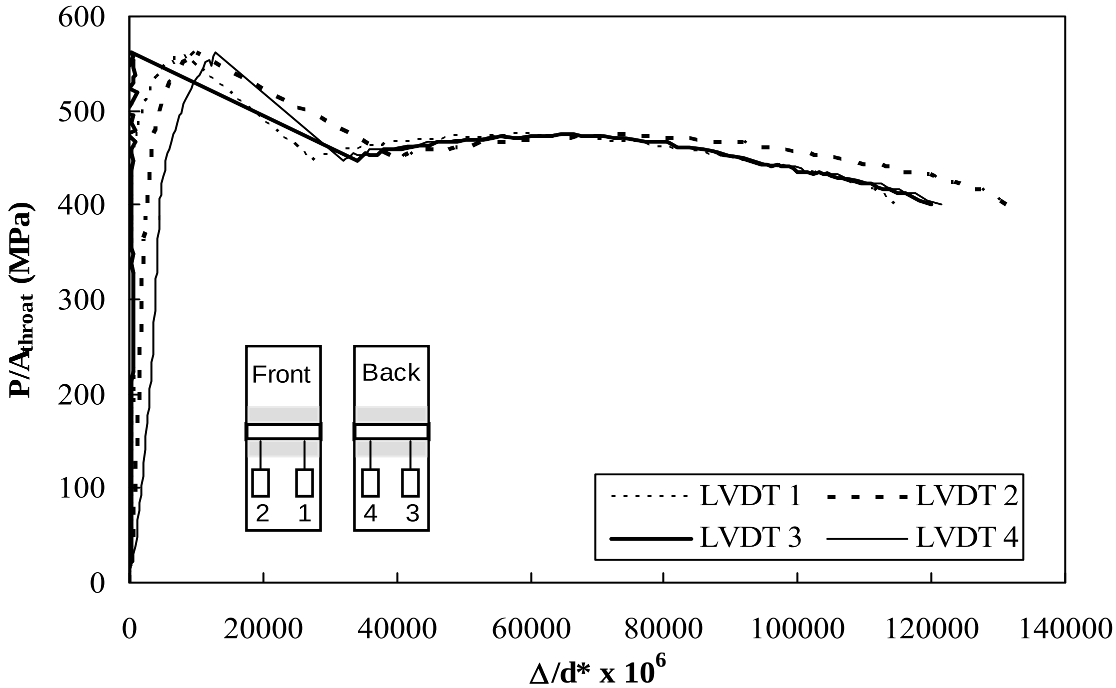


Figure D3 – Specimen CNY–3 Response Curve

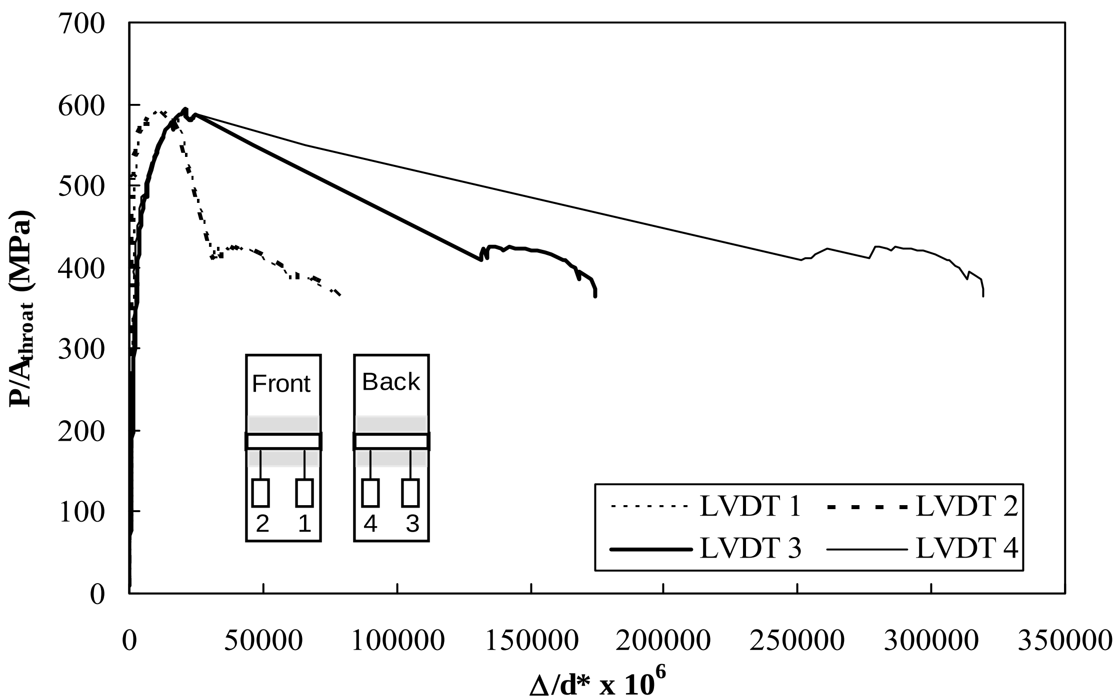


Figure D4 – Specimen CNY–4 Response Curve

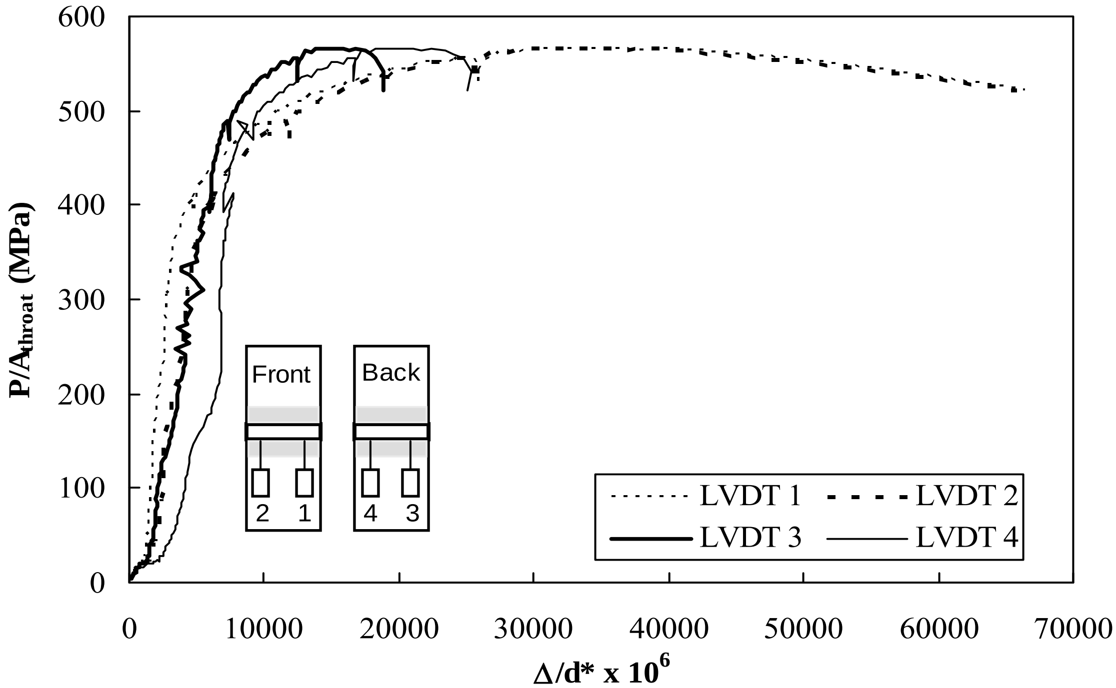


Figure D5 – Specimen CNY–5 Response Curve

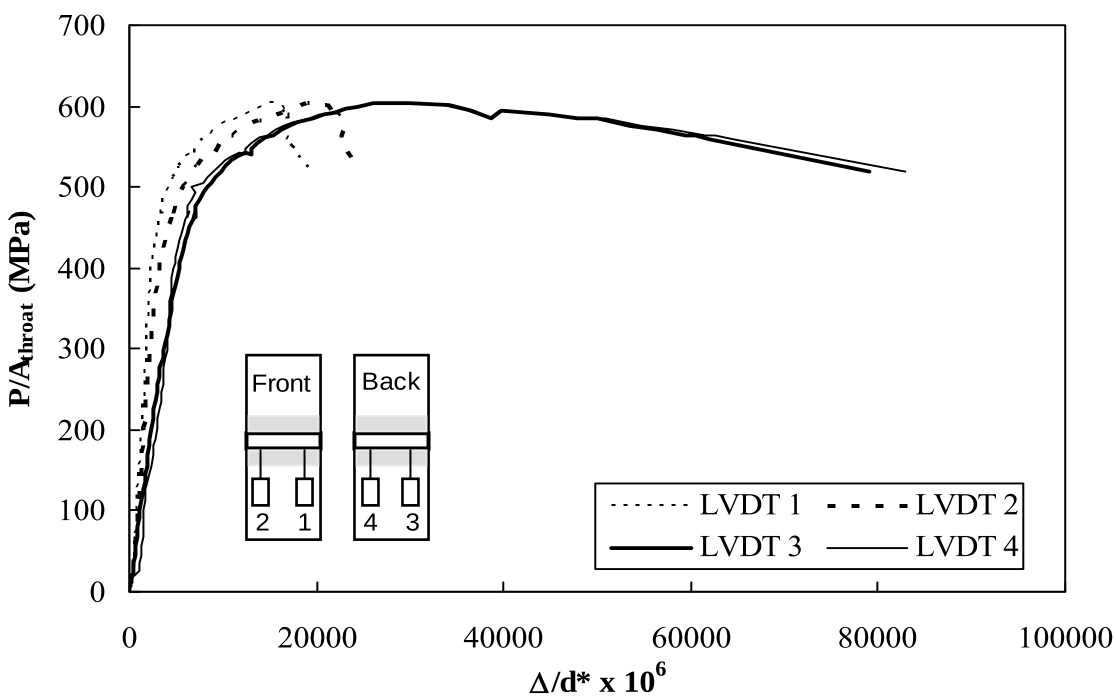


Figure D6 – Specimen CNY–9 Response Curve

APPENDIX E

RESULTS OF OTHER TEST PROGRAMS

APPENDIX E

RESULTS OF OTHER TEST PROGRAMS

E.1 Ligtenberg (1968)

E.1.1 Introduction to the Test Series

Ligtenberg (1968) reported various test series conducted internationally to investigate the strength of fillet welded connections. A total of ten countries participated in this study and each country conducted independent tests under the direction of IIW (International Institute of Welding) documents. The specimens consisted of lapped joints loaded in tension. The general configuration of the specimens is depicted in Figure E1, which illustrates a joint with multiple orientation fillet welds (MOFW). Connections with single orientation fillet welds (SOFW) were also tested. Two types of steel were used in the test program. Approximately 76% of the specimens were fabricated with plates of a quality comparable to St.37 (DIN 17100) (minimum ultimate tensile strength 360 MPa), A7-58 (ASTM A7-58) or similar steel grades from the participating countries. Approximately 24% of the specimens were fabricated with plates of a quality comparable to St.52 (DIN 17100) (minimum ultimate tensile strength 510 MPa) or similar steel. Three types of electrodes (*i.e.* acid coated, basic and rutile), which were locally manufactured and commonly used in the participating country where the tests were performed, were selected. The measured (or reported by manufacturers) weld metal tensile strength ranged from about 450 MPa to 580 MPa and the weld throat size ranged from 3 mm to 10 mm.

E.1.2 Test Parameters

Four factors were considered in the design of the test matrix: the ratio of transverse weld length, L_1, to the longitudinal weld length, L_2 (see Figure E1), the ratio of the transverse weld throat dimension, a_1, to the longitudinal weld throat dimension, a_2, the type of electrodes and the predicted stress level in the plates at rupture of the connection, which depends on the plate thickness and the strength of the fillet weld. The variables were chosen as listed below:

the ratio of the weld length L_1 to L_2:

I: L_1=45 mm, L_2=80 mm ($L_1 / L_2 = 0.56$)

II: L_1=55 mm, L_2=55 mm ($L_1 / L_2 = 1.00$)

III: $L_1 = 80$ mm, $L_2 = 40$ mm ($L_1 / L_2 = 2.00$)

the ratio of throat dimension a_1 to a_2:

a: $a_1 = 0.5a_2$

b: $a_1 = a_2$

c: $a_1 = 2a_2$

the predicted stress level in the plates at rupture:

s: small (approximately 150 MPa)

m: medium (approximately 200 MPa)

h: high (approximately 250 MPa)

the type of electrodes:

A: acid coated

B: basic

R: rutile

The possible 81 combinations of 4 factors listed above are shown in Table E1.1. As indicated in this table, the designation of the general configuration of specimens consists of a roman numeral from I to III indicating the weld length ratio, followed by a three letter designation indicating the weld throat dimension ratio, the plate stress level, and the electrode type. Each of the 9 participating countries tested 9 out of 81 combinations, which were chosen in such a way that every possible combination of any 2 out of the 4 factors occurred once, with the exception that Yugoslavia tested 18 specimens, which repeated some of the specimens tested by the other 9 countries. In order to check the repeatability of the tests between countries, each country conducted tests on the test pieces [IIbmA], [IIbmB] and [IIbmR].

The connections with single orientation welds were tested to examine the force distribution between the different weld segments of a multi-orientation weld. Therefore, in addition to the above general configurations, 4 special configurations were designed, which were designated by adding a number from 1 to 4 into the middle of the basic designation (*e.g.* [xx1xx], [xx2xx], [xx3xx] and [xx4xx], where the first x represents the Roman numeral, regardless of the number of characters it contains). These 4 special configurations used the same parent material, electrode and weld throat dimension and weld length as the corresponding basic configuration [xxxx] except that:

[xx1xx] had only a transverse weld, a_1.

[xx2xx] had only two longitudinal welds, a_2.

[xx3xx] had only two longitudinal welds with throat dimension, a_3, larger than a_2.

[xx4xx] had two transverse welds and two longitudinal welds as shown in Figure E2.

A summary of nominal weld throat dimensions, weld length and plate thickness for every configuration is presented in Table E1.2.

Specimens from St.52 steel were prepared from 19 mm and 24 mm plates depending on the material availability and one matching electrode (the grade was not specified in the literature) so the designation of those specimens omitted last two letters. As for St.37 steel specimens the numeral 1, 2, or 3 designates the weld configuration in the test joints.

To get comparable test results, details for the execution of the tests were specified and followed by all participating countries. In order to minimize variability in the test results, all tests conducted within one country had to be performed in one laboratory and with the same equipment. The test specimens were welded manually by a welder of "good average skills" (Ligtenberg 1968). Before testing, the weld throat dimension was measured with a dial gauge at the 45º point of the weld face.

E.1.3 Weld Measurements, Test Result and Analysis

The weld dimensions and test results presented in Tables E1.3 through E1.16 are reproduced from Appendices I and II of Ligtenberg (1968) for different countries and steel grades. The symbols used in these tables are explained below:

$a_1,\ a_2,\ a_4$: weld throat dimension, as shown in Figures E1 and E2.

a_3: longitudinal weld throat dimension in a single orientation fillet weld specimen designated as [xx3xx].

A_1: $A_1 = \Sigma(a_1 \times L_1)$ for double lapped splice joints as shown in Figure E1 and

$A_1 = a_1 \times L_1$ for single lapped splice joints as shown in Figure E2.

A_2: $A_2 = \Sigma(a_2 \times L_2)$.

A_3: $A_3 = \Sigma(a_3 \times L_2)$.

A_4: $A_4 = a_4 \times L_1$.

$L_1,\ L_2$: weld lengths as shown in Figures E1 and E2.

P_u: maximum applied load.

σ_u: measured ultimate tensile strength of the weld metal.

The geometry factor ρ_G is taken as the ratio of the measured to nominal throat area of the fillet weld segments. A summary of the values of ρ_G for different weld sizes is presented in Table E1.17. Because the geometry factor is calculated from weld throat areas, it reflects variation of both weld throat dimension and weld length. The variation in the length of transverse weld segments, L_1, was analyzed and the results are presented in Table E1.18, in which the geometry factor ρ_L is the ratio of the measured to nominal weld length. The results show that the variation of weld length was negligible compared to the variation in throat dimension. Therefore, it is concluded that the results in Table E1.17 are also representative of the variation in weld throat dimension.

The statistical parameters ρ_{M2} and ρ_P were calculated as discussed in Section 4.1, except that the throat areas were calculated from measured throat dimensions instead of from the minimum throat dimension calculated from the measured leg sizes. The results of these calculations are presented in Tables E1.19 through E1.32. The columns with the heading 'Specimen with a_2 or a_3 only' list the material parameters for the specimens with longitudinal welds only, namely, those of types [xx2xx] and [xx3xx]. The shear strength, τ_u , was obtained by dividing the test capacity, P_u , presented in the second column, by the measured weld throat area, A_2 or A_3, which did not include penetration but included reinforcement. The shear strength predicted from the tensile strength of the filler metal, σ_u , is listed in column 4, followed by the ratio of column 3 to column 4, ρ_{M2}. The columns with the heading 'Specimens with a_1 only' list the predicted capacity and the test-to-predicted capacity ratio, ρ_P , using Equation 4.7 for the specimens with a transverse weld only, namely, those of type [xx1xx]. The columns with the heading 'Specimens with a_1 and a_2' list the predicted capacity and the test-to-predicted capacity for test specimens that combined longitudinal and transverse welds. Three different models, presented in Section 4.1, were used to predict the capacity of the test specimens. The columns with the heading 'Specimens with a_1, a_2 and a_4' list the predicted capacity using Equation 4.9 and the test-to-predicted ratio for specimens of the type [xx4xx], which combined longitudinal and transverse welds and were loaded eccentrically in the out-of-plane direction.

The mean values for the ratios ρ_{M2} and ρ_P for the various sources reported by Ligtenberg (1968) are summarized in Table E1.33.

E.2 Bornscheuer and Feder (1966)

Bornscheuer and Feder (1966) designed a series of tests to investigate the effects of weld length, weld throat dimension and the ratio of the area of the plate to the area of the weld on fillet weld strength. The test specimens consisted of double lapped joints fabricated in three configurations: (a) connections with longitudinal welds only, (b) connections with transverse welds only, and (c) five test specimens with the same dimensions as those from group [IIbmR] of the international test series to replicate some of the results from Ligtenberg (1968). The plates were of Fe37 steel and welding was performed with rutile electrodes. The nominal throat dimensions for the specimens with a single weld orientation were 4 mm, 8 mm and 12 mm. The nominal throat dimension for the test specimens with combined transverse and longitudinal welds was 5 mm.

The weld measurements and the test results from Bornscheuer and Feder (1966) are presented in Table E2.1 where A_{throat} is the total measured throat area, which did not include penetration but included reinforcement, and the shear strength τ_u is equal to P_u divided by A_{throat} for specimen with longitudinal weld only. The geometry factor ρ_G is taken as the ratio of the measured to nominal throat dimension of the fillet weld segments. The professional factor, ρ_P, for specimens with only a transverse weld and specimens with transverse and longitudinal welds were calculated as discussed in Section E.1.3 for Tables E1.19 through E1.32. The results of these calculations are presented in Table E2.2.

E.3 Kato and Morita (1969)

The tests presented by Kato and Morita (1969) were designed to investigate the effect of weld metal strength, depth of fusion and weld leg size on fillet weld strength. The tests consisted of three groups of connections: specimens with longitudinal welds only, specimens with transverse welds only, and specimens with combined longitudinal and transverse welds.

The test specimens were double lapped joints. The plates were of SM50 steel, which has almost the same properties as St.52 steel, and the welding electrodes were of the basic and rutile types. The measurements and test results are presented in Table E3.1, in which A_1 is the measured throat area of transverse welds and A_2 is the measured throat area of longitudinal welds. The weld throat area in Table E3.1 was calculated based on the measured throat dimension and did not include root penetration. The geometry factor ρ_G is taken as the ratio of the measured to nominal throat dimension of the fillet weld segments. The statistical parameters ρ_{M2} and ρ_P for specimens with longitudinal welds, specimens with a transverse weld and specimens with combined transverse and longitudinal welds were calculated as discussed in Section E.1.3 for Tables E1.19 through E1.32. The results of these calculations are presented in Tables E3.2.

E.4 Butler and Kulak (1969, 1971)

A series of 23 concentrically loaded double lapped joints and eight full-scale eccentrically loaded connections were tested. The tests on concentrically loaded connections with fillet welds oriented at different angles were conducted to establish the load–deformation response curves for fillet welds loaded at different angles. The test results indicated that both weld capacity and ductility varied with the angle between the axis of the weld and the line of the action of the load. The full-scale tests were eccentrically loaded and were conducted to verify the method of the instantaneous centre of rotation to predict the ultimate capacity of such connections.

Table E4.1 presents a summary of the test specimen parameters and the results are summarized in Table E4.2. Because eccentrically loaded joints are not part of the current study, weld deformations and strength of the full-scale specimen are not presented in Table E4.2. The weld size given in the table represents the average of several measurements. The geometry factor, ρ_G, is taken as the ratio of the average measured weld size to nominal weld size of the specimens. The professional factor ρ_P is calculated using Equation 4.7.

E.5 Dawe and Kulak (1972)

The main objective of the work presented by Dawe and Kulak (1972) was to develop a method for determining the ultimate strength of eccentrically loaded welded joints in which the weld in the compression zone is not free to rotate. Sixteen such joints, which consisted of three series of different weld configurations, and 15 “weld tension coupons,” which were essentially lapped joints of longitudinal welds, were tested. The “weld tension coupons” were tested to establish the load–deformation response for elemental lengths of fillet weld. The electrode used was AWS E60XX and the plates were of ASTM A36 steel. Because no weld-metal coupon tests were conducted in the test program, only weld size measurements are presented in Table E5.1. The fillet weld leg dimension was taken as the average of 36 individual measurements for each specimen in series A, B and C and 24 measurements for each tension specimen in series 1, 2 and 3. The geometry factor, ρ_G , is taken as the ratio of the average measured leg size to nominal leg size of the specimens.

E.6 Clark (1971)

Clark (1971) reported a series of 18 tests conducted to investigate the variation of strength and ductility as a function of the angle between the axis of a fillet weld and the applied load. Although details of steel plates and electrodes are not presented in the paper, it is still useful to examine the weld leg size variation and strength variation with the load direction. The results and analysis are presented in Table E6.1. The geometry factor, ρ_G , is taken as the ratio of the average measured throat size to nominal throat size of the specimens. The throat area A_{throat} is calculated by multiplying the measured throat size by the weld length. The professional factor, ρ_P , is calculated using Equation 4.7.

E.7 Swannell and Skewes (1979 b)

Swannell and Skewes (1979b) presented tests that were designed to verify the theoretical ultimate load models and computational techniques for general in-plane loaded weld groups. The nominal weld leg size was 6.4 mm and the measured weld sizes are summarized in Table E7.1. The data presented in the table represent the average of several weld segment measurements. The geometry factor, ρ_G , is taken as the ratio of the average measured leg size to nominal leg size of the specimens.

Four series of material tests were conducted. The first series was the all-weld metal tension coupon tests with a cross-sectional area of 100 mm^2. The other three series were longitudinal welds in lapped splice joints. The results of the ancillary tests are presented in Table E7.2. The material factor ρ_{M2} is calculated using Equation 4.6a.

E.8 Pham (1981)

A total of 25 specimens from three series were tested with the welds loaded eccentrically in plane. Rutile electrodes were used for the preparation of the test specimens. The objective of the test program was to investigate the effect of weld size on the strength of fillet welds. All welding was performed by one welder using run-on and run-off tabs. Because the welded joint specimens were loaded eccentrically, only the weld size measurements are relevant to the current investigation and are listed in Table E8.1. The first letter in the specimen designation indicates the test series, the second letter indicates the specimen type and the third is the sequence number in a test series. Specimen type A had transverse welds loaded eccentrically and specimen type B had longitudinal welds loaded eccentrically. The geometry factor, ρ_G , is taken as the ratio of the average measured throat size to nominal throat size of the specimens.

E.9 Pham (1983a, b)

Pham tested both cruciform specimens (Pham, 1983a) and Werner specimens (Pham, 1983b) to investigate the effect of weld size on fillet weld strength. The Werner specimens, shown in Figure E3, were designed to eliminate both in-plane and out-of-plane eccentricities for the longitudinal fillet welds tested.

A summary of the test program is presented in Table E9.1 for cruciform test specimens (Pham, 1983a) and Table E9.2 for the Werner specimens (Pham, 1983b).

The fillet weld size measurements are presented in Table E9.3 and Table E9.4. The weld throat measurements presented in the table were measured directly and did not include root penetration. The geometry factor ρ_G is taken as the ratio of the minimum throat dimension (MTD) calculated from the measured leg sizes to the nominal throat size obtained from the nominal leg size.

The test results are summarized in Table E9.5 and Table E9.6, in which A_{throat} is the product of the minimum throat dimension calculated from the measured leg sizes and measured weld length. The material factor ρ_{M2} is calculated using Equation 4.6a and the professional factor ρ_P is calculated using Equation 4.7.

E.10 Miazga and Kennedy (1986)

A series of 42 fillet weld specimens were tested to investigate the effect of loading direction on the strength of fillet welds. The specimens consisted of double lapped joints loaded concentrically and the weld size and plate thicknesses were chosen to ensure that the welds fractured before the plates yielded. Seven loading angles and two weld sizes were examined with three specimens for each combination. The test matrix is presented in Table E10.1.

The fillet weld size measurements and statistical analysis are presented in Table E10.2 and Table E10.3. The geometry factor, ρ_G, is taken as the ratio of the average of two measured leg sizes to the nominal leg size of the specimens, since Miazga and Kennedy (1986) only reported the average of the two leg sizes.

The test results were analyzed as shown in Table E10.4. The weld throat areas, A_{throat}, were calculated from the average measured leg size and measured weld length. The ultimate tensile strength $\sigma_u = 538\text{MPa}$ was obtained from tests on three all-weld-metal tension coupons. The material factor ρ_{M2} is calculated using Equation 4.6a and the professional factor ρ_P is calculated using Equation 4.7.

E.11 Quinn (1991) and Bowman and Quinn (1994)

A series of 18 fillet weld specimens were tested. The variables studied included weld leg size, weld orientation, and fabrication weld root gaps. The specimens were double lapped joints loaded concentrically in tension. The test matrix is shown in Table E11.1.

The weld size measurements are shown in Table E11.2. The geometry factor, ρ_G, is taken as the ratio of the minimum throat dimension (MTD) calculated from the measured leg sizes to the nominal throat size obtained from the nominal leg size.

The test results and analysis are shown in Table E11.3, in which the results of specimens with root gaps were not included. The weld throat areas, A_{throat}, are the product of the minimum throat dimension calculated from the measured leg sizes and measured weld length. The ultimate tensile strength $\sigma_u = 476\ \text{MPa}$ was obtained by three all-weld-metal tension coupon tests. The material factor ρ_{M2} is calculated per Equation 4.6a and the professional factor ρ_P is calculated per Equation 4.7.

E.12 Ng *et al.* (2002), Deng *et al.* (2003) and Callele *et al.* (2005)

The weld leg dimensions reported by Ng *et al*. (2002), Deng *et al.* (2003), and Callele *et al.* (2005) are shown in Figure E4. The weld leg on the main plate (MPL) was referred to as the shear leg and the weld leg on the lap plate (LPL) was referred to as the tension leg. The minimum throat dimension (MTD) was calculated from the measured leg sizes using the following equation:

$$\text{MTD} = \frac{\text{MPL} \times \text{LPL}}{\sqrt{\text{MPL}^2 + \text{LPL}^2}} \tag{E.1}$$

The geometric factor, ρ_G, is then calculated by using Equation 4.4a, which is represented by the following equation:

$$\rho_G = \text{Mean}\left(\frac{\text{MTD calculated by using Equation (E.1)}}{0.707 \times (\text{nominal weld leg size})}\right) \tag{E.2}$$

Of all the research compiled in this report from the literature, only that of Ng *et al*. (2002), Deng *et al.* (2003), and Callele *et al.* (2005) and current test program reported both measured leg and throat dimensions, thereby giving an opportunity to assess directly the degree of face reinforcement in the fillet weld as deposited. Two ratios defined by Equations 4.14a and 4.14b are represented as follows:

$$\alpha_1 = \text{Mean}\left(\frac{45^\circ\ \text{Meas}}{\text{MTD}}\right) \tag{E.3}$$

$$\alpha_2 = \text{Mean}\left(\frac{45^\circ\ \text{Meas}}{0.707 \times (\text{average of MPL and LPL})}\right) \tag{E.4}$$

The measurements of MPL, LPL, and 45^o Meas, the calculated MTD, and the ratios α_1 , α_2, and ρ_G for the specimens of Ng *et al*. (2002), Deng *et al.* (2003) and Callele *et al.* (2005) are presented in Tables E12.1 through E12.5. A summary is presented in Table 4.3.

Results of all-weld-metal tension coupon tests from the various phases of a weld research program reported by Ng *et al*. (2002), Deng *et al.* (2003) and Callele *et al.* (2005) are reproduced in Table E12.6 and the material factor ρ_{M1} is calculated using Equation 4.5.

The results of tests on longitudinal weld specimens from Deng *et al.* (2003) and Callele *et al.* (2005) are presented in Table E12.7 and the material factor ρ_{M2} is calculated using Equation 4.6a.

The test results from specimens with transverse and longitudinal welds from Callele *et al.* (2005) are analyzed in Table E12.8 using three models, as discussed in Section 4.1.

Table E1.1 – 81 Combinations of 4 Test Parameters for the Test Program Reported by Ligtenberg (1968)

Test Parameters†		a			b			c		
		s	m	h	s	m	h	s	m	h
I	A	IasA	IamA	IahA	IbsA	IbmA	IbhA	IcsA	IcmA	IchA
	B	IasB	IamB	IahB	IbsB	IbmB	IbhB	IcsB	IcmB	IchB
	R	IasR	IamR	IahR	IbsR	IbmR	IbhR	IcsR	IcmR	IchR
II	A	IIasA	IIamA	IIahA	IIbsA	IIbmA	IIbhA	IIcsA	IIcmA	IIchA
	B	IIasB	IIamB	IIahB	IIbsB	IIbmB	IIbhB	IIcsB	IIcmB	IIchB
	R	IIasR	IIamR	IIahR	IIbsR	IIbmR	IIbhR	IIcsR	IIcmR	IIchR
III	A	IIIasA	IIIamA	IIIahA	IIIbsA	IIIbmA	IIIbhA	IIIcsA	IIIcmA	IIIchA
	B	IIIasB	IIIamB	IIIahB	IIIbsB	IIIbmB	IIIbhB	IIIcsB	IIIcmB	IIIchB
	R	IIIasR	IIIamR	IIIahR	IIIbsR	IIIbmR	IIIbhR	IIIcsR	IIIcmR	IIIchR

† Refer to section E.1.2 for a description of the test parameters

Table E1.2 – Nominal Dimensions of Test Specimens* from Ligtenberg (1968)

Specimen Designation†	L_1 (mm)	L_2 (mm)	a_1 ‡ (mm)	a_2 (mm)	a_3 (mm)	A_1 (mm^2)	A_2 (mm^2)	A_3 (mm^2)	t_1 (mm)	t_2 (mm)
Iasx									24	12
Iamx	45	80	3	5	6	270	1600	1920	30	15
Iahx									38	19
Ibsx									19	10
Ibmx	45	80	3.5	3.5	4.5	315	1120	1440	24	12
Ibhx									30	15
Icsx									19	10
Icmx	45	80	6	3	4	540	960	1280	24	12
Ichx									30	15
IIasx									19	10
IIamx	55	55	3	6	7.5	330	1320	1650	24	12
IIahx									30	15
IIbsx									19	10
IIbmx	55	55	5	5	7.5	550	1100	1650	24	12
IIbhx									30	15
IIcsx									19	10
IIcmx	55	55	8	4	7.5	880	880	1650	24	12
IIchx									30	15
IIIasx									15	8
IIIamx	80	40	4	8	10	640	1280	1600	19	10
IIIahx									24	12
IIIbsx									15	8
IIIbmx	80	40	6	6	10	960	960	1600	19	10
IIIbhx									24	12
IIIcsx									15	8
IIIcmx	80	40	8	4	10	1280	640	1600	19	10
IIIchx									24	12

* See Section E.1.3 and Figure E1, E2 for the definition of the symbols in the tables.

† In the designations, x represents R, or A, or B, which are the first letter of the three types of electrodes, *i.e.* Rutile, Acid coated and Basic.

‡ $a_4 = a_1$ for specimens shown in Figure E2.

Table E1.3 – British Test Results on St.37 Steel as Reported by Ligtenberg (1968)

Specimen Designation	t_1* (mm)	t_2 (mm)	L_1 † (mm)	A_1 (mm^2)	A_2 (mm^2)	A_3 (mm^2)	A_4 (mm^2)	P_u (kN)	σ_u (MPa)	Rupture Mode‡
Ia sA	23.7	—	45.0	311	1709	—	—	681	451	w
Ia1sA	23.7	—	45.0	292	—	—	—	182	451	w
Ia2sA	23.7	—	45.0	—	1770	—	—	645	451	w
Ia3sA	23.7	—	45.1	—	—	2060	—	719	451	w
Ia4sA	23.7	11.7	45.1	170	827	—	138	342	451	w
Ib mB	23.8	—	45.0	390	1354	—	—	579	569	s
Ib1mB	23.8	—	45.0	375	—	—	—	272	569	w
Ib2mB	23.8	—	44.9	—	1210	—	—	491	569	w
Ib3mB	23.8	—	44.9	—	—	1529	—	539	569	w
Ib4mB	23.8	11.6	44.8	191	623	—	173	318	569	w
Ic hR	30.0	—	44.9	577	1124	—	—	712	491	w
Ic1hR	30.0	—	44.8	521	—	—	—	284	491	w
Ic2hR	30.0	—	45.0	—	1138	—	—	429	491	w
Ic3hR	30.0	—	44.8	—	—	1278	—	454	491	w
Ic4hR	30.0	15.0	45.5	269	595	—	253	437	491	w
IIa hB	30.0	—	54.9	419	1438	—	—	726	569	w
IIa1hB	30.0	—	54.9	372	—	—	—	187	569	w
IIa2hB	30.0	—	54.8	—	1483	—	—	579	569	w
IIa3hB	30.0	—	54.8	—	—	1755	—	649	569	w
IIa4hB	30.0	14.9	54.7	202	660	—	194	363	569	w
IIb sR	19.0	—	54.9	601	1272	—	—	719	491	w
IIb1sR	19.0	—	54.9	601	—	—	—	303	491	w
IIb2sR	19.0	—	54.9	—	1267	—	—	483	491	w
IIb3sR	19.0	—	54.9	—	—	1711	—	590	491	w
IIb4sR	19.0	9.8	54.7	336	623	—	299	405	491	w
IIc mA	23.8	—	55.0	919	966	—	—	877	451	w
IIc1mA	23.8	—	55.1	919	—	—	—	507	451	w
IIc2mA	23.8	—	54.9	—	973	—	—	342	451	w
IIc3mA	23.8	—	55.0	—	—	1702	—	645	451	w
IIc4mA	23.8	11.6	55.2	472	435	—	446	525	451	w
IIIa mR	18.9	—	80.5	779	1386	—	—	837	491	w
IIIa1mR	18.9	—	80.3	665	—	—	—	316	491	w
IIIa2mR	18.9	—	80.4	—	1386	—	—	437	491	w
IIIa3mR	18.9	—	80.2	—	—	1680	—	507	491	w
IIIa4mR	18.9	9.7	80.3	315	704	—	340	928	491	w
IIIb hA	23.7	—	80.7	1063	1042	—	—	930	451	w
IIIb1hA	23.7	—	80.3	1029	—	—	—	592	451	w
IIIb2hA	23.7	—	80.3	—	1034	—	—	381	451	w
IIIb3hA	23.7	—	80.7	—	—	1713	—	545	451	w
IIIb4hA	23.7	11.6	80.2	550	514	—	507	619	451	w

Table E1.3 (cont.)

Specimen Designation	t_1 (mm)	t_2 (mm)	L_1 (mm)	A_1 (mm^2)	A_2 (mm^2)	A_3 (mm^2)	A_4 (mm^2)	P_u (kN)	σ_u (MPa)	Rupture Mode
IIIc sB	14.9	—	80.1	1330	701	—	—	991	569	s
IIIc1sB	14.9	—	80.1	1359	—	—	—	801	569	w
IIIc2sB	14.9	—	80.1	—	683	—	—	276	569	w
IIIc3sB	14.9	—	80.0	—	—	1663	—	619	569	w
IIIc4sB	14.9	8.1	80.1	664	335	—	669	432	569	w
IIbmA 1	23.7	—	54.8	572	1152	—	—	735	451	w
IIbmA 2	23.7	—	54.9	610	1194	—	—	765	451	w
IIbmA 3	23.7	—	54.9	653	1230	—	—	763	451	w
IIbmB 1	23.6	—	55.0	602	1190	—	—	851	569	s
IIbmB 2	23.6	—	54.8	603	1243	—	—	939	569	w
IIbmB 3	23.6	—	54.8	635	1144	—	—	948	569	w
IIbmR 1	23.6	—	54.8	640	1307	—	—	837	491	w
IIbmR 2	23.6	—	54.8	655	1325	—	—	810	491	w
IIbmR 3	23.6	—	55.0	632	1177	—	—	645	491	w

* See Figure E1, Figure E2 and Section E.1.2 for dimensions and definition of symbols.

† In Ligtenberg (1968), L_1 was reported as *h*.

‡ In this column, *w* represents rupture in welds and *s* represents rupture in steel plates.

Table E1.4 – Japanese Test Results on St.37 Steel as Reported by Ligtenberg (1968)

Specimen Designation	t_1* (mm)	t_2 (mm)	L_1† (mm)	A_1 (mm^2)	A_2 (mm^2)	A_3 (mm^2)	A_4 (mm^2)	P_u (kN)	σ_u (MPa)	Rupture Mode‡
Ia hA	37.8	—	45.0	311	1391	—	—	699	446	w
Ia1hA	37.8	—	45.0	288	—	—	—	202	446	w
Ia2hA	37.8	—	45.0	—	1356	—	—	557	446	w
Ia3hA	37.8	—	45.0	—	—	1475	—	580	446	w
Ib sB	19.3	—	45.1	406	1437	—	—	718	507	s
Ib1sB	19.3	—	45.1	440	—	—	—	277	507	w
Ib2sB	19.3	—	45.1	—	1538	—	—	549	507	w
Ib3sB	19.3	—	45.1	—	—	1678	—	586	507	w
Ic mR	24.8	—	45.0	473	961	—	—	645	560	w
Ic1mR	24.8	—	45.0	468	—	—	—	262	560	w
Ic2mR	24.8	—	45.0	—	887	—	—	379	560	w
Ic3mR	24.8	—	45.0	—	—	987	—	439	560	w
IIa mB	24.3	—	55.1	526	1496	—	—	715	507	w
IIa1mB	24.3	—	55.1	505	—	—	—	297	507	w
IIa2mB	24.3	—	55.0	—	1515	—	—	502	507	w
IIa3mB	24.3	—	55.1	—	—	1576	—	577	507	w
IIb hR	30.0	—	55.0	462	890	—	—	554	560	w
IIb1hR	30.0	—	55.0	489	—	—	—	293	560	w
IIb2hR	30.0	—	55.0	—	990	—	—	337	560	w
IIb3hR	30.0	—	55.0	—	—	1729	—	598	560	w
IIc sA	19.1	—	55.1	682	899	—	—	746	446	w
IIc1sA	19.1	—	55.1	666	—	—	—	418	446	w
IIc2sA	19.1	—	55.0	—	896	—	—	378	446	w
IIc3sA	19.1	—	55.1	—	—	972	—	369	446	w
IIIa sR	15.7	—	80.0	560	1371	—	—	728	560	w
IIIa1sR	15.7	—	80.0	676	—	—	—	387	560	w
IIIa2sR	15.7	—	80.0	—	1399	—	—	477	560	w
IIIa3sR	15.7	—	80.0	—	—	1606	—	549	560	w
IIIb mA	19.1	—	80.1	776	783	—	—	752	446	w
IIIb1mA	19.1	—	80.1	778	—	—	—	553	446	w
IIIb2mA	19.1	—	80.1	—	814	—	—	302	446	w
IIIb3mA	19.1	—	80.2	—	—	1276	—	454	446	w
IIIc hB	25.8	—	80.1	1416	817	—	—	908	507	w
IIIc1hB	25.8	—	80.1	1416	—	—	—	694	507	w
IIIc2hB	25.8	—	80.1	—	831	—	—	285	507	w
IIIc3hB	25.8	—	80.1	—	—	1720	—	548	507	w

Table E1.4 (cont.)

Specimen Designation	t_1 (mm)	t_2 (mm)	L_1 (mm)	A_1 (mm^2)	A_2 (mm^2)	A_3 (mm^2)	A_4 (mm^2)	P_u (kN)	σ_u (MPa)	Rupture Mode
IIbmA 1	24.6	—	55.1	517	884	—	—	613	446	w
IIbmA 2	24.6	—	55.0	496	886	—	—	604	446	w
IIbmA 3	24.6	—	55.1	489	893	—	—	615	446	w
IIbmB 1	24.7	—	54.7	617	1243	—	—	730	507	s
IIbmB 2	24.7	—	54.8	606	1296	—	—	736	507	w
IIbmB 3	24.7	—	54.8	663	1292	—	—	743	507	w
IIbmR 1	24.9	—	55.0	473	946	—	—	619	560	w
IIbmR 2	24.9	—	55.0	446	938	—	—	606	560	w
IIbmR 3	24.9	—	55.0	462	909	—	—	610	560	w

* See Figure E1, Figure E2 and Section E.1.2 for dimensions and definition of symbols.

† In Ligtenberg (1968), L_1 was reported as *h*.

‡ In this column, *w* represents rupture in welds and *s* represents rupture in steel plates.

Table E1.5 – USA Test Results on St.37 Steel as Reported by Ligtenberg (1968)

Specimen Designation	t_1* (mm)	t_2 (mm)	L_1† (mm)	A_1 (mm^2)	A_2 (mm^2)	A_3 (mm^2)	A_4 (mm^2)	P_u (kN)	σ_u (MPa)	Rupture Mode‡
Ia mR	32.7	—	45.0	302	1350	—	—	557	472	w
Ia1mR	32.7	—	45.1	323	—	—	—	169	472	w
Ia2mR	32.7	—	45.0	—	1428	—	—	490	472	w
Ia3mR	32.7	—	45.0	—	—	1570	—	533	472	w
Ia4mR	32.7	15.6	45.1	161	637	—	154	381	472	w
Ib hA	32.7	—	45.1	347	997	—	—	659	454	w
Ib1hA	32.7	—	45.1	358	—	—	—	238	454	w
Ib2hA	32.7	—	45.1	—	1140	—	—	511	454	w
Ib3hA	32.7	—	45.2	—	—	1462	—	575	454	w
Ib4hA	32.7	15.6	45.0	171	514	—	160	383	454	w
Ic sB	18.9	—	45.1	526	1028	—	—	713	545	w
Ic1sB	18.9	—	45.1	531	—	—	—	291	545	w
Ic2sB	18.9	—	45.0	—	1007	—	—	499	545	w
Ic3sB	18.9	—	45.0	—	—	1306	—	617	545	w
Ic4sB	18.9	9.5	45.0	246	495	—	240	342	545	w
IIa sA	18.9	—	55.0	323	1146	—	—	604	454	w
IIa1sA	18.9	—	55.1	357	—	—	—	227	454	w
IIa2sA	18.9	—	55.0	—	1095	—	—	395	454	w
IIa3sA	18.9	—	55.1	—	—	1460	—	523	454	w
IIa4sA	18.9	9.5	55.0	150	601	—	154	303	454	w
IIb mB	25.8	—	55.1	497	934	—	—	684	545	w
IIb1mB	25.8	—	55.1	565	—	—	—	363	545	w
IIb2mB	25.8	—	55.0	—	965	—	—	414	545	w
IIb3mB	25.8	—	55.1	—	—	1550	—	666	545	w
IIb4mB	25.8	12.7	55.0	244	456	—	222	462	545	w
IIc hA	32.7	—	55.0	831	801	—	—	715	472	w
IIc1hA	32.7	—	55.0	880	—	—	—	445	472	w
IIc2hA	32.7	—	54.9	—	859	—	—	325	472	w
IIc3hA	32.7	—	55.1	—	—	1700	—	597	472	w
IIc4hA	32.7	15.6	55.1	434	384	—	444	581	472	w
IIIa hB	25.8	—	79.8	640	1047	—	—	951	545	w
IIIa1hB	25.8	—	80.1	689	—	—	—	543	545	w
IIIa2hB	25.8	—	80.0	—	1009	—	—	470	545	w
IIIa3hB	25.8	—	80.0	—	—	1437	—	615	545	w
IIIa4hB	25.8	12.7	80.0	316	579	—	288	575	545	w
IIIb sR	15.6	—	80.0	745	790	—	—	710	472	w
IIIb1sR	15.6	—	80.0	815	—	—	—	461	472	w
IIIb2sR	15.6	—	80.1	—	841	—	—	292	472	w
IIIb3sR	15.6	—	80.0	—	—	1352	—	471	472	w
IIIb4sR	15.6	7.9	80.0	323	342	—	325	399	472	w

Table E1.5 (cont.)

Specimen Designation	t_1 (mm)	t_2 (mm)	L_1 (mm)	A_1 (mm^2)	A_2 (mm^2)	A_3 (mm^2)	A_4 (mm^2)	P_u (kN)	σ_u (MPa)	Rupture Mode
IIIc mA	18.9	—	80.1	1293	608	—	—	890	454	w
IIIc1mA	18.9	—	80.0	1347	—	—	—	708	454	w
IIIc2mA	18.9	—	80.0	—	590	—	—	303	454	w
IIIc3mA	18.9	—	80.0	—	—	1390	—	539	454	w
IIIc4mA	18.9	9.5	80.0	518	313	—	367	497	454	w
IIbmA 1	25.7	—	55.1	605	1086	—	—	734	454	w
IIbmA 2	25.7	—	55.0	580	1107	—	—	774	454	w
IIbmA 3	25.7	—	55.1	639	1157	—	—	757	454	w
IIbmB 1	25.8	—	55.0	510	972	—	—	742	545	w
IIbmB 2	25.8	—	55.0	462	916	—	—	744	545	w
IIbmB 3	25.8	—	55.1	517	966	—	—	726	545	w
IIbmR 1	25.8	—	55.1	482	997	—	—	606	472	w
IIbmR 2	25.8	—	55.1	450	923	—	—	619	472	w
IIbmR 3	25.8	—	55.1	506	937	—	—	601	472	w

* See Figure E1, Figure E2 and Section E.1.2 for dimensions and definition of symbols.

† In Ligtenberg (1968), L_1 was reported as *h*.

‡ In this column, *w* represents rupture in welds and *s* represents rupture in steel plates.

Table E1.6 – French Test Results on St.37 Steel as Reported by Ligtenberg (1968)

Specimen Designation	t_1 * (mm)	t_2 (mm)	L_1 † (mm)	A_1 (mm^2)	A_2 (mm^2)	A_3 (mm^2)	A_4 (mm^2)	P_u (kN)	σ_u (MPa)	Rupture Mode ‡
Ia hB	37.6	—	45.0	315	1581	—	—	785	516	—
Ia1hB	37.6	—	45.0	279	—	—	—	155	516	—
Ia2hB	37.6	—	46.0	—	1700	—	—	618	516	—
Ia3hB	37.6	—	45.0	—	—	2060	—	697	516	—
Ia4hB	37.6	19.0	46.0	127	760	—	150	383	516	—
IbsR	19.0	—	47.0	282	960	—	—	667	563	—
Ib1sR	19.0	—	46.0	299	—	—	—	196	563	—
Ib2sR	19.0	—	46.0	—	1140	—	—	500	563	—
Ib3sR	19.0	—	45.0	—	—	1360	—	515	563	—
Ib4sR	19.0	10.5	45.0	135	544	—	124	309	563	—
Ic mA	24.0	—	46.0	560	1060	—	—	755	494	—
Ic1mA	24.0	—	47.0	634	—	—	—	353	494	—
Ic2mA	24.0	—	45.0	—	1056	—	—	451	494	—
Ic3mA	24.0	—	47.0	—	—	1312	—	491	494	—
Ic4mA	24.0	12.0	46.0	276	512	—	276	383	494	—
IIa mR	24.0	—	57.0	342	1210	—	—	608	563	—
IIa1mR	24.0	—	56.0	325	—	—	—	216	563	—
IIa2mR	24.0	—	56.0	—	1360	—	—	491	563	—
IIa3mR	24.0	—	56.0	—	—	1590	—	569	563	—
IIa4mR	24.0	12.0	56.0	168	671	—	168	373	563	—
IIb hA	29.7	—	57.0	570	1100	—	—	834	494	—
IIb1hA	29.7	—	56.0	549	—	—	—	341	494	—
IIb2hA	29.7	—	57.0	—	990	—	—	461	494	—
IIb3hA	29.7	—	55.0	—	—	1630	—	638	494	—
IIb4hA	29.7	15.0	57.0	285	550	—	270	491	494	—
IIc sB	19.0	—	56.0	896	792	—	—	706	516	—
IIc1sB	19.0	—	55.0	854	—	—	—	491	516	—
IIc2sB	19.0	—	55.0	—	704	—	—	304	516	—
IIc3sB	19.0	—	55.0	—	—	1770	—	559	516	—
IIc4sB	19.0	10.5	57.0	428	451	—	413	422	516	—
IIIa sA	15.0	—	81.0	608	1280	—	—	775	494	—
IIIa1sA	15.0	—	82.0	590	—	—	—	392	494	—
IIIa2sA	15.0	—	83.0	—	1220	—	—	461	494	—
IIIa3sA	15.0	—	83.0	—	—	1600	—	549	494	—
IIIa4sA	15.0	7.9	82.0	246	568	—	308	402	494	—
IIIb mB	19.0	—	82.0	1025	1040	—	—	903	516	—
IIIb1mB	19.0	—	81.0	972	—	—	—	486	516	—
IIIb2mB	19.0	—	81.0	—	950	—	—	343	516	—
IIIb3mB	19.0	—	82.0	—	—	1580	—	530	516	—
IIIb4mB	19.0	10.5	81.0	466	480	—	466	564	516	—

Table E1.6 (cont.)

Specimen Designation	t_1 (mm)	t_2 (mm)	L_1 (mm)	A_1 (mm^2)	A_2 (mm^2)	A_3 (mm^2)	A_4 (mm^2)	P_u (kN)	σ_u (MPa)	Rupture Mode
IIIc hR	24.0	—	82.0	1214	608	—	—	1079	563	—
IIIc1hR	24.0	—	82.0	1230	—	—	—	724	563	—
IIIc2hR	24.0	—	81.0	—	600	—	—	255	563	—
IIIc3hR	24.0	—	82.0	—	—	1504	—	549	563	—
IIIc4hR	24.0	12.0	83.0	623	320	—	623	638	563	—
IIbmA 1	24.0	—	57.0	580	1140	—	—	800	494	—
IIbmA 2	24.0	—	56.0	560	1078	—	—	785	494	—
IIbmA 3	24.0	—	57.0	598	1155	—	—	667	494	—
IIbmB 1	24.0	—	56.0	616	1144	—	—	746	516	—
IIbmB 2	24.0	—	56.0	616	1045	—	—	697	516	—
IIbmB 3	24.0	—	57.0	570	1100	—	—	584	516	—
IIbmR 1	24.0	—	57.0	467	792	—	—	598	563	—
IIbmR 2	24.0	—	57.0	445	860	—	—	598	563	—
IIbmR 3	24.0	—	58.0	435	825	—	—	598	563	—

* See Figure E1, Figure E2 and Section E.1.2 for dimensions and definition of symbols.

† In Ligtenberg (1968), L_1 was reported as *h*.

‡ The rupture mode was not reported.

Table E1.7 – German Test Results on St.37 Steel as Reported by Ligtenberg (1968)

Specimen Designation	t_1* (mm)	t_2 (mm)	L_1† (mm)	A_1 (mm^2)	A_2 (mm^2)	A_3 (mm^2)	A_4 (mm^2)	P_u (kN)	σ_u (MPa)	Rupture Mode‡
Ia sB	24.3	—	46.0	490	2202	—	—	787	491	w
Ia1sB	24.3	—	46.0	416	—	—	—	287	491	w
Ia2sB	24.3	—	47.0	—	1837	—	—	700	491	w and s
Ia3sB	24.3	—	47.0	—	—	2181	—	776	491	w and s
Ia4sB	24.3	11.8	46.0	221	1021	—	217	363	491	w
Ib mR	24.5	—	47.0	446	1475	—	—	765	471	w
Ib1mR	24.5	—	46.0	418	—	—	—	289	471	w
Ib2mR	24.5	—	47.0	—	1507	—	—	553	471	w
Ib3mR	24.5	—	47.0	—	—	1772	—	606	471	w
Ib4mR	24.5	11.8	46.0	182	758	—	204	378	471	s
Ic hA	30.2	—	46.0	677	1543	—	—	687	491	w
Ic1hA	30.2	—	46.0	655	—	—	—	414	491	w
Ic2hA	30.2	—	46.0	—	1522	—	—	539	491	w
Ic3hA	30.2	—	46.0	—	—	1698	—	688	491	w
Ic4hA	30.2	15.2	46.0	345	869	—	340	502	491	s
IIa hR	30.3	—	56.0	493	1591	—	—	710	471	w
IIa1hR	30.3	—	56.0	500	—	—	—	327	471	w
IIa2hR	30.3	—	56.0	—	1581	—	—	529	471	w
IIa3hR	30.3	—	56.0	—	—	1825	—	615	471	w
IIa4hR	30.3	15.2	56.0	248	815	—	246	439	471	w
IIb sA	20.4	—	56.0	686	1407	—	—	787	491	w
IIb1sA	20.4	—	55.0	739	—	—	—	379	491	w
IIb2sA	20.4	—	55.0	—	1479	—	—	498	491	w
IIb3sA	20.4	—	56.0	—	—	1728	—	608	491	w
IIb4sA	20.4	10.1	55.0	346	814	—	365	442	491	s
IIc mB	24.5	—	56.0	948	1245	—	—	978	491	s
IIc1mB	24.5	—	56.0	892	—	—	—	561	491	w
IIc2mB	24.5	—	57.0	—	1087	—	—	452	491	w
IIc3mB	24.5	—	57.0	—	—	1695	—	645	491	w
IIc4mB	24.5	12.1	55.0	446	598	—	428	457	491	s
IIIa mA	20.5	—	82.0	857	1289	—	—	937	491	w
IIIa1mA	20.5	—	82.0	825	—	—	—	434	491	w
IIIa2mA	20.5	—	82.0	—	1400	—	—	439	491	w
IIIa3mA	20.5	—	82.0	—	—	1477	—	445	491	w
IIIa4mA	20.5	10.2	80.0	602	521	—	492	459	491	s
IIIb hB	24.4	—	82.0	1098	1303	—	—	1011	491	w
IIIb1hB	24.4	—	81.0	1424	—	—	—	731	491	w
IIIb2hB	24.4	—	82.0	—	1288	—	—	454	491	w
IIIb3hB	24.4	—	82.0	—	—	1587	—	599	491	w
IIIb4hB	24.4	11.8	80.0	593	689	—	610	569	491	s

Table E1.7 (cont.)

Specimen Designation	t_1 (mm)	t_2 (mm)	L_1 (mm)	A_1 (mm^2)	A_2 (mm^2)	A_3 (mm^2)	A_4 (mm^2)	P_u (kN)	σ_u (MPa)	Rupture Mode
IIIc sR	15.2	—	81.0	1291	748	—	—	785	471	w
IIIc1sR	15.2	—	82.0	1377	—	—	—	725	471	w
IIIc2sR	15.2	—	82.0	—	960	—	—	288	471	w
IIIc3sR	15.2	—	81.0	—	—	1320	—	445	471	w
IIIc4sR	15.2	7.8	81.0	588	420	—	310	419	471	s
IIbmA 1	24.5	—	56.0	744	1497	—	—	835	491	w
IIbmA 2	24.5	—	58.0	681	1448	—	—	846	491	w
IIbmA 3	24.5	—	56.0	745	1523	—	—	807	491	w
IIbmB 1	24.7	—	56.0	783	1564	—	—	914	491	w and s
IIbmB 2	24.7	—	56.0	735	1601	—	—	951	491	w and s
IIbmB 3	24.7	—	56.0	753	1606	—	—	912	491	w and s
IIbmR 1	24.5	—	57.0	618	1343	—	—	789	471	w
IIbmR 2	24.5	—	56.0	615	1242	—	—	783	471	w
IIbmR 3	24.5	—	57.0	579	1204	—	—	757	471	w

* See Figure E1, Figure E2 and Section E.1.2 for dimensions and definition of symbols.

† In Ligtenberg (1968), L_1 was reported as *h*.

‡ In this column, *w* represents rupture in welds and *s* represents rupture in steel plates.

Table E1.8 – Belgian Test Results on St.37 Steel as Reported by Ligtenberg (1968)

Specimen Designation	t_1* (mm)	t_2 (mm)	L_1† (mm)	A_1 (mm^2)	A_2 (mm^2)	A_3 (mm^2)	A_4 (mm^2)	P_u (kN)	σ_u (MPa)	Rupture Mode‡
Ia mA	30.1	—	45.1	326	1634	—	—	755	505	w
Ia1mA	30.1	—	45.0	341	—	—	—	255	505	w
Ia2mA	30.1	—	45.9	—	1728	—	—	671	505	w
Ia3mA	30.1	—	45.2	—	—	1908	—	723	505	w
Ia4mA	30.1	15.5	45.2	130	804	—	172	387	505	w
Ib sR	19.2	—	46.2	348	1205	—	—	608	523	s
Ib1sR	19.2	—	46.6	419	—	—	—	243	523	w
Ib2sR	19.2	—	46.8	—	1249	—	—	538	523	w
Ib3sR	19.2	—	46.5	—	—	1552	—	569	523	w
Ib4sR	19.2	10.0	46.5	219	623	—	191	294	523	s
Ic hB	30.0	—	45.1	641	1405	—	—	944	554	w
Ic1hB	30.0	—	45.2	570	—	—	—	343	554	w
Ic2hB	30.0	—	44.7	—	1136	—	—	579	554	w
Ic3hB	30.0	—	45.3	—	—	1463	—	659	554	w
Ic4hB	30.0	15.3	44.3	326	516	—	255	445	554	w
IIa hR	30.0	—	54.5	442	1327	—	—	687	523	w
IIa1hR	30.0	—	55.0	447	—	—	—	245	523	w
IIa2hR	30.0	—	55.0	—	1466	—	—	555	523	w
IIa3hR	30.0	—	55.1	—	—	1531	—	577	523	w
IIa4hR	30.0	15.5	55.0	272	654	—	183	387	523	w
IIb mB	24.0	—	55.6	669	1294	—	—	1079	554	w
IIb1mB	24.0	—	55.8	613	—	—	—	512	554	w
IIb2mB	24.0	—	55.7	—	1266	—	—	589	554	w
IIb3mB	24.0	—	55.7	—	—	1623	—	753	554	w
IIb4mB	24.0	12.2	55.0	363	599	—	292	520	554	s
IIc sA	19.1	—	56.2	821	941	—	—	701	505	s
IIc1sA	19.1	—	55.6	940	—	—	—	569	505	w
IIc2sA	19.1	—	56.4	—	986	—	—	381	505	w
IIc3sA	19.1	—	55.1	—	—	1620	—	585	505	w
IIc4sA	19.1	10.0	55.0	460	503	—	387	353	505	w
IIIa sB	15.2	—	80.4	804	1151	—	—	844	554	w
IIIa1sB	15.2	—	80.5	673	—	—	—	536	554	w
IIIa2sB	15.2	—	79.9	—	1304	—	—	475	554	w and s
IIIa3sB	15.2	—	80.9	—	—	1727	—	538	554	w and s
IIIa4sB	15.2	8.6	81.5	353	588	—	588	459	554	s
IIIb hA	24.1	—	80.3	919	967	—	—	867	505	w
IIIb1hA	24.1	—	81.0	913	—	—	—	626	505	w
IIIb2hA	24.1	—	80.7	—	986	—	—	390	505	w
IIIb3hA	24.1	—	80.5	—	—	1705	—	626	505	w
IIIb4hA	24.1	12.4	80.0	435	518	—	478	677	505	s

Table E1.8 (cont.)

Specimen Designation	t_1 (mm)	t_2 (mm)	L_1 (mm)	A_1 (mm^2)	A_2 (mm^2)	A_3 (mm^2)	A_4 (mm^2)	P_u (kN)	σ_u (MPa)	Rupture Mode
IIIc mR	19.0	—	79.9	1321	702	—	—	940	523	w
IIIc1mR	19.0	—	80.1	1285	—	—	—	742	523	w
IIIc2mR	19.0	—	81.6	—	764	—	—	267	523	w
IIIc3mR	19.0	—	80.2	—	—	1598	—	491	523	w
IIIc4mR	19.0	10.2	80.0	560	384	—	580	518	523	s
IIbmA 1	24.2	—	55.2	561	1156	—	—	829	505	w
IIbmA 2	24.2	—	55.7	591	1075	—	—	736	505	w
IIbmA 3	24.2	—	55.4	592	1095	—	—	770	505	w
IIbmB 1	24.2	—	55.4	606	1261	—	—	1020	554	w
IIbmB 2	24.2	—	54.8	540	1182	—	—	976	554	w
IIbmB 3	24.2	—	56.0	568	1261	—	—	1010	554	w
IIbmR 1	24.3	—	56.0	574	1137	—	—	893	523	w
IIbmR 2	24.3	—	55.5	518	1118	—	—	785	523	w
IIbmR 3	24.3	—	55.5	495	1204	—	—	834	523	w

* See Figure E1, Figure E2 and Section E.1.2 for dimensions and definition of symbols.

† In Ligtenberg (1968), L_1 was reported as *h*.

‡ In this column, *w* represents rupture in welds and *s* represents rupture in steel plates.

Table E1.9 – Netherlands' Test Results on St.37 Steel as Reported by Ligtenberg (1968)

Specimen Designation	t_1 * (mm)	t_2 (mm)	L_1 † (mm)	A_1 (mm^2)	A_2 (mm^2)	A_3 (mm^2)	A_4 (mm^2)	P_u (kN)	σ_u (MPa)	Rupture Mode‡
Ia hA	38.0	—	46.0	390	1780	—	—	780	474	w
Ia1hA	38.0	—	46.0	366	—	—	—	231	474	w
Ia2hA	38.0	—	46.0	—	1754	—	—	711	474	w
Ia3hA	38.0	—	46.0	—	—	2192	—	814	474	w
Ia4hA	38.0	19.0	45.0	198	906	—	158	441	474	w
Ib mR	24.0	—	45.0	464	1572	—	—	766	477	w
Ib1mR	24.0	—	45.0	418	—	—	—	251	477	w
Ib2mR	24.0	—	46.0	—	1284	—	—	603	477	w
Ib3mR	24.0	—	46.0	—	—	1838	—	700	477	w
Ib4mR	24.0	12.5	50.0	202	676	—	198	432	477	w
Ic sB	19.0	—	46.0	664	1422	—	—	775	559	s
Ic1sB	19.0	—	46.0	686	—	—	—	466	559	w
Ic2sB	19.0	—	46.0	—	1722	—	—	687	559	w
Ic3sB	19.0	—	46.0	—	—	1906	—	736	559	s
Ic4sB	19.0	10.0	44.0	355	722	—	267	358	559	s
IIa sR	19.0	—	56.0	419	1530	—	—	826	477	w
IIa1sR	19.0	—	56.0	490	—	—	—	294	477	w
IIa2sR	19.0	—	56.0	—	1650	—	—	623	477	w
IIa3sR	19.0	—	56.0	—	—	1762	—	687	477	w
IIa4sR	19.0	10.5	57.0	241	680	—	194	420	477	s
IIb hB	31.0	—	56.0	838	1494	—	—	1079	559	w
IIb1hB	31.0	—	55.0	736	—	—	—	540	559	w
IIb2hB	31.0	—	55.0	—	1326	—	—	633	559	w
IIb3hB	31.0	—	55.0	—	—	1900	—	800	559	w
IIb4hB	31.0	15.0	57.5	421	773	—	425	643	559	s
IIc mA	24.0	—	56.0	1000	1214	—	—	956	474	w
IIc1mA	24.0	—	55.0	972	—	—	—	528	474	w
IIc2mA	24.0	—	55.0	—	1182	—	—	446	474	w
IIc3mA	24.0	—	55.0	—	—	1868	—	746	474	w
IIc4mA	24.0	12.0	58.0	523	465	—	452	638	474	s
IIIa mB	19.0	—	82.0	873	1310	—	—	1099	559	w and s
IIIa1mB	19.0	—	80.0	817	—	—	—	638	559	w
IIIa2mB	19.0	—	80.0	—	1324	—	—	592	559	w
IIIa3mB	19.0	—	81.0	—	—	1836	—	785	559	w
IIIa4mB	19.0	10.5	78.0	443	754	—	339	579	559	w
IIIb sA	16.0	—	80.0	924	1032	—	—	853	474	w and s
IIIb1sA	16.0	—	81.0	1008	—	—	—	540	474	w
IIIb2sA	16.0	—	81.0	—	1005	—	—	392	474	w
IIIb3sA	16.0	—	81.0	—	—	1552	—	589	474	w
IIIb4sA	16.0	8.0	82.0	364	568	—	440	437	474	s

Table E1.9 (cont.)

Specimen Designation	t_1 (mm)	t_2 (mm)	L_1 (mm)	A_1 (mm^2)	A_2 (mm^2)	A_3 (mm^2)	A_4 (mm^2)	P_u (kN)	σ_u (MPa)	Rupture Mode
IIIc hR	24.0	—	82.0	1478	854	—	—	1177	477	w
IIIc1hR	24.0	—	81.0	1445	—	—	—	858	477	w
IIIc2hR	24.0	—	81.0	—	844	—	—	294	477	w
IIIc3hR	24.0	—	80.0	—	—	1712	—	706	477	w
IIIc4hR	24.0	12.0	82.0	687	392	—	648	799	477	w
IIbmA 1	25.0	—	56.0	576	1254	—	—	775	474	w
IIbmA 2	25.0	—	56.0	604	1204	—	—	726	474	w
IIbmA 3	25.0	—	56.0	650	1206	—	—	770	474	w
IIbmB 1	25.0	—	56.0	820	1550	—	—	947	559	w and s
IIbmB 2	25.0	—	56.0	852	1660	—	—	947	559	w and s
IIbmB 3	25.0	—	56.0	780	1480	—	—	932	559	w and s
IIbmR 1	25.0	—	55.0	654	1216	—	—	726	477	w
IIbmR 2	25.0	—	55.0	584	1172	—	—	701	477	w
IIbmR 3	25.0	—	55.0	668	1270	—	—	736	477	w

* See Figure E1, Figure E2 and Section E.1.2 for dimensions and definition of symbols.

† In Ligtenberg (1968), L_1 was reported as *h*.

‡ In this column, *w* represents rupture in welds and *s* represents rupture in steel plates.

Table E1.10 – Canadian Test Results on St.37 Steel as Reported by Ligtenberg (1968)

Specimen Designation	t_1* (mm)	t_2 (mm)	L_1† (mm)	A_1 (mm^2)	A_2 (mm^2)	A_3 (mm^2)	A_4 (mm^2)	P_u (kN)	σ_u (MPa)	Rupture Mode‡
Ia mR	38.1	—	43.9	342	1507	—	—	832	580	w
Ia1mR	38.1	—	43.8	310	—	—	—	190	580	w
Ia2mR	38.1	—	44.5	—	1456	—	—	693	580	w
Ia3mR	38.1	—	44.5	—	—	1778	—	808	580	w
Ib hB	23.6	—	46.5	336	1299	—	—	990	562	w
Ib1hB	23.6	—	47.4	379	—	—	—	323	562	w
Ib2hB	23.6	—	44.4	—	1234	—	—	667	562	w
Ib3hB	23.6	—	44.6	—	—	1432	—	713	562	w
Ic sA	19.3	—	44.5	471	1174	—	—	749	486	w
Ic1sA	19.3	—	44.5	458	—	—	—	323	486	w
Ic2sA	19.3	—	44.5	—	1304	—	—	512	486	w
Ic3sA	19.3	—	44.5	—	—	1455	—	534	486	w
IIa sB	19.3	—	57.1	437	1213	—	—	913	562	w
IIa1sB	19.3	—	57.1	428	—	—	—	338	562	w
IIa2sB	19.3	—	56.1	—	1251	—	—	652	562	w
IIa3sB	19.3	—	56.1	—	—	1654	—	699	562	w
IIb mA	29.4	—	54.6	472	913	—	—	751	451	w
IIb1mA	29.4	—	55.2	471	—	—	—	347	451	w
IIb2mA	29.4	—	54.2	—	859	—	—	430	451	w
IIb3mA	29.4	—	56.4	—	—	1669	—	666	451	w
IIc hR	24.1	—	55.6	788	1079	—	—	1024	580	w
IIc1hR	24.1	—	55.4	870	—	—	—	730	580	w
IIc2hR	24.1	—	55.4	—	929	—	—	449	580	w
IIc3hR	24.1	—	56.6	—	—	1713	—	753	580	w
IIIa hA	19.3	—	81.8	802	1182	—	—	908	451	w
IIIa1hA	19.3	—	82.3	735	—	—	—	501	451	w
IIIa2hA	19.3	—	80.5	—	1173	—	—	427	451	w
IIIa3hA	19.3	—	80.3	—	—	1512	—	501	451	w
IIIb sR	14.0	—	79.2	893	889	—	—	853	580	w
IIIb1sR	14.0	—	80.8	812	—	—	—	622	580	w
IIIb2sR	14.0	—	81.0	—	841	—	—	367	580	w
IIIb3sR	14.0	—	80.0	—	—	1503	—	559	580	w
IIIc mB	23.6	—	80.0	1427	788	—	—	1247	562	w
IIIc1mB	23.6	—	80.3	1059	—	—	—	945	562	w
IIIc2mB	23.6	—	80.8	—	720	—	—	372	562	w
IIIc3mB	23.6	—	77.5	—	—	1591	—	684	562	w

Table E1.10 (cont.)

Specimen Designation	t_1 (mm)	t_2 (mm)	L_1 (mm)	A_1 (mm^2)	A_2 (mm^2)	A_3 (mm^2)	A_4 (mm^2)	P_u (kN)	σ_u (MPa)	Rupture Mode
IIbmA 1	24.6	—	57.0	403	851	—	—	632	451	w
IIbmA 2	24.6	—	57.0	425	878	—	—	639	451	w
IIbmB 1	24.4	—	58.2	588	1105	—	—	917	562	w
IIbmB 2	24.4	—	56.0	538	1250	—	—	954	562	w
IIbmR 1	23.6	—	57.1	427	1041	—	—	851	580	w
IIbmR 2	23.6	—	57.1	450	969	—	—	854	580	w

* See Figure E1, Figure E2 and Section E.1.2 for dimensions and definition of symbols.

† In Ligtenberg (1968), L_1 was reported as *h*.

‡ In this column, *w* represents rupture in welds and *s* represents rupture in steel plates.

Table E1.11 – Swedish Test Results on St.37 Steel as Reported by Ligtenberg (1968)

Specimen Designation	t_1* (mm)	t_2 (mm)	L_1† (mm)	A_1 (mm^2)	A_2 (mm^2)	A_3 (mm^2)	A_4 (mm^2)	P_u (kN)	σ_u (MPa)	Rupture Mode‡
Ia sR	25.3	—	47.8	277	1610	—	—	675	508	w
Ia1sR	25.3	—	46.3	294	—	—	—	193	508	w
Ia2sR	25.3	—	46.0	—	1575	—	—	608	508	w
Ia3sR	25.3	—	45.7	—	—	1882	—	738	508	w
Ib hB	30.2	—	47.8	312	1068	—	—	736	506	w
Ib1hB	30.2	—	46.2	333	—	—	—	234	506	w
Ib2hB	30.2	—	46.9	—	1066	—	—	541	506	w
Ib3hB	30.2	—	47.4	—	—	1537	—	665	506	w
Ic mA	25.3	—	45.7	571	981	—	—	771	486	w
Ic1mA	25.3	—	46.0	535	—	—	—	302	486	w
Ic2mA	25.3	—	46.1	—	969	—	—	472	486	w
Ic3mA	25.3	—	46.6	—	—	1237	—	491	486	w
IIa mB	25.3	—	56.1	337	1303	—	—	676	506	w
IIa1mB	25.3	—	55.6	347	—	—	—	264	506	w
IIa2mB	25.3	—	56.0	—	1357	—	—	588	506	w
IIa3mB	25.3	—	56.5	—	—	1493	—	597	506	w
IIb sA	20.4	—	56.6	581	1148	—	—	692	486	w
IIb1sA	20.4	—	56.8	546	—	—	—	346	486	w
IIb2sA	20.4	—	56.2	—	1231	—	—	397	486	w
IIb3sA	20.4	—	58.7	—	—	1608	—	579	486	w
IIc hR	30.2	—	54.8	877	905	—	—	859	508	w
IIc1hR	30.2	—	55.4	913	—	—	—	525	508	w
IIc2hR	30.2	—	55.2	—	913	—	—	371	508	w
IIc3hR	30.2	—	55.9	—	—	1351	—	498	508	w
IIIa hA	25.4	—	82.0	590	1404	—	—	783	486	w
IIIa1hA	25.4	—	81.8	611	—	—	—	374	486	w
IIIa2hA	25.4	—	80.9	—	1249	—	—	428	486	w
IIIa3hA	25.4	—	82.6	—	—	1607	—	463	486	w
IIIb mR	21.5	—	80.3	866	973	—	—	894	508	w
IIIb1mR	21.5	—	80.9	913	—	—	—	542	508	w
IIIb2mR	21.5	—	79.9	—	1028	—	—	391	508	w
IIIb3mR	21.5	—	80.4	—	—	1611	—	591	508	w
IIIc sB	16.2	—	80.6	1192	782	—	—	727	506	w
IIIc1sB	16.2	—	80.2	1306	—	—	—	564	506	w
IIIc2sB	16.2	—	81.1	—	656	—	—	228	506	w
IIIc3sB	16.2	—	80.3	—	—	1649	—	509	506	w

Table E1.11 (cont.)

Specimen Designation	t_1 (mm)	t_2 (mm)	L_1 (mm)	A_1 (mm^2)	A_2 (mm^2)	A_3 (mm^2)	A_4 (mm^2)	P_u (kN)	σ_u (MPa)	Rupture Mode
IIbmA 1	25.2	—	56.2	599	1182	—	—	701	486	w
IIbmA 2	25.2	—	56.3	608	1217	—	—	754	486	w
IIbmA 3	25.2	—	55.8	571	1217	—	—	721	486	w
IIbmB 1	25.2	—	56.2	579	1135	—	—	734	506	w
IIbmB 2	25.2	—	55.8	592	1140	—	—	703	506	w
IIbmB 3	25.2	—	55.7	567	1206	—	—	706	506	w
IIbmR 1	25.4	—	55.7	503	1089	—	—	701	508	w
IIbmR 2	25.4	—	56.0	515	1158	—	—	711	508	w
IIbmR 3	25.4	—	56.4	518	1086	—	—	647	508	w

* See Figure E1, Figure E2 and Section E.1.2 for dimensions and definition of symbols.

† In Ligtenberg (1968), L_1 was reported as *h*.

‡ In this column, *w* represents rupture in welds and *s* represents rupture in steel plates.

Table E1.12 – Yugoslavian Test Results on St.37 Steel as Reported by Ligtenberg (1968)

Specimen Designation	t_1* (mm)	t_2 (mm)	L_1† (mm)	A_1 (mm^2)	A_2 (mm^2)	A_3 (mm^2)	A_4 (mm^2)	P_u (kN)	σ_u (MPa)	Rupture Mode‡
Ia mA	15.9	—	60.0	228	1244	—	—	491	491	w
Ia1mA	15.9	—	60.0	211	—	—	—	83	491	w
Ia2mA	15.9	—	60.0	—	1196	—	—	481	491	w
Ia mB	15.9	—	59.0	226	1206	—	—	585	549	w
Ia1mB	15.9	—	60.0	239	—	—	—	145	549	w
Ia2mB	15.9	—	60.0	—	1279	—	—	471	549	w
Ib mA	16.0	—	60.0	257	967	—	—	434	491	w
Ib1mA	16.0	—	60.0	250	—	—	—	108	491	w
Ib2mA	16.0	—	60.0	—	922	—	—	360	491	w
Ib mB	15.8	—	60.0	269	960	—	—	541	549	w
Ib1mB	15.8	—	60.0	335	—	—	—	180	549	w
Ib2mB	15.8	—	60.0	—	917	—	—	435	549	w
Ic mA	15.8	—	60.0	302	724	—	—	511	491	w
Ic1mA	15.8	—	60.0	328	—	—	—	177	491	w
Ic2mA	15.8	—	60.0	—	758	—	—	342	491	w
Ic mB	15.7	—	60.0	329	842	—	—	>589+	549	w
Ic1mB	15.7	—	60.0	316	—	—	—	210	549	w
Ic2mB	15.7	—	60.0	—	887	—	—	408	549	w
IIa mA	16.2	—	60.0	430	1082	—	—	497	491	w
IIa1mA	16.2	—	60.0	329	—	—	—	180	491	w
IIa2mA	16.2	—	60.0	—	998	—	—	392	491	w
IIa mB	16.1	—	59.0	349	1002	—	—	563	549	w
IIa1mB	16.1	—	60.0	329	—	—	—	280	549	w
IIa2mB	16.1	—	60.0	—	988	—	—	409	549	w
IIb mA	16.1	—	60.0	366	773	—	—	452	491	w
IIb1mA	16.1	—	60.0	376	—	—	—	221	491	w
IIb2mA	16.1	—	60.0	—	782	—	—	274	491	w
IIb mB	16.1	—	59.0	418	882	—	—	>589+	549	w
IIb1mB	16.1	—	60.0	376	—	—	—	300	549	w
IIb2mB	16.1	—	60.0	—	829	—	—	401	549	w
IIc mA	16.1	—	59.0	428	710	—	—	507	491	w
IIc1mA	16.1	—	60.0	479	—	—	—	279	491	w
IIc2mA	16.1	—	60.0	—	712	—	—	250	491	w
IIc mB	16.0	—	59.0	498	787	—	—	>589+	549	w
IIc1mB	16.0	—	60.0	482	—	—	—	288	549	w
IIc2mB	16.0	—	60.0	—	825	—	—	362	549	w
IIIa mA	16.1	—	80.0	386	654	—	—	511	491	w
IIIa1mA	16.1	—	80.0	439	—	—	—	258	491	w
IIIa2mA	16.1	—	80.0	—	612	—	—	243	491	w

Table E1.12 (cont.)

Specimen Designation	t_1 (mm)	t_2 (mm)	L_1 (mm)	A_1 (mm^2)	A_2 (mm^2)	A_3 (mm^2)	A_4 (mm^2)	P_u (kN)	σ_u (MPa)	Rupture Mode
IIIa mB	16.0	—	80.0	386	695	—	—	563	549	w
IIIa1mB	16.0	—	80.0	457	—	—	—	290	549	w
IIIa2mB	16.0	—	80.0	—	630	—	—	271	549	w
IIIb mA	16.1	—	80.0	473	528	—	—	430	491	w
IIIb1mA	16.1	—	80.0	461	—	—	—	260	491	w
IIIb2mA	16.1	—	80.0	—	492	—	—	184	491	w
IIIb mB	16.0	—	80.0	498	517	—	—	577	549	w
IIIb1mB	16.0	—	80.0	469	—	—	—	320	549	w
IIIb2mB	16.0	—	80.0	—	520	—	—	261	549	w
IIIc mA	16.1	—	80.0	596	442	—	—	512	491	w
IIIc1mA	16.1	—	80.0	633	—	—	—	340	491	w
IIIc2mA	16.1	—	80.0	—	468	—	—	160	491	w
IIIc mB	16.0	—	80.0	644	491	—	—	>589$^+$	549	w
IIIc1mB	16.0	—	80.0	603	—	—	—	378	549	w
IIIc2mB	16.0	—	80.0	—	492	—	—	236	549	w

* See Figure E1, Figure E2 and Section E.1.2 for dimensions and definition of symbols.

† In Ligtenberg (1968), L_1 was reported as *h*.

‡ In this column, *w* represents rupture in welds and *s* represents rupture in steel plates.

+ Exceeded test machine capacity.

Table E1.13 – Netherlands' Test Results on St.52 Steel as Reported by Ligtenberg (1968)

Specimen Designation	t_1 * (mm)	L_1 † (mm)	A_1 (mm^2)	A_2 (mm^2)	P_u (kN)	σ_u (MPa)
Ib	23.3	48.0	445	1123	895	544
Ib1	23.3	46.0	392	—	235	544
Ib2	23.3	45.0	—	1243	623	544
Ib3	23.3	47.0	—	1545	682	544
IIa	23.3	57.0	398	1378	804	544
IIa1	23.3	56.0	442	—	303	544
IIa2	23.3	56.0	—	1392	564	544
IIa3	23.3	56.0	—	1738	660	544
IIb	23.3	56.0	719	1235	814	544
IIb1	23.3	56.0	734	—	348	544
IIb2	23.3	55.0	—	1293	532	544
IIb3	23.3	57.0	—	1726	674	544
IIc	23.3	57.0	804	996	917	544
IIc1	23.3	56.0	882	—	523	544
IIc2	23.3	59.0	—	961	471	544
IIc3	23.3	56.0	—	1566	657	544
IIIb	23.3	82.0	1181	1178	1138	544
IIIb1	23.3	81.0	1162	—	719	544
IIIb2	23.3	82.0	—	1228	530	544
IIIb3	23.3	81.0	—	1272	579	544
II1 b	23.3	56.0	525	986	741	544
II2 b	23.3	56.0	609	1098	798	544
II3 b	23.3	57.0	533	1167	831	544
II4 b	23.3	57.0	532	1136	736	544
II5 b	23.3	54.0	562	1092	831	544
II6 b	23.3	56.0	588	1058	769	544
II7 b	23.3	56.0	585	1012	780	544
II8 b	23.3	55.0	634	1146	809	544
II b‡	23.3	—	612	1215	883	570
II b	23.3	—	566	1245	852	570
II b	23.3	—	567	1126	910	570
II b	23.3	—	532	1090	860	570
II b	23.3	—	591	1091	890	570

* See Figure E1, Figure E2 and Section E.1.2 for dimensions and definition of symbols.

† In Ligtenberg (1968), L_1 was reported as *h*.

‡ This group of specimens was not used in the reliability analysis because no measured shear strength is available for the weld metal used in this group.

Table E1.14 – German Test Results on St.52 Steel as Reported by Ligtenberg (1968)

Specimen Designation	t_1 * (mm)	L_1 † (mm)	A_1 (mm^2)	A_2 (mm^2)	P_u (kN)	σ_u (MPa)
Ib	20.0	46.0	277	1070	781	549
Ib1	20.0	46.0	350	—	291	549
Ib2	20.0	46.0	—	982	549	549
Ib3	20.0	46.0	—	1330	594	549
IIa	20.0	56.0	348	1285	840	549
IIa1	20.0	56.0	381	—	332	549
IIa2	20.0	56.0	—	1278	623	549
IIa3	20.0	56.0	—	1645	689	549
IIb	20.0	56.0	532	1140	954	549
IIb1	20.0	56.0	538	—	409	549
IIb2	20.0	56.0	—	1036	505	549
IIb3	20.0	56.0	—	1665	673	549
IIc	20.0	55.0	935	880	1077	549
IIc1	20.0	55.0	885	—	573	549
IIc2	20.0	55.0	—	866	433	549
IIc3	20.0	55.0	—	1700	685	549
IIIb	20.0	81.0	955	990	1148	549
IIIb1	20.0	81.0	970	—	806	549
IIIb2	20.0	81.0	—	935	426	549
IIIb3	20.0	81.0	—	1530	603	549
II1 b	20.0	56.0	582	1070	903	549
II2 b	20.0	56.0	590	1190	907	549
II3 b	20.0	56.0	550	1110	869	549
II4 b	20.0	56.0	549	1155	926	549
II5 b	20.0	56.0	534	1045	918	549
II6 b	20.0	56.0	582	1120	903	549
II7 b	20.0	56.0	560	1140	921	549
II8 b	20.0	56.0	527	1140	902	549

* See Figure E1, Figure E2 and Section E.1.2 for dimensions and definition of symbols.

† In Ligtenberg (1968), L_1 was reported as *h*.

Table E1.15 – Italian Test Results on St.52 Steel as Reported by Ligtenberg (1968)

Specimen Designation	t_1 * (mm)	L_1 † (mm)	A_1 (mm^2)	A_2 (mm^2)	P_u (kN)	σ_u (MPa)
Ib	20.0	45.5	386	1059	834	553
Ib1	20.0	45.3	460	—	277	553
Ib2	20.0	45.0	—	1158	562	553
Ib3	20.0	45.0	—	1460	687	553
IIa	20.0	55.6	382	1490	844	553
IIa1	20.0	56.0	563	—	358	553
IIa2	20.0	55.5	—	1460	663	553
IIa3	20.0	55.4	—	1554	698	553
IIb	20.0	55.5	499	1145	827	553
IIb1	20.0	55.5	572	—	339	553
IIb2	20.0	55.5	—	1197	535	553
IIb3	20.0	55.2	—	1702	740	553
IIc	20.0	55.2	884	1018	1064	553
IIc1	20.0	55.5	932	—	571	553
IIc2	20.0	55.5	—	990	495	553
IIc3	20.0	55.5	—	1774	756	553
IIIb	20.0	80.3	1076	1149	1152	553
IIIb1	20.0	81.0	1038	—	559	553
IIIb2	20.0	80.5	—	966	461	553
IIIb3	20.0	80.5	—	1546	640	553
II1 b	20.0	55.0	489	1168	776	553
II2 b	20.0	55.5	555	1175	820	553
II3 b	20.0	56.0	537	1146	811	553
II4 b	20.0	55.3	564	1279	878	553
II5 b	20.0	55.3	559	1281	882	553
II6 b	20.0	55.3	553	1224	845	553
II7 b	20.0	55.7	557	1284	876	553
II8 b	20.0	55.3	574	1105	843	553

* See Figure E1, Figure E2 and Section E.1.2 for dimensions and definition of symbols.

† In Ligtenberg (1968), L_1 was reported as *h*.

Table E1.16 – Swedish Test Results on St.52 Steel as Reported by Ligtenberg (1968)

Specimen Designation	t_1* (mm)	L_1 † (mm)	A_1 (mm^2)	A_2 (mm^2)	P_u (kN)	σ_u (MPa)
Ib	22.5	44.0	312	974	656	558
Ib1	22.5	44.0	281	—	228	558
Ib2	22.5	43.0	—	777	481	558
Ib3	22.5	45.0	—	1560	663	558
IIa	22.5	55.0	402	1243	761	558
IIa1	22.5	55.0	389	—	281	558
IIa2	22.5	54.0	—	1156	561	558
IIa3	22.5	55.0	—	1451	702	558
IIb	22.5	55.0	524	987	864	558
IIb	22.5	55.0	582	1056	852	558
IIb	22.5	55.0	578	1041	793	558
IIb1	22.5	55.0	540	—	392	558
IIb1	22.5	55.0	545	—	398	558
IIb1	22.5	55.0	583	—	399	558
IIb2	22.5	54.0	—	1000	467	558
IIb2	22.5	52.0	—	1077	483	558
IIb2	22.5	55.0	—	964	535	558
IIb3	22.5	54.0	—	1550	709	558
IIb3	22.5	54.0	—	1472	681	558
IIb3	22.5	53.0	—	1476	702	558
IIc	22.5	56.0	860	843	1012	558
IIc1	22.5	55.0	858	—	618	558
IIc2	22.5	55.0	—	741	466	558
IIc3	22.5	55.0	—	1496	705	558
IIIb	22.5	80.0	795	968	1048	558
IIIb1	22.5	81.0	866	—	710	558
IIIb2	22.5	79.0	—	1009	463	558
IIIb3	22.5	79.0	—	1658	657	558
II b‡	22.5	56.0	600	1056	932	677
II b	22.5	55.0	550	1016	991	677
II b	22.5	55.0	451	1108	961	677
II b	22.5	56.0	532	1077	1010	677
II b	22.5	55.0	578	985	969	677

* See Figure E1, Figure E2 and Section E.1.2 for dimensions and definition of symbols.

† In Ligtenberg (1968), L_1 was reported as *h*.

‡ This group of specimens was not used in the reliability analysis because no measured shear strength is available for the weld metal used in this group.

Table E1.17 – Summary of Ratio ρ_G for Specimens Reported by Ligtenberg (1968)

Nominal Throat Size (mm)	3	3.5	4	4.5	5	6	7.5	8	10
Corresponding Leg Size (mm)	4.2	4.9	5.7	6.4	7.1	8.5	10.6	11.3	14.1
Sample Size	97	67	91	13	302	145	41	87	31
Mean ρ_G	1.230	1.121	1.109	1.071	1.056	1.039	0.986	0.997	0.996
V_G	0.168	0.163	0.171	0.096	0.155	0.147	0.098	0.100	0.124

Table E1.18 – Summary of Ratio ρ_L for Specimens Reported by Ligtenberg (1968)

	England	Japan	USA	France	Germany	Belgium	Netherlands	Canada	Sweden
Sample Size	54	45	54	54	54	54	54	42	45
Mean ρ_L	1.000	1.000	1.001	1.022	1.022	1.009	1.015	1.010	1.021
V_L	0.004	0.002	0.001	0.014	0.012	0.011	0.019	0.022	0.016

Table E1.19 – Analysis of British Test Results on St.37 Steel as Reported by Ligtenberg (1968)

Specimen Designation		Specimens with a_2 or a_3 only			Specimens with a_1 only		Specimens with a_1 and a_2						Specimens with a_1, a_2 and a_4	
	Model	Equation 4.6a			Equation 4.7		Equation 4.9		Equation 4.10		Equation 4.10a and b		Equation 4.9	
	P_u (kN)	τ_u (MPa)	$0.67\sigma_u$ (MPa)	Ratio ρ_{M2}	Predicted Capacity (kN)	Ratio ρ_P	Predicted Capacity (kN)	Ratio ρ_P	Predicted Capacity (kN)	Ratio ρ_P	Predicted Capacity (kN)	Ratio ρ_P	Predicted Capacity (kN)	Ratio ρ_P
Ia sA	681	—	—	—	—	—	682	0.999	773	0.881	718	0.949	—	—
Ia1sA	182	—	—	—	156	1.173	—	—	—	—	—	—	—	—
Ia2sA	645	365	302	1.206	—	—	—	—	—	—	—	—	—	—
Ia3sA	719	349	302	1.155	—	—	—	—	—	—	—	—	—	—
Ia4sA	342	—	—	—	—	—	—	—	—	—	—	—	414	0.827
Ib mB	579	—	—	—	—	—	664	0.872	742	0.781	667	0.868	—	—
Ib1mB	272	—	—	—	215	1.263	—	—	—	—	—	—	—	—
Ib2mB	491	406	381	1.065	—	—	—	—	—	—	—	—	—	—
Ib3mB	539	352	381	0.924	—	—	—	—	—	—	—	—	—	—
Ib4mB	318	—	—	—	—	—	—	—	—	—	—	—	411	0.773
Ic hR	712	—	—	—	—	—	630	1.131	688	1.035	630	1.131	—	—
Ic1hR	284	—	—	—	270	1.053	—	—	—	—	—	—	—	—
Ic2hR	429	377	329	1.146	—	—	—	—	—	—	—	—	—	—
Ic3hR	454	355	329	1.081	—	—	—	—	—	—	—	—	—	—
Ic4hR	437	—	—	—	—	—	—	—	—	—	—	—	446	0.980
IIa hB	726	—	—	—	—	—	708	1.026	790	0.919	710	1.022	—	—
IIa1hB	187	—	—	—	213	0.878	—	—	—	—	—	—	—	—
IIa2hB	579	390	381	1.024	—	—	—	—	—	—	—	—	—	—
IIa3hB	649	370	381	0.971	—	—	—	—	—	—	—	—	—	—
IIa4hB	363	—	—	—	—	—	—	—	—	—	—	—	442	0.822

Table E1.19 (cont.)

Specimen Designation		Specimens with a_2 or a_3 only			Specimens with a_1 only		Specimens with a_1 and a_2						Specimens with a_1, a_2 and a_4	
	Model	Equation 4.6a			Equation 4.7		Equation 4.9		Equation 4.10		Equation 4.10a and b		Equation 4.9	
	P_u (kN)	τ_u (MPa)	$0.67\sigma_u$ (MPa)	Ratio ρ_{M2}	Predicted Capacity (kN)	Ratio ρ_P	Predicted Capacity (kN)	Ratio ρ_P	Predicted Capacity (kN)	Ratio ρ_P	Predicted Capacity (kN)	Ratio ρ_P	Predicted Capacity (kN)	Ratio ρ_P
IIb sR	719	—	—	—	—	—	686	1.049	751	0.957	686	1.049	—	—
IIb1sR	303	—	—	—	312	0.973	—	—	—	—	—	—	—	—
IIb2sR	483	381	329	1.159	—	—	—	—	—	—	—	—	—	—
IIb3sR	590	345	329	1.049	—	—	—	—	—	—	—	—	—	—
IIb4sR	405	—	—	—	—	—	—	—	—	—	—	—	512	0.791
IIc mA	877	—	—	—	—	—	781	1.122	833	1.053	781	1.122	—	—
IIc1mA	507	—	—	—	490	1.036	—	—	—	—	—	—	—	—
IIc2mA	342	352	302	1.164	—	—	—	—	—	—	—	—	—	—
IIc3mA	645	379	302	1.254	—	—	—	—	—	—	—	—	—	—
IIc4mA	525	—	—	—	—	—	—	—	—	—	—	—	621	0.846
IIIa mR	837	—	—	—	—	—	811	1.031	883	0.947	811	1.031	—	—
IIIa1mR	316	—	—	—	345	0.916	—	—	—	—	—	—	—	—
IIIa2mR	437	315	329	0.958	—	—	—	—	—	—	—	—	—	—
IIIa3mR	507	302	329	0.919	—	—	—	—	—	—	—	—	—	—
IIIa4mR	928	—	—	—	—	—	—	—	—	—	—	—	547	1.698
IIIb hA	930	—	—	—	—	—	881	1.056	937	0.993	881	1.056	—	—
IIIb1hA	592	—	—	—	548	1.079	—	—	—	—	—	—	—	—
IIIb2hA	381	368	302	1.218	—	—	—	—	—	—	—	—	—	—
IIIb3hA	545	318	302	1.053	—	—	—	—	—	—	—	—	—	—
IIIb4hA	619	—	—	—	—	—	—	—	—	—	—	—	718	0.862

Table E1.19 (cont.)

Specimen Designation		Specimens with a_2 or a_3 only			Specimens with a_1 only		Specimens with a_1 and a_2						Specimens with a_1, a_2 and a_4	
	Model	Equation 4.6a			Equation 4.7		Equation 4.9		Equation 4.10		Equation 4.10a and b		Equation 4.9	
	P_u (kN)	τ_u (MPa)	$0.67\sigma_u$ (MPa)	Ratio ρ_{M2}	Predicted Capacity (kN)	Ratio ρ_P	Predicted Capacity (kN)	Ratio ρ_P	Predicted Capacity (kN)	Ratio ρ_P	Predicted Capacity (kN)	Ratio ρ_P	Predicted Capacity (kN)	Ratio ρ_P
IIIc sB	991†	—	—	—	—	—	—	—	—	—	—	—	—	—
IIIc1sB	801	—	—	—	780	1.028	—	—	—	—	—	—	—	—
IIIc2sB	276	404	381	1.059	—	—	—	—	—	—	—	—	—	—
IIIc3sB	619	372	381	0.976	—	—	—	—	—	—	—	—	—	—
IIIc4sB	432	—	—	—	—	—	—	—	—	—	—	—	874	0.494
IIbmA 1	735	—	—	—	—	—	653	1.126	714	1.029	653	1.126	—	—
IIbmA 2	765	—	—	—	—	—	686	1.116	749	1.021	686	1.116	—	—
IIbmA 3	763	—	—	—	—	—	719	1.061	785	0.972	719	1.061	—	—
IIbmB 1	851†	—	—	—	—	—	—	—	—	—	—	—	—	—
IIbmB 2	939	—	—	—	—	—	750	1.252	821	1.143	750	1.252	—	—
IIbmB 3	948	—	—	—	—	—	736	1.287	802	1.182	736	1.287	—	—
IIbmR 1	837	—	—	—	—	—	716	1.169	784	1.068	716	1.169	—	—
IIbmR 2	810	—	—	—	—	—	729	1.111	798	1.016	729	1.111	—	—
IIbmR 3	645	—	—	—	—	—	674	0.958	735	0.879	674	0.958	—	—

† Specimen ruptured in steel plate.

Table E1.20 – Analysis of Japanese Test Results on St.37 Steel as Reported by Ligtenberg (1968)

Specimen Designation		Specimens with a_2 or a_3 only			Specimens with a_1 only		Specimens with a_1 and a_2						Specimens with a_1, a_2 and a_4	
	Model	Equation 4.6a			Equation 4.7		Equation 4.9		Equation 4.10		Equation 4.10a and b		Equation 4.9	
	P_u (kN)	τ_u (MPa)	$0.67\sigma_u$ (MPa)	Ratio ρ_{M2}	Predicted Capacity (kN)	Ratio ρ_P	Predicted Capacity (kN)	Ratio ρ_P	Predicted Capacity (kN)	Ratio ρ_P	Predicted Capacity (kN)	Ratio ρ_P	Predicted Capacity (kN)	Ratio ρ_P
Ia hA	699	—	—	—	—	—	641	1.091	722	0.969	662	1.057	—	—
Ia1hA	202	—	—	—	168	1.204	—	—	—	—	—	—	—	—
Ia2hA	557	411	299	1.374	—	—	—	—	—	—	—	—	—	—
Ia3hA	580	393	299	1.314	—	—	—	—	—	—	—	—	—	—
Ib sB	718†	—	—	—	—	—	—	—	—	—	—	—	—	—
Ib1sB	277	—	—	—	227	1.217	—	—	—	—	—	—	—	—
Ib2sB	549	357	340	1.051	—	—	—	—	—	—	—	—	—	—
Ib3sB	586	349	340	1.027	—	—	—	—	—	—	—		—	—
Ic mR	645	—	—	—	—	—	570	1.132	624	1.034	570	1.132	—	—
Ic1mR	262	—	—	—	262	0.999	—	—	—	—	—	—	—	—
Ic2mR	379	427	375	1.138	—	—	—	—	—	—	—	—	—	—
Ic3mR	439	445	375	1.186	—	—	—	—	—	—	—	—	—	—
IIa mB	715	—	—	—	—	—	710	1.008	787	0.909	710	1.008	—	—
IIa1mB	297	—	—	—	261	1.140	—	—	—	—	—	—	—	—
IIa2mB	502	332	340	0.976	—	—	—	—	—	—	—	—	—	—
IIa3mB	577	366	340	1.077	—	—	—	—	—	—	—	—	—	—
IIb hR	554	—	—	—	—	—	542	1.023	592	0.937	542	1.023	—	—
IIb1hR	293	—	—	—	274	1.070	—	—	—	—	—	—	—	—
IIb2hR	337	341	375	0.908	—	—	—	—	—	—	—	—	—	—
IIb3hR	598	346	375	0.922	—	—	—	—	—	—	—	—	—	—

Table E1.20 (cont.)

Specimen Designation		Specimens with a_2 or a_3 only			Specimens with a_1 only		Specimens with a_1 and a_2						Specimens with a_1, a_2 and a_4	
	Model	Equation 4.6a			Equation 4.7		Equation 4.9		Equation 4.10		Equation 4.10a and b		Equation 4.9	
	P_u (kN)	τ_u (MPa)	$0.67\sigma_u$ (MPa)	Ratio ρ_{M2}	Predicted Capacity (kN)	Ratio ρ_P	Predicted Capacity (kN)	Ratio ρ_P	Predicted Capacity (kN)	Ratio ρ_P	Predicted Capacity (kN)	Ratio ρ_P	Predicted Capacity (kN)	Ratio ρ_P
IIc sA	746	—	—	—	—	—	695	1.073	747	0.998	695	1.073	—	—
IIc1sA	418	—	—	—	388	1.076	—	—	—	—	—	—	—	—
IIc2sA	378	422	299	1.410	—	—	—	—	—	—	—	—	—	—
IIc3sA	369	379	299	1.269	—	—	—	—	—	—	—	—	—	—
IIIa sR	728	—	—	—	—	—	749	0.971	826	0.881	749	0.971	—	—
IIIa1sR	387	—	—	—	379	1.023	—	—	—	—	—	—	—	—
IIIa2sR	477	341	375	0.908	—	—	—	—	—	—	—	—	—	—
IIIa3sR	549	342	375	0.911	—	—	—	—	—	—	—	—	—	—
IIIb mA	752	—	—	—	—	—	711	1.058	757	0.994	757	0.994	—	—
IIIb1mA	553	—	—	—	454	1.220	—	—	—	—	—	—	—	—
IIIb2mA	302	371	299	1.241	—	—	—	—	—	—	—	—	—	—
IIIb3mA	454	356	299	1.190	—	—	—	—	—	—	—	—	—	—
IIIc hB	908	—	—	—	—	—	971	0.936	1013	0.897	1013	0.897	—	—
IIIc1hB	694	—	—	—	731	0.948	—	—	—	—	—	—	—	—
IIIc2hB	285	344	340	1.011	—	—	—	—	—	—	—	—	—	—
IIIc3hB	548	319	340	0.938	—	—	—	—	—	—	—	—	—	—

Table E1.20 (cont.)

Specimen Designation		Specimens with a_2 or a_3 only			Specimens with a_1 only		Specimens with a_1 and a_2						Specimens with a_1, a_2 and a_4	
	Model	Equation 4.6a			Equation 4.7		Equation 4.9		Equation 4.10		Equation 4.10a and b		Equation 4.9	
	P_u (kN)	τ_u (MPa)	$0.67\sigma_u$ (MPa)	Ratio ρ_{M2}	Predicted Capacity (kN)	Ratio ρ_P	Predicted Capacity (kN)	Ratio ρ_P	Predicted Capacity (kN)	Ratio ρ_P	Predicted Capacity (kN)	Ratio ρ_P	Predicted Capacity (kN)	Ratio ρ_P
IIbmA 1	613	—	—	—	—	—	593	1.033	645	0.951	593	1.033	—	—
IIbmA 2	604	—	—	—	—	—	582	1.038	634	0.954	582	1.038	—	—
IIbmA 3	615	—	—	—	—	—	580	1.060	632	0.973	580	1.060	—	—
IIbmB 1	730	—	—	—	—	—	683	1.069	747	0.977	683	1.069	—	—
IIbmB 2	736	—	—	—	—	—	692	1.063	759	0.969	692	1.063	—	—
IIbmB 3	743	—	—	—	—	—	721	1.031	787	0.943	721	1.031	—	—
IIbmR 1	619	—	—	—	—	—	566	1.094	619	1.001	566	1.094	—	—
IIbmR 2	606	—	—	—	—	—	548	1.106	600	1.010	548	1.106	—	—
IIbmR 3	610	—	—	—	—	—	548	1.114	599	1.019	548	1.114	—	—

† Specimen ruptured in steel plate.

Table E1.21 – Analysis of USA Test Results on St.37 Steel as Reported by Ligtenberg (1968)

Specimen Designation		Specimens with a_2 or a_3 only			Specimens with a_1 only		Specimens with a_1 and a_2						Specimens with a_1, a_2 and a_4	
	Model	Equation 4.6a			Equation 4.7		Equation 4.9		Equation 4.10		Equation 4.10a and b		Equation 4.9	
	P_u (kN)	τ_u (MPa)	$0.67\sigma_u$ (MPa)	Ratio ρ_{M2}	Predicted Capacity (kN)	Ratio ρ_P	Predicted Capacity (kN)	Ratio ρ_P	Predicted Capacity (kN)	Ratio ρ_P	Predicted Capacity (kN)	Ratio ρ_P	Predicted Capacity (kN)	Ratio ρ_P
Ia mR	557	—	—	—	—	—	551	1.011	621	0.897	569	0.979	—	—
Ia1mR	169	—	—	—	167	1.014	—	—	—	—	—	—	—	—
Ia2mR	490	343	316	1.085	—	—	—	—	—	—	—	—	—	—
Ia3mR	533	339	316	1.073	—	—	—	—	—	—	—	—	—	—
Ia4mR	381	—	—	—	—	—	—	—	—	—	—	—	349	1.091
Ib hA	659	—	—	—	—	—	546	1.208	605	1.089	546	1.208	—	—
Ib1hA	238	—	—	—	214	1.112	—	—	—	—	—	—	—	—
Ib2hA	511	448	304	1.473	—	—	—	—	—	—	—	—	—	—
Ib3hA	575	393	304	1.291	—	—	—	—	—	—	—	—	—	—
Ib4hA	383	—	—	—	—	—	—	—	—	—	—	—	372	1.029
Ic sB	713	—	—	—	—	—	754	0.945	824	0.865	754	0.945	—	—
Ic1sB	291	—	—	—	361	0.805	—	—	—	—	—	—	—	—
Ic2sB	499	495	365	1.357	—	—	—	—	—	—	—	—	—	—
Ic3sB	617	472	365	1.294	—	—	—	—	—	—	—	—	—	—
Ic4sB	342	—	—	—	—	—	—	—	—	—	—	—	521	0.656
IIa sA	604	—	—	—	—	—	582	1.037	650	0.928	586	1.030	—	—
IIa1sA	227	—	—	—	214	1.063	—	—	—	—	—	—	—	—
IIa2sA	395	361	304	1.186	—	—	—	—	—	—	—	—	—	—
IIa3sA	523	358	304	1.178	—	—	—	—	—	—	—	—	—	—
IIa4sA	303	—	—	—	—	—	—	—	—	—	—	—	386	0.785

Table E1.21 (cont.)

Specimen Designation		Specimens with a_2 or a_3 only			Specimens with a_1 only		Specimens with a_1 and a_2						Specimens with a_1, a_2 and a_4	
	Model	Equation 4.6a			Equation 4.7		Equation 4.9		Equation 4.10		Equation 4.10a and b		Equation 4.9	
	P_u (kN)	τ_u (MPa)	$0.67\sigma_u$ (MPa)	Ratio ρ_{M2}	Predicted Capacity (kN)	Ratio ρ_P	Predicted Capacity (kN)	Ratio ρ_P	Predicted Capacity (kN)	Ratio ρ_P	Predicted Capacity (kN)	Ratio ρ_P	Predicted Capacity (kN)	Ratio ρ_P
IIb mB	684	—	—	—	—	—	698	0.981	761	0.899	698	0.981	—	—
IIb1mB	363	—	—	—	384	0.945	—	—	—	—	—	—	—	—
IIb2mB	414	429	365	1.176	—	—	—	—	—	—	—	—	—	—
IIb3mB	666	430	365	1.176	—	—	—	—	—	—	—	—	—	—
IIb4mB	462	—	—	—	—	—	—	—	—	—	—	—	493	0.938
IIc hA	715	—	—	—	—	—	769	0.930	817	0.875	769	0.930	—	—
IIc1hA	445	—	—	—	527	0.845	—	—	—	—	—	—	—	—
IIc2hA	325	378	316	1.197	—	—	—	—	—	—	—	—	—	—
IIc3hA	597	351	316	1.111	—	—	—	—	—	—	—	—	—	—
IIc4hA	581	—	—	—	—	—	—	—	—	—	—	—	656	0.887
IIIa hB	951	—	—	—	—	—	839	1.134	910	1.045	839	1.134	—	—
IIIa1hB	543	—	—	—	468	1.160	—	—	—	—	—	—	—	—
IIIa2hB	470	466	365	1.276	—	—	—	—	—	—	—	—	—	—
IIIa3hB	615	428	365	1.171	—	—	—	—	—	—	—	—	—	—
IIIa4hB	575	—	—	—	—	—	—	—	—	—	—	—	634	0.907
IIIb sR	710	—	—	—	—	—	616	1.153	657	1.081	616	1.153	—	—
IIIb1sR	461	—	—	—	421	1.095	—	—	—	—	—	—	—	—
IIIb2sR	292	347	316	1.097	—	—	—	—	—	—	—	—	—	—
IIIb3sR	471	348	316	1.102	—	—	—	—	—	—	—	—	—	—
IIIb4sR	399	—	—	—	—	—	—	—	—	—	—	—	435	0.917

Table E1.21 (cont.)

Specimen Designation		Specimens with a_2 or a_3 only			Specimens with a_1 only		Specimens with a_1 and a_2						Specimens with a_1, a_2 and a_4	
	Model	Equation 4.6a			Equation 4.7		Equation 4.9		Equation 4.10		Equation 4.10a and b		Equation 4.9	
	P_u (kN)	τ_u (MPa)	$0.67\sigma_u$ (MPa)	Ratio ρ_{M2}	Predicted Capacity (kN)	Ratio ρ_P	Predicted Capacity (kN)	Ratio ρ_P	Predicted Capacity (kN)	Ratio ρ_P	Predicted Capacity (kN)	Ratio ρ_P	Predicted Capacity (kN)	Ratio ρ_P
IIIc mA	890	—	—	—	—	—	980	0.908	1016	0.875	980	0.908	—	—
IIIc1mA	708	—	—	—	806	0.879	—	—	—	—	—	—	—	—
IIIc2mA	303	513	304	1.687	—	—	—	—	—	—	—	—	—	—
IIIc3mA	539	388	304	1.274	—	—	—	—	—	—	—	—	—	—
IIIc4mA	497		—	—	—	—	—	—	—	—	—	—	636	0.781
IIbmA 1	734	—	—	—	—	—	730	1.005	795	0.923	730	1.005	—	—
IIbmA 2	774	—	—	—	—	—	722	1.071	789	0.981	722	1.071	—	—
IIbmA 3	757	—	—	—	—	—	775	0.977	844	0.897	775	0.977	—	—
IIbmB 1	742	—	—	—	—	—	721	1.028	787	0.942	721	1.028	—	—
IIbmB 2	744	—	—	—	—	—	667	1.115	729	1.020	667	1.115	—	—
IIbmB 3	726	—	—	—	—	—	724	1.003	789	0.920	724	1.003	—	—
IIbmR 1	606	—	—	—	—	—	541	1.120	592	1.022	541	1.120	—	—
IIbmR 2	619	—	—	—	—	—	503	1.231	550	1.125	503	1.231	—	—
IIbmR 3	601	—	—	—	—	—	536	1.122	584	1.029	536	1.122	—	—

Table E1.22 – Analysis of French Test Results on St.37 Steel as Reported by Ligtenberg (1968)

Specimen Designation		Specimens with a_2 or a_3 only			Specimens with a_1 only		Specimens with a_1 and a_2						Specimens with a_1, a_2 and a_4	
	Model	Equation 4.6a			Equation 4.7		Equation 4.9		Equation 4.10		Equation 4.10a and b		Equation 4.9	
	P_u (kN)	τ_u (MPa)	$0.67\sigma_u$ (MPa)	Ratio ρ_{M2}	Predicted Capacity (kN)	Ratio ρ_P	Predicted Capacity (kN)	Ratio ρ_P	Predicted Capacity (kN)	Ratio ρ_P	Predicted Capacity (kN)	Ratio ρ_P	Predicted Capacity (kN)	Ratio ρ_P
Ia hB	785	—	—	—	—	—	650	1.208	735	1.068	678	1.157	—	—
Ia1hB	155	—	—	—	150	1.035	—	—	—	—	—	—	—	—
Ia2hB	618	364	346	1.052	—	—	—	—	—	—	—	—	—	—
Ia3hB	697	338	346	0.978	—	—	—	—	—	—	—	—	—	—
Ia4hB	383	—	—	—	—	—	—	—	—	—	—	—	380	1.008
IbsR	667	—	—	—	—	—	480	1.389	536	1.244	482	1.385	—	—
Ib1sR	196	—	—	—	174	1.128	—	—	—	—	—	—	—	—
Ib2sR	500	439	377	1.163	—	—	—	—	—	—	—	—	—	—
Ib3sR	515	379	377	1.004	—	—	—	—	—	—	—	—	—	—
Ib4sR	309	—	—	—	—	—	—	—	—	—	—	—	330	0.937
Ic mA	755	—	—	—	—	—	690	1.094	753	1.003	690	1.094	—	—
Ic1mA	353	—	—	—	377	0.936	—	—	—	—	—	—	—	—
Ic2mA	451	427	331	1.290	—	—	—	—	—	—	—	—	—	—
Ic3mA	491	374	331	1.129	—	—	—	—	—	—	—	—	—	—
Ic4mA	383	—	—	—	—	—	—	—	—	—	—	—	501	0.764
IIa mR	608	—	—	—	—	—	598	1.018	668	0.910	602	1.011	—	—
IIa1mR	216	—	—	—	189	1.142	—	—	—	—	—	—	—	—
IIa2mR	491	361	377	0.956	—	—	—	—	—	—	—	—	—	—
IIa3mR	569	358	377	0.949	—	—	—	—	—	—	—	—	—	—
IIa4mR	373	—	—	—	—	—	—	—	—	—	—	—	417	0.895

Table E1.22 (cont.)

Specimen Designation		Specimens with a_2 or a_3 only			Specimens with a_1 only		Specimens with a_1 and a_2						Specimens with a_1, a_2 and a_4	
	Model	Equation 4.6a			Equation 4.7		Equation 4.9		Equation 4.10		Equation 4.10a and b		Equation 4.9	
	P_u (kN)	τ_u (MPa)	$0.67\sigma_u$ (MPa)	Ratio ρ_{M2}	Predicted Capacity (kN)	Ratio ρ_P	Predicted Capacity (kN)	Ratio ρ_P	Predicted Capacity (kN)	Ratio ρ_P	Predicted Capacity (kN)	Ratio ρ_P	Predicted Capacity (kN)	Ratio ρ_P
IIb hA	834	—	—	—	—	—	710	1.175	775	1.076	710	1.175	—	—
IIb1hA	341	—	—	—	327	1.045	—	—	—	—	—	—	—	—
IIb2hA	461	466	331	1.406	—	—	—	—	—	—	—	—	—	—
IIb3hA	638	391	331	1.181	—	—	—	—	—	—	—	—	—	—
IIb4hA	491	—	—	—	—	—	—	—	—	—	—	—	516	0.951
IIc sB	706	—	—	—	—	—	722	0.979	764	0.924	722	0.979	—	—
IIc1sB	491	—	—	—	458	1.070	—	—	—	—	—	—	—	—
IIc2sB	304	432	346	1.249	—	—	—	—	—	—	—	—	—	—
IIc3sB	559	316	346	0.914	—	—	—	—	—	—	—	—	—	—
IIc4sB	422	—	—	—	—	—	—	—	—	—	—	—	588	0.717
IIIa sA	775	—	—	—	—	—	793	0.977	869	0.892	793	0.977	—	—
IIIa1sA	392	—	—	—	351	1.118	—	—	—	—	—	—	—	—
IIIa2sA	461	378	331	1.141	—	—	—	—	—	—	—	—	—	—
IIIa3sA	549	343	331	1.036	—	—	—	—	—	—	—	—	—	—
IIIa4sA	402	—	—	—	—	—	—	—	—	—	—	—	521	0.772
IIIb mB	903	—	—	—	—	—	866	1.042	922	0.979	866	1.042	—	—
IIIb1mB	486	—	—	—	522	0.931	—	—	—	—	—	—	—	—
IIIb2mB	343	361	346	1.045	—	—	—	—	—	—	—	—	—	—
IIIb3mB	530	335	346	0.970	—	—	—	—	—	—	—	—	—	—
IIIb4mB	564	—	—	—	—	—	—	—	—	—	—	—	646	0.873

Table E1.22 (cont.)

Specimen Designation		Specimens with a_2 or a_3 only			Specimens with a_1 only		Specimens with a_1 and a_2						Specimens with a_1, a_2 and a_4	
	Model	Equation 4.6a			Equation 4.7		Equation 4.9		Equation 4.10		Equation 4.10a and b		Equation 4.9	
	P_u (kN)	τ_u (MPa)	$0.67\sigma_u$ (MPa)	Ratio ρ_{M2}	Predicted Capacity (kN)	Ratio ρ_P	Predicted Capacity (kN)	Ratio ρ_P	Predicted Capacity (kN)	Ratio ρ_P	Predicted Capacity (kN)	Ratio ρ_P	Predicted Capacity (kN)	Ratio ρ_P
IIIc hR	1079	—	—	—	—	—	906	1.191	942	1.146	906	1.191	—	—
IIIc1hR	724	—	—	—	715	1.012	—	—	—	—	—	—	—	—
IIIc2hR	255	425	377	1.127	—	—	—	—	—	—	—	—	—	—
IIIc3hR	549	365	377	0.968	—	—	—	—	—	—	—	—	—	—
IIIc4hR	638	—	—	—	—	—	—	—	—	—	—	—	830	0.769
IIbmA 1	800	—	—	—	—	—	729	1.096	797	1.003	729	1.096	—	—
IIbmA 2	785	—	—	—	—	—	696	1.127	761	1.032	696	1.127	—	—
IIbmA 3	667	—	—	—	—	—	745	0.895	814	0.820	745	0.895	—	—
IIbmB 1	746	—	—	—	—	—	678	1.099	740	1.008	678	1.099	—	—
IIbmB 2	697	—	—	—	—	—	648	1.074	704	0.989	648	1.074	—	—
IIbmB 3	584	—	—	—	—	—	640	0.912	699	0.835	640	0.912	—	—
IIbmR 1	598	—	—	—	—	—	533	1.123	579	1.034	533	1.123	—	—
IIbmR 2	598	—	—	—	—	—	542	1.104	592	1.010	542	1.104	—	—
IIbmR 3	598	—	—	—	—	—	525	1.140	573	1.045	525	1.140	—	—

Table E1.23 – Analysis of German Test Results on St.37 Steel as Reported by Ligtenberg (1968)

Specimen Designation		Specimens with a_2 or a_3 only			Specimens with a_1 only		Specimens with a_1 and a_2						Specimens with a_1, a_2 and a_4	
	Model	Equation 4.6a			Equation 4.7		Equation 4.9		Equation 4.10		Equation 4.10a and b		Equation 4.9	
	P_u (kN)	τ_u (MPa)	$0.67\sigma_u$ (MPa)	Ratio ρ_{M2}	Predicted Capacity (kN)	Ratio ρ_P	Predicted Capacity (kN)	Ratio ρ_P	Predicted Capacity (kN)	Ratio ρ_P	Predicted Capacity (kN)	Ratio ρ_P	Predicted Capacity (kN)	Ratio ρ_P
Ia sB	787†	—	—	—	—	—	—	—	—	—	—	—	—	—
Ia1sB	287	—	—	—	235	1.221	—	—	—	—	—	—	—	—
Ia2sB	700	381	329	1.160	—	—	—	—	—	—	—	—	—	—
Ia3sB	776	356	329	1.083	—	—	—	—	—	—	—	—	—	—
Ia4sB	363†	—	—	—	—	—	—	—	—	—	—	—	—	—
Ib mR	765	—	—	—	—	—	647	1.183	721	1.061	647	1.183	—	—
Ib1mR	289	—	—	—	211	1.372	—	—	—	—	—	—	—	—
Ib2mR	553	367	315	1.164	—	—	—	—	—	—	—	—	—	—
Ib3mR	606	342	315	1.084	—	—	—	—	—	—	—	—	—	—
Ib4mR	378†	—	—	—	—	—	—	—	—	—	—	—	—	—
Ic hA	687	—	—	—	—	—	800	0.858	880	0.781	800	0.858	—	—
Ic1hA	414	—	—	—	338	1.226	—	—	—	—	—	—	—	—
Ic2hA	539	354	329	1.077	—	—	—	—	—	—	—	—	—	—
Ic3hA	688	405	329	1.232	—	—	—	—	—	—	—	—	—	—
Ic4hA	502†	—	—	—	—	—	—	—	—	—	—	—	—	—
IIa hR	710	—	—	—	—	—	704	1.009	784	0.906	704	1.009	—	—
IIa1hR	327	—	—	—	252	1.295	—	—	—	—	—	—	—	—
IIa2hR	529	334	315	1.060	—	—	—	—	—	—	—	—	—	—
IIa3hR	615	337	315	1.068	—	—	—	—	—	—	—	—	—	—
IIa4hR	439	—	—	—	—	—	—	—	—	—	—	—	482	0.909

Table E1.23 (cont.)

Specimen Designation		Specimens with a_2 or a_3 only			Specimens with a_1 only		Specimens with a_1 and a_2						Specimens with a_1, a_2 and a_4	
	Model	Equation 4.6a			Equation 4.7		Equation 4.9		Equation 4.10		Equation 4.10a and b		Equation 4.9	
	P_u (kN)	τ_u (MPa)	$0.67\sigma_u$ (MPa)	Ratio ρ_{M2}	Predicted Capacity (kN)	Ratio ρ_P	Predicted Capacity (kN)	Ratio ρ_P	Predicted Capacity (kN)	Ratio ρ_P	Predicted Capacity (kN)	Ratio ρ_P	Predicted Capacity (kN)	Ratio ρ_P
IIb sA	787	—	—	—	—	—	765	1.029	837	0.940	765	1.029	—	—
IIb1sA	379	—	—	—	381	0.994	—	—	—	—	—	—	—	—
IIb2sA	498	337	329	1.025	—	—	—	—	—	—	—	—	—	—
IIb3sA	608	352	329	1.071	—	—	—	—	—	—	—	—	—	—
IIb4sA	442†	—	—	—	—	—	—	—	—	—	—	—	—	—
IIc mB	978†	—	—	—	—	—	—	—	—	—	—	—	—	—
IIc1mB	561	—	—	—	505	1.112	—	—	—	—	—	—	—	—
IIc2mB	452	416	329	1.266	—	—	—	—	—	—	—	—	—	—
IIc3mB	645	380	329	1.157	—	—	—	—	—	—	—	—	—	—
IIc4mB	457†	—	—	—	—	—	—	—	—	—	—	—	—	—
IIIa mA	937	—	—	—	—	—	819	1.145	885	1.059	819	1.145	—	—
IIIa1mA	434	—	—	—	425	1.019	—	—	—	—	—	—	—	—
IIIa2mA	439	313	329	0.953	—	—	—	—	—	—	—	—	—	—
IIIa3mA	445	302	329	0.918	—	—	—	—	—	—	—	—	—	—
IIIa4mA	459†	—	—	—	—	—	—	—	—	—	—	—	—	—
IIIb hB	1011	—	—	—	—	—	1039	0.973	1113	0.909	1039	0.973	—	—
IIIb1hB	731	—	—	—	806	0.907	—	—	—	—	—	—	—	—
IIIb2hB	454	353	329	1.073	—	—	—	—	—	—	—	—	—	—
IIIb3hB	599	378	329	1.149	—	—	—	—	—	—	—	—	—	—
IIIb4hB	569†	—	—	—	—	—	—	—	—	—	—	—	—	—

Table E1.23 (cont.)

Specimen Designation		Specimens with a_2 or a_3 only			Specimens with a_1 only		Specimens with a_1 and a_2						Specimens with a_1, a_2 and a_4	
	Model	Equation 4.6a			Equation 4.7		Equation 4.9		Equation 4.10		Equation 4.10a and b		Equation 4.9	
	P_u (kN)	τ_u (MPa)	$0.67\sigma_u$ (MPa)	Ratio ρ_{M2}	Predicted Capacity (kN)	Ratio ρ_P	Predicted Capacity (kN)	Ratio ρ_P	Predicted Capacity (kN)	Ratio ρ_P	Predicted Capacity (kN)	Ratio ρ_P	Predicted Capacity (kN)	Ratio ρ_P
IIIc sR	785	—	—	—	—	—	865	0.907	903	0.869	865	0.907	—	—
IIIc1sR	725	—	—	—	695	1.043	—	—	—	—	—	—	—	—
IIIc2sR	288	300	315	0.952	—	—	—	—	—	—	—	—	—	—
IIIc3sR	445	337	315	1.069	—	—	—	—	—	—	—	—	—	—
IIIc4sR	419†	—	—	—	—	—	—	—	—	—	—	—	—	—
IIbmA 1	835	—	—	—	—	—	821	1.017	898	0.929	821	1.017	—	—
IIbmA 2	846	—	—	—	—	—	774	1.092	849	0.996	774	1.092	—	—
IIbmA 3	807	—	—	—	—	—	829	0.974	908	0.889	829	0.974	—	—
IIbmB 1	914	—	—	—	—	—	945	0.968	1033	0.885	945	0.968	—	—
IIbmB 2	951	—	—	—	—	—	929	1.023	1020	0.932	929	1.023	—	—
IIbmB 3	912	—	—	—	—	—	941	0.969	1032	0.884	941	0.969	—	—
IIbmR 1	789	—	—	—	—	—	696	1.133	764	1.033	696	1.133	—	—
IIbmR 2	783	—	—	—	—	—	666	1.176	728	1.075	666	1.176	—	—
IIbmR 3	757	—	—	—	—	—	636	1.190	697	1.086	636	1.190	—	—

† Specimen ruptured in steel plate.

Table E1.24 – Analysis of Belgian Test Results on St.37 Steel as Reported by Ligtenberg (1968)

Specimen Designation		Specimens with a_2 or a_3 only			Specimens with a_1 only		Specimens with a_1 and a_2						Specimens with a_1, a_2 and a_4	
	Model	Equation 4.6a			Equation 4.7		Equation 4.9		Equation 4.10		Equation 4.10a and b		Equation 4.9	
	P_u (kN)	τ_u (MPa)	$0.67\sigma_u$ (MPa)	Ratio ρ_{M2}	Predicted Capacity (kN)	Ratio ρ_P	Predicted Capacity (kN)	Ratio ρ_P	Predicted Capacity (kN)	Ratio ρ_P	Predicted Capacity (kN)	Ratio ρ_P	Predicted Capacity (kN)	Ratio ρ_P
Ia mA	755	—	—	—	—	—	713	1.060	806	0.937	744	1.015	—	—
Ia1mA	255	—	—	—	194	1.314	—	—	—	—	—	—	—	—
Ia2mA	671	388	338	1.148	—	—	—	—	—	—	—	—	—	—
Ia3mA	723	379	338	1.120	—	—	—	—	—	—	—	—	—	—
Ia4mA	387	—	—	—	—	—	—	—	—	—	—	—	431	0.896
Ib sR	608†	—	—	—	—	—	—	—	—	—	—	—	—	—
Ib1sR	243	—	—	—	231	1.052	—	—	—	—	—	—	—	—
Ib2sR	538	430	350	1.229	—	—	—	—	—	—	—	—	—	—
Ib3sR	569	367	350	1.047	—	—	—	—	—	—	—	—	—	—
Ib4sR	294†	—	—	—	—	—	—	—	—	—	—	—	—	—
Ic hB	944	—	—	—	—	—	921	1.024	1012	0.933	921	1.024	—	—
Ic1hB	343	—	—	—	365	0.939	—	—	—	—	—	—	—	—
Ic2hB	579	509	371	1.372	—	—	—	—	—	—	—	—	—	—
Ic3hB	659	451	371	1.214	—	—	—	—	—	—	—	—	—	—
Ic4hB	445	—	—	—	—	—	—	—	—	—	—	—	560	0.795
IIa hR	687	—	—	—	—	—	659	1.042	733	0.937	659	1.042	—	—
IIa1hR	245	—	—	—	247	0.994	—	—	—	—	—	—	—	—
IIa2hR	555	379	350	1.082	—	—	—	—	—	—	—	—	—	—
IIa3hR	577	377	350	1.076	—	—	—	—	—	—	—	—	—	—
IIa4hR	387	—	—	—	—	—	—	—	—	—	—	—	456	0.848

Table E1.24 (cont.)

Specimen Designation		Specimens with a_2 or a_3 only			Specimens with a_1 only		Specimens with a_1 and a_2						Specimens with a_1, a_2 and a_4	
	Model	Equation 4.6a			Equation 4.7		Equation 4.9		Equation 4.10		Equation 4.10a and b		Equation 4.9	
	P_u (kN)	τ_u (MPa)	$0.67\sigma_u$ (MPa)	Ratio ρ_{M2}	Predicted Capacity (kN)	Ratio ρ_P	Predicted Capacity (kN)	Ratio ρ_P	Predicted Capacity (kN)	Ratio ρ_P	Predicted Capacity (kN)	Ratio ρ_P	Predicted Capacity (kN)	Ratio ρ_P
IIb mB	1079	—	—	—	—	—	899	1.200	982	1.099	899	1.200	—	—
IIb1mB	512	—	—	—	393	1.303	—	—	—	—	—	—	—	—
IIb2mB	589	465	371	1.252	—	—	—	—	—	—	—	—	—	—
IIb3mB	753	464	371	1.250	—	—	—	—	—	—	—	—	—	—
IIb4mB	520†	—	—	—	—	—	—	—	—	—	—	—	—	—
IIc sA	701†	—	—	—	—	—	—	—	—	—	—	—	—	—
IIc1sA	569	—	—	—	535	1.063	—	—	—	—	—	—	—	—
IIc2sA	381	386	338	1.141	—	—	—	—	—	—	—	—	—	—
IIc3sA	585	361	338	1.067	—	—	—	—	—	—	—	—	—	—
IIc4sA	353†	—	—	—	—	—	—	—	—	—	—	—	—	—
IIIa sB	844	—	—	—	—	—	934	0.904	1007	0.837	934	0.904	—	—
IIIa1sB	536	—	—	—	431	1.241	—	—	—	—	—	—	—	—
IIIa2sB	475	364	371	0.981	—	—	—	—	—	—	—	—	—	—
IIIa3sB	538	311	371	0.839	—	—	—	—	—	—	—	—	—	—
IIIa4sB	459†	—	—	—	—	—	—	—	—	—	—	—	—	—
IIIb hA	867	—	—	—	—	—	835	1.038	890	0.974	835	1.038	—	—
IIIb1hA	626	—	—	—	520	1.204	—	—	—	—	—	—	—	—
IIIb2hA	390	396	338	1.171	—	—	—	—	—	—	—	—	—	—
IIIb3hA	626	367	338	1.085	—	—	—	—	—	—	—	—	—	—
IIIb4hA	677†	—	—	—	—	—	—	—	—	—	—	—	—	—

Table E1.24 (cont.)

Specimen Designation		Specimens with a_2 or a_3 only			Specimens with a_1 only		Specimens with a_1 and a_2						Specimens with a_1, a_2 and a_4	
	Model	Equation 4.6a			Equation 4.7		Equation 4.9		Equation 4.10		Equation 4.10a and b		Equation 4.9	
	P_u (kN)	τ_u (MPa)	$0.67\sigma_u$ (MPa)	Ratio ρ_{M2}	Predicted Capacity (kN)	Ratio ρ_P	Predicted Capacity (kN)	Ratio ρ_P	Predicted Capacity (kN)	Ratio ρ_P	Predicted Capacity (kN)	Ratio ρ_P	Predicted Capacity (kN)	Ratio ρ_P
IIIc mR	940	—	—	—	—	—	949	0.990	988	0.951	949	0.990	—	—
IIIc1mR	742	—	—	—	710	1.045	—	—	—	—	—	—	—	—
IIIc2mR	267	349	350	0.998	—	—	—	—	—	—	—	—	—	—
IIIc3mR	491	307	350	0.877	—	—	—	—	—	—	—	—	—	—
IIIc4mR	518†	—	—	—	—	—	—	—	—	—	—	—	—	—
IIbmA 1	829	—	—	—	—	—	692	1.197	758	1.093	692	1.197	—	—
IIbmA 2	736	—	—	—	—	—	683	1.077	744	0.988	683	1.077	—	—
IIbmA 3	770	—	—	—	—	—	690	1.116	753	1.023	690	1.116	—	—
IIbmB 1	1020	—	—	—	—	—	847	1.205	928	1.100	847	1.205	—	—
IIbmB 2	976	—	—	—	—	—	776	1.258	851	1.146	776	1.258	—	—
IIbmB 3	1010	—	—	—	—	—	822	1.229	903	1.119	822	1.229	—	—
IIbmR 1	893	—	—	—	—	—	673	1.327	736	1.214	673	1.327	—	—
IIbmR 2	785	—	—	—	—	—	636	1.234	698	1.125	636	1.234	—	—
IIbmR 3	834	—	—	—	—	—	650	1.283	717	1.164	650	1.283	—	—

† Specimen ruptured in steel plate.

Table E1.25 – Analysis of Netherlands' Test Results on St.37 Steel as Reported by Ligtenberg (1968)

Specimen Designation		Specimens with a_2 or a_3 only			Specimens with a_1 only		Specimens with a_1 and a_2						Specimens with a_1, a_2 and a_4	
	Model	Equation 4.6a			Equation 4.7		Equation 4.9		Equation 4.10		Equation 4.10a and b		Equation 4.9	
	P_u (kN)	τ_u (MPa)	$0.67\sigma_u$ (MPa)	Ratio ρ_{M2}	Predicted Capacity (kN)	Ratio ρ_P	Predicted Capacity (kN)	Ratio ρ_P	Predicted Capacity (kN)	Ratio ρ_P	Predicted Capacity (kN)	Ratio ρ_P	Predicted Capacity (kN)	Ratio ρ_P
Ia hA	780	—	—	—	—	—	812	0.960	916	0.852	840	0.928	—	—
Ia1hA	231	—	—	—	213	1.084	—	—	—	—	—	—	—	—
Ia2hA	711	405	317	1.277	—	—	—	—	—	—	—	—	—	—
Ia3hA	814	371	317	1.170	—	—	—	—	—	—	—	—	—	—
Ia4hA	441	—	—	—	—	—	—	—	—	—	—	—	505	0.874
Ib mR	766	—	—	—	—	—	806	0.951	899	0.852	807	0.949	—	—
Ib1mR	251	—	—	—	249	1.010	—	—	—	—	—	—	—	—
Ib2mR	603	470	319	1.471	—	—	—	—	—	—	—	—	—	—
Ib3mR	700	381	319	1.193	—	—	—	—	—	—	—	—	—	—
Ib4mR	432	—	—	—	—	—	—	—	—	—	—	—	466	0.927
Ic sB	775†	—	—	—	—	—	—	—	—	—	—	—	—	—
Ic1sB	466	—	—	—	439	1.063	—	—	—	—	—	—	—	—
Ic2sB	687	399	375	1.064	—	—	—	—	—	—	—	—	—	—
Ic3sB	736†	—	—	—	—	—	—	—	—	—	—	—	—	—
Ic4sB	358†	—	—	—	—	—	—	—	—	—	—	—	—	—
IIa sR	826	—	—	—	—	—	765	1.080	856	0.965	773	1.069	—	—
IIa1sR	294	—	—	—	291	1.010	—	—	—	—	—	—	—	—
IIa2sR	623	378	319	1.182	—	—	—	—	—	—	—	—	—	—
IIa3sR	687	390	319	1.220	—	—	—	—	—	—	—	—	—	—
IIa4sR	420†	—	—	—	—	—	—	—	—	—	—	—	—	—

Table E1.25 (cont.)

Specimen Designation		Specimens with a_2 or a_3 only			Specimens with a_1 only		Specimens with a_1 and a_2						Specimens with a_1, a_2 and a_4	
	Model	Equation 4.6a			Equation 4.7		Equation 4.9		Equation 4.10		Equation 4.10a and b		Equation 4.9	
	P_u (kN)	τ_u (MPa)	$0.67\sigma_u$ (MPa)	Ratio ρ_{M2}	Predicted Capacity (kN)	Ratio ρ_P	Predicted Capacity (kN)	Ratio ρ_P	Predicted Capacity (kN)	Ratio ρ_P	Predicted Capacity (kN)	Ratio ρ_P	Predicted Capacity (kN)	Ratio ρ_P
IIb hB	1079	—	—	—	—	—	1077	1.002	1172	0.920	1077	1.002	—	—
IIb1hB	540	—	—	—	470	1.147	—	—	—	—	—	—	—	—
IIb2hB	633	477	375	1.274	—	—	—	—	—	—	—	—	—	—
IIb3hB	800	421	375	1.123	—	—	—	—	—	—	—	—	—	—
IIb4hB	643†	—	—	—	—	—	—	—	—	—	—	—	—	—
IIc mA	956	—	—	—	—	—	980	0.976	1051	0.910	980	0.976	—	—
IIc1mA	528	—	—	—	565	0.935	—	—	—	—	—	—	—	—
IIc2mA	446	378	317	1.190	—	—	—	—	—	—	—	—	—	—
IIc3mA	746	399	317	1.257	—	—	—	—	—	—	—	—	—	—
IIc4mA	638†	—	—	—	—	—	—	—	—	—	—	—	—	—
IIIa mB	1099	—	—	—	—	—	1033	1.064	1116	0.984	1033	1.064	—	—
IIIa1mB	638	—	—	—	522	1.221	—	—	—	—	—	—	—	—
IIIa2mB	592	447	375	1.193	—	—	—	—	—	—	—	—	—	—
IIIa3mB	785	427	375	1.141	—	—	—	—	—	—	—	—	—	—
IIIa4mB	579†	—	—	—	—	—	—	—	—	—	—	—	—	—
IIIb sA	853	—	—	—	—	—	876	0.974	936	0.912	876	0.974	—	—
IIIb1sA	540	—	—	—	585	0.922	—	—	—	—	—	—	—	—
IIIb2sA	392	390	317	1.230	—	—	—	—	—	—	—	—	—	—
IIIb3sA	589	379	317	1.195	—	—	—	—	—	—	—	—	—	—
IIIb4sA	437†	—	—	—	—	—	—	—	—	—	—	—	—	—

Table E1.25 (cont.)

Specimen Designation		Specimens with a_2 or a_3 only			Specimens with a_1 only		Specimens with a_1 and a_2						Specimens with a_1, a_2 and a_4	
	Model	Equation 4.6a			Equation 4.7		Equation 4.9		Equation 4.10		Equation 4.10a and b		Equation 4.9	
	P_u (kN)	τ_u (MPa)	$0.67\sigma_u$ (MPa)	Ratio ρ_{M2}	Predicted Capacity (kN)	Ratio ρ_P	Predicted Capacity (kN)	Ratio ρ_P	Predicted Capacity (kN)	Ratio ρ_P	Predicted Capacity (kN)	Ratio ρ_P	Predicted Capacity (kN)	Ratio ρ_P
IIIc hR	1177	—	—	—	—	—	1167	1.009	1218	0.967	1167	1.009	—	—
IIIc1hR	858	—	—	—	860	0.999	—	—	—	—	—	—	—	—
IIIc2hR	294	349	319	1.092	—	—	—	—	—	—	—	—	—	—
IIIc3hR	706	413	319	1.292	—	—	—	—	—	—	—	—	—	—
IIIc4hR	799				—	—	—	—	—	—	—	—	926	0.862
IIbmA 1	775	—	—	—	—	—	747	1.037	820	0.945	747	1.037	—	—
IIbmA 2	726	—	—	—	—	—	747	0.972	817	0.888	747	0.972	—	—
IIbmA 3	770	—	—	—	—	—	775	0.994	845	0.912	775	0.994	—	—
IIbmB 1	947	—	—	—	—	—	1086	0.872	1185	0.799	1086	0.872	—	—
IIbmB 2	947	—	—	—	—	—	1146	0.826	1252	0.756	1146	0.826	—	—
IIbmB 3	932	—	—	—	—	—	1035	0.901	1129	0.825	1035	0.901	—	—
IIbmR 1	726	—	—	—	—	—	799	0.909	871	0.833	799	0.909	—	—
IIbmR 2	701	—	—	—	—	—	742	0.945	812	0.864	742	0.945	—	—
IIbmR 3	736	—	—	—	—	—	825	0.891	901	0.817	825	0.891	—	—

† Specimen ruptured in steel plate.

Table E1.26 – Analysis of Canadian Test Results on St.37 Steel as Reported by Ligtenberg (1968)

Specimen Designation		Specimens with a_2 or a_3 only			Specimens with a_1 only		Specimens with a_1 and a_2						Specimens with a_1, a_2 and a_4	
	Model	Equation 4.6a			Equation 4.7		Equation 4.9		Equation 4.10		Equation 4.10a and b		Equation 4.9	
	P_u (kN)	τ_u (MPa)	$0.67\sigma_u$ (MPa)	Ratio ρ_{M2}	Predicted Capacity (kN)	Ratio ρ_P	Predicted Capacity (kN)	Ratio ρ_P	Predicted Capacity (kN)	Ratio ρ_P	Predicted Capacity (kN)	Ratio ρ_P	Predicted Capacity (kN)	Ratio ρ_P
Ia mR	832	—	—	—	—	—	796	1.046	896	0.929	820	1.015	—	—
Ia1mR	190	—	—	—	206	0.921	—	—	—	—	—	—	—	—
Ia2mR	693	476	388	1.227	—	—	—	—	—	—	—	—	—	—
Ia3mR	808	454	388	1.170	—	—	—	—	—	—	—	—	—	—
Ib hB	990	—	—	—	—	—	785	1.262	880	1.125	798	1.241	—	—
Ib1hB	323	—	—	—	277	1.166	—	—	—	—	—	—	—	—
Ib2hB	667	541	377	1.435	—	—	—	—	—	—	—	—	—	—
Ib3hB	713	498	377	1.321	—	—	—	—	—	—	—	—	—	—
Ic sA	749	—	—	—	—	—	669	1.120	738	1.015	669	1.120	—	—
Ic1sA	323	—	—	—	270	1.199	—	—	—	—	—	—	—	—
Ic2sA	512	392	326	1.205	—	—	—	—	—	—	—	—	—	—
Ic3sA	534	367	326	1.126	—	—	—	—	—	—	—	—	—	—
IIa sB	913	—	—	—	—	—	823	1.109	912	1.001	823	1.109	—	—
IIa1sB	338	—	—	—	313	1.079	—	—	—	—	—	—	—	—
IIa2sB	652	522	377	1.384	—	—	—	—	—	—	—	—	—	—
IIa3sB	699	422	377	1.121	—	—	—	—	—	—	—	—	—	—
IIb mA	751	—	—	—	—	—	582	1.290	636	1.181	582	1.290	—	—
IIb1mA	347	—	—	—	277	1.252	—	—	—	—	—	—	—	—
IIb2mA	430	501	302	1.659	—	—	—	—	—	—	—	—	—	—
IIb3mA	666	399	302	1.322	—	—	—	—	—	—	—	—	—	—

Table E1.26 (cont.)

Specimen Designation		Specimens with a_2 or a_3 only			Specimens with a_1 only		Specimens with a_1 and a_2						Specimens with a_1, a_2 and a_4	
	Model	Equation 4.6a			Equation 4.7		Equation 4.9		Equation 4.10		Equation 4.10a and b		Equation 4.9	
	P_u (kN)	τ_u (MPa)	$0.67\sigma_u$ (MPa)	Ratio ρ_{M2}	Predicted Capacity (kN)	Ratio ρ_P	Predicted Capacity (kN)	Ratio ρ_P	Predicted Capacity (kN)	Ratio ρ_P	Predicted Capacity (kN)	Ratio ρ_P	Predicted Capacity (kN)	Ratio ρ_P
IIc hR	1024	—	—	—	—	—	931	1.100	1003	1.021	931	1.100	—	—
IIc1hR	730	—	—	—	579	1.261	—	—	—	—	—	—	—	—
IIc2hR	449	484	388	1.245	—	—	—	—	—	—	—	—	—	—
IIc3hR	753	439	388	1.131	—	—	—	—	—	—	—	—	—	—
IIIa hA	908	—	—	—	—	—	866	1.048	936	0.970	866	1.048	—	—
IIIa1hA	501	—	—	—	433	1.158	—	—	—	—	—	—	—	—
IIIa2hA	427	364	302	1.205	—	—	—	—	—	—	—	—	—	—
IIIa3hA	501	332	302	1.098	—	—	—	—	—	—	—	—	—	—
IIIb sR	853	—	—	—	—	—	930	0.917	989	0.862	930	0.917	—	—
IIIb1sR	622	—	—	—	540	1.151	—	—	—	—	—	—	—	—
IIIb2sR	367	436	388	1.123	—	—	—	—	—	—	—	—	—	—
IIIb3sR	559	372	388	0.959	—	—	—	—	—	—	—	—	—	—
IIIc mB	1247	—	—	—	—	—	1372	0.909	1429	0.873	1372	0.909	—	—
IIIc1mB	945	—	—	—	775	1.219	—	—	—	—	—	—	—	—
IIIc2mB	372	516	377	1.370	—	—	—	—	—	—	—	—	—	—
IIIc3mB	684	430	377	1.141	—	—	—	—	—	—	—	—	—	—
IIbmA 1	632	—	—	—	—	—	521	1.212	571	1.106	521	1.212	—	—
IIbmA 2	639	—	—	—	—	—	543	1.176	595	1.074	543	1.176	—	—
IIbmB 1	917	—	—	—	—	—	889	1.031	970	0.945	889	1.031	—	—
IIbmB 2	954	—	—	—	—	—	913	1.046	1004	0.950	913	1.046	—	—
IIbmR 1	851	—	—	—	—	—	677	1.258	746	1.141	677	1.258	—	—
IIbmR 2	854	—	—	—	—	—	665	1.284	729	1.171	665	1.284	—	—

Table E1.27 – Analysis of Swedish Test Results on St.37 Steel as Reported by Ligtenberg (1968)

Specimen Designation		Specimens with a_2 or a_3 only			Specimens with a_1 only		Specimens with a_1 and a_2						Specimens with a_1, a_2 and a_4	
	Model	Equation 4.6a			Equation 4.7		Equation 4.9		Equation 4.10		Equation 4.10a and b		Equation 4.9	
	P_u (kN)	τ_u (MPa)	$0.67\sigma_u$ (MPa)	Ratio ρ_{M2}	Predicted Capacity (kN)	Ratio ρ_P	Predicted Capacity (kN)	Ratio ρ_P	Predicted Capacity (kN)	Ratio ρ_P	Predicted Capacity (kN)	Ratio ρ_P	Predicted Capacity (kN)	Ratio ρ_P
Ia sR	675	—	—	—	—	—	684	0.987	777	0.869	724	0.933	—	—
Ia1sR	193	—	—	—	169	1.143	—	—	—	—	—	—	—	—
Ia2sR	608	386	340	1.135	—	—	—	—	—	—	—	—	—	—
Ia3sR	738	392	340	1.152	—	—	—	—	—	—	—	—	—	—
Ib hB	736	—	—	—	—	—	557	1.321	622	1.183	559	1.317	—	—
Ib1hB	234	—	—	—	202	1.160	—	—	—	—	—	—	—	—
Ib2hB	541	507	339	1.495	—	—	—	—	—	—	—	—	—	—
Ib3hB	665	433	339	1.276	—	—	—	—	—	—	—	—	—	—
Ic mA	771	—	—	—	—	—	619	1.245	673	1.146	619	1.245	—	—
Ic1mA	302	—	—	—	294	1.028	—	—	—	—	—	—	—	—
Ic2mA	472	487	325	1.497	—	—	—	—	—	—	—	—	—	—
Ic3mA	491	397	325	1.221	—	—	—	—	—	—	—	—	—	—
IIa mB	676	—	—	—	—	—	653	1.035	732	0.923	664	1.018	—	—
IIa1mB	264	—	—	—	211	1.253	—	—	—	—	—	—	—	—
IIa2mB	588	433	339	1.277	—	—	—	—	—	—	—	—	—	—
IIa3mB	597	400	339	1.180	—	—	—	—	—	—	—	—	—	—
IIb sA	692	—	—	—	—	—	677	1.022	740	0.935	677	1.022	—	—
IIb1sA	346	—	—	—	300	1.154	—	—	—	—	—	—	—	—
IIb2sA	397	323	325	0.992	—	—	—	—	—	—	—	—	—	—
IIb3sA	579	360	325	1.106	—	—	—	—	—	—	—	—	—	—

Table E1.27 (cont.)

Specimen Designation		Specimens with a_2 or a_3 only			Specimens with a_1 only		Specimens with a_1 and a_2						Specimens with a_1, a_2 and a_4	
	Model	Equation 4.6a			Equation 4.7		Equation 4.9		Equation 4.10		Equation 4.10a and b		Equation 4.9	
	P_u (kN)	τ_u (MPa)	$0.67\sigma_u$ (MPa)	Ratio ρ_{M2}	Predicted Capacity (kN)	Ratio ρ_P	Predicted Capacity (kN)	Ratio ρ_P	Predicted Capacity (kN)	Ratio ρ_P	Predicted Capacity (kN)	Ratio ρ_P	Predicted Capacity (kN)	Ratio ρ_P
IIc hR	859	—	—	—	—	—	799	1.075	851	1.009	799	1.075	—	—
IIc1hR	525	—	—	—	525	1.000	—	—	—	—	—	—	—	—
IIc2hR	371	406	340	1.194	—	—	—	—	—	—	—	—	—	—
IIc3hR	498	369	340	1.084	—	—	—	—	—	—	—	—	—	—
IIIa hA	783	—	—	—	—	—	761	1.028	838	0.934	761	1.028	—	—
IIIa1hA	374	—	—	—	336	1.113	—	—	—	—	—	—	—	—
IIIa2hA	428	342	325	1.053	—	—	—	—	—	—	—	—	—	—
IIIa3hA	463	288	325	0.886	—	—	—	—	—	—	—	—	—	—
IIIb mR	894	—	—	—	—	—	815	1.096	871	1.026	815	1.096	—	—
IIIb1mR	542	—	—	—	525	1.031	—	—	—	—	—	—	—	—
IIIb2mR	391	381	340	1.119	—	—	—	—	—	—	—	—	—	—
IIIb3mR	591	367	340	1.078	—	—	—	—	—	—	—	—	—	—
IIIc sB	727	—	—	—	—	—	993	0.732	1040	0.699	993	0.732	—	—
IIIc1sB	564	—	—	—	793	0.711	—	—	—	—	—	—	—	—
IIIc2sB	228	347	339	1.023	—	—	—	—	—	—	—	—	—	—
IIIc3sB	509	309	339	0.910	—	—	—	—	—	—	—	—	—	—

Table E1.27 (cont.)

Specimen Designation		Specimens with a_2 or a_3 only			Specimens with a_1 only		Specimens with a_1 and a_2						Specimens with a_1, a_2 and a_4	
	Model	Equation 4.6a			Equation 4.7		Equation 4.9		Equation 4.10		Equation 4.10a and b		Equation 4.9	
	P_u (kN)	τ_u (MPa)	$0.67\sigma_u$ (MPa)	Ratio ρ_{M2}	Predicted Capacity (kN)	Ratio ρ_P	Predicted Capacity (kN)	Ratio ρ_P	Predicted Capacity (kN)	Ratio ρ_P	Predicted Capacity (kN)	Ratio ρ_P	Predicted Capacity (kN)	Ratio ρ_P
IIbmA 1	701	—	—	—	—	—	697	1.006	762	0.920	697	1.006	—	—
IIbmA 2	754	—	—	—	—	—	713	1.058	780	0.967	713	1.058	—	—
IIbmA 3	721	—	—	—	—	—	693	1.041	759	0.949	693	1.041	—	—
IIbmB 1	734	—	—	—	—	—	742	0.989	811	0.905	742	0.989	—	—
IIbmB 2	703	—	—	—	—	—	752	0.936	821	0.857	752	0.936	—	—
IIbmB 3	706	—	—	—	—	—	759	0.930	832	0.849	759	0.930	—	—
IIbmR 1	701	—	—	—	—	—	644	1.089	707	0.992	644	1.089	—	—
IIbmR 2	711	—	—	—	—	—	674	1.056	740	0.961	674	1.056	—	—
IIbmR 3	647	—	—	—	—	—	652	0.993	714	0.906	652	0.993	—	—

Table E1.28 – Analysis of Yugoslavian Test Results on St.37 Steel as Reported by Ligtenberg (1968)

Specimen Designation		Specimens with a_2 or a_3 only			Specimens with a_1 only		Specimens with a_1 and a_2						Specimens with a_1, a_2 and a_4	
	Model	Equation 4.6a			Equation 4.7		Equation 4.9		Equation 4.10		Equation 4.10a and b		Equation 4.9	
	P_u (kN)	τ_u (MPa)	$0.67\sigma_u$ (MPa)	Ratio ρ_{M2}	Predicted Capacity (kN)	Ratio ρ_P	Predicted Capacity (kN)	Ratio ρ_P	Predicted Capacity (kN)	Ratio ρ_P	Predicted Capacity (kN)	Ratio ρ_P	Predicted Capacity (kN)	Ratio ρ_P
Ia mA	491	—	—	—	—	—	537	0.913	609	0.806	565	0.868	—	—
Ia1mA	83	—	—	—	121	0.686	—	—	—	—	—	—	—	—
Ia2mA	481	402	329	1.224	—	—	—	—	—	—	—	—	—	—
Ia mB	585	—	—	—	—	—	614	0.952	695	0.841	644	0.907	—	—
Ia1mB	145	—	—	—	161	0.900	—	—	—	—	—	—	—	—
Ia2mB	471	369	368	1.001	—	—	—	—	—	—	—	—	—	—
Ib mA	434	—	—	—	—	—	463	0.936	519	0.835	470	0.923	—	—
Ib1mA	108	—	—	—	144	0.750	—	—	—	—	—	—	—	—
Ib2mA	360	390	329	1.188	—	—	—	—	—	—	—	—	—	—
Ib mB	541	—	—	—	—	—	549	0.986	614	0.882	553	0.978	—	—
Ib1mB	180	—	—	—	226	0.794	—	—	—	—	—	—	—	—
Ib2mB	435	474	368	1.288	—	—	—	—	—	—	—	—	—	—
Ic mA	511	—	—	—	—	—	410	1.246	452	1.131	410	1.246	—	—
Ic1mA	177	—	—	—	189	0.935	—	—	—	—	—	—	—	—
Ic2mA	342	452	329	1.374	—	—	—	—	—	—	—	—	—	—
Ic mB	>589†	—	—	—	—	—	—	—	—	—	—	—	—	—
Ic1mB	210	—	—	—	213	0.984	—	—	—	—	—	—	—	—
Ic2mB	408	460	368	1.250	—	—	—	—	—	—	—	—	—	—
IIa mA	497	—	—	—	—	—	601	0.828	663	0.750	601	0.828	—	—
IIa1mA	180	—	—	—	189	0.948	—	—	—	—	—	—	—	—
IIa2mA	392	393	329	1.196	—	—	—	—	—	—	—	—	—	—

Table E1.28 (cont.)

Specimen Designation		Specimens with a_2 or a_3 only			Specimens with a_1 only		Specimens with a_1 and a_2						Specimens with a_1, a_2 and a_4	
	Model	Equation 4.6a			Equation 4.7		Equation 4.9		Equation 4.10		Equation 4.10a and b		Equation 4.9	
	P_u (kN)	τ_u (MPa)	$0.67\sigma_u$ (MPa)	Ratio ρ_{M2}	Predicted Capacity (kN)	Ratio ρ_P	Predicted Capacity (kN)	Ratio ρ_P	Predicted Capacity (kN)	Ratio ρ_P	Predicted Capacity (kN)	Ratio ρ_P	Predicted Capacity (kN)	Ratio ρ_P
IIa mB	563	—	—	—	—	—	619	0.910	687	0.820	619	0.910	—	—
IIa1mB	280	—	—	—	222	1.259	—	—	—	—	—	—	—	—
IIa2mB	409	414	368	1.125	—	—	—	—	—	—	—	—	—	—
IIb mA	452	—	—	—	—	—	463	0.977	507	0.891	463	0.977	—	—
IIb1mA	221	—	—	—	216	1.020	—	—	—	—	—	—	—	—
IIb2mA	274	350	329	1.065	—	—	—	—	—	—	—	—	—	—
IIb mB	>589†	—	—	—	—	—	—	—	—	—	—	—	—	—
IIb1mB	300	—	—	—	254	1.183	—	—	—	—	—	—	—	—
IIb2mB	401	484	368	1.315	—	—	—	—	—	—	—	—	—	—
IIc mA	507	—	—	—	—	—	478	1.061	519	0.977	478	1.061	—	—
IIc1mA	279	—	—	—	276	1.012	—	—	—	—	—	—	—	—
IIc2mA	250	351	329	1.069	—	—	—	—	—	—	—	—	—	—
IIc mB	>589†	—	—	—	—	—	—	—	—	—	—	—	—	—
IIc1mB	288	—	—	—	325	0.886	—	—	—	—	—	—	—	—
IIc2mB	362	439	368	1.192	—	—	—	—	—	—	—	—	—	—
IIIa mA	511	—	—	—	—	—	—	—	—	—	—	—	—	—
IIIa1mA	258	—	—	—	253	1.021	—	—	—	—	—	—	—	—
IIIa2mA	243	398	329	1.210	—	—	—	—	—	—	—	—	—	—
IIIa mB	563	—	—	—	—	—	526	1.070	573	0.982	526	1.070	—	—
IIIa1mB	290	—	—	—	309	0.941	—	—	—	—	—	—	—	—
IIIa2mB	271	430	368	1.168	—	—	—	—	—	—	—	—	—	—

Table E1.28 (cont.)

Specimen Designation		Specimens with a_2 or a_3 only			Specimens with a_1 only		Specimens with a_1 and a_2						Specimens with a_1, a_2 and a_4	
	Model	Equation 4.6a			Equation 4.7		Equation 4.9		Equation 4.10		Equation 4.10a and b		Equation 4.9	
	P_u (kN)	τ_u (MPa)	$0.67\sigma_u$ (MPa)	Ratio ρ_{M2}	Predicted Capacity (kN)	Ratio ρ_P	Predicted Capacity (kN)	Ratio ρ_P	Predicted Capacity (kN)	Ratio ρ_P	Predicted Capacity (kN)	Ratio ρ_P	Predicted Capacity (kN)	Ratio ρ_P
IIIb mA	430	—	—	—	—	—	445	0.967	475	0.905	445	0.967	—	—
IIIb1mA	260	—	—	—	265	0.980	—	—	—	—	—	—	—	—
IIIb2mA	184	375	329	1.141	—	—	—	—	—	—	—	—	—	—
IIIb mB	577	—	—	—	—	—	534	1.080	569	1.014	534	1.080	—	—
IIIb1mB	320	—	—	—	317	1.010	—	—	—	—	—	—	—	—
IIIb2mB	261	502	368	1.363	—	—	—	—	—	—	—	—	—	—
IIIc mA	512	—	—	—	—	—	487	1.051	513	0.999	487	1.051	—	—
IIIc1mA	340	—	—	—	364	0.934	—	—	—	—	—	—	—	—
IIIc2mA	160	343	329	1.043	—	—	—	—	—	—	—	—	—	—
IIIc mB	>589†	—	—	—	—	—	—	—	—	—	—	—	—	—
IIIc1mB	378	—	—	—	407	0.928	—	—	—	—	—	—	—	—
IIIc2mB	236	480	368	1.303	—	—	—	—	—	—	—	—	—	—

† Exceeded test machine capacity.

Table E1.29 – Analysis of Netherlands' Test Results on St.52 Steel as Reported by Ligtenberg (1968)

Specimen Designation		Specimens with a_2 or a_3 only			Specimens with a_1 only		Specimens with a_1 and a_2					
	Model	Equation 4.6a			Equation 4.7		Equation 4.9		Equation 4.10		Equation 4.10a and b	
	P_u (kN)	τ_u (MPa)	$0.67\sigma_u$ (MPa)	Ratio ρ_{M2}	Predicted Capacity (kN)	Ratio ρ_P	Predicted Capacity (kN)	Ratio ρ_P	Predicted Capacity (kN)	Ratio ρ_P	Predicted Capacity (kN)	Ratio ρ_P
Ib	895	—	—	—	—	—	702	1.275	774	1.155	702	1.275
Ib1	235	—	—	—	254	0.926	—	—	—	—	—	—
Ib2	623	501	365	1.374	—	—	—	—	—	—	—	—
Ib3	682	441	365	1.210	—	—	—	—	—	—	—	—
IIa	804	—	—	—	—	—	765	1.052	854	0.942	768	1.047
IIa1	303	—	—	—	287	1.057	—	—	—	—	—	—
IIa2	564	405	365	1.111	—	—	—	—	—	—	—	—
IIa3	660	380	365	1.041	—	—	—	—	—	—	—	—
IIb	814	—	—	—	—	—	921	0.885	1001	0.814	921	0.885
IIb1	348	—	—	—	476	0.731	—	—	—	—	—	—
IIb2	532	411	365	1.127	—	—	—	—	—	—	—	—
IIb3	674	390	365	1.070	—	—	—	—	—	—	—	—
IIc	917	—	—	—	—	—	888	1.033	952	0.963	888	1.033
IIc1	523	—	—	—	572	0.914	—	—	—	—	—	—
IIc2	471	490	365	1.343	—	—	—	—	—	—	—	—
IIc3	657	420	365	1.151	—	—	—	—	—	—	—	—
IIIb	1138	—	—	—	—	—	1199	0.949	1276	0.892	1199	0.949
IIIb1	719	—	—	—	754	0.954	—	—	—	—	—	—
IIIb2	530	431	365	1.183	—	—	—	—	—	—	—	—
IIIb3	579	455	365	1.247	—	—	—	—	—	—	—	—

Table E1.29 (cont.)

Specimen Designation		Specimens with a_2 or a_3 only			Specimens with a_1 only		Specimens with a_1 and a_2					
	Model	Equation 4.6a			Equation 4.7		Equation 4.9		Equation 4.10		Equation 4.10a and b	
	P_u (kN)	τ_u (MPa)	$0.67\sigma_u$ (MPa)	Ratio ρ_{M2}	Predicted Capacity (kN)	Ratio ρ_P	Predicted Capacity (kN)	Ratio ρ_P	Predicted Capacity (kN)	Ratio ρ_P	Predicted Capacity (kN)	Ratio ρ_P
II1b	741	—	—	—	—	—	703	1.053	767	0.966	703	1.053
II2b	798	—	—	—	—	—	799	0.998	870	0.917	799	0.998
II3b	831	—	—	—	—	—	775	1.072	851	0.977	775	1.072
II4b	736	—	—	—	—	—	763	0.965	837	0.880	763	0.965
II5b	831	—	—	—	—	—	766	1.085	837	0.993	766	1.085
II6b	769	—	—	—	—	—	770	0.998	839	0.917	770	0.998
II7b	780	—	—	—	—	—	752	1.038	817	0.954	752	1.038
II8b	809	—	—	—	—	—	833	0.972	907	0.892	833	0.972

Table E1.30 – Analysis of German Test Results on St.52 Steel as Reported by Ligtenberg (1968)

Specimen Designation		Specimens with a_2 or a_3 only			Specimens with a_1 only		Specimens with a_1 and a_2					
	Model	Equation 4.6a			Equation 4.7		Equation 4.9		Equation 4.10		Equation 4.10a and b	
	P_u (kN)	τ_u (MPa)	$0.67\sigma_u$ (MPa)	Ratio ρ_{M2}	Predicted Capacity (kN)	Ratio ρ_P	Predicted Capacity (kN)	Ratio ρ_P	Predicted Capacity (kN)	Ratio ρ_P	Predicted Capacity (kN)	Ratio ρ_P
Ib	781	—	—	—	—	—	604	1.294	677	1.154	614	1.273
Ib1	291	—	—	—	239	1.218	—	—	—	—	—	—
Ib2	549	559	368	1.520	—	—	—	—	—	—	—	—
Ib3	594	446	368	1.212	—	—	—	—	—	—	—	—
IIa	840	—	—	—	—	—	735	1.142	823	1.020	744	1.129
IIa1	332	—	—	—	260	1.274	—	—	—	—	—	—
IIa2	623	487	368	1.324	—	—	—	—	—	—	—	—
IIa3	689	419	368	1.137	—	—	—	—	—	—	—	—
IIb	954	—	—	—	—	—	805	1.185	883	1.080	805	1.185
IIb1	409	—	—	—	368	1.113	—	—	—	—	—	—
IIb2	505	488	368	1.325	—	—	—	—	—	—	—	—
IIb3	673	404	368	1.098	—	—	—	—	—	—	—	—
IIc	1077	—	—	—	—	—	980	1.099	1040	1.036	980	1.099
IIc1	573	—	—	—	605	0.947	—	—	—	—	—	—
IIc2	433	500	368	1.357	—	—	—	—	—	—	—	—
IIc3	685	403	368	1.094	—	—	—	—	—	—	—	—
IIIb	1148	—	—	—	—	—	1036	1.108	1104	1.040	1036	1.108
IIIb1	806	—	—	—	663	1.217	—	—	—	—	—	—
IIIb2	426	455	368	1.237	—	—	—	—	—	—	—	—
IIIb3	603	394	368	1.071	—	—	—	—	—	—	—	—

Table E1.30 (cont.)

Specimen Designation		Specimens with a_2 or a_3 only			Specimens with a_1 only		Specimens with a_1 and a_2					
	Model	Equation 4.6a			Equation 4.7		Equation 4.9		Equation 4.10		Equation 4.10a and b	
	P_u (kN)	τ_u (MPa)	$0.67\sigma_u$ (MPa)	Ratio ρ_{M2}	Predicted Capacity (kN)	Ratio ρ_P	Predicted Capacity (kN)	Ratio ρ_P	Predicted Capacity (kN)	Ratio ρ_P	Predicted Capacity (kN)	Ratio ρ_P
II1b	903	—	—	—	—	—	812	1.111	885	1.020	812	1.111
II2b	907	—	—	—	—	—	864	1.050	945	0.960	864	1.050
II3b	869	—	—	—	—	—	806	1.079	882	0.986	806	1.079
II4b	926	—	—	—	—	—	822	1.126	901	1.027	822	1.126
II5b	918	—	—	—	—	—	770	1.193	841	1.092	770	1.193
II6b	903	—	—	—	—	—	831	1.086	908	0.994	831	1.086
II7b	921	—	—	—	—	—	824	1.118	902	1.021	824	1.118
II8b	902	—	—	—	—	—	802	1.125	879	1.025	802	1.125

Table E1.31 – Analysis of Italian Test Results on St.52 Steel as Reported by Ligtenberg (1968)

Specimen Designation		Specimens with a_2 or a_3 only			Specimens with a_1 only		Specimens with a_1 and a_2					
	Model	Equation 4.6a			Equation 4.7		Equation 4.9		Equation 4.10		Equation 4.10a and b	
	P_u (kN)	τ_u (MPa)	$0.67\sigma_u$ (MPa)	Ratio ρ_{M2}	Predicted Capacity (kN)	Ratio ρ_P	Predicted Capacity (kN)	Ratio ρ_P	Predicted Capacity (kN)	Ratio ρ_P	Predicted Capacity (kN)	Ratio ρ_P
Ib	834	—	—	—	—	—	674	1.237	747	1.117	674	1.237
Ib1	277	—	—	—	315	0.881	—	—	—	—	—	—
Ib2	562	485	371	1.309	—	—	—	—	—	—	—	—
Ib3	687	470	371	1.269	—	—	—	—	—	—	—	—
IIa	844	—	—	—	—	—	839	1.006	940	0.897	853	0.989
IIa1	358	—	—	—	385	0.930	—	—	—	—	—	—
IIa2	663	454	371	1.225	—	—	—	—	—	—	—	—
IIa3	698	449	371	1.212	—	—	—	—	—	—	—	—
IIb	827	—	—	—	—	—	785	1.054	863	0.958	785	1.054
IIb1	339	—	—	—	391	0.868	—	—	—	—	—	—
IIb2	535	447	371	1.205	—	—	—	—	—	—	—	—
IIb3	740	435	371	1.172	—	—	—	—	—	—	—	—
IIc	1064	—	—	—	—	—	999	1.066	1069	0.996	999	1.066
IIc1	571	—	—	—	637	0.896	—	—	—	—	—	—
IIc2	495	500	371	1.350	—	—	—	—	—	—	—	—
IIc3	756	426	371	1.150	—	—	—	—	—	—	—	—
IIIb	1152	—	—	—	—	—	1181	0.975	1260	0.914	1181	0.975
IIIb1	559	—	—	—	710	0.788	—	—	—	—	—	—
IIIb2	461	477	371	1.288	—	—	—	—	—	—	—	—
IIIb3	640	414	371	1.116	—	—	—	—	—	—	—	—

Table E1.31 (cont.)

Specimen Designation		Specimens with a_2 or a_3 only			Specimens with a_1 only		Specimens with a_1 and a_2					
	Model	Equation 4.6a			Equation 4.7		Equation 4.9		Equation 4.10		Equation 4.10a and b	
	P_u (kN)	τ_u (MPa)	$0.67\sigma_u$ (MPa)	Ratio ρ_{M2}	Predicted Capacity (kN)	Ratio ρ_P	Predicted Capacity (kN)	Ratio ρ_P	Predicted Capacity (kN)	Ratio ρ_P	Predicted Capacity (kN)	Ratio ρ_P
II1b	776	—	—	—	—	—	787	0.986	867	0.896	787	0.986
II2b	820	—	—	—	—	—	835	0.982	915	0.896	835	0.982
II3b	811	—	—	—	—	—	811	0.999	890	0.911	811	0.999
II4b	878	—	—	—	—	—	881	0.996	969	0.906	881	0.996
II5b	882	—	—	—	—	—	879	1.004	966	0.913	879	1.004
II6b	845	—	—	—	—	—	852	0.991	936	0.903	852	0.991
II7b	876	—	—	—	—	—	878	0.997	966	0.907	878	0.997
II8b	843	—	—	—	—	—	821	1.027	896	0.940	821	1.027

Table E1.32 – Analysis of Swedish Test Results on St.52 Steel as Reported by Ligtenberg (1968)

Specimen Designation		Specimens with a_2 or a_3 only			Specimens with a_1 only		Specimens with a_1 and a_2					
	Model	Equation 4.6a			Equation 4.7		Equation 4.9		Equation 4.10		Equation 4.10a and b	
	P_u (kN)	τ_u (MPa)	$0.67\sigma_u$ (MPa)	Ratio ρ_{M2}	Predicted Capacity (kN)	Ratio ρ_P	Predicted Capacity (kN)	Ratio ρ_P	Predicted Capacity (kN)	Ratio ρ_P	Predicted Capacity (kN)	Ratio ρ_P
Ib	656	—	—	—	—	—	633	1.037	704	0.932	633	1.037
Ib1	228	—	—	—	206	1.106	—	—	—	—	—	—
Ib2	481	619	374	1.656	—	—	—	—	—	—	—	—
Ib3	663	425	374	1.138	—	—	—	—	—	—	—	—
IIa	761	—	—	—	—	—	810	0.940	901	0.845	810	0.940
IIa1	281	—	—	—	285	0.985	—	—	—	—	—	—
IIa2	561	485	374	1.299	—	—	—	—	—	—	—	—
IIa3	702	484	374	1.296	—	—	—	—	—	—	—	—
IIb	864	—	—	—	—	—	793	1.089	866	0.999	793	1.089
IIb	852	—	—	—	—	—	864	0.986	942	0.905	864	0.986
IIb	793	—	—	—	—	—	855	0.927	931	0.851	855	0.927
IIb1	392	—	—	—	395	0.992	—	—	—	—	—	—
IIb1	398	—	—	—	399	0.998	—	—	—	—	—	—
IIb1	399	—	—	—	427	0.935	—	—	—	—	—	—
IIb2	467	467	374	1.250	—	—	—	—	—	—	—	—
IIb2	483	448	374	1.199	—	—	—	—	—	—	—	—
IIb2	535	555	374	1.484	—	—	—	—	—	—	—	—
IIb3	709	458	374	1.225	—	—	—	—	—	—	—	—
IIb3	681	463	374	1.238	—	—	—	—	—	—	—	—
IIb3	702	476	374	1.274	—	—	—	—	—	—	—	—

Table E1.32 (cont.)

Specimen Designation		Specimens with a_2 or a_3 only			Specimens with a_1 only		Specimens with a_1 and a_2					
	Model	Equation 4.6a			Equation 4.7		Equation 4.9		Equation 4.10		Equation 4.10a and b	
	P_u (kN)	τ_u (MPa)	$0.67\sigma_u$ (MPa)	Ratio ρ_{M2}	Predicted Capacity (kN)	Ratio ρ_P	Predicted Capacity (kN)	Ratio ρ_P	Predicted Capacity (kN)	Ratio ρ_P	Predicted Capacity (kN)	Ratio ρ_P
IIc	1012	—	—	—	—	—	980	1.034	1041	0.972	980	1.034
IIc1	618	—	—	—	628	0.984	—	—	—	—	—	—
IIc2	466	629	374	1.683	—	—	—	—	—	—	—	—
IIc3	705	471	374	1.262	—	—	—	—	—	—	—	—
IIIb	1048	—	—	—	—	—	984	1.065	1055	0.993	984	1.065
IIIb1	710	—	—	—	634	1.120	—	—	—	—	—	—
IIIb2	463	459	374	1.228	—	—	—	—	—	—	—	—
IIIb3	657	396	374	1.061	—	—	—	—	—	—	—	—

Table E1.33 – Summary of Analysis of Test Results as Reported by Ligtenberg (1968)

Country	Model	Specimens with a_2 or a_3 only			Specimens with a_1 only			Specimens with a_1 and a_2							Specimens with a_1, a_2 and a_4		
		Equation 4.6a			Equation 4.7				Equation 4.9		Equation 4.10		Equation 4.10a and b			Equation 4.9	
	Steel	Sample Size	ρ_{M2}	V_{M2}	Sample Size	ρ_P	V_P	Sample Size	ρ_P	V_P	ρ_P	V_P	ρ_P	V_P	Sample Size	ρ_P	V_P
England	St.37	18	1.077	0.096	9	1.044	0.115	16	1.085	0.095	0.992	0.101	1.082	0.100	9	0.899	0.363
Japan		18	1.103	0.152	9	1.100	0.092	17	1.053	0.048	0.966	0.045	1.045	0.055	—	—	—
USA		18	1.234	0.125	9	0.991	0.129	18	1.054	0.090	0.967	0.086	1.052	0.091	9	0.888	0.149
France		18	1.087	0.124	9	1.047	0.074	18	1.091	0.106	1.001	0.103	1.088	0.104	9	0.854	0.119
Germany		18	1.087	0.085	9	1.132	0.137	16	1.040	0.098	0.952	0.094	1.040	0.098	—	—	—
Belgium		18	1.108	0.121	9	1.128	0.123	16	1.136	0.107	1.040	0.102	1.134	0.109	3	0.846	0.060
Netherlands		17	1.210	0.077	9	1.043	0.093	17	0.962	0.071	0.882	0.074	0.960	0.070	3	0.888	0.039
Canada		18	1.236	0.129	9	1.156	0.090	15	1.115	0.122	1.024	0.102	1.117	0.111	—	—	—
Sweden		18	1.149	0.145	9	1.066	0.145	18	1.036	0.118	0.946	0.114	1.031	0.120	—	—	—
Yugoslavia		18	1.195	0.091	18	0.954	0.142	18	1.003	0.103	0.922	0.120	1.003	0.117	—	—	—
All specimens of St. 37 steel		179	1.147	0.126	99	1.053	0.130	169	1.051	0.111	0.965	0.107	1.050	0.110	33	0.878	0.211
Netherlands	St.52	10	1.186	0.093	5	0.916	0.129	13	1.029	0.090	0.943	0.085	1.028	0.090	—	—	—
Germany		10	1.238	0.117	5	1.154	0.112	13	1.132	0.055	1.035	0.048	1.129	0.051	—	—	—
Italy		10	1.230	0.060	5	0.873	0.060	13	1.025	0.067	0.935	0.066	1.023	0.068	—	—	—
Sweden		14	1.306	0.138	7	1.009	0.087	14	1.011	0.061	0.948	0.067	1.011	0.061	—	—	—
All specimens of St.52 steel		44	1.246	0.113	22	0.992	0.139	53	1.054	0.083	0.965	0.077	1.047	0.080	—	—	—
All specimens		223	1.167	0.128	121	1.042	0.133	222	1.052	0.105	0.965	0.100	1.050	0.104	—	—	—

Table E2.1 – Weld Measurements and Test Results from Bornscheuer and Feder (1966)

Series No.	Specimen	Weld Orientation	Nominal Values			Test Results				
			Weld Length L (mm)	Throat Size a (mm)	L/a	Throat Size a (mm)	Ratio ρ_G	P_u (kN)	A_{throat} (mm^2)	τ_u (MPa)
1.11	1	Longitudinal	200	4	50	3.7	0.925	1478	2965	499
	2					3.6	0.900	1460	2827	516
	3					3.6	0.900	1469	2784	527
1.12	4		300	4	75	3.6	0.900	2308	4325	534
	5					3.4	0.850	2261	4122	549
	6					3.9	0.975	2296	4678	491
1.21	7		100	4	25	4.1	1.025	733	1636	448
	8					4.2	1.050	723	1656	437
	9					4.0	1.000	763	1586	481
1.22	10		160	8	20	7.4	0.925	1988	4746	419
	11					7.7	0.963	2072	4893	423
	12					7.5	0.938	2080	4800	433
1.23	13		240	12	20	11.3	0.942	3532	10947	323
	14					11.0	0.917	3610	10539	343
	15					11.0	0.917	3625	10573	343
1.31	16		200	4	50	3.5	0.875	1403	2850	492
	17					3.3	0.825	1411	2668	529
	18					3.3	0.825	1413	2644	534
1.32	19		300	4	75	4.2	1.050	2453	5036	487
	20					3.8	0.950	2438	4599	530
	21					3.9	0.975	2256	4713	479

Table E2.1 (cont.)

Series No.	Specimen	Weld Orientation	Nominal Values: Weld Length L (mm)	Nominal Values: Throat Size a (mm)	Nominal Values: L/a	Test Results: Throat Size a (mm)	Test Results: Ratio ρ_G	Test Results: P_u (kN)	Test Results: A_{throat} (mm^2)	Test Results: τ_u (MPa)
1.41	22	Transverse	100	4	25	4.3	1.075	694	844	—
	23					4.2	1.050	718	846	—
	24					4.3	1.075	765	887	—
1.42	25		160	8	20	6.9	0.863	1572	2234	—
	26					8.0	1.000	1755	2574	—
	27					7.5	0.938	1863	2414	—
1.43	28		240	12	20	10.9	0.908	3855	5241	—
	29					11.4	0.950	3787	5491	—
1.51	31	Transverse + Longitudinal	55 + 55	5	11	—†	—	771	1540	—
	32					—†	—	730	1633	—
	33					—†	—	749	1619	—
	34					—†	—	757	1626	—
	35					—†	—	769	1612	—

† Measured throat sizes were not reported

Table E2.2 – Analysis of Test Results from Bornscheuer and Feder (1966)

Series No.	Specimen		Specimens with transverse weld only		Specimens with transverse and longitudinal welds					
		Model	Equation 4.7		Equation 4.9		Equation 4.10		Equation 4.10a and b	
		P_u (kN)	Predicted Capacity (kN)	Ratio ρ_P	Predicted Capacity (kN)	Ratio ρ_P	Predicted Capacity (kN)	Ratio ρ_P	Predicted Capacity (kN)	Ratio ρ_P
1.41	22	694	592	1.172	—	—	—	—	—	—
	23	718	593	1.211	—	—	—	—	—	—
	24	765	622	1.230	—	—	—	—	—	—
1.42	25	1572	1566	1.003	—	—	—	—	—	—
	26	1755	1805	0.972	—	—	—	—	—	—
	27	1863	1693	1.101	—	—	—	—	—	—
1.43	28	3855	3675	1.049	—	—	—	—	—	—
	29	3787	3850	0.984	—	—	—	—	—	—
1.51	31	771	—	—	768	1.004	840	0.918	768	1.004
	32	730	—	—	814	0.896	891	0.820	814	0.847
	33	749	—	—	807	0.927	883	0.848	807	0.841
	34	757	—	—	811	0.934	887	0.854	811	0.848
	35	769	—	—	804	0.957	879	0.875	804	0.868

Table E3.1 – Weld Measurements and Test Results from Kato and Morita (1969)

Specimen	Weld Orientation	Nominal Throat Size		Nominal Throat Size			Test Results		
		a_1 (mm)	a_2 (mm)	a_1 (mm)	a_2 (mm)	Ratio ρ_G	P_u (kN)	Throat Area A_1 (mm^2)	Throat Area A_2 (mm^2)
$S_2$5B	Longitudinal	—	3.5	—	3.6	1.029	106	—	215
$S_2$7B		—	4.9	—	5.1	1.041	185	—	421
$S_2$10B		—	7.1	—	7.0	0.986	344	—	846
$S_2$12B		—	8.5	—	8.1	0.953	473	—	1175
$S_2$15B		—	10.6	—	10.7	1.009	824	—	1910
$S_2$20B		—	14.1	—	14.2	1.007	1416	—	3446
$S_2$22B		—	15.6	—	14.5	0.929	1552	—	3800
$S_2$5R	Longitudinal	—	3.5	—	3.4	0.971	78	—	204
$S_2$10R		—	7.1	—	7.3	1.028	312	—	892
$S_2$15R		—	10.6	—	10.7	1.009	1005	—	2966
$S_2$20R		—	14.1	—	12.3	0.872	736	—	1934
$S_1$5B	Transverse	3.5	—	3.5	—	1.000	202	277	—
$S_1$10B		7.1	—	7.2	—	1.014	340	571	—
$S_1$15B		10.6	—	10.8	—	1.019	508	862	—
$S_1$20B		14.1	—	14.1	—	1.000	662	1137	—
$S_1$30B		21.2	—	21.2	—	1.000	870	1697	—
$S_1$40B		28.3	—	28.3	—	1.000	1296	2259	—
$S_1$5R		3.5	—	3.5	—	1.000	150	277	—
$S_1$15R		10.6	—	10.7	—	1.009	452	848	—
$S_1$40R		28.3	—	24.9	—	0.880	916	2005	—
S5–5B	Longitudinal + Transverse	3.5	3.5	3.7	3.7	1.057 / 1.057	578	488	494
S15–5B		10.6	3.5	10.8	3.9	1.019 / 1.114	1366	1628	517
S5–15B		3.5	10.6	4.0	10.8	1.143 / 1.019	931	538	1654

Table E3.2 – Analysis of Test Results from Kato and Morita (1969)

Specimen		Specimens with a_2 only			Specimens with a_1 only		Specimens with a_1 and a_2					
	Model	Equation 4.6a			Equation 4.7		Equation 4.9		Equation 4.10		Equation 4.10a and b	
	P_u (kN)	τ_u (MPa)	$0.67\sigma_u$ (MPa)	Ratio ρ_{M2}	Predicted Capacity (kN)	Ratio ρ_P	Predicted Capacity (kN)	Ratio ρ_P	Predicted Capacity (kN)	Ratio ρ_P	Predicted Capacity (kN)	Ratio ρ_P
$S_2$5B	106	491		1.297	—	—	—	—	—	—	—	—
$S_2$7B	185	439		1.160	—	—	—	—	—	—	—	—
$S_2$10B	344	408		1.077	—	—	—	—	—	—	—	—
$S_2$12B	473	403	379	1.066	—	—	—	—	—	—	—	—
$S_2$15B	824	432		1.141	—	—	—	—	—	—	—	—
$S_2$20B	1416	411		1.086	—	—	—	—	—	—	—	—
$S_2$22B	1552	409		1.080	—	—	—	—	—	—	—	—
$S_2$5R	78	385		1.155	—	—	—	—	—	—	—	—
$S_2$10R	312	350	333	1.053	—	—	—	—	—	—	—	—
$S_2$15R	1005	339		1.020	—	—	—	—	—	—	—	—
$S_2$20R	736	381		1.146	—	—	—	—	—	—	—	—
$S_1$5B	202	—	—	—	178	1.136	—	—	—	—	—	—
$S_1$10B	340	—	—	—	366	0.930	—	—	—	—	—	—
$S_1$15B	508	—	—	—	553	0.920	—	—	—	—	—	—
$S_1$20B	662	—	—	—	729	0.908	—	—	—	—	—	—
$S_1$30B	870	—	—	—	1088	0.800	—	—	—	—	—	—
$S_1$40B	1296	—	—	—	1449	0.895	—	—	—	—	—	—
$S_1$5R	150	—	—	—	151	0.996	—	—	—	—	—	—
$S_1$15R	452	—	—	—	463	0.978	—	—	—	—	—	—
$S_1$40R	916	—	—	—	1095	0.838	—	—	—	—	—	—
S5–5B	578	—	—	—	—	—	493	1.175	524	1.104	493	1.175
S15–5B	1366	—	—	—	—	—	1232	1.110	1265	1.081	1232	1.110
S5–15B	931	—	—	—	—	—	946	0.985	1052	0.886	946	0.985

Table E4.1 – Summary of Test Program from Butler and Kulak (1969)

Weld Metal Classification	AWS E60XX (AWS, 1969)				
Fabricator (welder)	fabrication was carried out by a local steel fabricator using qualified welders and standard shop procedure				
Specified Tensile Strength	414 MPa (60 ksi)				
Welding Process	SMAW				
Specimen Configuration	double lapped, 0º weld	double lapped, 30º weld	double lapped, 60º weld	double lapped, 90º weld	full size connection
Lap Plate Thickness (mm)	12.7	15.9	12.7	12.7	
Main Plate Thickness (mm)	25.4	31.8	25.4	25.4	
Base Metal Grade	CSA G40.12, 1964: specified yield stress of 303 MPa (44 ksi), and a minimum tensile strength of 427 MPa (62 ksi)				
Test Temperature	room temperature				
Plate Stress at Peak Load	elastic (calculated by the presented results)				
Specimen Designation	L–1, L–2 , L–3, L–4, L– 5	30–1, 30–2, 30–3, 30–4, 30–5, 30–6	60–1, 60–2, 60–3, 60–4, 60–5, 60–6	T–1, T–2, T–3, T–4, T–5, T–6	B–1, B–2, B–3, B–4, B–5, B–6, B–7, B–8
Nominal Leg Size (mm)	6.4				
Number of Passes	1				

Table E4.2 – Weld measurements and Test Results as Reported by Butler and Kulak (1969)

<table>
<tr><th rowspan="3">Specimen</th><th rowspan="3">Average Weld Size (mm)</th><th rowspan="3">Ratio ρ_G</th><th colspan="3">Model</th><th colspan="2">Equation 4.7</th></tr>
<tr><th colspan="3">Ultimate Load (kN/mm)†</th><th rowspan="2">Ratio ρ_P</th><th rowspan="2">V_P</th></tr>
<tr><th>Mean</th><th>σ</th><th>V</th></tr>
<tr><td>L–1</td><td>7.4</td><td>1.160</td><td rowspan="5">1.91</td><td rowspan="5">0.117</td><td rowspan="5">0.061</td><td rowspan="5">—</td><td rowspan="5">—</td></tr>
<tr><td>L–2</td><td>6.9</td><td>1.080</td></tr>
<tr><td>L–3</td><td>6.9</td><td>1.080</td></tr>
<tr><td>L–4</td><td>6.9</td><td>1.080</td></tr>
<tr><td>L–5</td><td>7.4</td><td>1.160</td></tr>
<tr><td>30–1</td><td>6.9</td><td>1.080</td><td rowspan="6">2.56</td><td rowspan="6">0.005</td><td rowspan="6">0.002</td><td rowspan="6">1.225</td><td rowspan="6">0.002</td></tr>
<tr><td>30–2</td><td>6.1</td><td>0.960</td></tr>
<tr><td>30–3</td><td>6.6</td><td>1.040</td></tr>
<tr><td>30–4</td><td>6.4</td><td>1.000</td></tr>
<tr><td>30–5</td><td>6.4</td><td>1.000</td></tr>
<tr><td>30–6</td><td>7.1</td><td>1.120</td></tr>
<tr><td>60–1</td><td>7.6</td><td>1.200</td><td rowspan="6">2.47</td><td rowspan="6">0.089</td><td rowspan="6">0.036</td><td rowspan="6">0.845</td><td rowspan="6">0.036</td></tr>
<tr><td>60–2</td><td>7.9</td><td>1.240</td></tr>
<tr><td>60–3</td><td>7.4</td><td>1.160</td></tr>
<tr><td>60–4</td><td>7.9</td><td>1.240</td></tr>
<tr><td>60–5</td><td>7.6</td><td>1.200</td></tr>
<tr><td>60–6</td><td>7.9</td><td>1.240</td></tr>
<tr><td>T–1</td><td>6.9</td><td>1.080</td><td rowspan="6">2.71</td><td rowspan="6">0.166</td><td rowspan="6">0.061</td><td rowspan="6">0.914</td><td rowspan="6">0.061</td></tr>
<tr><td>T–2</td><td>7.4</td><td>1.160</td></tr>
<tr><td>T–3</td><td>7.9</td><td>1.240</td></tr>
<tr><td>T–4</td><td>7.4</td><td>1.160</td></tr>
<tr><td>T–5</td><td>6.6</td><td>1.040</td></tr>
<tr><td>T–6</td><td>7.9</td><td>1.240</td></tr>
<tr><td>B–1‡</td><td>7.2</td><td>1.132</td><td>—</td><td>—</td><td>—</td><td>—</td><td>—</td></tr>
<tr><td>B–2</td><td>7.3</td><td>1.156</td><td>—</td><td>—</td><td>—</td><td>—</td><td>—</td></tr>
<tr><td>B–3</td><td>7.5</td><td>1.188</td><td>—</td><td>—</td><td>—</td><td>—</td><td>—</td></tr>
<tr><td>B–4</td><td>7.5</td><td>1.184</td><td>—</td><td>—</td><td>—</td><td>—</td><td>—</td></tr>
<tr><td>B–5</td><td>7.6</td><td>1.196</td><td>—</td><td>—</td><td>—</td><td>—</td><td>—</td></tr>
<tr><td>B–6</td><td>7.4</td><td>1.168</td><td>—</td><td>—</td><td>—</td><td>—</td><td>—</td></tr>
<tr><td>B–7</td><td>7.7</td><td>1.208</td><td>—</td><td>—</td><td>—</td><td>—</td><td>—</td></tr>
<tr><td>B–8</td><td>6.8</td><td>1.072</td><td>—</td><td>—</td><td>—</td><td>—</td><td>—</td></tr>
<tr><td rowspan="2">All specimen</td><td>Mean ρ_G</td><td>1.138</td><td>—</td><td>—</td><td>—</td><td>—</td><td>—</td></tr>
<tr><td>V_G</td><td>0.069</td><td>—</td><td>—</td><td>—</td><td>—</td><td>—</td></tr>
</table>

† Load reported as capacity of per linear length (mm) weld.

‡ This group of specimens was loaded eccentrically.

Table E5.1 – Weld Measurements from Dawe and Kulak (1972)

Connection Type	Specimen	Weld Location	Average Weld Leg Size (mm)	Ratio ρ_G	Mean ρ_G	V_G
series A	A–1	vertical weld only	7.9	1.244	1.158	0.075
	A–2	vertical weld only	7.9	1.244		
	A–3	vertical weld only	7.6	1.197		
	A–4	vertical weld only	7.6	1.197		
	A–5	vertical weld only	7.6	1.197		
	A–6	vertical weld only	8.1	1.276		
	A–7	vertical weld only	7.4	1.165		
	A–8	vertical weld only	7.9	1.244		
series B	B–1	tension flange	7.1	1.118		
		web	7.6	1.197		
	B–2	tension flange	7.9	1.244		
		web	7.6	1.197		
	B–3	tension flange	7.9	1.244		
		web	7.6	1.197		
	B–4	tension flange	7.9	1.244		
		web	7.6	1.197		
series C	C–1	compression flange	7.4	1.165		
		tension flange	7.6	1.197		
		web	7.9	1.244		
	C–2	compression flange	7.4	1.165		
		tension flange	7.4	1.165		
		web	7.4	1.165		
	C–3	compression flange	7.9	1.244		
		tension flange	8.1	1.276		
		web	6.9	1.087		
	C–4	compression flange	6.6	1.039		
		tension flange	7.4	1.165		
		web	8.1	1.276		
series 1	1–1	longitudinal weld	6.4	1.008		
	1–2		6.9	1.087		
	1–3		6.6	1.039		
	1–4		6.6	1.039		
	1–5		6.6	1.039		
series 2	2 - 1	longitudinal weld	6.9	1.087		
	2–2		6.4	1.008		
	2–3		6.4	1.008		
	2–4		6.4	1.008		
	2–5		6.6	1.039		
series 3	3–1	longitudinal weld	7.9	1.244		
	3–2		7.4	1.165		
	3–3		7.1	1.118		
	3–4		7.6	1.197		
	3–5		7.6	1.197		

Table E6.1 – Weld Measurements and Test Results from Clark (1971)

Series	Specimen	Loading Angle	Nominal Throat Size (mm)	Average Throat Size (mm)	Ratio ρ_G	Mean ρ_G	V_G	Model P_u / A_{throat} (MPa)	Equation 4.7 τ_u (MPa)	Equation 4.7 Ratio ρ_P	Equation 4.7 Mean ρ_P	Equation 4.7 V_P
Series I	1a	0°	5.6	5.2	0.929	0.985	0.065	325	343	—	—	—
	1b			5.2	0.929			332		—		—
	2a			5.1	0.905			329		—		—
	2b			5.8	1.030			328		—		—
	3a			6.1	1.082			337		—		—
	3b			5.6	1.000			368		—		—
	4a			6.0	1.071			340		—		—
	4b			5.8	1.027			357		—		—
	5a			6.1	1.082			352		—		—
	5b			5.9	1.048			357		—		—
Series II	1a	90°	5.6	5.7	1.014			580	—	1.129	1.139	0.134
	1b			5.6	1.007			561		1.092		
	2a			5.3	0.952			590		1.148		
	2b			5.3	0.952			609		1.185		
Series III	1a	30°	5.6	5.5	0.973			566		1.404		
	1b			5.3	0.939			524		1.300		
	2a	60°	5.6	5.1	0.904			597		1.242		
	2b			4.9	0.880			428		0.891		

Table E7.1 – Weld Measurements as Reported by Swannell (1979b)

Specimen	Nominal Leg Size (mm)	Measured Leg Size (mm)	Ratio ρ_G	Mean ρ_G	V_G
1	6.4	6.6	1.031	1.070	0.031
2	6.4	6.4	1.000		
3	6.4	6.6	1.031		
4	6.4	6.8	1.063		
5	6.4	6.7	1.047		
6a	6.4	6.9	1.078		
6b	6.4	6.7	1.047		
6c	6.4	6.8	1.063		
6d	6.4	7.2	1.125		
6e	6.4	7.0	1.094		
6f	6.4	6.8	1.063		
7	6.4	6.8	1.063		
8	6.4	6.8	1.063		
9	6.4	6.9	1.078		
10a	6.4	6.4	1.000		
10b	6.4	7.1	1.109		
10c	6.4	6.8	1.063		
10d	6.4	6.8	1.063		
10e	6.4	7.1	1.109		
10f	6.4	6.7	1.047		
11	6.4	6.9	1.078		

Table E7.2 – Analysis of Test Results as Reported by Swannell (1979b)

Test Type	Series No.	Specimen	Model	Equation 4.6a				
			σ_u (MPa)	τ_u (MPa)	$0.67\sigma_u$	Ratio ρ_{M2}	Mean ρ_{M2}	V_{M2}
All Weld Metal Coupon	1	1	546	—	361	—	—	—
		2	531	—		—	—	—
Welded Joints with Longitudinal Welds only	2	1	—	394	—	1.091	1.045	0.041
		2	—	398	—	1.103		
	3	1	—	373	—	1.033		
		2	—	374	—	1.036		
	4	1	—	361	—	1.000		
		2	—	357	—	0.989		
		3	—	384	—	1.064		

Table E8.1 – Weld Measurements from Pham (1981)

Specimen	Nominal Throat Size (mm)	Average Throat Size (mm)	Ratio ρ_G	Mean ρ_G	V_G
a–B–1	3.5	4.0	1.143	1.072	0.102
a–B–2		3.5	1.000		
a–B–3		4.4	1.257		
a–B–4		4.0	1.143		
a–B–5		4.0	1.143		
a–B–6		3.8	1.086		
b–A–1		3.8	1.086		
b–A–2		3.7	1.057		
b–A–3		3.8	1.086		
b–A–4		4.2	1.200		
b–B–1		4.2	1.200		
b–B–2		3.9	1.114		
b–B–3		3.0	0.857		
b–B–4		3.0	0.857		
c–A–1		3.9	1.114		
c–A–2		3.6	1.029		
c–B–1		3.9	1.114		
c–A–3	7.1	7.3	1.028	1.058	0.051
c–A–4		7.4	1.042		
c–A–5		7.3	1.028		
c–A–6		7.1	1.000		
c–B–2		8.0	1.127		
c–B–3		7.9	1.113		
c–A–7	11.3	11.2	0.991	1.030	0.054
c–A–8		12.4	1.097		
c–B–4		11.3	1.000		

Table E9.1 – Test Matrix of Test Program from Pham (1983a)

weld metal classification	Fluxofil 11Ni (with CO_2 shield)			AWS class F70-EL12		
Tensile strength of electrode	570 MPa			646 MPa		
Welding procedure	FCAW			SAW		
Specimen configuration	Cruciform			Cruciform		
Lap-plate thick (mm)	20	32	50	20	32	50
Main-plate thick (mm)	20	32	50	20	32	50
Specimen designation	6F1, 6F2, 6F3, 6F4, 6F5, 6F6	10F1, 10F2, 10F3, 10F4, 10F5, 10F6	16F1, 16F2, 16F3, 16F4, 16F5, 16F6	6S1, 6S2, 6S3, 6S4, 6S5, 6S6	10S1, 10S2, 10S3, 10S4, 10S5, 10S6	16S1, 16S2, 16S3, 16S4, 16S5, 16S6
Nominal leg size (mm)	6	10	16	6	10	16

Table E9.2 – Test Matrix of Test Program from Pham (1983b)

Weld metal classification	Fluxofil 11Ni (with CO_2 shield)			AWS class F70-EL12		
Tensile strength of electrode	570 MPa			646 MPa		
Welding procedure	FCAW			SAW		
Specimen configuration	Werner Specimen			Werner Specimen		
Lap-plate thick (mm)	10	16	25	10	16	25
Main-plate thick (mm)	10	16	25	10	16	25
Specimen designation	6F7, 6F8, 6F9, 6F7#, 6F8#, 6F9#	10F7, 10F8, 10F9, 10F10, 10F11, 10F12	16F7, 16F8, 16F9, 16F10, 16F11, 16F12	6S7, 6S7#, 6S9, 6S10#, 6S11, 6S11#	10S7, 10S8, 10S9, 10S10, 10S11, 10S12	16S7, 16S8, 16S9, 16S10, 16S11, 16S12
Nominal leg size (mm)	6	10	16	6	10	16

Table E9.3 – Weld Measurements from Pham (1983a)

Specimen	Nominal Leg Size (mm)	Measured Dimensions				Ratio ρ_G	Mean ρ_G	V_G
		Leg Size s_1 (mm)	Leg Size s_2 (mm)	MTD (mm)	Length (mm)			
6F1	6	9.5	8.0	6.1	30.9	1.443	1.326	0.045
6F2	6	9.0	7.0	5.5	30.1	1.303		
6F3	6	8.0	8.0	5.7	31.0	1.334		
6F4	6	9.0	7.0	5.5	30.6	1.303		
6F5	6	9.0	7.0	5.5	30.0	1.303		
6F6	6	8.5	7.0	5.4	30.7	1.274		
10F1	10	10.0	9.5	6.9	49.2	0.974	1.010	0.065
10F2	10	10.5	10.5	7.4	49.3	1.050		
10F3	10	9.5	9.5	6.7	50.0	0.950		
10F4	10	9.5	9.5	6.7	49.3	0.950		
10F5	10	12.0	10.5	7.9	51.1	1.118		
10F6	10	9.5	11.0	7.2	51.4	1.017		
16F1	16	18.5	16.5	12.3	81.0	1.089	1.130	0.106
16F2	16	21.0	18.9	14.0	80.1	1.242		
16F3	16	16.0	15.5	11.1	80.8	0.984		
16F4	16	17.0	15.5	11.5	80.6	1.013		
16F5	16	20.6	20.1	14.4	79.2	1.272		
16F6	16	18.0	20.0	13.4	79.4	1.183		
6S1	6	8.0	7.0	5.3	29.5	1.242	1.322	0.031
6S2	6	10.0	7.0	5.7	29.3	1.352		
6S3	6	9.5	7.0	5.6	29.5	1.328		
6S4	6	10.0	7.0	5.7	30.7	1.352		
6S5	6	9.5	7.0	5.6	31.7	1.328		
6S6	6	9.5	7.0	5.6	29.8	1.328		
10S1	10	13.5	12.5	9.2	48.8	1.297	1.224	0.031
10S2	10	12.5	11.5	8.5	50.3	1.197		
10S3	10	12.5	12.0	8.7	50.4	1.224		
10S4	10	12.5	12.0	8.7	50.6	1.224		
10S5	10	12.0	12.0	8.5	50.1	1.200		
10S6	10	12.0	12.0	8.5	49.4	1.200		
16S1	16	18.0	16.5	12.2	79.9	1.075	1.068	0.049
16S2	16	17.0	17.0	12.0	78.8	1.063		
16S3	16	17.0	16.0	11.7	80.9	1.030		
16S4	16	17.0	16.0	11.7	80.5	1.030		
16S5	16	17.5	16.0	11.8	81.3	1.044		
16S6	16	19.5	18.0	13.2	81.5	1.169		

Table E9.4 – Weld Measurements from Pham (1983b)

Specimen	Nominal Leg Size (mm)	Measured Dimensions				Ratio ρ_G	Mean ρ_G	V_G
		Leg Size s_1 (mm)	Leg Size s_2 (mm)	MTD (mm)	Length (mm)			
6F7	6	7.3	8.0	5.4	40.7	1.275	1.294	0.013
6F8	6	7.0	8.6	5.4	39.9	1.300		
6F9	6	7.3	8.4	5.5	40.8	1.308		
6F7#	6	7.3	8.0	5.4	40.4	1.275		
6F8#	6	7.0	8.6	5.4	40.9	1.300		
6F9#	6	7.3	8.4	5.5	40.5	1.308		
10F7	10	9.5	10.8	7.1	75.0	1.015	1.003	0.040
10F8	10	9.6	10.4	7.1	75.1	1.000		
10F9	10	9.4	10.8	7.1	75.0	1.010		
10F10	10	8.5	10.3	6.6	75.1	0.940		
10F11	10	—†	—†	—	75.0	—		
10F12	10	10.6	10.4	7.4	75.0	1.050		
16F7	16	14.1	18.1	11.1	132.2	1.006	0.987	0.031
16F8	16	15.1	16.5	11.1	132.3	0.988		
16F9	16	13.9	16.5	10.6	132.2	0.950		
16F10	16	15.1	15.4	10.8	132.1	0.953		
16F11	16	15.3	16.6	11.3	131.9	0.997		
16F12	16	15.1	17.8	11.5	131.9	1.028		
6S7	6	8.6	8.9	6.2	40.0	1.458	1.492	0.032
6S7#	6	8.6	8.9	6.2	40.0	1.458		
6S9	6	—†	—†	—	—	—		
6S10#	6	—†	—†	—	—	—		
6S11	6	9.4	8.9	6.5	40.1	1.525		
6S11#	6	9.4	8.9	6.5	40.1	1.525		
10S7	10	12.5	11.8	8.6	75.1	1.215	1.216	0.038
10S8	10	11.5	12.3	8.4	75.1	1.190		
10S9	10	11.5	12.3	8.4	75.1	1.190		
10S10	10	11.3	12.3	8.3	75.3	1.180		
10S11	10	11.7	12.6	8.6	75.0	1.215		
10S12	10	13.1	13.0	9.2	75.0	1.305		
16S7	16	—†	18.3	—	132.4	—	1.107	0.039
16S8	16	18.3	17.3	12.6	132.0	1.113		
16S9	16	17.8	18.4	12.8	132.0	1.131		
16S10	16	17.9	18.8	13.0	131.5	1.147		
16S11	16	17.6	17.9	12.5	131.6	1.109		
16S12	16	16.0	17.1	11.7	131.9	1.034		

† Measured dimensions were not reported.

Table E9.5 – Test Results and Analysis of the Test Program as Reported by Pham (1983a)

Specimen	Model		Equation 4.7			
	P_u (kN)	A_{throat} (mm^2)	Predicted Load (kN)	Ratio ρ_P	Mean ρ_P	V_P
6F1	264	378	238	1.111	1.206	0.042
6F2	255	333	209	1.220		
6F3	265	351	220	1.203		
6F4	258	338	212	1.214		
6F5	255	332	208	1.224		
6F6	263	332	208	1.262		
10F1	385	678	426	0.904	0.888	0.072
10F2	411	732	460	0.894		
10F3	408	672	422	0.967		
10F4	377	662	416	0.906		
10F5	392	808	507	0.773		
10F6	410	739	464	0.883		
16F1	1184	1995	1253	0.945	0.906	0.099
16F2	1166	2251	1414	0.825		
16F3	1126	1799	1130	0.996		
16F4	1175	1846	1160	1.013		
16F5	1179	2279	1432	0.824		
16F6	1112	2125	1335	0.833		
6S1	213	311	189	1.127	1.091	0.033
6S2	213	336	204	1.042		
6S3	225	332	202	1.113		
6S4	225	352	214	1.051		
6S5	240	357	217	1.104		
6S6	227	336	204	1.111		
10S1	642	895	545	1.179	1.251	0.030
10S2	660	851	518	1.274		
10S3	670	873	531	1.262		
10S4	660	876	533	1.239		
10S5	660	850	517	1.276		
10S6	650	838	510	1.275		
16S1	1157	1944	1182	0.979	0.981	0.054
16S2	1112	1894	1152	0.965		
16S3	1188	1885	1147	1.036		
16S4	1148	1876	1141	1.006		
16S5	1183	1920	1168	1.013		
16S6	1160	2156	1311	0.885		

Table E9.6 – Test Results and Analysis of the Test Program as Reported by Pham (1983b)

Specimen	Model		Equation 4.6a				
	P_u (kN)	A_{throat} (mm^2)	τ_u (MPa)	$0.67\sigma_u$ (MPa)	Ratio ρ_{M2}	Mean ρ_{M2}	V_{M2}
6F7	81.50	155	525	382	1.374	1.226	0.156
6F8	84.00	156	537		1.407		
6F9	85.00	159	536		1.403		
6F7#	65.80	155	424		1.109		
6F8#	58.25	156	373		0.976		
6F9#	65.75	159	414		1.085		
10F7	267.00	713	374	382	0.980	1.037	0.045
10F8	284.00	705	403		1.054		
10F9	282.00	709	398		1.041		
10F10	276.00	656	421		1.102		
10F11	—	—	—		—		
10F12	285.00	742	384		1.005		
16F7	689.00	1780	387	382	1.014	1.018	0.043
16F8	681.00	1782	382		1.000		
16F9	703.00	1701	413		1.082		
16F10	694.00	1725	402		1.053		
16F11	659.00	1800	366		0.959		
16F12	703.00	1842	382		0.999		
6S7	104.00	190	546	433	1.261	1.082	0.181
6S7#	64.50	160	404		0.934		
6S9#	77.80	—	—		—		
6S10#	—	—	—		—		
6S11	93.00	173	537		1.241		
6S11#	63.50	164	387		0.894		
10S7	320.00	858	373	433	0.862	0.894	0.067
10S8	310.00	840	369		0.853		
10S9	329.00	840	392		0.905		
10S10	326.00	832	392		0.905		
10S11	372.00	857	434		1.002		
10S12	334.00	923	362		0.836		
16S7	765.00	—	—	433	—	0.872	0.046
16S8	756.00	2011	376		0.868		
16S9	743.00	2047	363		0.839		
16S10	761.00	2074	367		0.848		
16S11	752.00	2008	375		0.865		
16S12	761.00	1869	407		0.941		

Table E10.1 – Test Matrix of Test Program from Miazga and Kennedy (1986)

Weld metal classification	CSA Standard W48.1-M80, E48014						
Electrode manufacturer	Hobart Brothers of Canada						
Steel fabricator (welder)	Welding Research Laboratory of the Dept. of Mineral Eng. U of A						
Specified tensile strength	480MPa						
Welding process	SMAW, Semi-automatic						
Loading angle	90º	75º	60º	45º	30º	15º	0º
Lap plate thickness (mm)	9 mm						
Main plate thickness (mm)	18 mm						
Base metal grade	CAN3-G40.21 - M81 grade 300W						
Plate stress at peak load	elastic						
Specimen designation	90.1, 90.2, 90.3	75.1, 75.2, 75.3	60.1, 60.2, 60.3	45.1, 45.2, 45.3	30.1, 30.2, 30.3	15.1, 15.2, 15.3	00.1, 00.2, 00.3
Nominal leg size (mm)	5 mm						
Number of passes	1 pass						

Table E10.1 (cont.)

Weld metal classification	CSA Standard W48.1-M80, E48014						
Electrode manufacturer	Hobart Brothers of Canada						
Steel fabricator (welder)	Welding Research Laboratory of the Dept. of Mineral Eng. U of A						
Specified tensile strength	480MPa						
Welding process	SMAW, Semi-automatic						
Loading angle	90º	75º	60º	45º	30º	15º	0º
Lap plate thickness (mm)	18 mm						
Main plate thickness (mm)	35 mm						
Base metal grade	CAN3-G40.21 - M81 grade 300W						
Plate stress at peak load	elastic						
Specimen designation	90.11, 90.12, 90.13	75.11, 75.12, 75.13	60.11, 60.12, 60.13	45.11, 45.12, 45.13	30.11, 30.12, 30.13	15.11, 15.12, 15.13	00.11, 00.12, 00.13
Nominal leg size (mm)	9 mm						
Number of passes	3 passes						

Table E10.2 – Weld Measurements as Reported by Miazga and Kennedy (1986)

Specimen	n †	Measured Leg Size				
		Mean (mm)	s (mm)	V	Ratio ρ_G	Weld Length (mm)
90.1	44	5.25	0.31	0.058	1.050	200
90.2	44	5.33	0.34	0.064	1.066	200
90.3	44	5.29	0.39	0.072	1.058	201
75.1	44	5.14	0.36	0.070	1.028	215
75.2	44	5.01	0.35	0.071	1.002	211
75.3	44	5.12	0.29	0.060	1.024	210
60.1	48	5.12	0.33	0.064	1.024	230
60.2	48	5.06	0.32	0.063	1.012	231
60.3	48	5.03	0.37	0.072	1.006	226
45.1	48	5.37	0.52	0.099	1.074	204
45.2	48	5.10	0.52	0.101	1.020	200
45.3	48	5.12	0.37	0.071	1.024	196
30.1	64	5.31	0.40	0.075	1.062	294
30.2	62	5.50	0.39	0.071	1.100	302
30.3	60	5.27	0.34	0.065	1.054	296
15.1	58	5.19	0.50	0.099	1.038	306
15.2	58	5.14	0.37	0.072	1.028	313
15.3	59	5.09	0.45	0.089	1.018	311
00.1	72	4.94	0.40	0.081	0.988	316
00.2	72	5.22	0.39	0.075	1.044	309
00.3	72	5.16	0.32	0.062	1.032	315
90.11	44	9.10	0.49	0.054	1.011	197
90.12	44	9.26	0.39	0.043	1.029	200
90.13	44	9.16	0.54	0.058	1.018	200
75.11	44	9.18	0.58	0.064	1.020	211
75.12	44	9.08	0.53	0.058	1.009	207
75.13	44	9.24	0.42	0.045	1.027	209
60.11	48	9.42	0.38	0.041	1.047	226
60.12	48	9.65	0.35	0.036	1.072	229
60.13	48	9.88	0.41	0.042	1.098	228
45.11	56	9.43	0.50	0.054	1.048	272
45.12	56	9.46	0.48	0.050	1.051	279
45.13	58	9.18	0.50	0.056	1.020	279
30.11	64	9.41	0.36	0.038	1.046	296
30.12	60	9.16	0.40	0.043	1.018	296
30.13	58	9.74	0.40	0.041	1.082	294
15.11	54	8.79	0.34	0.088	0.977	300
15.12	52	9.23	0.40	0.044	1.026	294
15.13	54	9.06	0.38	0.042	1.007	294
00.11	64	9.50	0.35	0.037	1.056	300
00.12	72	9.10	0.44	0.049	1.011	321
00.13	72	9.20	0.34	0.037	1.022	316

† Number of measurements.

Table E10.3 – Summary of Weld Measurements of Test Program as Reported by Miazga and Kennedy (1986)

	Weld Size	
	5 mm	9 mm
Mean Measured Leg Size (mm)	5.18	9.30
s (mm)	0.13	0.25
V	0.026	0.027
Mean of Mean/Nominal ρ_G	1.036	1.033
V_G	0.026	0.027

Table E10.4 – Test Results and Analysis as Reported by Miazga and Kennedy (1986)

Specimen	Model		Equation 4.6a			Equation 4.7			
	P_u (kN)	A_{throat} (mm^2)	τ_u (MPa)	$0.67\sigma_u$ (MPa)	Ratio ρ_{M2}	Predicted Capacity (kN)	Ratio ρ_P	Mean ρ_P	V_P
90.1	421	742	—	—	—	458	0.920	0.954	0.056
90.2	431	754	—	—	—	465	0.928		
90.3	407	752	—	—	—	464	0.879		
90.11	789	1267	—	—	—	782	1.010		
90.12	807	1309	—	—	—	808	1.000		
90.13	791	1295	—	—	—	799	0.990		
75.1	466	781	—	—	—	473	0.984	0.996	0.018
75.2	451	747	—	—	—	453	0.996		
75.3	471	760	—	—	—	461	1.022		
75.11	822	1369	—	—	—	830	0.990		
75.12	810	1329	—	—	—	805	1.006		
75.13	805	1365	—	—	—	827	0.972		
60.1	568	833	—	—	—	481	1.183	1.105	0.112
60.2	566	826	—	—	—	477	1.188		
60.3	589	804	—	—	—	464	1.270		
60.11	895	1505	—	—	—	868	1.031		
60.12	892	1562	—	—	—	901	0.989		
60.13	894	1593	—	—	—	919	0.973		
45.1	447	775	—	—	—	413	1.081	0.990	0.129
45.2	433	721	—	—	—	384	1.126		
45.3	419	709	—	—	—	378	1.107		
45.11	842	1813	—	—	—	966	0.871		
45.12	858	1866	—	—	—	995	0.862		
45.13	861	1811	—	—	—	965	0.891		
30.1	614	1104	—	—	—	534	1.150	1.079	0.056
30.2	626	1174	—	—	—	568	1.103		
30.3	610	1103	—	—	—	534	1.143		
30.11	980	1969	—	—	—	953	1.029		
30.12	968	1917	—	—	—	928	1.044		
30.13	989	2025	—	—	—	980	1.009		
15.1	484	1123	—	—	—	492	0.984	0.953	0.051
15.2	477	1137	—	—	—	498	0.957		
15.3	482	1119	—	—	—	490	0.983		
15.11	773	1864	—	—	—	816	0.946		
15.12	724	1919	—	—	—	841	0.861		
15.13	815	1883	—	—	—	825	0.987		
00.1	513	1104	464	360	1.284	—	—	—	—
00.2	487	1140	427		1.186	—	—	—	—
00.3	483	1149	420		1.167	—	—	—	—
00.11	752	2015	373		1.036	—	—	—	—
00.12	825	2065	399		1.108	—	—	—	—
00.13	787	2055	383		1.064	—	—	—	—

Table E11.1 – Test Matrix of Test Program from Bowman and Quinn (1994)

Weld metal classification	E7018, 3/16-in diameter electrode									
Specified tensile strength	496 MPa (72 ksi)									
Welding process	SMAW									
Weld orientation	Longitudinal			Transverse			Longitudinal		Transverse	
Lap plate thick (mm)	25.4	38.1	50.8	12.7	19.1	25.4	25.4	50.8	12.7	25.4
Main plate thick (mm)	25.4	38.1	50.8	25.4	38.1	50.8	25.4	50.8	25.4	50.8
Base metal grade	ASTM A572 Grade 50									
Plate stress at peak load	elastic									
Specimen designation	1–2–L–0 2–2–L–0	3–3–L–0 4–3–L–0	5–4–L–0 6–4–L–0	7–2–T–0 8–2–T–0	9–3–T–0 10–3–T–0	11–4–T–0 12–4–T–0	13–2–L–1 14–2–L–2	15–4–L–1	16–2–T–1 17–2–T–2	18–4–T–1
Nominal leg size (mm)	6.4	9.5	12.7	6.4	9.5	12.7	6.4	12.7	6.4	12.7
Root opening (mm)	none			none			1.6	1.6	1.6	1.6
Number of passes	1	2	3 or 4	1	2	4	1	4	1	4

Table E11.2 – Weld Measurements as Reported by Bowman and Quinn (1994)

Specimen	Nominal Leg Size (mm)	Bottom Leg Size (mm)	Top Leg Size (mm)	MTD (mm)	Ratio ρ_G	Mean ρ_G	V_G
1–2–L–0	6.4	7.0	6.8	4.9	1.086	1.182	0.082
2–2–L–0		7.2	7.0	5.0	1.122		
7–2–T–0		8.1	7.8	5.6	1.246		
8–2–T–0		7.8	9.3	6.0	1.337		
13–2–L–1		6.7	8.2	5.2	1.158		
14–2–L–2		5.9	8.3	4.8	1.066		
16–2–T–1		7.8	8.6	5.8	1.286		
17–2–T–2		6.4	9.0	5.2	1.158		
3–3–L–0	9.5	10.4	11.0	7.6	1.121	1.128	0.040
4–3–L–0		9.7	10.7	7.2	1.067		
9–3–T–0		10.5	11.9	7.9	1.169		
10–3–T–0		10.7	11.3	7.8	1.154		
5–4–L–0	12.7	13.7	13.5	9.6	1.070	1.087	0.030
6–4–L–0		14.5	14.1	10.1	1.126		
11–4–T–0		14.0	12.6	9.4	1.047		
12–4–T–0		13.7	13.2	9.5	1.058		
15–4–L–1		14.5	13.6	9.9	1.105		
18–4–T–1		15.7	13.0	10.0	1.115		

Table E11.3 – Analysis of Test Program as Reported by Bowman and Quinn (1994)

Specimen	Model		Equation 4.6a			Equation 4.7			
	P_u (kN)	A_{throat} (mm^2)	τ_u (MPa)	$0.67\sigma_u$ (MPa)	Ratio ρ_{M2}	Predicted Capacity (kN)	Ratio ρ_P	Mean ρ_P	V_P
1–2–L–0	1099	1952	563	319	1.766	—	—	—	—
2–2–L–0	1081	2024	534		1.676	—	—	—	—
3–3–L–0	1495	3027	494		1.549	—	—	—	—
4–3–L–0	1477	2868	515		1.615	—	—	—	—
5–4–L–0	1566	3856	406		1.274	—	—	—	—
6–4–L–0	1690	4154	407		1.276	—	—	—	—
7–2–T–0	818	1126	—	—	—	821	0.996	0.956	0.030
8–2–T–0	845	1208	—	—	—	881	0.959		
9–3–T–0	1099	1609	—	—	—	1173	0.936		
10–3–T–0	1139	1587	—	—	—	1157	0.984		
11–4–T–0	1303	1912	—	—	—	1394	0.934		
12–4–T–0	1308	1933	—	—	—	1410	0.927		

Table E12.1 – Weld Size Measurements from Ng *et al.* (2002) – 6.4 mm welds

Specimen	Nominal Leg Size (mm)	Weld	MPL (mm)	LPL (mm)	45° Meas. (mm)	MTD (mm)	Ratio α_1	Ratio α_2	Ratio ρ_G
T1–1	6.4	Front	6.5	6.6	5.7	4.6	1.231	1.231	1.024
		Back	5.7	6.3	5.2	4.2	1.230	1.226	0.934
T1–2	6.4	Front	6.5	6.2	5.5	4.5	1.226	1.225	0.992
		Back	6.2	5.9	5.3	4.3	1.240	1.239	0.945
T1–3	6.4	Front	6.0	6.5	5	4.4	1.134	1.132	0.974
		Back	6.0	6.6	5.1	4.4	1.149	1.145	0.981
T2–1	6.4	Front	5.5	6.2	4.1	4.1	0.996	0.991	0.909
		Back	6.6	6.1	4.4	4.5	0.982	0.980	0.990
T2–2	6.4	Front	6.0	6.1	4.4	4.3	1.029	1.029	0.945
		Back	6.1	6.2	4.3	4.3	0.989	0.989	0.961
T2–3	6.4	Front	6.1	6.7	4.7	4.5	1.042	1.039	0.997
		Back	6.4	5.8	4.6	4.3	1.070	1.067	0.950
T3–1	6.4	Front	7.5	6.6	5.4	5.0	1.090	1.083	1.095
		Back	7.9	7.4	5.2	5.4	0.963	0.961	1.194
T3–2	6.4	Front	8.0	6.8	5.4	5.2	1.042	1.032	1.145
		Back	8.2	7.2	5.3	5.4	0.980	0.974	1.196
T3–3	6.4	Front	7.6	7.3	5.4	5.3	1.026	1.025	1.164
		Back	7.9	6.9	5.3	5.2	1.020	1.013	1.149
T4–1	6.4	Front	5.9	6.2	5.4	4.3	1.263	1.262	0.945
		Back	6.1	6.1	5.5	4.3	1.275	1.275	0.953
T4–2	6.4	Front	6.1	6.4	5.4	4.4	1.223	1.222	0.976
		Back	6.3	6.1	5.6	4.4	1.278	1.278	0.969
T4–3	6.4	Front	6.0	6.3	5.2	4.3	1.197	1.196	0.960
		Back	6.0	6.0	5.5	4.2	1.296	1.297	0.938
T5–1	6.4	Front	6.4	5.8	4.8	4.3	1.117	1.113	0.950
		Back	6.0	6.1	5	4.3	1.169	1.169	0.945
T5–2	6.4	Front	6.5	5.8	4.9	4.3	1.132	1.127	0.956
		Back	6.3	6.2	5	4.4	1.131	1.132	0.977
T5–3	6.4	Front	6.3	5.8	4.9	4.3	1.148	1.146	0.943
		Back	5.8	5.9	4.7	4.1	1.136	1.136	0.914
T6–1	6.4	Front	6.6	5.1	4.6	4.0	1.140	1.112	0.892
		Back	6.5	5.5	4.7	4.2	1.119	1.108	0.928
T6–2	6.4	Front	6.3	5.7	4.7	4.2	1.112	1.108	0.934
		Back	6.7	5.1	4.4	4.1	1.084	1.055	0.897
T6–3	6.4	Front	6.5	5.8	4.8	4.3	1.109	1.104	0.956
		Back	6.5	5.4	4.5	4.2	1.083	1.070	0.918
T7–1	6.4	Front	6.5	5.8	4.4	4.3	1.017	1.012	0.956
		Back	6.5	5.4	4.7	4.2	1.132	1.117	0.918
T7–2	6.4	Front	5.1	4.5	3.9	3.4	1.156	1.149	0.746
		Back	5.9	4.4	4	3.5	1.134	1.099	0.780
T7–3	6.4	Front	5.2	4.5	4.2	3.4	1.234	1.225	0.752
		Back	5.6	4.7	4.4	3.6	1.222	1.208	0.796
T8–1	6.4	Front	5.9	7.3	5.8	4.6	1.264	1.243	1.014
		Back	6.5	7.6	6.2	4.9	1.255	1.244	1.092

Table E12.1 (cont.)

Specimen	Nominal Leg Size (mm)	Weld	MPL (mm)	LPL (mm)	45º Meas. (mm)	MTD (mm)	Ratio α_1	Ratio α_2	Ratio ρ_G
T8–2	6.4	Front	6.0	7.7	6.1	4.7	1.289	1.260	1.046
		Back	6.5	7.3	6.1	4.9	1.257	1.250	1.073
T8–3	6.4	Front	6.5	7.8	6.2	5.0	1.242	1.226	1.104
		Back	6.9	7.1	6.1	4.9	1.233	1.233	1.094
T9–1	6.4	Front	7.4	6.0	5.6	4.7	1.202	1.182	1.030
		Back	8.6	5.8	5.5	4.8	1.144	1.080	1.063
T9–2	6.4	Front	8.2	5.6	5.3	4.6	1.146	1.086	1.022
		Back	8.3	6.1	5.3	4.9	1.078	1.041	1.086
T9–3	6.4	Front	8.3	6.1	6	4.9	1.221	1.179	1.086
		Back	8.0	6.1	5.6	4.9	1.154	1.124	1.072
T10–1	6.4	Front	7.7	6.6	5.9	5.0	1.177	1.167	1.107
		Back	8.8	6.6	6.5	5.3	1.231	1.194	1.167
T10–2	6.4	Front	7.9	6.3	5.8	4.9	1.178	1.155	1.089
		Back	8.2	6.3	6.1	5.0	1.221	1.190	1.104
T10–3	6.4	Front	7.8	6.3	6.1	4.9	1.245	1.224	1.083
		Back	8.6	6.6	6.1	5.2	1.165	1.135	1.157
T11–1	6.4	Front	6.4	6.7	6.2	4.6	1.340	1.339	1.023
		Back	7.6	6.8	6.3	5.1	1.243	1.238	1.120
T11–2	6.4	Front	6.7	7.2	6.3	4.9	1.284	1.282	1.084
		Back	7.1	6.8	5.9	4.9	1.201	1.201	1.085
T11–3	6.4	Front	6.5	7.2	6.2	4.8	1.285	1.280	1.066
		Back	7.1	6.9	6.3	4.9	1.273	1.273	1.094
T12–1	6.4	Front	7.9	6.3	6.1	4.9	1.238	1.215	1.089
		Back	7.8	5.4	5.1	4.4	1.149	1.093	0.981
T12–2	6.4	Front	8.0	5.9	5.7	4.7	1.200	1.160	1.049
		Back	7.8	5.1	5.1	4.3	1.195	1.118	0.943
T12–3	6.4	Front	7.5	6.2	5.7	4.8	1.193	1.177	1.056
		Back	8.2	5.4	5.1	4.5	1.131	1.061	0.997
T13–1	6.4	Front	6.7	5.2	4.8	4.1	1.168	1.141	0.908
		Back	6.8	6.6	4.8	4.7	1.014	1.013	1.047
T13–2	6.4	Front	6.5	6.0	5.1	4.4	1.157	1.154	0.974
		Back	7.3	5.9	5.5	4.6	1.199	1.179	1.014
T13–3	6.4	Front	6.2	5.6	4.9	4.2	1.179	1.175	0.918
		Back	5.5	5.8	5	4.0	1.253	1.252	0.882
T14–1	6.4	Front	8.2	6.8	6.2	5.2	1.184	1.169	1.157
		Back	8.7	6.9	6	5.4	1.110	1.088	1.195
T14–2	6.4	Front	8.3	6.8	5.9	5.3	1.122	1.105	1.163
		Back	8.7	6.7	5.8	5.3	1.093	1.065	1.173
T14–3	6.4	Front	7.9	6.9	6.1	5.2	1.174	1.166	1.149
		Back	8.5	6.6	5.9	5.2	1.132	1.105	1.152
T15–1	6.4	Front	6.8	6.7	5.5	4.8	1.152	1.152	1.055
		Back	7.7	6.8	6.3	5.1	1.236	1.229	1.126

Table E12.1 (cont.)

Specimen	Nominal Leg Size (mm)	Weld	MPL (mm)	LPL (mm)	45º Meas. (mm)	MTD (mm)	Ratio α_1	Ratio α_2	Ratio ρ_G
T15–2	6.4	Front	7.4	7.3	5.9	5.2	1.135	1.135	1.149
		Back	7.7	7.3	6.2	5.3	1.170	1.169	1.171
T15–3	6.4	Front	7.2	7.0	5.8	5.0	1.156	1.155	1.109
		Back	7.5	7.1	6.2	5.2	1.202	1.201	1.140
T16–1	6.4	Front	6.7	7.1	5.4	4.9	1.108	1.107	1.077
		Back	7.7	7.5	6.5	5.4	1.210	1.210	1.187
T16–2	6.4	Front	6.7	6.8	5.4	4.8	1.131	1.132	1.055
		Back	8.1	7.9	6.5	5.7	1.149	1.149	1.250
T16–3	6.4	Front	6.9	7.1	5.4	4.9	1.091	1.091	1.094
		Back	7.2	6.5	5.8	4.8	1.202	1.198	1.066
T17–1	6.4	Front	9.0	5.1	5	4.4	1.127	1.003	0.981
		Back	9.2	5.4	5.4	4.7	1.160	1.046	1.029
T17–2	6.4	Front	9.6	4.2	4.2	3.8	1.092	0.861	0.850
		Back	9.1	6.3	5.9	5.2	1.139	1.084	1.145
T17–3	6.4	Front	9.8	4.4	4.7	4.0	1.171	0.936	0.887
		Back	8.4	6.6	6	5.2	1.156	1.132	1.147
T18–1	6.4	Front	5.5	6.5	5	4.2	1.191	1.179	0.928
		Back	5.7	6.4	5.2	4.3	1.222	1.216	0.941
T18–2	6.4	Front	5.2	6.9	5	4.2	1.204	1.169	0.918
		Back	5.3	6.1	5.1	4.0	1.275	1.266	0.884
T18–3	6.4	Front	5.7	7.0	5.1	4.4	1.154	1.136	0.977
		Back	5.3	6.4	5.1	4.1	1.249	1.233	0.902
T19–1	6.4	Front	8.1	6.9	5.4	5.3	1.028	1.018	1.161
		Back	7.8	6.8	5.6	5.1	1.093	1.085	1.133
T19–2	6.4	Front	8.8	7.6	5.8	5.8	1.008	1.000	1.271
		Back	8.1	6.0	5.5	4.8	1.141	1.103	1.066
T19–3	6.4	Front	8.7	7.2	5.6	5.5	1.010	0.996	1.226
		Back	8.0	6.2	5.6	4.9	1.143	1.116	1.083
C1–1	6.4	Front	7.2	5.1	5.5	4.2	1.322	1.265	0.920
		Back	7.8	6.1	5.6	4.8	1.165	1.140	1.062
C1–2	6.4	Front	7.3	5.1	5.5	4.2	1.316	1.255	0.924
		Back	7.7	6.4	5.6	4.9	1.138	1.124	1.088
C1–3	6.4	Front	6.7	5.5	5.5	4.3	1.294	1.275	0.940
		Back	7.7	6.4	5.6	4.9	1.138	1.124	1.088
C2–1	6.4	Front	5.8	6.5	5.5	4.3	1.271	1.265	0.956
		Back	7.4	6.5	5.6	4.9	1.147	1.140	1.079
C2–2	6.4	Front	7.7	5.7	5.5	4.6	1.201	1.161	1.012
		Back	5.9	7.0	5.6	4.5	1.241	1.228	0.997
C2–3	6.4	Front	7.3	5.6	5.5	4.4	1.238	1.206	0.982
		Back	5.8	7.7	5.6	4.6	1.209	1.173	1.024
All Specimens			Mean of Ratios				1.165	1.145	1.026
			Coefficient of Variation, V				0.070	0.077	0.102

Table E12.2 – Weld Size Measurements from Ng *et al.* (2002) – 12.7 mm welds

Specimen	Nominal Leg Size (mm)	Weld	MPL (mm)	LPL (mm)	45º Meas. (mm)	MTD (mm)	Ratio α_1	Ratio α_2	Ratio ρ_G
T20–1	12.7	Front	13.4	14.2	9.8	9.7	1.006	1.004	1.085
		Back	13.3	13.7	10.3	9.5	1.079	1.079	1.063
T20–2	12.7	Front	12.8	13.2	9.2	9.2	1.001	1.001	1.023
		Back	13.4	14.6	9.6	9.9	0.972	0.970	1.099
T20–3	12.7	Front	13.3	14.1	10.1	9.7	1.044	1.043	1.078
		Back	13.9	13.6	9.4	9.7	0.967	0.967	1.083
T21–1	12.7	Front	11.3	14.0	11.1	8.8	1.262	1.241	0.979
		Back	12.2	13.1	11.6	8.9	1.299	1.297	0.994
T21–2	12.7	Front	12.2	13.7	11.3	9.1	1.240	1.234	1.015
		Back	12.1	13.7	12.1	9.1	1.334	1.327	1.010
T21–3	12.7	Front	12.1	13.5	10.9	9.0	1.210	1.204	1.004
		Back	12.2	13.5	11.7	9.1	1.293	1.288	1.008
T22–1	12.7	Front	9.4	10.6	7.8	7.0	1.109	1.103	0.783
		Back	11.1	11.9	9.2	8.1	1.133	1.132	0.904
T22–2	12.7	Front	10.3	10.0	8	7.2	1.115	1.115	0.799
		Back	10.8	11.5	9	7.9	1.143	1.142	0.877
T22–3	12.7	Front	11.1	10.1	8.4	7.5	1.124	1.121	0.832
		Back	10.1	11.6	8.5	7.6	1.116	1.108	0.848
T23–1	12.7	Front	12.6	12.8	10.2	9.0	1.136	1.136	1.000
		Back	13.5	13.0	10	9.4	1.068	1.067	1.043
T23–2	12.7	Front	12.5	12.7	10.5	8.9	1.179	1.179	0.992
		Back	13.4	13.0	10.2	9.3	1.093	1.093	1.039
T23–3	12.7	Front	12.7	13.3	10.5	9.2	1.143	1.142	1.023
		Back	13.2	12.8	9.9	9.2	1.077	1.077	1.023
T24–1	12.7	Front	11.6	10.9	8.2	7.9	1.032	1.031	0.885
		Back	11.7	11.8	8.6	8.3	1.035	1.035	0.925
T24–2	12.7	Front	12.7	10.5	8.4	8.1	1.038	1.024	0.901
		Back	12.0	11.4	8.9	8.3	1.077	1.076	0.920
T24–3	12.7	Front	13.4	10.7	8.4	8.4	1.005	0.986	0.931
		Back	12.0	11.1	8.2	8.1	1.006	1.004	0.908
T25–1	12.7	Front	13.8	11.4	9.5	8.8	1.081	1.066	0.979
		Back	14.8	10.7	10.2	8.7	1.176	1.132	0.966
T25–2	12.7	Front	12.3	11.8	9.1	8.5	1.069	1.068	0.948
		Back	12.4	11.4	9.4	8.4	1.120	1.117	0.935
T25–3	12.7	Front	13.7	11.7	9.7	8.9	1.090	1.080	0.991
		Back	13.3	10.9	9.5	8.4	1.127	1.111	0.939
T26–1	12.7	Front	12.4	11.6	9.5	8.5	1.121	1.120	0.943
		Back	13.2	10.6	9	8.3	1.089	1.070	0.920
T26–2	12.7	Front	12.4	11.9	9.5	8.6	1.106	1.106	0.956
		Back	12.7	11.2	9.2	8.4	1.095	1.089	0.936
T26–3	12.7	Front	13.0	11.7	9.3	8.7	1.069	1.065	0.969
		Back	13.0	11.6	9.3	8.7	1.074	1.069	0.964
T27–1	12.7	Front	12.8	11.4	8	8.5	0.940	0.935	0.948
		Back	11.6	12.1	8.4	8.4	1.003	1.003	0.933

Table E12.2 (cont.)

Specimen	Nominal Leg Size (mm)	Weld	MPL (mm)	LPL (mm)	45º Meas. (mm)	MTD (mm)	Ratio α_1	Ratio α_2	Ratio ρ_G
T27–2	12.7	Front	12.5	11.8	8.3	8.6	0.967	0.966	0.956
		Back	11.8	12.0	8.3	8.4	0.986	0.987	0.937
T27–3	12.7	Front	12.2	12.1	8.4	8.6	0.978	0.978	0.957
		Back	11.6	11.8	8.4	8.3	1.015	1.015	0.921
T28–1	12.7	Front	13.8	10.6	8.9	8.4	1.059	1.032	0.936
		Back	12.5	10.7	8.3	8.1	1.021	1.012	0.905
T28–2	12.7	Front	13.3	10.7	9.1	8.3	1.092	1.073	0.929
		Back	12.2	10.8	8.3	8.1	1.026	1.021	0.901
T28–3	12.7	Front	13.0	11.2	9	8.5	1.061	1.052	0.945
		Back	12.9	10.9	8.4	8.3	1.009	0.998	0.927
T29–1	12.7	Front	12.7	12.0	10.2	8.7	1.169	1.168	0.971
		Back	16.3	12.6	9.3	10.0	0.933	0.910	1.110
T29–2	12.7	Front	13.4	12.8	10.3	9.3	1.113	1.112	1.031
		Back	16.8	12.2	9.3	9.9	0.942	0.907	1.099
T29–3	12.7	Front	16.0	12.0	9.7	9.6	1.010	0.980	1.069
		Back	13.4	13.7	10.7	9.6	1.117	1.117	1.067
T30–1	12.7	Front	12.7	11.2	8.8	8.4	1.048	1.042	0.936
		Back	13.1	10.3	8.5	8.1	1.050	1.028	0.902
T30–2	12.7	Front	12.6	10.3	8.8	8.0	1.104	1.087	0.888
		Back	13.7	9.6	8.5	7.9	1.081	1.032	0.876
T30–3	12.7	Front	12.3	10.4	8.2	7.9	1.033	1.022	0.884
		Back	13.2	10.3	8.3	8.1	1.022	0.999	0.904
T31–1	12.7	Front	11.5	10.7	8.7	7.8	1.111	1.109	0.872
		Back	10.5	12.4	9.4	8.0	1.173	1.161	0.892
T31–2	12.7	Front	11.4	11.8	8.8	8.2	1.073	1.073	0.913
		Back	10.7	12.1	9.3	8.0	1.160	1.154	0.893
T31–3	12.7	Front	11.4	12.4	9.4	8.4	1.120	1.117	0.935
		Back	10.3	11.4	9.3	7.6	1.217	1.212	0.851
T32–1	12.7	Front	12.3	11.2	8.8	8.3	1.063	1.059	0.922
		Back	12.2	12.7	8.9	8.8	1.012	1.011	0.980
T32–2	12.7	Front	11.4	11.7	9.1	8.2	1.115	1.114	0.909
		Back	12.1	12.7	9	8.8	1.027	1.027	0.976
T32–3	12.7	Front	10.5	12.9	8.7	8.1	1.068	1.052	0.907
		Back	12.2	11.8	9	8.5	1.061	1.061	0.945
All Specimens			Mean of Ratios				1.084	1.076	0.954
			Coefficient of Variation, V				0.076	0.077	0.073

Table E12.3 – Weld Size Measurements from Deng *et al.* (2003) – 12.7 mm welds

Specimen	Nominal Leg Size (mm)	Weld	MPL (mm)	LPL (mm)	45º Meas. (mm)	MTD (mm)	Ratio α_1	Ratio α_2	Ratio ρ_G
F1–1	12.7	Front	11.3	10.8	8.7	7.8	1.114	1.114	0.870
		Back	11.8	11.0	8.6	8.0	1.069	1.067	0.896
F1–2	12.7	Front	9.9	9.5	7.1	6.9	1.036	1.035	0.763
		Back	10.9	9.7	7.4	7.2	1.021	1.016	0.807
F1–3	12.7	Front	9.5	10.0	8.0	6.9	1.162	1.161	0.767
		Back	11.1	10.4	8.3	7.6	1.094	1.092	0.845
F2–1	12.7	Front	9.5	10.1	7.6	6.9	1.098	1.097	0.771
		Back	9.9	11.4	7.6	7.5	1.017	1.009	0.832
F2–2	12.7	Front	10.7	11.2	8.1	7.7	1.047	1.046	0.862
		Back	10.3	11.0	8.2	7.5	1.091	1.089	0.837
F2–3	12.7	Front	9.3	11.0	7.5	7.1	1.056	1.045	0.791
		Back	11.0	11.0	8.1	7.8	1.041	1.042	0.866
F3–1	12.7	Front	10.0	12.3	8.8	7.8	1.134	1.116	0.864
		Back	10.5	13.4	8.8	8.3	1.065	1.042	0.920
F3–2	12.7	Front	10.3	10.7	7.6	7.4	1.024	1.024	0.826
		Back	9.5	11.5	7.6	7.3	1.038	1.024	0.816
F3–3	12.7	Front	9.2	12.6	7.6	7.4	1.023	0.986	0.828
		Back	9.5	13.0	8.6	7.7	1.121	1.081	0.854
L1–1	12.7	Weld 1	10.6	11.4	5.9	7.8	0.760	0.759	0.865
		Weld 2	8.7	9.4	7.2	6.4	1.128	1.125	0.711
		Weld 3	10.5	10.6	8.4	7.5	1.126	1.126	0.831
		Weld 4	10.0	11.0	7.6	7.4	1.027	1.024	0.824
L1–2	12.7	Weld 1	11.3	11.5	7.8	8.1	0.968	0.968	0.898
		Weld 2	11.7	10.4	7.8	7.8	1.003	0.998	0.866
		Weld 3	11.0	9.6	7.6	7.2	1.051	1.044	0.806
		Weld 4	10.9	9.4	7.4	7.1	1.040	1.031	0.793
L1–3	12.7	Weld 1	10.8	11.5	8.0	7.9	1.016	1.015	0.877
		Weld 2	9.4	10.7	6.9	7.1	0.977	0.971	0.787
		Weld 3	10.8	10.1	7.6	7.4	1.030	1.029	0.822
		Weld 4	10.3	10.4	7.3	7.3	0.997	0.998	0.815
L2–1	12.7	Weld 1	10.9	12.0	9.2	8.1	1.140	1.136	0.899
		Weld 2	10.7	11.4	8.2	7.8	1.051	1.050	0.869
		Weld 3	10.8	11.3	8.0	7.8	1.025	1.024	0.870
		Weld 4	11.6	11.2	7.3	8.1	0.906	0.906	0.897
L2–2	12.7	Weld 1	10.3	11.0	6.9	7.5	0.918	0.916	0.837
		Weld 2	10.0	10.1	6.8	7.1	0.957	0.957	0.791
		Weld 3	12.3	11.0	7.7	8.2	0.939	0.935	0.913
		Weld 4	9.8	11.6	6.5	7.5	0.868	0.859	0.834
L2–3	12.7	Weld 1	11.2	11.9	9.0	8.2	1.104	1.102	0.908
		Weld 2	9.8	11.2	7.3	7.4	0.990	0.983	0.821
		Weld 3	10.5	11.8	8.2	7.8	1.045	1.040	0.874
		Weld 4	10.5	11.0	7.9	7.6	1.040	1.039	0.846

Table E12.3 (cont.)

Specimen	Nominal Leg Size (mm)	Weld	MPL (mm)	LPL (mm)	45º Meas. (mm)	MTD (mm)	Ratio α_1	Ratio α_2	Ratio ρ_G
L3–1	12.7	Weld 1	10.0	11.9	9.1	7.7	1.189	1.175	0.853
		Weld 2	10.3	10.8	9.7	7.5	1.301	1.300	0.830
		Weld 3	9.8	10.7	8.0	7.2	1.107	1.104	0.805
		Weld 4	9.0	10.7	8.2	6.9	1.191	1.177	0.767
L3–2	12.7	Weld 1	9.5	12.2	7.6	7.5	1.014	0.991	0.835
		Weld 2	9.7	11.4	6.8	7.4	0.920	0.912	0.823
		Weld 3	9.6	12.0	8.3	7.5	1.107	1.087	0.835
		Weld 4	10.0	11.1	7.4	7.4	0.996	0.992	0.827
L3–3	12.7	Weld 1	9.3	11.3	7.5	7.2	1.044	1.030	0.800
		Weld 2	11.7	11.5	8.9	8.2	1.085	1.085	0.913
		Weld 3	10.7	10.2	8.6	7.4	1.165	1.164	0.822
		Weld 4	9.7	9.8	8.2	6.9	1.189	1.190	0.768
All Specimens			Mean of Ratios				1.049	1.043	0.836
			Coefficient of Variation, *V*				0.085	0.086	0.053

Table E12.4 – Weld Size Measurements from Callele *et al.* (2005) – 7.9 mm welds

Specimen	Nominal Leg Size (mm)	Weld	MPL (mm)	LPL (mm)	45º Meas. (mm)	MTD (mm)	Ratio α_1	Ratio α_2	Ratio ρ_G
TFa–1	7.9	Front–1	9.4	8.7	7.6	6.4	1.190	1.188	1.138
		Front–2	9.2	9.2	7.7	6.5	1.190	1.190	1.159
		Front–3	9.0	8.8	7.9	6.3	1.252	1.252	1.121
		Back–1	8.4	7.5	5.8	5.6	1.037	1.032	0.997
		Back–2	9.6	8.2	6.2	6.2	0.998	0.989	1.111
		Back–3	9.1	8.4	6.8	6.2	1.094	1.091	1.100
TFa–2	7.9	Front–1	9.4	8.2	7.1	6.2	1.149	1.141	1.101
		Front–2	9.5	8.0	6.3	6.1	1.036	1.025	1.090
		Front–3	9.6	8.8	7.0	6.5	1.083	1.080	1.156
		Back–1	8.4	7.5	6.5	5.6	1.162	1.156	0.997
		Back–2	8.9	7.7	6.1	5.8	1.051	1.043	1.038
		Back–3	9.0	7.1	5.8	5.6	1.040	1.019	0.993
TFa–3	7.9	Front–1	9.0	8.3	7.1	6.1	1.155	1.153	1.087
		Front–2	9.0	8.5	7.0	6.2	1.133	1.132	1.101
		Front–3	8.8	8.1	7.7	6.0	1.288	1.285	1.062
		Back–1	8.9	8.1	6.3	6.0	1.043	1.040	1.067
		Back–2	9.2	7.7	6.6	5.9	1.118	1.105	1.052
		Back–3	9.1	8.2	6.4	6.1	1.051	1.047	1.086

Table E12.4 (cont.)

Specimen	Nominal Leg Size (mm)	Weld	MPL (mm)	LPL (mm)	45º Meas. (mm)	MTD (mm)	Ratio α_1	Ratio α_2	Ratio ρ_G
TFa–4	7.9	Front–1	9.3	9.6	7.9	6.7	1.183	1.182	1.190
		Front–2	9.6	9.9	8.1	6.9	1.178	1.178	1.228
		Front–3	8.5	9.3	7.3	6.3	1.160	1.156	1.118
		Back–1	8.5	9.4	7.4	6.3	1.170	1.166	1.123
		Back–2	8.8	9.2	7.5	6.4	1.179	1.179	1.133
		Back–3	8.4	7.4	6.2	5.6	1.121	1.115	0.989
TL50a–1	7.9	Front–1	9.6	7.8	6.2	6.1	1.016	1.000	1.084
		Front–2	10.7	8.3	7.1	6.6	1.077	1.051	1.174
		Front–3	9.2	8.4	6.6	6.2	1.056	1.053	1.111
		Back–1	8.4	7.4	5.9	5.6	1.067	1.061	0.994
		Back–2	10.7	8.2	7.1	6.5	1.097	1.069	1.165
		Back–3	8.6	8.5	6.8	6.0	1.117	1.117	1.082
TL50a–2	7.9	Front–1	9.6	7.8	6.1	6.1	1.008	0.992	1.084
		Front–2	10.7	8.3	7.0	6.6	1.070	1.045	1.174
		Front–3	9.8	8.2	6.3	6.3	0.994	0.982	1.126
		Back–1	9.3	8.5	6.9	6.3	1.096	1.093	1.123
		Back–2	11.3	8.2	7.2	6.6	1.088	1.047	1.188
		Back–3	10.0	8.4	7.0	6.4	1.081	1.069	1.152
TL50a–3	7.9	Front–1	8.4	7.6	6.3	5.6	1.122	1.118	1.009
		Front–2	10.7	8.2	7.1	6.5	1.094	1.066	1.165
		Front–3	9.7	8.0	7.0	6.2	1.126	1.111	1.105
		Back–1	9.0	9.2	6.2	6.4	0.960	0.960	1.152
		Back–2	10.7	8.2	7.3	6.5	1.128	1.099	1.165
		Back–3	9.7	8.0	6.7	6.2	1.082	1.067	1.105
TL50a–4	7.9	Front–1	10.0	8.5	6.8	6.5	1.054	1.044	1.160
		Front–2	11.8	9.1	7.6	7.2	1.052	1.026	1.290
		Front–3	9.1	9.6	7.2	6.6	1.090	1.089	1.182
		Back–1	10.8	8.7	7.3	6.8	1.077	1.059	1.213
		Back–2	12.3	7.9	7.4	6.6	1.119	1.042	1.190
		Back–3	10.0	9.5	8.1	6.9	1.180	1.179	1.233
All Specimens			Mean of Ratios				1.102	1.091	1.118
			Coefficient of Variation, V				0.061	0.065	0.061

Table E12.5 – Weld Measurements of Specimens of 12.7 mm Weld from Callele *et al.* (2005)

Specimen	Nominal Leg Size (mm)	Weld	MPL (mm)	LPL (mm)	45º Meas. (mm)	MTD (mm)	Ratio α_1	Ratio α_2	Ratio ρ_G
TF–1	12.7	Front–1	12.9	10.5	8.4	8.1	1.028	1.012	0.907
		Front–2	14.2	11.6	8.8	9.0	0.980	0.965	1.001
		Front–3	14.4	11.0	8.4	8.7	0.964	0.938	0.974
		Back–1	14.4	11.6	9.6	9.0	1.063	1.045	1.006
		Back–2	13.7	12.3	9.5	9.2	1.036	1.031	1.019
		Back–3	14.9	13.2	10.4	9.9	1.050	1.044	1.100
TF–2	12.7	Front–1	12.4	13.6	9.6	9.2	1.048	1.045	1.021
		Front–2	15.0	13.6	10.3	10.1	1.020	1.017	1.122
		Front–3	13.2	13.7	9.5	9.5	0.999	0.999	1.059
		Back–1	12.5	12.6	9.7	8.9	1.090	1.090	0.988
		Back–2	13.6	12.7	9.9	9.3	1.062	1.061	1.034
		Back–3	13.5	12.5	9.4	9.2	1.025	1.023	1.022
TF–3	12.7	Front–1	13.9	12.1	8.8	9.1	0.959	0.952	1.016
		Front–2	13.5	11.8	8.7	8.9	0.981	0.975	0.989
		Front–3	13.2	11.2	8.7	8.5	1.013	1.003	0.951
		Back–1	12.2	12.0	9.0	8.6	1.055	1.055	0.953
		Back–2	13.1	11.6	8.8	8.7	1.011	1.006	0.967
		Back–3	12.4	11.3	8.3	8.4	0.988	0.985	0.930
TF–4	12.7	Front–1	14.3	11.7	9.2	9.1	1.019	1.004	1.009
		Front–2	17.1	11.7	8.6	9.7	0.893	0.847	1.075
		Front–3	13.7	10.8	8.8	8.5	1.041	1.019	0.945
		Back–1	14.8	12.5	9.7	9.5	1.013	1.003	1.064
		Back–2	16.8	12.6	9.8	10.1	0.972	0.943	1.123
		Back–3	15.4	12.5	9.5	9.7	0.981	0.966	1.081
TL50–1	12.7	Front–1	15.7	11.5	8.0	9.3	0.862	0.832	1.033
		Front–2	16.4	12.3	11.9	9.8	1.207	1.171	1.096
		Front–3	12.9	12.9	9.9	9.1	1.085	1.085	1.016
		Back–1	14.1	10.1	7.7	8.2	0.941	0.903	0.914
		Back–2	16.0	11.0	8.5	9.1	0.940	0.893	1.010
		Back–3	12.8	11.6	9.2	8.6	1.065	1.061	0.957
TL50–2	12.7	Front–1	13.7	12.2	9.0	9.1	0.985	0.980	1.015
		Front–2	15.2	11.9	9.4	9.4	1.007	0.985	1.044
		Front–3	14.9	12.2	10.7	9.4	1.131	1.114	1.051
		Back–1	13.5	10.3	8.9	8.2	1.081	1.052	0.912
		Back–2	13.5	11.9	9.2	8.9	1.035	1.029	0.994
		Back–3	13.1	11.9	9.2	8.8	1.047	1.044	0.981
TL50–3	12.7	Front–1	14.2	10.7	8.3	8.5	0.974	0.946	0.952
		Front–2	15.3	12.8	10.3	9.8	1.049	1.037	1.093
		Front–3	12.0	12.9	9.1	8.8	1.030	1.028	0.979
		Back–1	14.0	11.1	8.9	8.7	1.017	0.997	0.969
		Back–2	15.3	11.8	9.6	9.3	1.030	1.004	1.041
		Back–3	12.8	9.8	8.0	7.8	1.025	0.998	0.867

Table E12.5 (cont.)

Specimen	Nominal Leg Size (mm)	Weld	MPL (mm)	LPL (mm)	45º Meas. (mm)	MTD (mm)	Ratio α_1	Ratio α_2	Ratio ρ_G
TL50–4	12.7	Front–1	17.1	10.2	9.2	8.8	1.050	0.953	0.976
		Front–2	18.3	11.0	9.8	9.4	1.039	0.946	1.050
		Front–3	13.7	11.8	9.9	8.9	1.107	1.098	0.996
		Back–1	13.1	11.3	9.3	8.6	1.090	1.081	0.953
		Back–2	15.8	11.2	10.6	9.1	1.156	1.106	1.018
		Back–3	14.6	11.8	11.1	9.2	1.210	1.189	1.022
TL100–1	12.7	Front–1	13.9	12.9	10.5	9.5	1.113	1.111	1.053
		Front–2	17.1	12.4	11.3	10.0	1.126	1.084	1.118
		Front–3	15.2	13.9	11.3	10.3	1.099	1.096	1.142
		Back–1	14.6	12.9	10.7	9.7	1.106	1.099	1.077
		Back–2	17.5	13.0	11.5	10.4	1.098	1.063	1.162
		Back–3	16.4	13.9	11.9	10.6	1.119	1.108	1.181
TL100–2	12.7	Front–1	14.1	10.6	9.2	8.5	1.083	1.051	0.944
		Front–2	14.6	11.0	9.2	8.8	1.045	1.014	0.978
		Front–3	13.5	10.6	10.1	8.3	1.207	1.181	0.929
		Back–1	15.4	12.6	10.9	9.8	1.116	1.100	1.086
		Back–2	16.7	11.9	10.6	9.7	1.098	1.052	1.079
		Back–3	15.3	11.5	10.8	9.2	1.172	1.137	1.024
TL100–3	12.7	Front–1	13.8	12.5	10.3	9.3	1.109	1.105	1.032
		Front–2	16.8	12.6	10.6	10.1	1.054	1.022	1.123
		Front–3	13.7	13.0	10.7	9.4	1.137	1.136	1.050
		Back–1	12.5	11.5	8.3	8.5	0.975	0.972	0.943
		Back–2	15.7	10.8	8.6	8.9	0.962	0.914	0.991
		Back–3	14.0	10.3	7.8	8.3	0.937	0.905	0.924
TL100SP–1	12.7	Front–1	12.9	10.6	9.8	8.2	1.200	1.183	0.912
		Front–2	12.2	9.3	9.0	7.4	1.214	1.182	0.824
		Front–3	11.9	9.7	8.5	7.5	1.126	1.108	0.837
		Back–1	11.7	9.3	9.0	7.3	1.229	1.206	0.811
		Back–2	12.8	9.7	9.1	7.7	1.172	1.139	0.861
		Back–3	13.9	11.7	10.9	9.0	1.212	1.199	0.997

Table E12.5 (cont.)

Specimen	Nominal Leg Size (mm)	Weld	MPL (mm)	LPL (mm)	45º Meas. (mm)	MTD (mm)	Ratio α_1	Ratio α_2	Ratio ρ_G
TL100SP–2	12.7	Front–1	11.9	9.9	8.3	7.6	1.086	1.072	0.848
		Front–2	12.2	10.1	8.4	7.8	1.082	1.068	0.866
		Front–3	14.0	11.6	9.8	8.9	1.100	1.086	0.995
		Back–1	11.9	10.8	8.6	8.0	1.071	1.067	0.891
		Back–2	13.9	9.7	8.9	8.0	1.124	1.072	0.886
		Back–3	14.1	10.7	9.4	8.5	1.104	1.074	0.949
TL100SP–3	12.7	Front–1	14.3	10.0	8.5	8.2	1.033	0.985	0.913
		Front–2	13.5	10.9	8.4	8.5	0.993	0.976	0.945
		Front–3	12.8	10.6	8.7	8.2	1.070	1.056	0.909
		Back–1	13.4	9.6	8.8	7.8	1.132	1.087	0.869
		Back–2	13.7	9.4	8.9	7.8	1.143	1.085	0.863
		Back–3	13.9	10.3	8.9	8.3	1.078	1.043	0.922
TL100D–1	12.7	Front–1	12.4	12.1	9.8	8.7	1.133	1.133	0.966
		Front–2	13.0	10.9	9.5	8.3	1.141	1.128	0.927
		Front–3	13.0	10.4	8.9	8.1	1.101	1.081	0.904
		Back–1	14.1	11.3	10.7	8.8	1.206	1.186	0.984
		Back–2	14.6	12.6	10.3	9.5	1.081	1.073	1.058
		Back–3	13.5	11.7	9.7	8.8	1.100	1.092	0.982
TL100D–2	12.7	Front–1	12.8	11.4	9.2	8.5	1.076	1.070	0.948
		Front–2	12.3	11.3	8.8	8.3	1.061	1.058	0.927
		Front–3	13.3	9.5	8.1	7.7	1.045	1.002	0.861
		Back–1	13.4	11.7	9.6	8.8	1.093	1.085	0.982
		Back–2	13.9	11.7	10.0	9.0	1.117	1.105	0.997
		Back–3	12.7	11.8	8.3	8.6	0.956	0.954	0.963
TL100D–3	12.7	Front–1	14.4	13.6	10.3	9.9	1.042	1.041	1.101
		Front–2	14.0	13.1	9.7	9.6	1.014	1.013	1.065
		Front–3	15.3	13.7	9.6	10.2	0.937	0.933	1.137
		Back–1	15.6	13.8	11.0	10.3	1.066	1.060	1.151
		Back–2	14.3	11.8	10.3	9.1	1.129	1.114	1.014
		Back–3	15.6	12.5	9.8	9.8	1.003	0.985	1.086
TL50D–1	12.7	Front–1	15.5	12.4	10.4	9.7	1.074	1.054	1.078
		Front–2	13.8	12.6	11.1	9.3	1.195	1.192	1.036
		Front–3	13.5	13.3	10.7	9.5	1.127	1.127	1.055
		Back–1	15.2	13.5	11.0	10.1	1.085	1.079	1.124
		Back–2	14.3	14.0	11.4	10.0	1.142	1.142	1.114
		Back–3	13.4	13.1	9.6	9.4	1.028	1.028	1.043
TL50D–2	12.7	Front–1	12.4	13.5	10.8	9.1	1.185	1.182	1.017
		Front–2	14.0	12.2	10.0	9.2	1.089	1.082	1.024
		Front–3	13.0	13.3	10.4	9.3	1.113	1.113	1.035
		Back–1	15.0	13.4	11.5	10.0	1.153	1.148	1.113
		Back–2	15.4	12.7	11.2	9.8	1.141	1.126	1.091
		Back–3	14.2	12.9	10.3	9.5	1.079	1.075	1.063

Table E12.5 (cont.)

Specimen	Nominal Leg Size (mm)	Weld	MPL (mm)	LPL (mm)	45° Meas. (mm)	MTD (mm)	Ratio α_1	Ratio α_2	Ratio ρ_G
TL50D–3	12.7	Front–1	12.2	14.1	10.1	9.2	1.097	1.089	1.028
		Front–2	16.7	11.8	10.0	9.6	1.038	0.993	1.073
		Front–3	15.4	11.6	9.6	9.3	1.031	1.001	1.032
		Back–1	16.9	12.7	10.4	10.2	1.027	0.996	1.131
		Back–2	14.9	10.5	8.9	8.6	1.042	0.996	0.956
		Back–3	14.4	10.8	8.9	8.6	1.033	1.002	0.962
L100–1	12.7	Front–1	12.9	12.2	9.8	8.9	1.106	1.104	0.987
		Front–2	12.3	11.3	9.7	8.3	1.166	1.163	0.927
		Back–3	12.3	11.6	9.8	8.4	1.161	1.160	0.940
		Back–4	12.9	12.0	9.8	8.8	1.115	1.113	0.979
L100–2	12.7	Front–1	14.7	12.6	11.0	9.6	1.150	1.140	1.065
		Front–2	14.2	10.9	10.9	8.6	1.261	1.228	0.963
		Back–3	13.1	11.7	10.6	8.7	1.215	1.209	0.972
		Back–4	13.8	10.6	9.1	8.4	1.083	1.055	0.936
L100–3	12.7	Front–1	13.4	12.8	10.7	9.3	1.156	1.155	1.031
		Front–2	13.7	12.7	11.2	9.3	1.203	1.200	1.037
		Back–3	12.3	13.0	10.9	8.9	1.220	1.219	0.995
		Back–4	13.1	12.9	11.1	9.2	1.208	1.208	1.024
L100–4	12.7	Front–1	12.3	8.9	9.3	7.2	1.290	1.241	0.803
		Front–2	12.6	9.7	9.5	7.7	1.236	1.205	0.856
		Back–3	12.0	9.1	8.4	7.3	1.158	1.126	0.808
		Back–4	12.6	10.0	10.2	7.8	1.302	1.277	0.872
L100–5	12.7	Front–1	11.9	10.4	9.9	7.8	1.264	1.256	0.872
		Front–2	12.3	9.2	10.2	7.4	1.385	1.342	0.820
		Back–3	14.1	10.4	10.5	8.4	1.255	1.212	0.932
		Back–4	12.9	9.9	10.7	7.9	1.362	1.328	0.875
L100–6	12.7	Front–1	11.1	10.8	10.2	7.7	1.318	1.318	0.862
		Front–2	11.2	10.8	10.2	7.8	1.312	1.312	0.866
		Back–3	11.2	10.5	10.6	7.7	1.384	1.382	0.853
		Back–4	12.3	9.9	9.9	7.7	1.284	1.262	0.859
L150–1 †	12.7	Front–1	12.5	11.2	9.2	8.3	1.103	1.099	0.929
		Front–2	12.4	12.3	9.6	8.7	1.100	1.100	0.972
		Back–3	14.2	11.6	9.5	9.0	1.058	1.042	1.000
		Back–4	13.2	12.3	9.9	9.0	1.104	1.102	0.999
L150–2 †	12.7	Front–1	13.3	11.4	9.3	8.6	1.075	1.066	0.963
		Front–2	12.9	11.8	9.4	8.7	1.081	1.078	0.969
		Back–3	12.9	11.2	9.3	8.4	1.101	1.093	0.941
		Back–4	13.2	11.0	9.5	8.5	1.122	1.109	0.943
L150–3 †	12.7	Front–1	12.3	10.6	9.0	8.1	1.117	1.108	0.897
		Front–2	12.2	10.2	8.9	7.8	1.141	1.127	0.869
		Back–3	12.8	10.7	9.4	8.2	1.148	1.135	0.912
		Back–4	12.6	11.1	9.4	8.3	1.127	1.120	0.929

Table E12.5 (cont.)

Specimen	Nominal Leg Size (mm)	Weld	MPL (mm)	LPL (mm)	45º Meas. (mm)	MTD (mm)	Ratio α_1	Ratio α_2	Ratio ρ_G
L150–4	12.7	Front–1	13.3	11.1	9.4	8.5	1.103	1.090	0.949
		Front–2	13.7	10.2	10.0	8.2	1.222	1.184	0.911
		Back–3	13.1	10.8	9.4	8.3	1.128	1.113	0.928
		Back–4	13.3	10.4	9.0	8.2	1.099	1.074	0.912
L150–5	12.7	Front–1	13.0	10.5	9.2	8.2	1.126	1.107	0.910
		Front–2	12.7	10.7	9.2	8.2	1.124	1.112	0.911
		Back–3	11.9	10.4	8.6	7.8	1.098	1.091	0.872
		Back–4	12.1	10.5	8.6	7.9	1.084	1.076	0.883
L150–6	12.7	Front–1	12.0	9.6	8.2	7.5	1.094	1.074	0.835
		Front–2	12.0	11.2	9.1	8.2	1.111	1.110	0.912
		Back–3	12.9	10.7	10.1	8.2	1.226	1.211	0.917
		Back–4	12.6	11.3	9.3	8.4	1.105	1.101	0.937
TNY–1	12.7	Front	13.4	12.2	10.7	9.0	1.190	1.186	1.002
		Back	13.9	12.3	10.7	9.2	1.160	1.154	1.027
TNY–2	12.7	Front	13.9	12.0	11.4	9.1	1.254	1.245	1.012
		Back	14.0	12.1	10.7	9.1	1.169	1.159	1.019
TNY–3	12.7	Front	14.5	12.0	10.9	9.3	1.177	1.163	1.031
		Back	13.6	12.5	10.7	9.2	1.162	1.159	1.026
TYa–1 †	12.7	Front	14.2	11.5	10.5	8.9	1.177	1.158	0.993
		Back	13.6	11.7	11.6	8.9	1.305	1.294	0.990
TYa–2 †	12.7	Front	13.9	12.3	11.4	9.2	1.238	1.231	1.025
		Back	14.1	11.0	10.9	8.7	1.255	1.226	0.968
TYa–3 †	12.7	Front	13.3	10.9	10.3	8.5	1.218	1.201	0.942
		Back	13.2	11.8	11.3	8.8	1.288	1.282	0.977
All Specimens			Mean of Ratios				1.106	1.090	0.981
			Coefficient of Variation, V				0.085	0.088	0.082

† Test results are reported in Appendix G of this report.

Table E12.6 – All-Weld-Metal Coupon Tests from Callele *et al.* (2005)

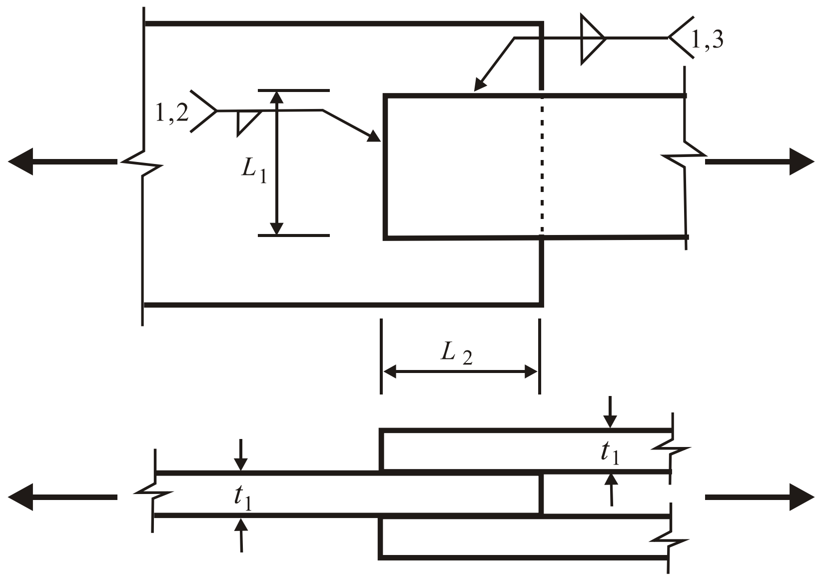
Electrode	σ_u (MPa)	X_u (MPa)	Ratio ρ_{M1}	Mean ρ_{M1}	V_{M1}
E70T–7	571	480	1.190	1.225	0.045
	576	480	1.200		
	578	480	1.204		
	568	480	1.183		
	566	480	1.179		
	574	480	1.196		
	609	480	1.269		
	600	480	1.250		
	584	480	1.217		
	652	480	1.358		
E70T–4	513	480	1.069	1.179	0.079
	513	480	1.069		
	557	480	1.160		
	557	480	1.160		
	562	480	1.171		
	563	480	1.173		
	630	480	1.313		
	631	480	1.315		
E70T7–K2	592	480	1.233	1.232	0.001
	591	480	1.231		
E71T8–K6	495	480	1.031	1.021	0.010
	484	480	1.008		
	488	480	1.017		
	485	480	1.010		
	494	480	1.029		
	495	480	1.031		
	491	480	1.023		
E7014	517	480	1.077	1.105	0.021
	523	480	1.090		
	543	480	1.131		
	529	480	1.102		
	541	480	1.127		
All Electrodes				1.151	0.084

Table E12.7 – Longitudinal Weld Tests from Deng *et al.* (2003) and Callele *et al.* (2005)

Specimen	Electrode	Model Phase	Equation 4.6a τ_u (MPa)	σ_u (MPa)	$0.67\sigma_u$ (MPa)	Ratio	Mean ρ_{M2}	V_{M2}
L1–1	E70T–4	2	505	631	423	1.195	1.174	0.025
L1–2			482			1.140		
L1–3			502			1.187		
L3–1	E71T8–K6	2	512	493	330	1.550	1.514	0.040
L3–2			477			1.444		
L3–3			511			1.547		
L2–1	E70T–7	2	536	605	405	1.322	1.226	0.092
L2–2			551			1.359		
L2–3			548			1.352		
L100–1		3	434	569	381	1.138		
L100–2			429			1.125		
L100–3			475			1.246		
L100–4			422			1.107		
L100–5			397			1.041		
L100–6			444			1.165		
L150–4			453			1.188		
L150–5			500			1.312		
L150–6			519			1.361		
All Specimens							1.266	0.118

Table E12.8 – Analysis of Test Results from Callele *et al.* (2005) – Combined Transverse and Longitudinal Welds

Specimen	Model	Specimen with Transverse and Longitudinal Weld					
		Equation 4.9		Equation 4.10		Equation 4.10a and b	
	P_u (kN)	Predicted Capacity (kN)	Ratio ρ_P	Predicted Capacity (kN)	Ratio ρ_P	Predicted Capacity (kN)	Ratio ρ_P
TL50–1	1484	1792	0.828	1923	0.772	1792	0.828
TL50–2	1664	1778	0.936	1911	0.871	1778	0.936
TL50–3	1573	1785	0.881	1911	0.823	1785	0.881
TL50–4	1700	1811	0.939	1945	0.874	1811	0.939
TL50a–1	1299	1573	0.826	1687	0.770	1573	0.826
TL50a–2	1186	1618	0.733	1738	0.683	1618	0.733
TL50a–3	1213	1592	0.762	1707	0.710	1592	0.762
TL50a–4	1472	1738	0.847	1866	0.789	1738	0.847
TL100–1	2359	2824	0.835	3116	0.757	2824	0.835
TL100–2	2218	2627	0.844	2903	0.764	2627	0.844
TL100–3	1976	2662	0.742	2933	0.674	2662	0.742
TL100SP–1	2032	2222	0.915	2462	0.825	2222	0.915
TL100SP–2	1866	2190	0.852	2425	0.769	2190	0.852
TL100SP–3	1813	2193	0.827	2424	0.748	2193	0.827
TL100D–1	2077	2235	0.929	2469	0.841	2235	0.929
TL100D–2	2040	2149	0.949	2370	0.861	2149	0.949
TL100D–3	2341	2709	0.864	3001	0.780	2709	0.864
TL50D–1	1486	1769	0.840	1902	0.781	1769	0.840
TL50D–2	1455	1836	0.793	1973	0.738	1836	0.793
TL50D–3	1412	1745	0.809	1882	0.750	1745	0.809
All specimen	Mean ρ_P		0.848		0.779		0.848
	V_P		0.075		0.073		0.075



Note 1. Same on both sides of joint
2. Nominal throat size a_1
3. Nominal throat size a_2

Figure E1 – General Configuration of Specimens (Ligtenberg, 1968)

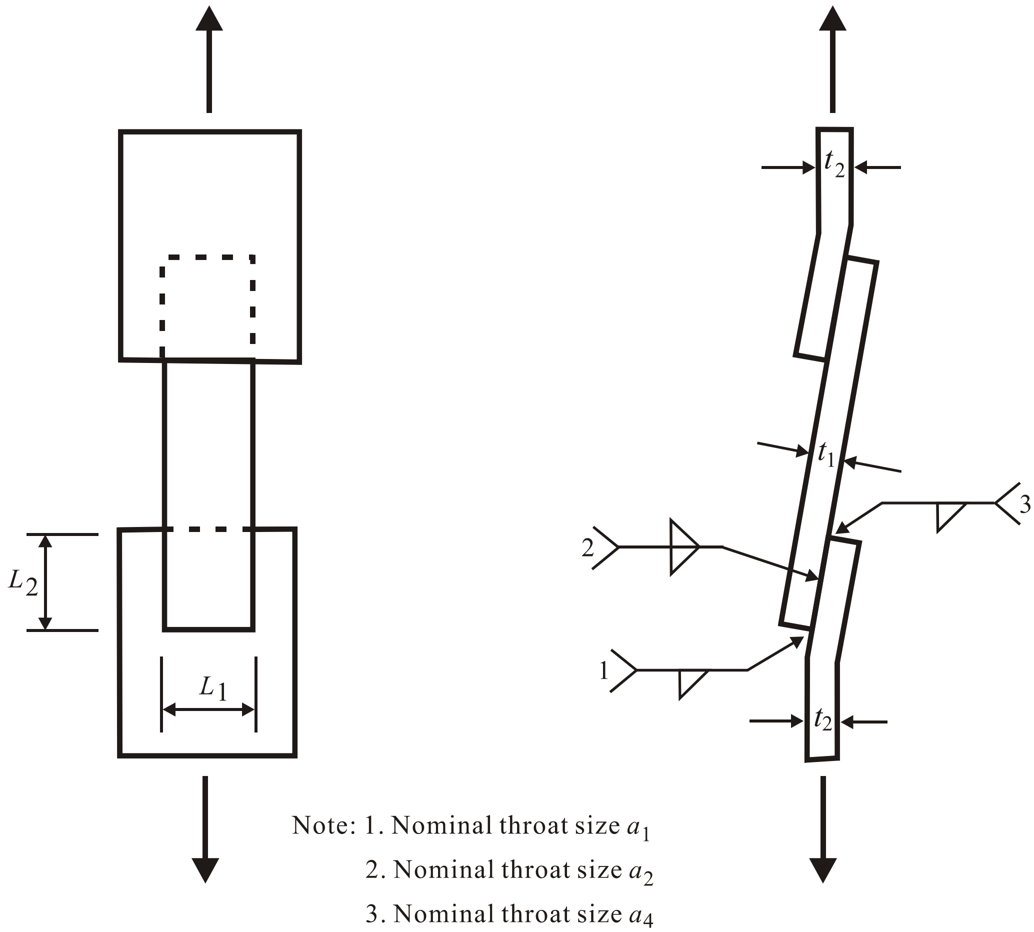


Figure E2 – Configuration of Type [xx4xx] Specimens

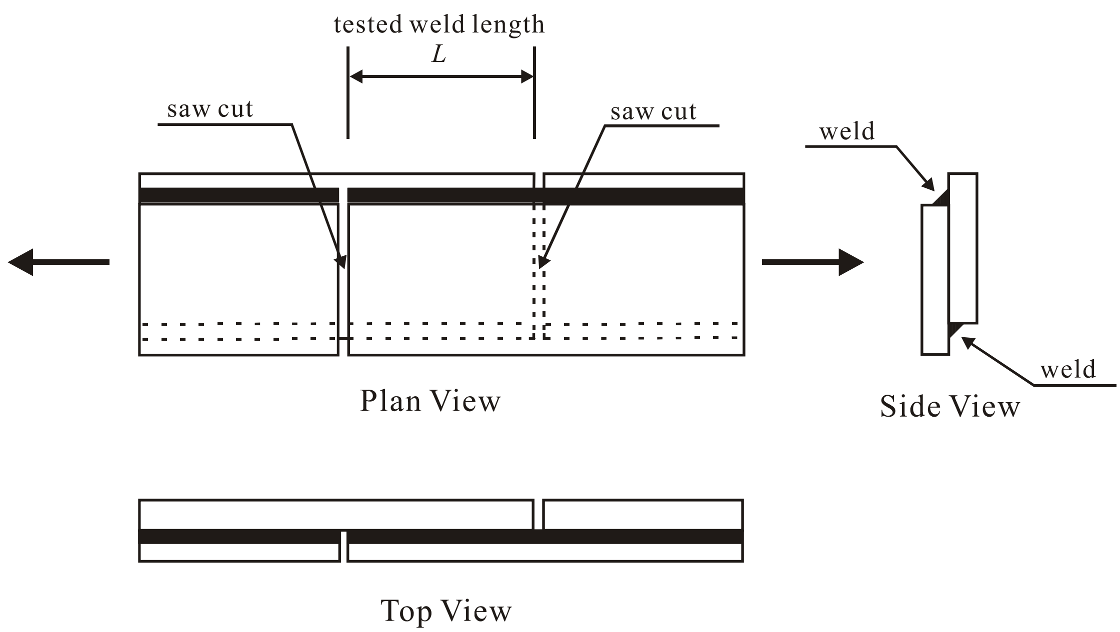
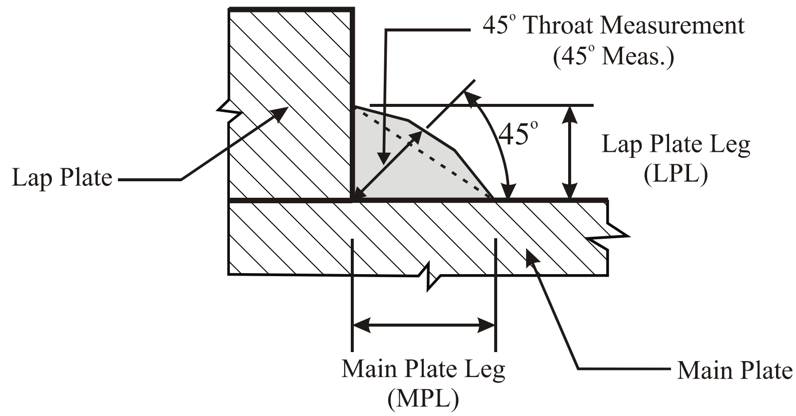


Figure E3 – Werner Specimen



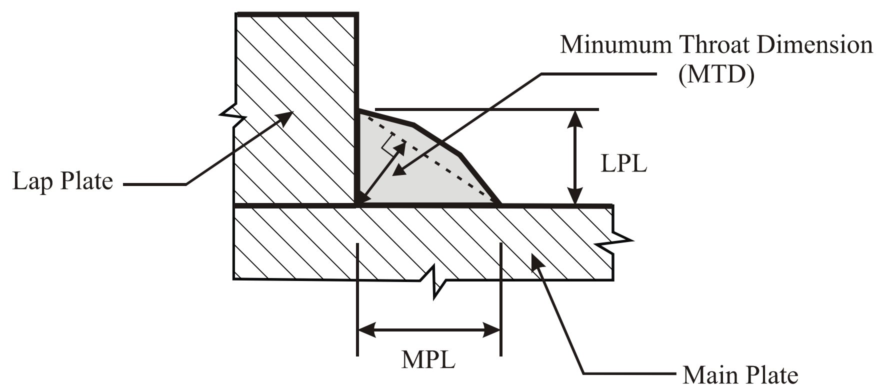


Figure E4 – Definition of Weld Legs

APPENDIX F

NEW SPECIMEN DESIGN DRAWINGS

APPENDIX F

NEW SPECIMEN DESIGN DRAWINGS

F.1 Introduction

This appendix presents the fabrication notes and drawings for specimens that were ordered but not fabricated yet. Aspects of these future tests have been discussed in Chapter 5.

F.2 General Notes

FABRICATION GENERAL NOTES

University of Alberta Fillet Weld Project—Phase 5

The attached drawings contain the information required to fabricate the specimens requested. The pertinent information for fabricating each specimen is found on the respective drawing; however the following General Notes apply to all fabrication.

At the top-right corner of every attached drawing there is a label, "PHASE 5". Use these labels to keep track of the number of specimens that are required to be fabricated. In total there are 10 joint-specimens and 3 all-weld-metal specimens that need to be fabricated.

1. Two steels are used in this phase. Some specimens use ASTM Grade 50 Steel, alternative of which is CAN/CSA-G40.21 350W. Some specimens use CAN/CSA-G40.21 300WT or 350WT, whichever is available. However, 350WT is preferred.

2. Do NOT grind the welds. No STOP/START allowed except at plate edges.

3. All plates of a particular thickness shall be of the same heat. There are three different plate thickness that are required for the specimen fabrication, namely, 2", 1-1/2" and 7/8".

4. Provide a copy of the mill certificate for each heat for approval prior to fabrication.

5. Two different AWS electrode classifications are required for fabrication: E70T-7 and E70T7-K2. Respectively, the manufacturer designation of electrodes is described below. Lincoln Electric designation for E70T-7 is Innershield NR311 and Lincoln Electric designation for E70T7-K2 is Innershield NR311Ni.

6. Produce all welds of the identical electrode classification from the same spool.

7. Produce three (3) all-weld-metal specimens shown on the drawing titled “Material Test Specimen”.

8. Provide the lot number for each electrode classification used.

9. A Welding Procedure Specification (WPS) shall be submitted for approval prior to fabrication.

10. Record and provide a copy of all welding parameters as measured during welding of the specimens.

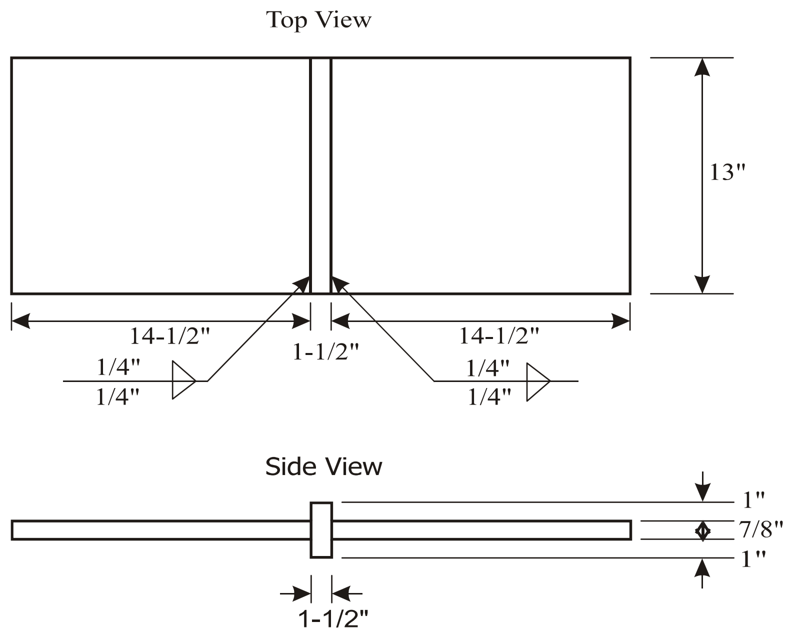
11. All specimens shall be marked with their respective specimen designations, see attached drawings. Use surface markings only; no punching or scoring is permitted.

F.3 Drawings

Eleven fabrication drawings are presented in the following pages.

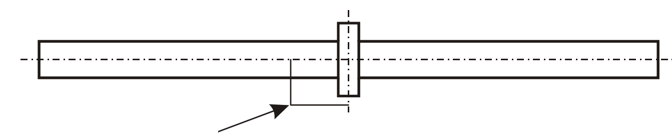
PHASE 5

Final Assembly



Quality Control Criteria

It is important to ensure that the lap plates are in line with each other and are at 90 degrees to the cruciform middle plate. Post-weld straightening is not permitted.



The center-lines of the plates need to be in line with each other as well as perpendicular to the center-line of the middle cruciform plate.

The plates should be clamped down to limit the plate distortion during welding and to ensure the plates are in line with each other. Alternate sides during welding to limit distortion.

ALTERNATIVE FABRICATION PROCEDURES WILL BE CONSIDERED

Weld Leg Size Tolerance: ±1/16"

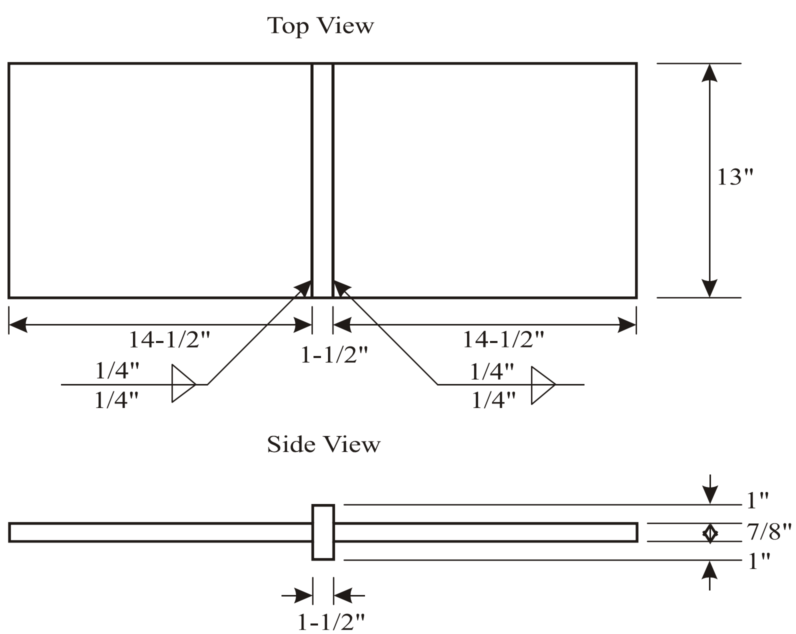
Notes: -Number of Specimens Required: 1
- -Plates to be of ASTM A572 Grade 50 Steel
- -Use AWS classification E70T-7 Electrodes i.e. Lincoln Electric designation: Innershield NR311
- -Do NOT grind the welds
- -No STOP/START allowed except at plate edges
- -Welds shall be deposited in ONE (1) pass

Drawn By: Li, C.	Cruciform Weld	
Checked By:	University of Alberta	Revision: 2
Date: Oct. 20,2005	Specimen CYa-1,2,3	
	Scale: NTS	Drawing 1 of 11

PHASE 5

Final Assembly

Top View

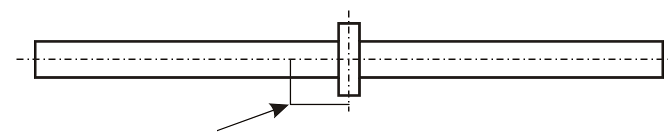


Weld Leg Size Tolerance: ±1/16"

Notes: -Number of Specimens Required: 1
-Plates to be of ASTM A572 Grade 50 Steel
-Use AWS classification E70T7-K2 Electrodes i.e. Lincoln Electric designation: NR311Ni.
-Do NOT grind the welds
-No STOP/START allowed except at plate edges
-Welds shall be deposited in ONE (1) pass

Quality Control Criteria

It is important to ensure that the lap plates are in line with each other and are at 90 degrees to the cruciform middle plate. Post-weld straightening is not permitted.

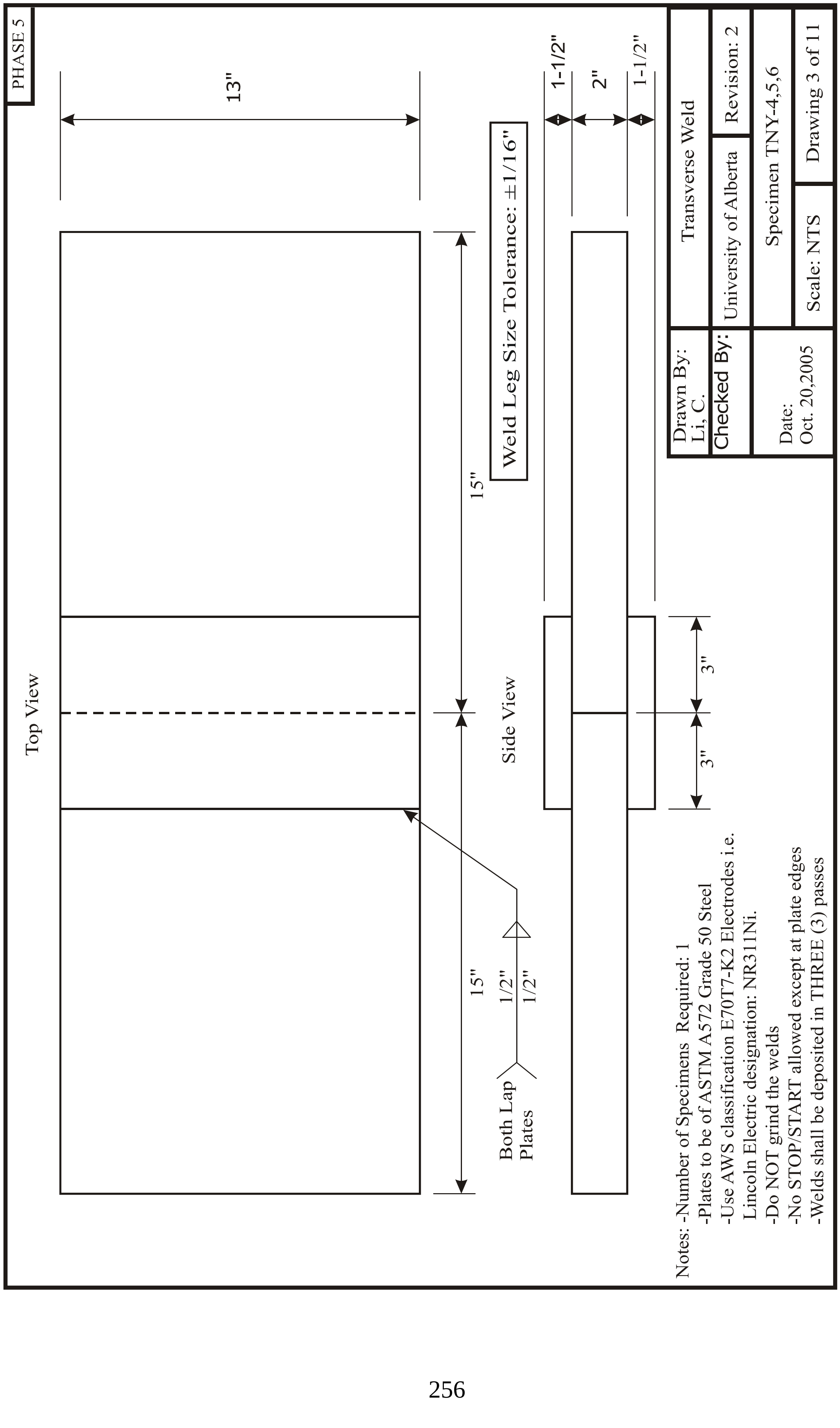


The center-lines of the plates need to be in line with each other as well as perpendicular to the center-line of the middle cruciform plate.

The plates should be clamped down to limit the plate distortion during welding and to ensure the plates are in line with each other. Alternate sides during welding to limit distortion.

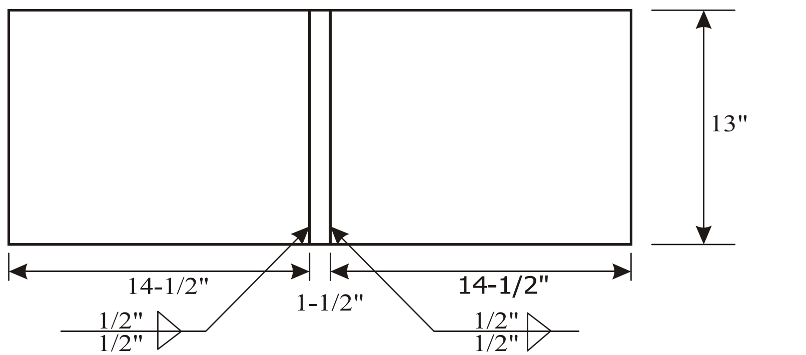
ALTERNATIVE FABRICATION PROCEDURES WILL BE CONSIDERED

Drawn By: Li, C.	Cruciform Weld	
Checked By:	University of Alberta	Revision: 2
Date: Oct. 20,2005	Specimen CYb-1,2,3	
	Scale: NTS	Drawing 2 of 11

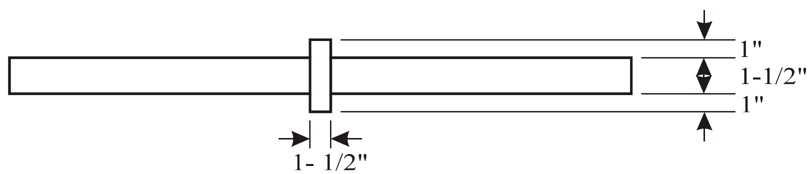

PHASE 5
Top View
13"
15"
15"
Both Lap Plates
1/2"
1/2"
Weld Leg Size Tolerance: ±1/16"
Side View
1-1/2"
2"
1-1/2"
3"
3"
Notes: -Number of Specimens Required: 1
-Plates to be of ASTM A572 Grade 50 Steel
-Use AWS classification E70T7-K2 Electrodes i.e.
Lincoln Electric designation: NR311Ni.
-Do NOT grind the welds
-No STOP/START allowed except at plate edges
-Welds shall be deposited in THREE (3) passes
Drawn By: Li, C.
Checked By:
Date: Oct. 20,2005
Transverse Weld
University of Alberta
Revision: 2
Specimen TNY-4,5,6
Scale: NTS
Drawing 3 of 11

Final Assembly

Top View



Side View

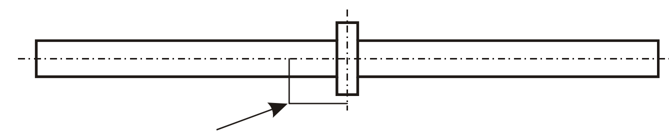


Weld Leg Size Tolerance: ±1/16"

Notes:
- Number of Specimens Required: 1
- Plates to be of ASTM A572 Grade 50 Steel
- Use AWS classification E70T-7 Electrodes i.e. Lincoln Electric designation: Innershield NR311
- Do NOT grind the welds
- No STOP/START allowed except at plate edges
- Welds shall be deposited in THREE (3) passes

Quality Control Criteria

It is important to ensure that the lap plates are in line with each other and are at 90 degrees to the cruciform middle plate. Post-weld straightening is not permitted.



The center-lines of the plates need to be in line with each other as well as perpendicular to the center-line of the middle cruciform plate.

The plates should be clamped down to limit the plate distortion during welding and to ensure that the plates are in line with each other. Alternate sides during welding to limit distortion.

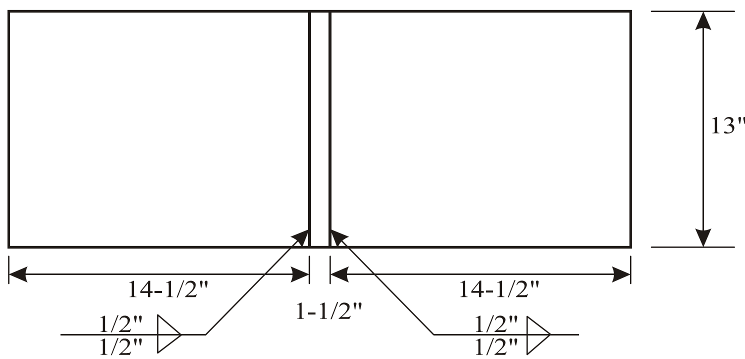
ALTERNATIVE FABRICATION PROCEDURES WILL BE CONSIDERED

Drawn By: Li, C.	Cruciform Weld	
Checked By:	University of Alberta	Revision: 2
Date: Oct. 20,2005	Specimen CNY-13,14,15	
	Scale: NTS	Drawing 4 of 11

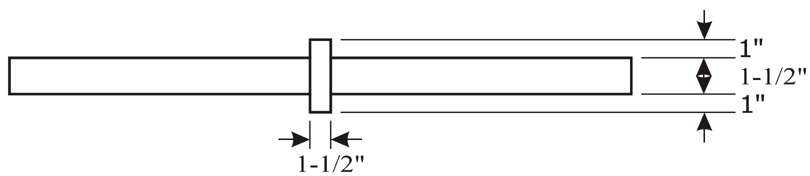
PHASE 5

Final Assembly

Top View



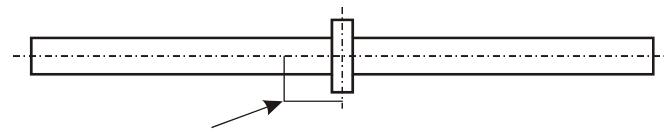
Side View



Weld Leg Size Tolerance: ±1/16"

Quality Control Criteria

It is important to ensure that the lap plates are in line with each other and are at 90 degrees to the cruciform middle plate. Post-weld straightening is not permitted.



The center-lines of the plates need to be in line with each other as well as perpendicular to the center-line of the middle cruciform plate.

The plates should be clamped down to limit the plate distortion during welding and to ensure that the plates are in line with each other. Alternate sides during welding to limit distortion.

ALTERNATIVE FABRICATION PROCEDURES WILL BE CONSIDERED

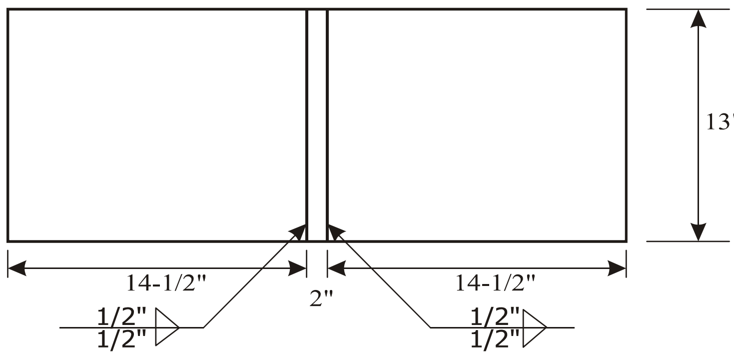
Notes:
- -Number of Specimens Required: 1
- -Plates to be of ASTM A572 Grade 50 Steel
- -Use AWS classification E70T7-K2 Electrodes i.e. Lincoln Electric designation: NR311Ni.
- -Do NOT grind the welds
- -No STOP/START allowed except at plate edges
- -Welds shall be deposited in THREE (3) passes

Drawn By: Li, C.	Cruciform Weld	
Checked By:	University of Alberta	Revision: 2
Date: Oct. 20,2005	Specimen CNY-16,17,18	
	Scale: NTS	Drawing 5 of 11

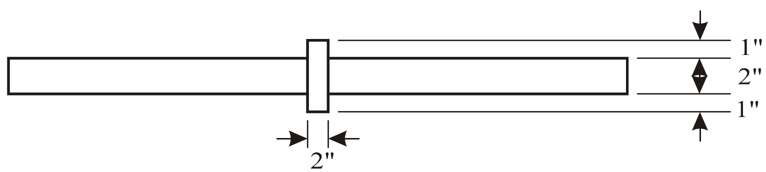
PHASE 5

Final Assembly

Top View



Side View

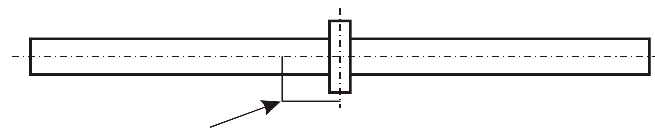


Weld Leg Size Tolerance: ±1/16"

Notes: -Number of Specimens Required: 1
- -Plates to be of CSA G40.21 Grade 300WT or 350WT Steel
- -Use AWS classification E70T7-K2 Electrodes i.e. Lincoln Electric designation: NR311Ni.
- -Do NOT grind the welds
- -No STOP/START allowed except at plate edges
- -Welds shall be deposited in THREE (3) passes

Quality Control Criteria

It is important to ensure that the lap plates are in line with each other and are at 90 degrees to the cruciform middle plate. Post-weld straightening is not permitted.



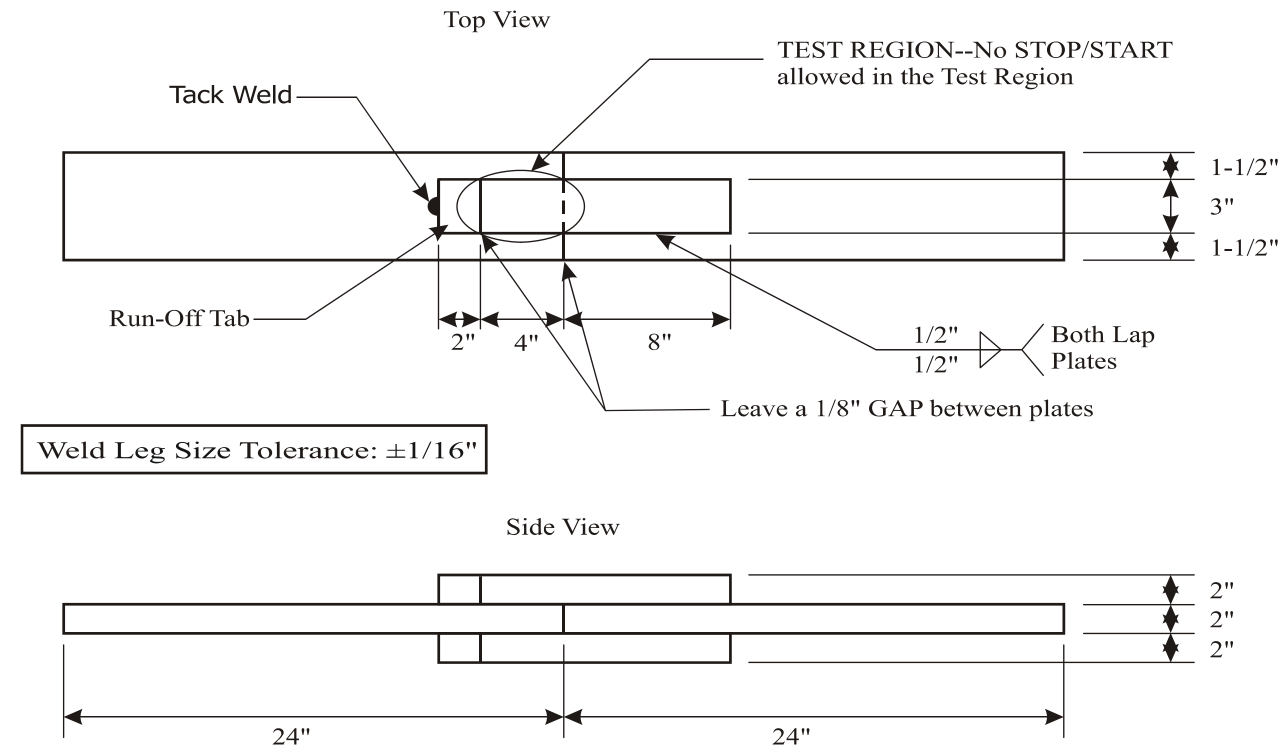
The center-lines of the plates need to be in line with each other as well as perpendicular to the center-line of the middle cruciform plate.

The plates should be clamped down to limit the plate distortion during welding and to ensure that the plates are in line with each other. Alternate sides during welding to limit distortion.

ALTERNATIVE FABRICATION PROCEDURES WILL BE CONSIDERED

Drawn By: Li, C.	Cruciform Weld	
Checked By:	University of Alberta	Revision: 2
Date: Oct. 20,2005	Specimen CNY-19,20,21	
	Scale: NTS	Drawing 6 of 11

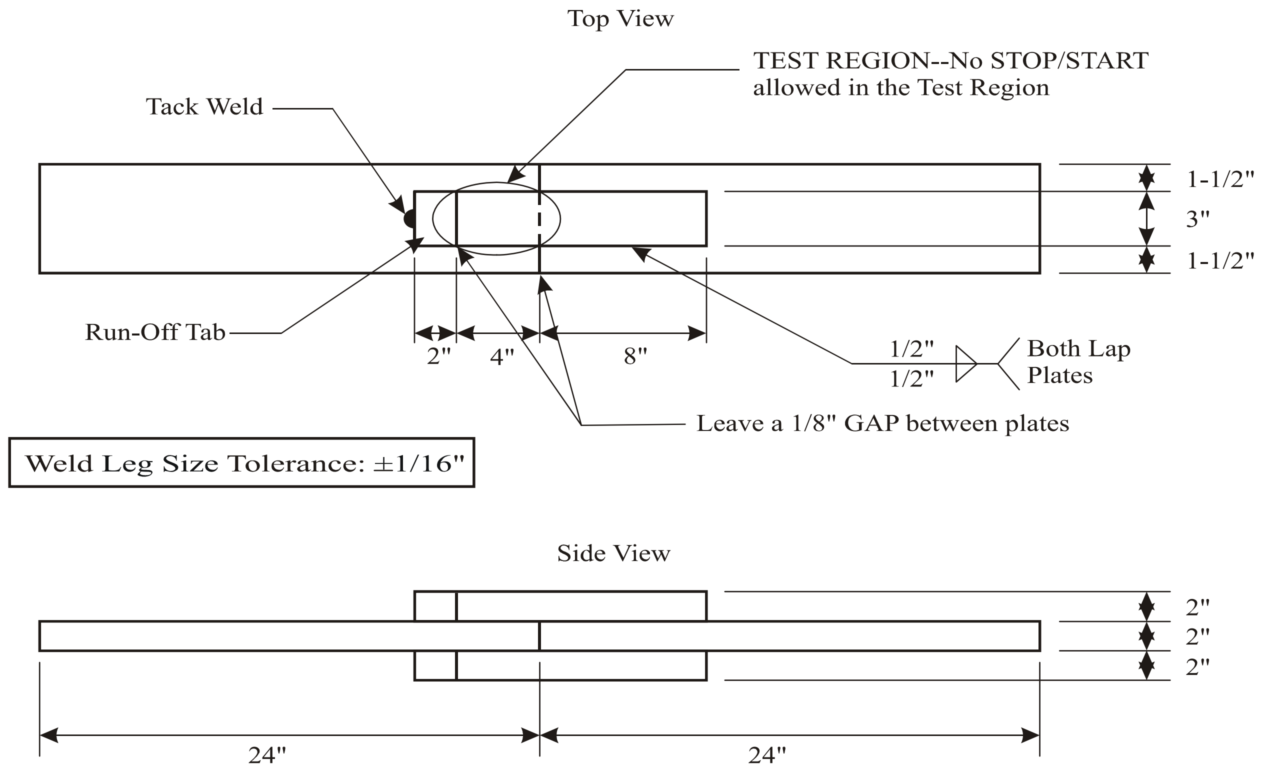
PHASE 5



Notes: -Number of Specimens Required: 3
- Plates to be of ASTM A572 Grade 50 Steel
- Use AWS classification E70T7-K2 Electrodes i.e. Lincoln Electric designation: NR311Ni.
- Do NOT grind the welds
- No STOP/START in test region
- Welds shall be deposited in THREE (3) passes

Drawn By: Li, C.	Longitudinal Weld	
Checked By:	University of Alberta	Revision: 2
Date: Oct. 20,2005	Specimen L100-7, 8, 9	
	Scale: NTS	Drawing 7 of 11

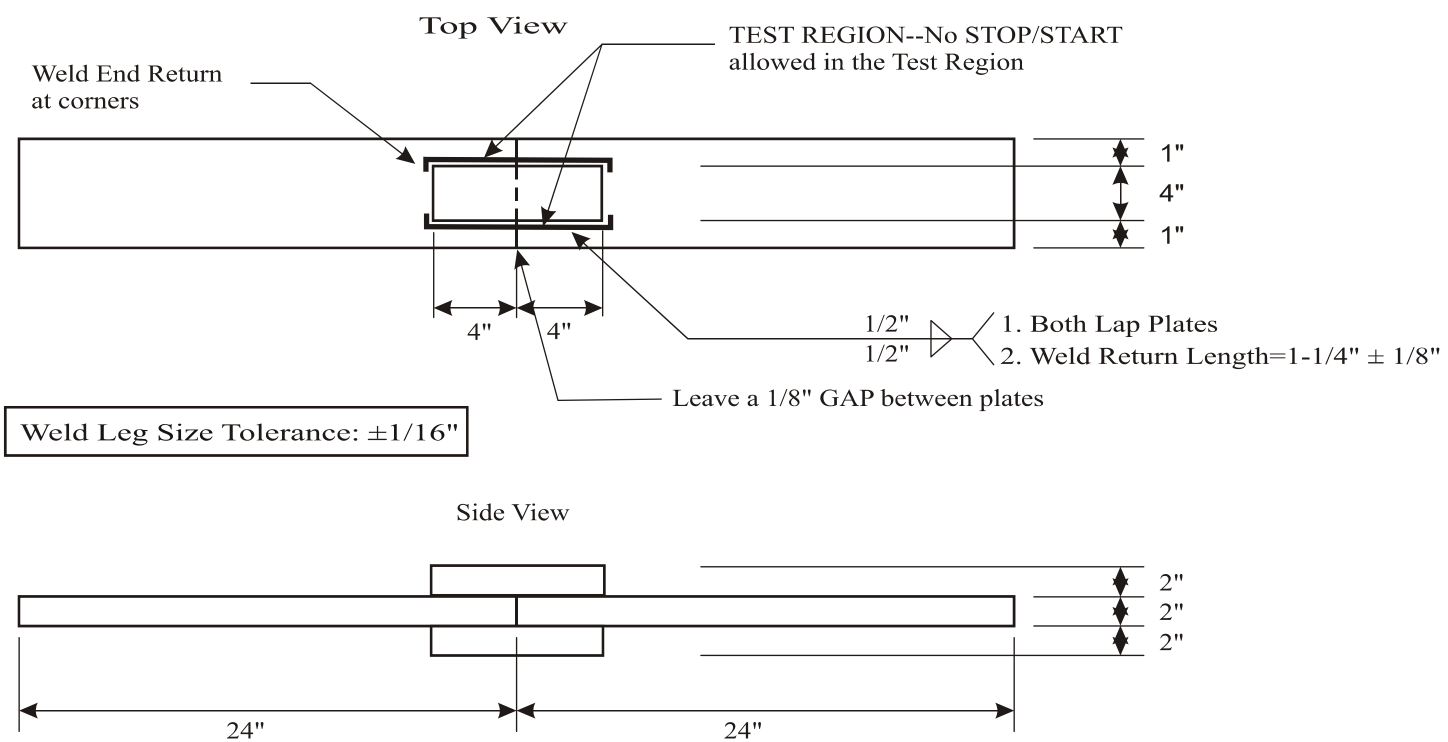
PHASE 5



Notes: -Number of Specimens Required: 3
-Plates to be of CSA G40.21 Grade 300WT or 350WT Steel
-Use AWS classification E70T7-K2 Electrodes i.e.
Lincoln Electric designation: NR311Ni.
-Do NOT grind the welds
-No STOP/START allowed in test region
-Welds shall be deposited in THREE (3) passes

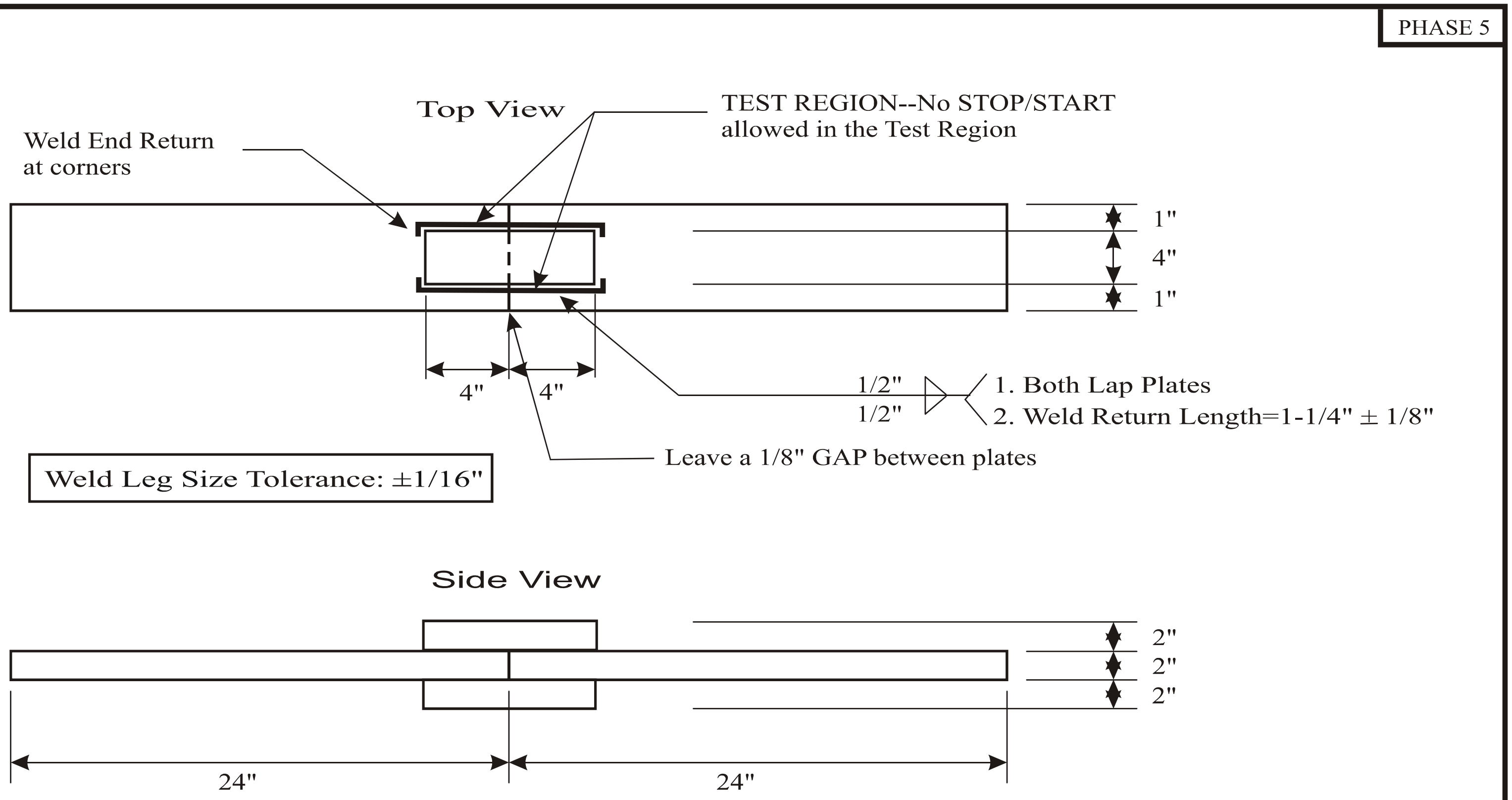
Drawn By: Li, C.	Longitudinal Weld	
Checked By:	University of Alberta	Revision: 2
Date: Oct. 20,2005	Specimen L100-10,11,12	
	Scale: NTS	Drawing 8 of 11

PHASE 5



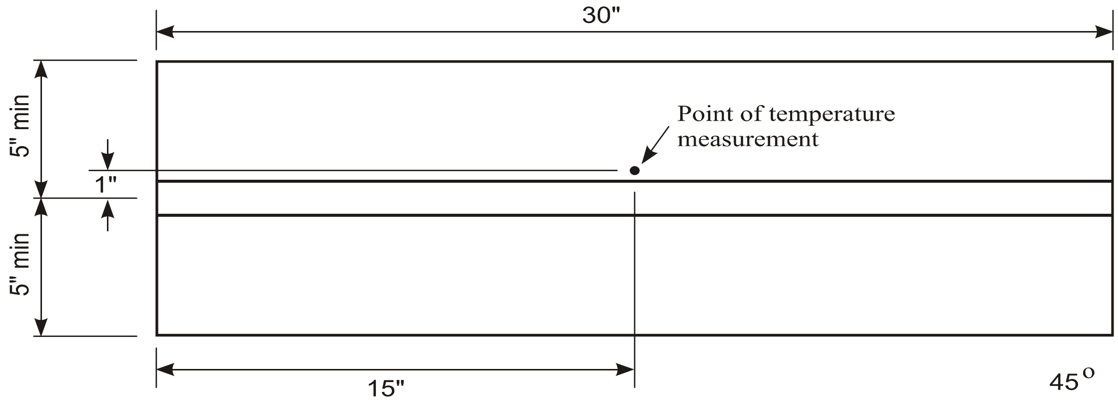
Notes: -Number of Specimens Required: 3
-Plates to be of ASTM A572 Grade 50 Steel
-Use AWS classification E70T-7 Electrodes i.e. Lincoln Electric designation: Innershield NR311
-Do NOT grind the welds
-No STOP/START allowed in test region
-Welds shall be deposited in THREE (3) passes

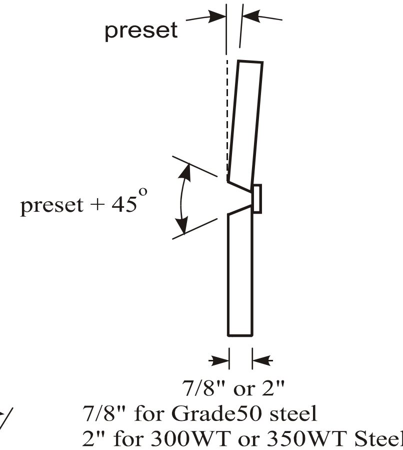
Drawn By: Li, C.	Longitudinal Weld with End Returns	
Checked By:	University of Alberta	Revision: 2
Date: Oct. 20,2005	Specimen L100e-1,2,3	
	Scale: NTS	Drawing 9 of 11

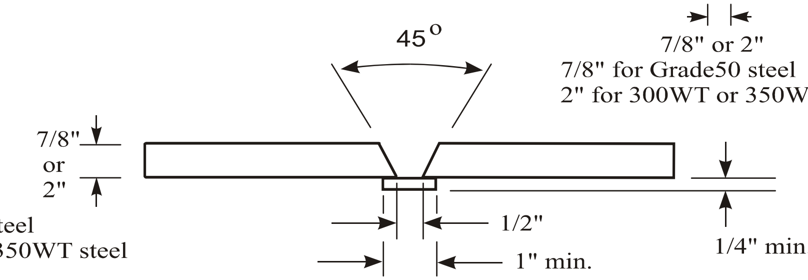


Notes: -Number of Specimens Required: 3
-Plates to be of ASTM A572 Grade 50 Steel
-Use AWS classification E70T7-K2 Electrodes i.e. Lincoln Electric designation: NR311Ni.
-Do NOT grind the welds
-No STOP/START allowed except at plate edges
-Welds shall be deposited in THREE (3) passes

Drawn By: Li, C.	Longitudinal Weld with End Returns	
Checked By:	University of Alberta	Revision: 2
Date: Oct. 20,2005	Specimen L100e-4,5,6	
	Scale: NTS	Drawing 10 of 11







General Notes:

1) Produce three (3) specimens:
   Specimen#1: E70T-7 electrode and ASTM A572 Grade 50 Steel
   Specimen#2: E70T7-K2 electrode and ASTM A572 Grade 50 Steel
   Specimen#3: E70T7-K2 electrode and CSA G40.21 300WT or 350WT steel

2) Welding shall be in the flat position and the assembly shall be restrained, or preset, or a combination of both, during welding to prevent warping in excess of 5 degrees. An assembly that is warped by more than 5 degrees from plane shall be discarded. It shall not be straightened.

3) The test assembly shall be tack welded at room temperature and welding shall begin at that temperature (16 °C minimum). Welding shall continue until the assembly has reached a temperature of 150 ± 14°C, measured by temperature indicating crayons or surface thermometers at the location shown in the figure. This interpass temperature shall be maintained for the remainder of the weld. Should it be necessary to interrupt welding, the assembly shall be allowed to cool in still air at room temperature. The assembly shall be heated to a temperature of 150 ± 14°C before welding is resumed.

Drawn By: GYG/RGD	Material Test Specimen	
Checked By:	University of Alberta	Revision: 2
Date: Oct. 20,2005	Phase 5 Weld Metal Coupons	
	Scale: NTS	Drawing 11 of 11

APPENDIX G

RESULTS OF ADDITIONAL SIX SPECIMENS TESTED IN PHASE 4

APPENDIX G

RESULTS OF ADDITIONAL SIX SPECIMENS TESTED IN PHASE 4

G.1 Introduction

This appendix presents six specimens tested in phase 4 but not reported elsewhere in the thesis. They will be incorporated into future work on fillet weld behaviour and are documented here as a record for future use.

Specimens L150-1, 2, 3 each had four 152 mm long longitudinal welds, as shown in Figure G1. The specimens were fabricated using filler metal E70T-7. The specimens were tested at -50 ºC and the plates remained elastic during testing. The pre-test measurements are presented in Tables G1 through G3. Specimens TYa-1, 2, 3 each had two transverse welds, as shown in Figure G2. The specimens were fabricated using filler metal E70T-7. The specimens were tested at room temperature and the plates yielded during testing. The pre-test measurements are presented in Tables G4 through G6.

The measured capacities are summarized in Table G7 and the measured deformations in Table G8. The response curves are presented in Figures G3 through G8.

The test setup for these specimens was the same as that described in Deng *et al.* (2003). The definitions of the pre-test measurements are also the same as in Deng *et al.* (2003).

Table G1 – Weld Measurements for Specimen L150–1

Meas. Number	Front Face							
	Weld 1				Weld 2			
	MPL (mm)	LPL (mm)	45° Meas. (mm)	Weld Length† / Gauge Length‡ (mm)	MPL (mm)	LPL (mm)	45° Meas. (mm)	Weld Length† / Gauge Length‡ (mm)
1	11.9	11.3	8.1	150.0†	12.2	12.3	8.9	148.8†
2	11.9	10.7	9.0	150.0†	11.2	13.0	9.7	148.7†
3	12.9	10.3	9.4	158.2‡	11.5	12.3	9.4	159.2‡
4	13.8	11.4	9.8		13.5	11.8	9.7	
5	12.6	11.3	8.9		12.9	12.3	9.8	
6	12.7	12.0	9.2		12.4	12.3	9.7	
7	12.9	12.1	9.5		13.0	12.0	9.7	
8	12.2	10.7	9.2		12.3	12.5	10.0	
9	11.7	11.0	8.9		12.3	12.2	9.7	
10	12.1	10.1	9.8		12.7	11.9	9.4	
Mean	12.5	11.1	9.2		12.4	12.3	9.6	

Meas. Number	Back Face							
	Weld 3				Weld 4			
	MPL (mm)	LPL (mm)	45° Meas. (mm)	Weld Length† / Gauge Length‡ (mm)	MPL (mm)	LPL (mm)	45° Meas. (mm)	Weld Length† / Gauge Length‡ (mm)
1	13.2	11.3	8.9	150.8†	13.1	11.2	9.5	149.9†
2	13.4	11.5	9.4	150.5†	13.9	11.7	10.0	149.5†
3	13.5	12.2	10.0	158.8‡	14.4	12.3	9.8	155.6‡
4	14.7	11.6	9.8		12.1	12.0	9.7	
5	14.9	12.1	9.8		13.1	12.8	10.2	
6	14.1	12.2	9.7		14.3	12.5	10.6	
7	13.8	10.7	9.0		12.9	12.5	10.0	
8	14.2	10.9	9.4		13.8	13.2	10.2	
9	15.3	11.2	9.4		12.1	13.1	9.7	
10	15.5	11.3	9.4		11.9	11.5	9.5	
Mean	14.2	11.5	9.5		13.2	12.3	9.9	

Table G2 – Weld Measurements for Specimen L150–2

Meas. Number	Front Face							
	Weld 1				Weld 2			
	MPL (mm)	LPL (mm)	45° Meas. (mm)	Weld Length† / Gauge Length‡ (mm)	MPL (mm)	LPL (mm)	45° Meas. (mm)	Weld Length† / Gauge Length‡ (mm)
1	13.1	10.5	8.9	151.0†	13.1	11.6	9.0	148.3†
2	12.2	11.1	9.2	150.6†	12.5	11.8	9.5	148.3†
3	13.1	11.9	9.2	158.6‡	13.4	11.4	9.4	160.2‡
4	13.7	11.2	9.7		13.5	11.3	9.2	
5	13.4	11.6	9.5		13.6	11.8	9.5	
6	14.1	11.7	10.0		13.3	12.3	9.7	
7	14.0	11.4	9.8		12.3	11.9	9.5	
8	14.2	11.8	9.4		12.0	12.6	9.0	
9	12.5	11.3	8.9		12.3	11.7	9.5	
10	12.6	11.5	8.6		12.4	11.7	9.4	
Mean	13.3	11.4	9.3		12.9	11.8	9.4	
Meas. Number	Back Face							
	Weld 3				Weld 4			
	MPL (mm)	LPL (mm)	45° Meas. (mm)	Weld Length† / Gauge Length‡ (mm)	MPL (mm)	LPL (mm)	45° Meas. (mm)	Weld Length† / Gauge Length‡ (mm)
1	13.2	10.3	9.4	151.6†	12.5	10.1	8.4	152.0†
2	13.0	10.0	8.4	151.7†	13.8	10.7	9.4	152.2†
3	13.3	10.9	9.4	160.9‡	13.1	11.0	9.8	160.5‡
4	12.4	11.7	9.8		13.8	11.3	10.2	
5	12.9	12.0	9.8		13.3	11.4	10.0	
6	13.2	12.1	9.5		13.4	11.1	10.5	
7	13.7	11.7	9.2		13.3	11.6	9.7	
8	12.5	11.7	9.5		12.2	11.2	8.6	
9	12.1	11.3	8.9		13.4	10.9	9.2	
10	12.4	10.5	9.2		13.3	11.2	9.5	
Mean	12.9	11.2	9.3		13.2	11.0	9.5	

Table G3 – Weld Measurements for Specimen L150–3

Meas. Number	Front Face							
	Weld 1				Weld 2			
	MPL (mm)	LPL (mm)	45° Meas. (mm)	Weld Length† / Gauge Length‡ (mm)	MPL (mm)	LPL (mm)	45° Meas. (mm)	Weld Length† / Gauge Length‡ (mm)
1	12.2	11.1	8.7	151.8†	11.6	10.7	8.3	150.5†
2	11.6	9.5	8.4	151.6†	11.9	10.6	8.3	150.8†
3	12.6	10.1	9.2	159.4‡	12.3	10.6	8.9	157.8‡
4	13.0	11.4	9.5		12.2	9.8	9.0	
5	13.1	11.4	9.8		12.4	9.6	8.9	
6	12.7	10.8	9.2		13.4	10.7	9.4	
7	13.3	10.1	9.0		12.7	11.1	9.7	
8	12.6	10.0	8.7		12.0	10.1	9.5	
9	11.5	11.1	9.0		11.8	9.1	9.0	
10	11.0	10.9	8.6		11.8	9.3	8.3	
Mean	12.3	10.6	9.0		12.2	10.2	8.9	
Meas. Number	Back Face							
	Weld 3				Weld 4			
	MPL (mm)	LPL (mm)	45° Meas. (mm)	Weld Length† / Gauge Length‡ (mm)	MPL (mm)	LPL (mm)	45° Meas. (mm)	Weld Length† / Gauge Length‡ (mm)
1	13.0	10.0	8.9	147.5†	12.1	11.0	9.0	148.1†
2	12.5	10.6	9.0	147.2†	12.6	11.3	9.5	148.3†
3	11.8	10.4	9.2	157.5‡	12.7	11.5	9.4	157.95‡
4	12.9	11.2	9.7		12.2	10.8	9.2	
5	14.0	11.0	10.0		12.9	11.3	9.5	
6	13.8	11.2	9.8		13.3	11.6	9.7	
7	12.4	11.3	9.4		13.3	11.0	9.5	
8	12.8	10.8	9.5		13.1	11.1	9.0	
9	12.3	9.8	9.5		12.3	10.8	9.5	
10	12.1	10.5	8.9		11.9	10.6	9.4	
Mean	12.8	10.7	9.4		12.6	11.1	9.4	

Table G4 – Weld Measurements for Specimen TYa–1

Meas. Number	Pre-Test Measurement							
	Front Face				Back Face			
	MPL (mm)	LPL (mm)	45^o Meas. (mm)	Weld Length (mm)	MPL (mm)	LPL (mm)	45^o Meas. (mm)	Weld Length (mm)
1	13.6	11.0	9.5	76.2	15.0	11.5	12.4	76.2
2	13.3	11.4	9.7	76.2	13.7	11.6	11.4	76.3
3	13.9	11.6	10.8	76.2	14.6	11.7	11.4	76.2
4	14.2	12.6	10.8	—	13.6	12.0	11.3	—
5	15.1	12.0	10.6	—	13.9	11.6	11.4	—
6	14.6	11.0	11.0	—	12.9	11.5	11.1	—
7	13.7	11.3	11.0	—	12.7	11.7	11.4	—
8	14.8	11.0	10.8	—	12.8	12.3	12.2	—
Mean	14.2	11.5	10.5	76.2	13.6	11.7	11.6	76.2
Gauge Length (mm)	LVDT1 = 19.0				LVDT2 = 16.5			
	LVDT3 = 22.5				LVDT4 = 21.0			

Table G5 – Weld Measurements for Specimen TYa–2

Meas. Number	Pre-Test Measurement							
	Front Face				Back Face			
	MPL (mm)	LPL (mm)	45^o Meas. (mm)	Weld Length (mm)	MPL (mm)	LPL (mm)	45^o Meas. (mm)	Weld Length (mm)
1	13.7	12.2	11.4	76.3	14.3	11.1	11.0	76.3
2	13.8	11.9	11.6	76.3	14.4	10.6	11.0	76.3
3	13.1	12.1	11.3	76.3	14.8	10.7	11.0	76.3
4	14.4	12.0	11.4	—	14.7	11.3	11.0	—
5	15.2	12.4	11.4	—	14.2	11.4	10.8	—
6	14.0	12.5	11.4	—	13.8	11.0	10.8	—
7	14.4	12.3	11.3	—	13.4	11.0	10.8	—
8	13.0	12.7	11.4	—	13.2	11.2	10.8	—
Mean	13.9	12.3	11.4	76.3	14.1	11.0	10.9	76.3
Gauge Length (mm)	LVDT1 = 17.6				LVDT2 = 15.0			
	LVDT3 = 16.7				LVDT4 = 15.7			

Table G6 – Weld Measurements for Specimen TYa–3

Meas. Number	Pre-Test Measurement							
	Front Face				Back Face			
	MPL (mm)	LPL (mm)	45° Meas. (mm)	Weld Length (mm)	MPL (mm)	LPL (mm)	45° Meas. (mm)	Weld Length (mm)
1	13.4	11.0	10.2	76.2	13.2	11.9	11.4	76.2
2	13.7	11.2	10.2	76.2	12.6	11.9	11.3	76.2
3	12.9	11.7	10.2	76.2	13.3	12.3	11.4	76.2
4	12.5	11.6	10.5	—	13.3	11.3	11.3	—
5	13.0	10.8	10.3	—	13.1	11.4	11.1	—
6	14.1	10.4	10.2	—	12.9	11.7	11.0	—
7	13.6	10.4	10.3	—	13.8	12.0	11.6	—
8	13.5	10.4	10.5	—	13.1	11.6	11.6	—
Mean	13.3	10.9	10.3	76.2	13.2	11.8	11.3	76.2
Gauge Length (mm)	LVDT1 = 17.8				LVDT2 = 13.9			
	LVDT3 = 19.7				LVDT4 = 13.9			

Table G7 – Summary of Specimens Capacity

Specimen	Electrode	P_u Ultimate Load (kN)	Static Drop			$P_{ST} = P_u - \Delta P$ (kN)	Total Area A_{throat} (mm^2)	P_{ST} / A_{throat} (MPa))	Average P_{ST} / A_{throat}	Weld Failed
			upper	lower	ΔP(kN)					
L150–1	E70T–7	2269	2208	2184	24	2245	5243	428	450	Back
L150–2		2389	2292	2258	34	2355	5161	456		Plate
L150–2		2299	2281	2243	38	2261	4840	467		Plate
TYa–1	E70T–7	1063	999	967	32	1031	1356	761	754	Back
TYa–2		1081	1072	1039	33	1048	1325	791		Back
TYa–3		990	988	959	29	961	1338	710		Back

Table G8 – Summary of Specimens Ductility

Specimen		LVDT 1	LVDT 2	LVDT 3	LVDT 4	LVDT 6	LVDT 7
		(mm)	(mm)	(mm)	(mm)	(mm)	(mm)
L150–1	Ultimate	0.925	1.050	1.802	1.898	1.327	2.040
L150–2	Ultimate	1.346	1.505	1.471	1.647	1.724	1.807
L150-3	Ultimate	1.346	1.505	1.471	1.647	1.724	1.807
TYa–1	Ultimate	1.470	1.493	1.734	1.771	—	—
	Fracture	1.523	1.571	2.480	2.440	—	—
TYa–2	Ultimate	1.784	1.888	1.472	1.980	—	—
	Fracture	2.462	2.637	1.607	2.077	—	—
TYa–3	Ultimate	1.067	1.113	1.461	1.819	—	—
	Fracture	1.118	1.150	1.870	2.291	—	—

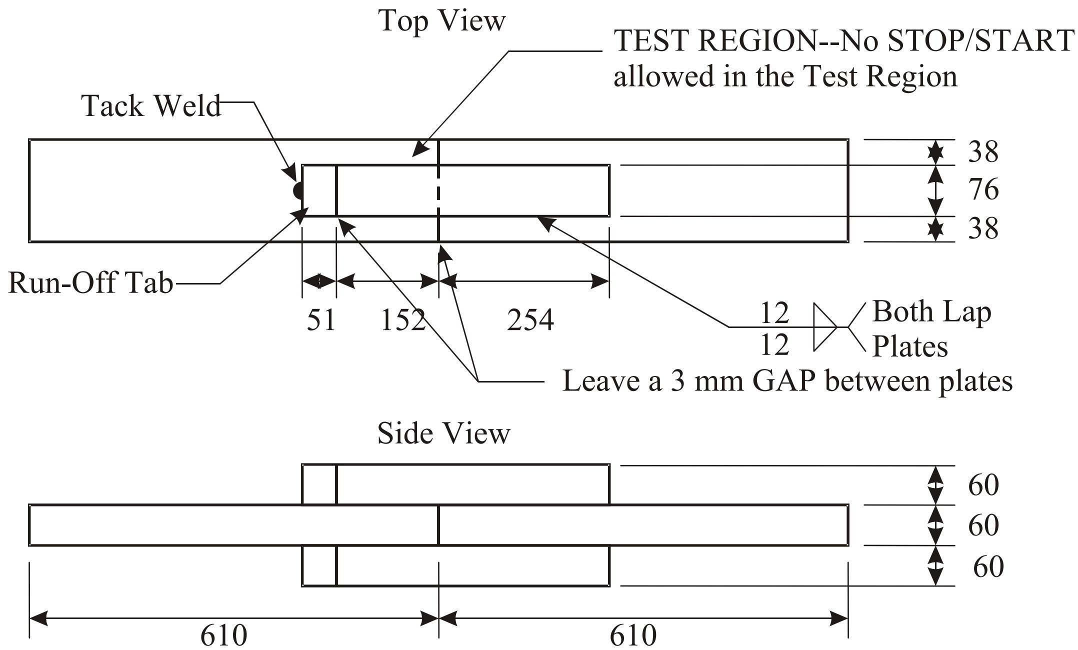


Figure G1 – Specimen L150–1, 2, 3 with Dimensions

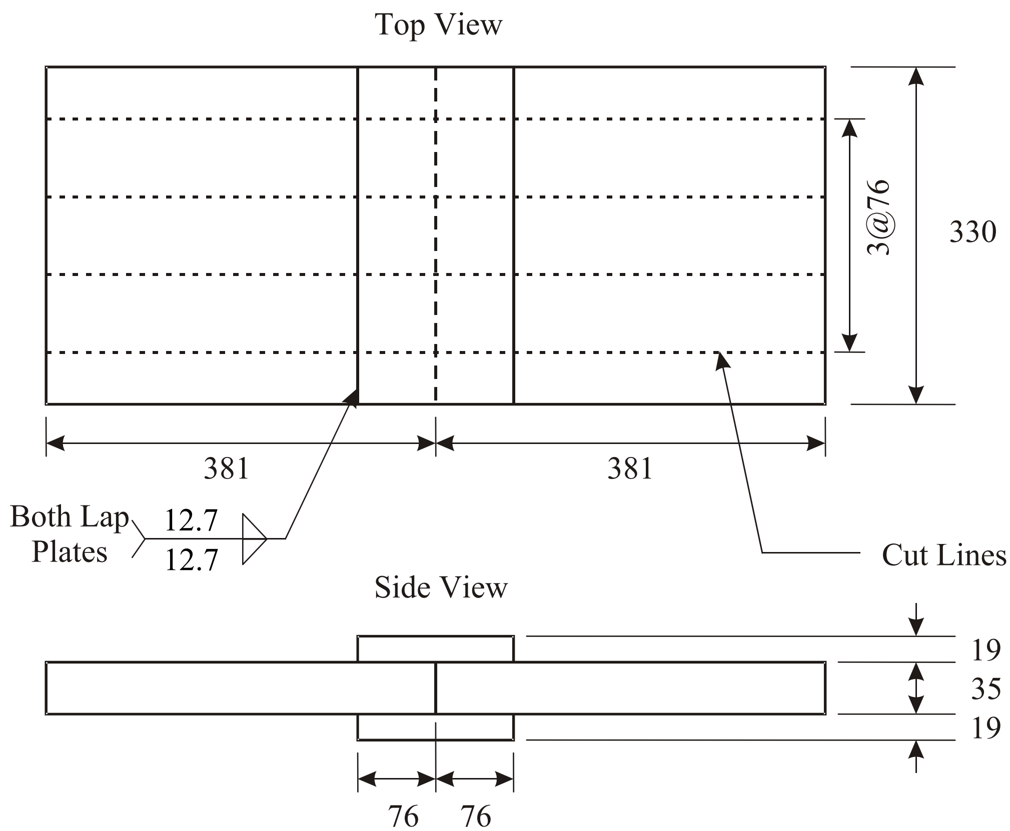


Figure G2 – Specimen TYa–1, 2, 3 with Dimensions

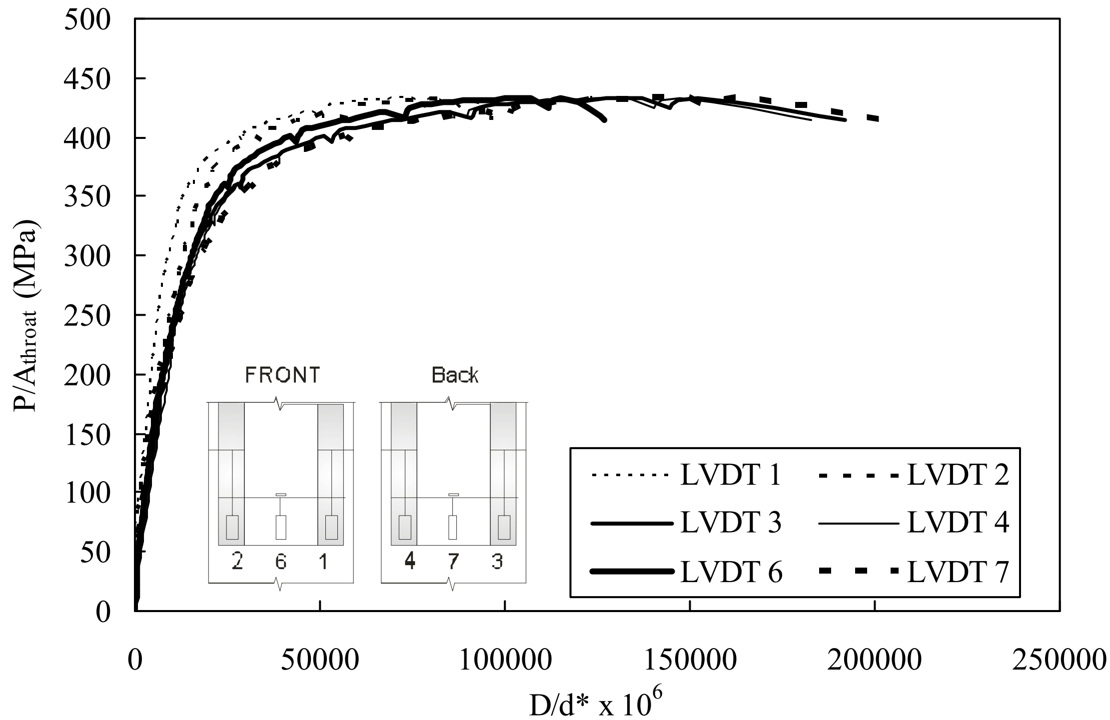


Figure G3 – Response Curve for Specimen L150–1

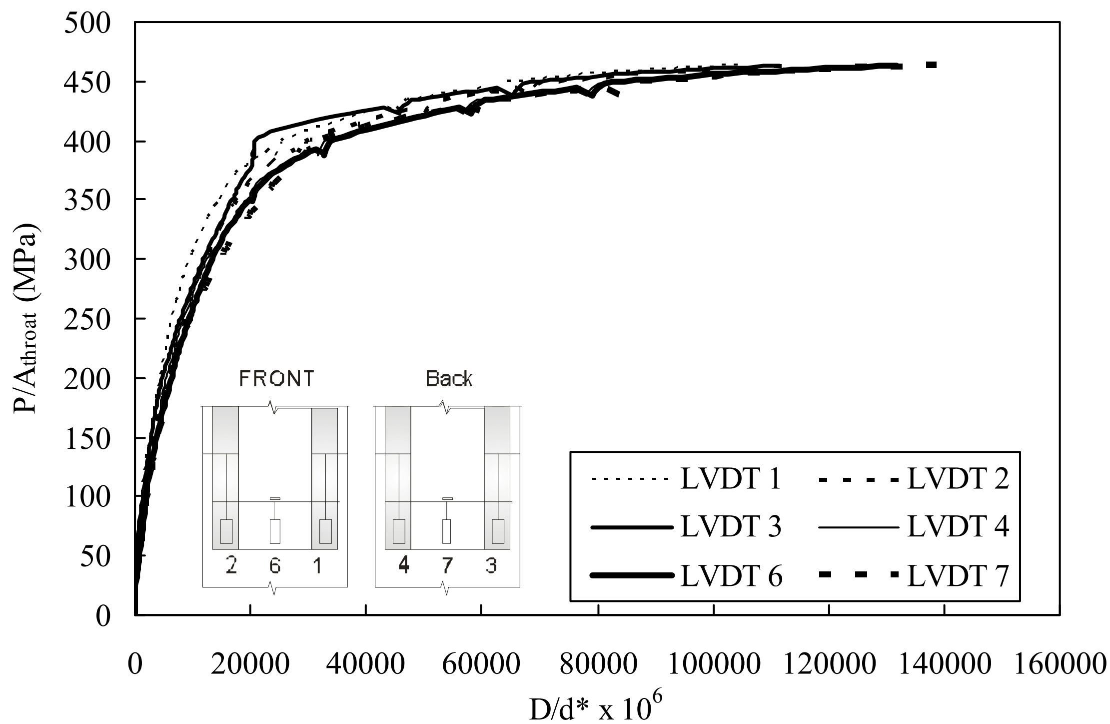


Figure G4 – Response Curve for Specimen L150–2

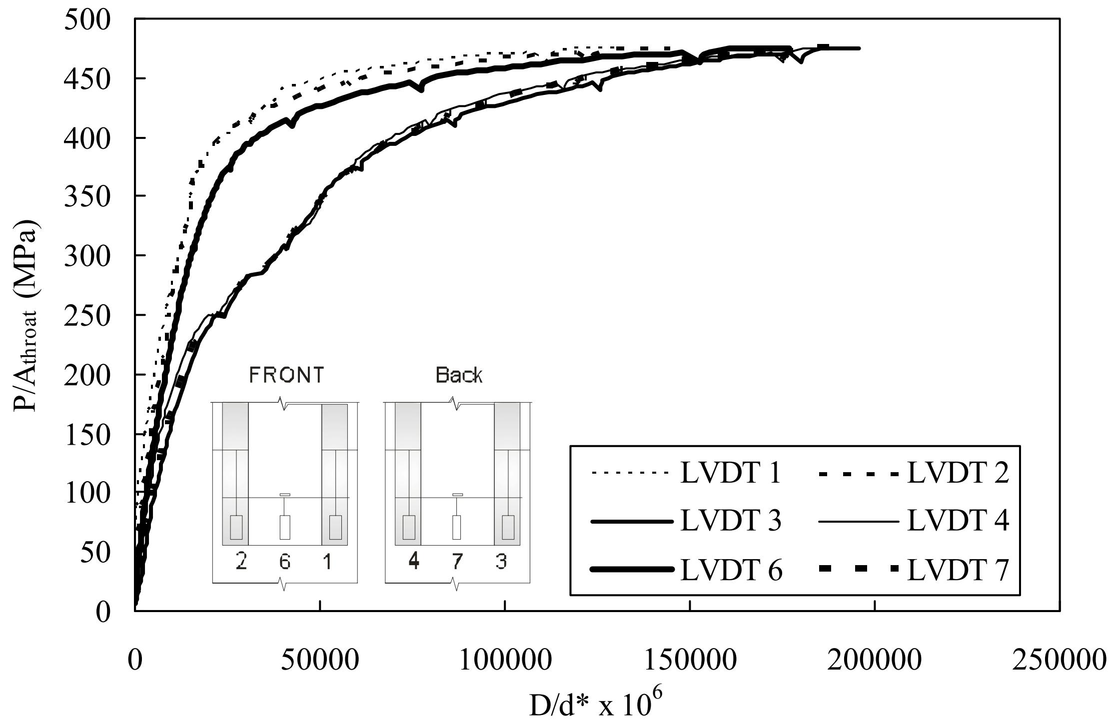


Figure G5 – Response Curve for Specimen L150–3

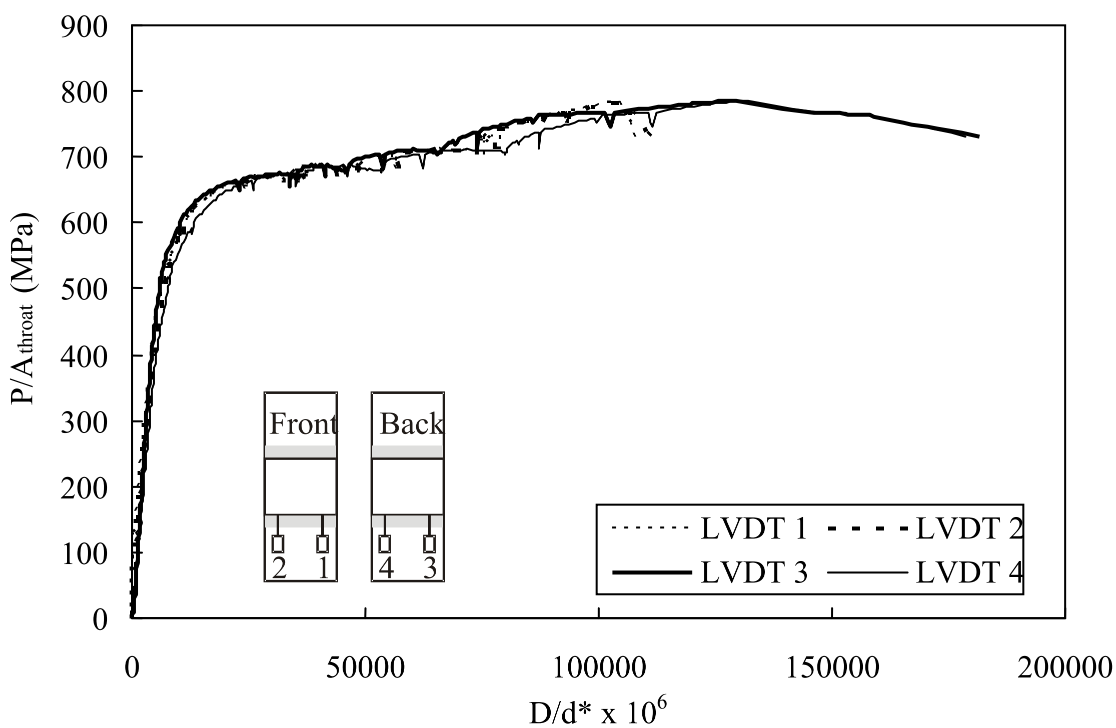


Figure G6 – Response Curve for Specimen TYa–1

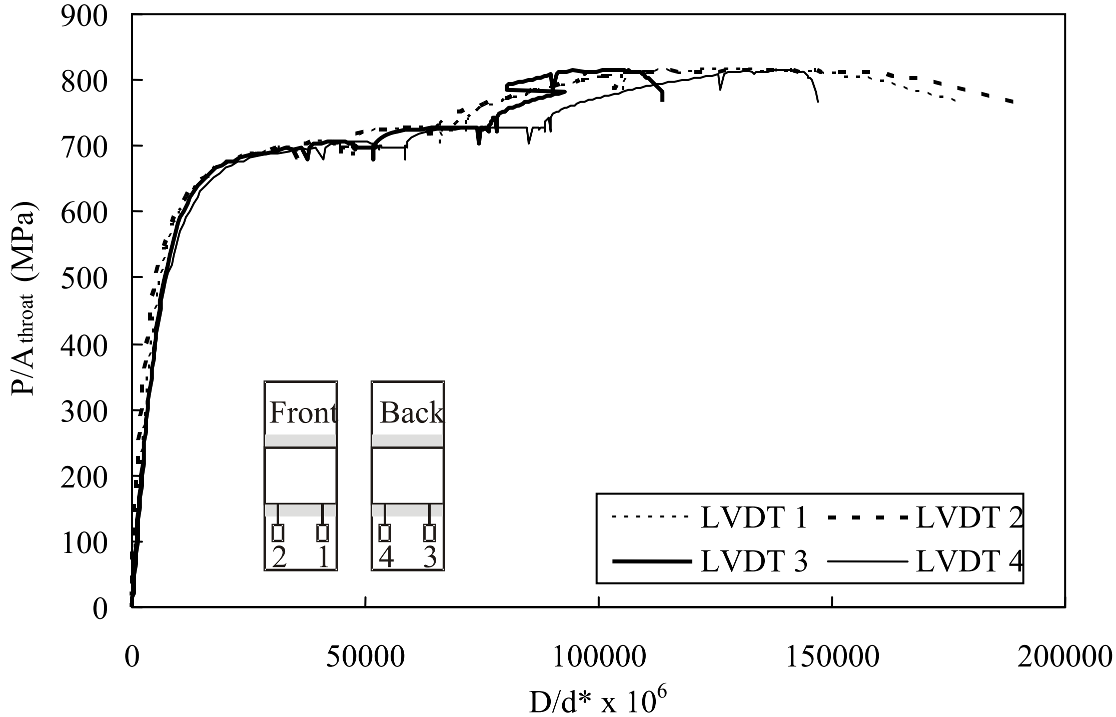


Figure G7 – Response Curve for Specimen TYa–2

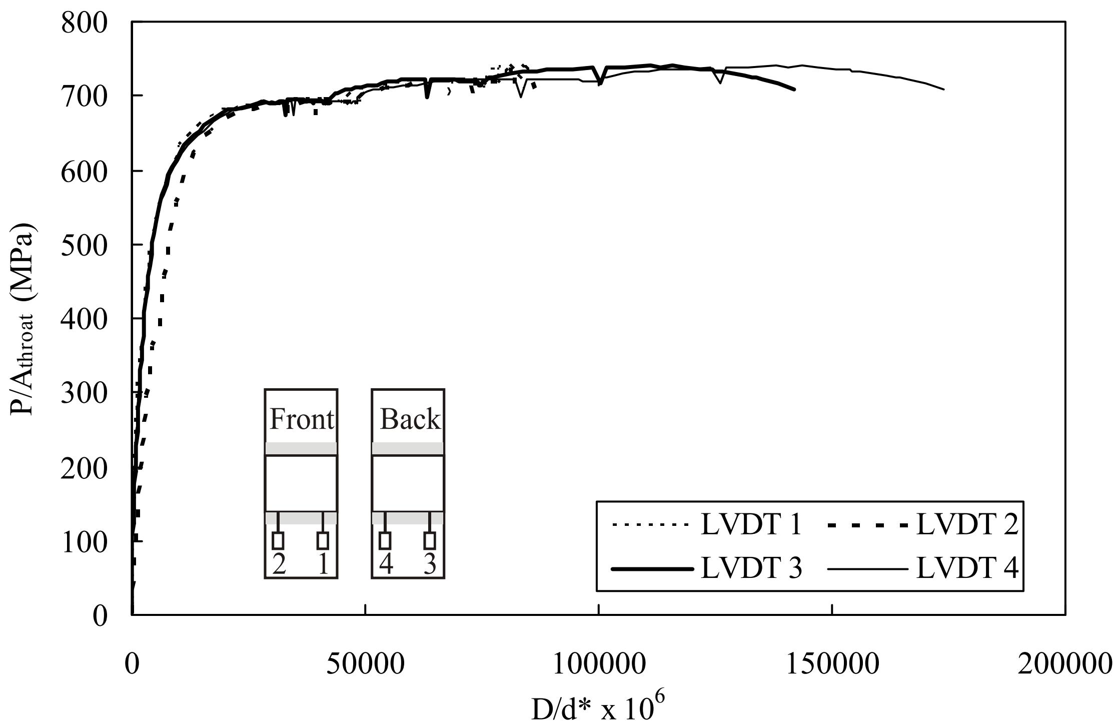


Figure G8 – Response Curve for Specimen TYa–3

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