Tensile and Fatigue Behavior of Punched Structural Steel Plates

by

David Jason Lubitz, B.C.E.

Thesis

Presented to the Faculty of the Graduate School of
The University of Texas at Austin
in Partial Fulfillment
of the Requirements
for the Degree of

Master of Science in Engineering

The University of Texas at Austin
May 2005

Tensile and Fatigue Behavior of Punched Structural Steel Plates

Approved by

Supervising Committee:

Karl H. Frank

Michael D. Engelhardt

For great family and friends

ACKNOWLEDGMENTS

This report is part of an ongoing research project entitled "Performance and Effects of Punched Holes and Cold Bending on Steel Bridge Fabrication," sponsored by the Texas Department of Transportation. The project is currently in progress at the Ferguson Structural Engineering Laboratory at The University of Texas at Austin as well as at Texas A&M University.

The author would like to express his appreciation to Dr. Karl H. Frank for the guidance and support he provided throughout the research and thesis writing processes. Gratitude is also extended to Dr. Michael D. Engelhardt for his editorial comments on and content suggestions for this thesis.

The author would also like to express his sincere appreciation to faculty, staff, and students at the Ferguson Structural Engineering Laboratory for their support.

David Jason Lubitz

Austin, Texas
May 2005

Tensile and Fatigue Behavior of Punched Structural Steel Plates

by

David Jason Lubitz, M.S.E.

The University of Texas at Austin, 2005

Supervisor: Karl H. Frank

The research work described in this report, “Tensile and Fatigue Behavior of Punched Structural Plates,” is part of a project entitled "Performance and Effects of Punched Holes and Cold Bending on Steel Bridge Fabrication,” sponsored by the Texas Department of Transportation. This research includes testing and analysis completed primarily at the Ferguson Structural Engineering Laboratory at The University of Texas at Austin.

This report discusses the method and ramifications of hole fabrication by punching in structural plate. Typically, punching is employed in the fabrication of structural elements related to connections, such as members, cross-frames, and gusset plates on bridges. AASHTO steel bridge specifications do not allow full size punched holes in primary load carrying members. Instead, holes are required to be formed by full-size drilling or reaming following punching.

In addition to literature review and analysis of previous research on the behavior and strength of connections with variables such as hole preparation, 120 plate specimens with punched, reamed, or drilled holes were tensile and fatigue tested during this study. Specimen variations included steel type, temperature, hole size, plate thickness, edge distance, edge preparation, punching clearance, punching operation, galvanizing, and amount of reaming. From this testing, net section stress, strength ratio, and usable elongation values at failure were determined for each specimen variation. While grade of steel, hole size, and plate thickness displayed some influence on strength ratio and usable elongation, edge distance, edge preparation, punching clearance, punching operation, galvanizing, and amount of reaming displayed little to no influence on strength ratio and usable elongation.

Overall, in strength performance, reamed specimens had the highest average strength ratio, followed by drilled and then punched specimens. In usable elongation performance, drilled and reamed specimens had the highest average elongation values, followed by punched specimens. Additionally, 41 replicate punched and drilled hole specimens were tensile tested to failure during this study in order to directly compare the performance of punched and drilled plate. Based on the strength performance of punched hole specimens, and particularly relative to drilled hole specimens, a capacity reduction factor is recommended for punched plate used in steel bridge connections.

TABLE OF CONTENTS

1. Introduction 1
   1.1 Background 1
   1.2 Objective and Scope 3
2. Background and Literature Review with Analysis 4
   2.1 The Punching Process and Ramifications of Punching 4
   2.2 Early Research 14
   2.3 University of Illinois at Urbana-Champaign Research 15
   2.4 Recent Research 21
   2.5 Use of Previous Research in Conjunction with Current Study 23
3. Experiment Design 24
   3.1 Plate Specimens 24
   3.2 Testing Matrices 24
      3.2.1 Steel Type and Temperature Investigation 25
      3.2.2 Hole Size and Plate Thickness Investigation 26
      3.2.3 Edge Distance and Preparation Investigation 28
      3.2.4 Punching Clearance Investigation 29
      3.2.5 Punching Operation Investigation 33
      3.2.6 Cold Tensile Testing Thickness Investigation 34
      3.2.7 Galvanizing Investigation 34
      3.2.8 Reaming Investigation 35
      3.2.9 Fatigue Investigation 36
4. Specimen Fabrication and Test Procedures 37
   4.1 Specimen Fabrication 37
      4.1.1 Drilled Plates 37
      4.1.2 Punched Plates 40

4.2 Galvanizing Procedure 46
4.3 Reaming Procedure 47
4.4 Testing Apparatus and Procedure 49
  4.4.1 Tensile Testing 49
    4.4.1.1 Room Temperature Tensile Testing 49
    4.4.1.2 Cold Temperature Tensile Testing 54
  4.4.2 Fatigue Testing 57
  4.4.3 Chemistry Analysis 61
  4.4.4 ASTM Coupon Testing 62
  4.4.5 Charpy V-Notch Testing 62
5. Test Results and Analysis 63
5.1 Chemistry Investigation 63
5.2 ASTM Coupon Testing 64
5.3 Charpy V-Notch Testing 66
5.4 Notes on Chemistry, Coupon, and Charpy Investigations 67
  5.4.1 Chemistry Considerations 67
  5.4.2 Influence of Coupon Tensile Strength Characteristics 68
  5.4.3 Influence of Notch Toughness Characteristics 68
5.5 Steel Type and Temperature Investigation 68
5.6 Room Temperature Tensile Observations 72
5.7 Hole Size and Plate Thickness Investigation 80
5.8 Edge Distance and Preparation Investigation 83
5.9 Punching Clearance Investigation 85
5.10 Punching Operation Investigation 87
5.11 Cold Tensile Testing Thickness Investigation 88
5.12 Galvanizing Investigation 89
5.13 Reaming Investigation 91

5.14 Fatigue Investigation 93
5.15 Summary of Tensile Test Results 96
5.16 Additional Considerations 107
6. Conclusions 108
Appendix 111
Bibliography 125
Vita 127

LIST OF FIGURES

Figure 2.1: Load versus Elongation and Effect of Strain Aging 7

Figure 2.2: Characteristics of Parent Material and Punched Hole (Brolund 2004) 8

Figure 2.3: Scheme of Three Different Zones around Hole after Punching (Sanchez 2002) 10

Figure 2.4: Punch Progression at Different Distances through Material (15/16 Inch Diameter Hole in 3/4 Inch Thickness Grade 50 Plate)................................. 10

Figure 2.5: Close-Up of Punch Progression (15/16 Inch Diameter Hole in 3/4 Inch Thickness Grade 50 Plate).. 11

Figure 2.6: Distribution of Hardness around a Punched Hole (Huhn 2004)......... 12

Figure 2.7: Stress-Strain Curves of Micro-Tensile Test Specimens (Huhn 2004) 13

Figure 2.8: Ductility of the Loaded (Stretched) Sheet with Orthogonal Grid (Gaylord 1972) 14

Figure 2.9: Typical Truss-Type Specimen Following Failure (Chesson and Munse, Behavior 1958) 16

Figure 2.10: Experimental versus Current Specification Limit States for Chesson and Munse Data... 20

Figure 2.11: Stress Range versus Number of Cycles for UC Data 22

Figure 3.1: Typical Plate Specimen Geometry 24

Figure 3.2: Deformation Due to Increasing Clearance (Brolund 2004)................ 32

Figure 3.3: Excessive Clearance and Unclean Fracture (Brolund 2004) 33

Figure 4.1: Typical Drilled Hole Preparation (with Slugger) 38

Figure 4.2: Close-Up of Drill, Bit, Slug, and Specimen during Preparation 38

Figure 4.3: Cross-Section of Typical Drilled Hole Specimen (15/16 Inch Diameter Hole in 3/4 Inch Thickness Grade 50 Plate)... 39

Figure 4.4: Close-Up of Cross-Section of Typical Drilled Hole Specimen (15/16 Inch Diameter Hole in 3/4 Inch Thickness Grade 50 Plate)................................39

Figure 4.5: Plate Inserted in Punch Press..40

Figure 4.6: Plate and Punched Holes Following Typical Specimen Preparation..41

Figure 4.7: Mechanical Punch Press at AIW 42

Figure 4.8: Cross-Section of Typical Punched Hole Specimen (15/16 Inch Diameter Hole in 3/4 Inch Thickness Grade 50 Plate)...43

Figure 4.9: Close-Up of Cross-Section of Typical Punched Hole Specimen (15/16 Inch Diameter Hole in 3/4 Inch Thickness Grade 50 Plate)................................44

Figure 4.10: Typical 15/16 Inch Diameter, 1/2 Inch Thickness and 15/16 Inch Diameter, 3/4 Inch Thickness Punched Holes (Grade 50) 45

Figure 4.11: AIW Typical 15/16 Inch Diameter, 1/2 Inch Thickness and 15/16 Inch Diameter, 3/4 Inch Thickness Punched Holes (Grade 50) 46

Figure 4.12: High Speed Radial Drill and Reamer 48

Figure 4.13: Reamer Bit and Finished Hole in Specimen...................................48

Figure 4.14: Close-Up of Reamer Bit and Hole in Specimen..............................49

Figure 4.15: 600-Kip UTS Used for Tensile Testing...51

Figure 4.16: Test Specimen in Grips of 600-Kip UTS 52

Figure 4.17: PDAQ System Used for Tensile Testing...53

Figure 4.18: Linear Potentiometer Used for Tensile Testing...............................53

Figure 4.19: Interior of Freezer Storing Cold Plates..55

Figure 4.20: Temperature Chamber Surrounding Specimen in 600-Kip UTS 56

Figure 4.21: Open Temperature Chamber Prior to Tensile Test..........................57

Figure 4.22: Profile of 220-Kip MTS Used for Fatigue Testing..........................58

Figure 4.23: Typical Specimen in Grips of 220-Kip MTS 59

Figure 4.24: Control System Used for Fatigue Testing 60

Figure 5.1: Load versus Displacement Comparison of Similar Punched and Drilled Hole Specimens 72

Figure 5.2: Punched Hole Specimen Yielding and Initial Fracture 74

Figure 5.3: Punched Hole Specimen Progression of Fracture 75

Figure 5.4: Fractured Punched Hole and Drilled Hole Specimens 76

Figure 5.5: Typical Punched and Drilled Hole Fracture Cross-Sections (3/4 Inch Thickness, 15/16 Inch Diameter Hole, Grade 50).. 78

Figure 5.6: Typical Punched and Drilled Hole Fracture Cross-Sections (3/8 Inch Thickness, 15/16 Inch Diameter Hole, Grade 50).. 79

Figure 5.7: Close-Up of Typical Punched and Drilled Hole Fracture Cross-Sections (3/8 Inch Thickness, 15/16 Inch Diameter Hole, Grade 50)................... 80

Figure 5.8: Typical Failure of Galvanized Specimen... 91

Figure 5.9: Punched and Drilled Fatigue Specimen... 93

Figure 5.10: Typical Failed Fatigue Specimen 94

Figure 5.11: Profile Close-Up of Fatigue Crack 95

Figure 5.12: Close-Up of Fatigue Crack Fracture Surface................................... 96

Figure 5.13: Experimental versus Specification Strength Limit State Summary of Tensile Tests.. 100

Figure 5.14: Punched versus Drilled and Reamed Holes Usable Elongation Histogram 102

Figure 5.15: Punched Strength Ratio/Drilled Strength Ratio Histogram............ 104

Figure 5.16: Punched/Drilled Holes Usable Elongation Histogram 105

Figure A.1: Energy versus Temperature for 3/8 Inch Grade 36 Plate................. 116

Figure A.2: Energy versus Temperature for 1/2 Inch Grade 36 Plate................. 117

Figure A.3: Energy versus Temperature for 3/4 Inch Grade 36 Plate................. 118

Figure A.4: Energy versus Temperature for 1/2 Inch Grade 36 (Sheared) Plate 119

Figure A.5: Energy versus Temperature for 3/8 Inch Grade 50 Plate................. 120

Figure A.6: Energy versus Temperature for 1/2 Inch Grade 50 Plate................ 121
Figure A.7: Energy versus Temperature for 3/4 Inch Grade 50 Plate................ 122
Figure A.8: Energy versus Temperature for 1/2 Inch Grade 50 (Sheared) Plate 123
Figure A.9: Energy versus Temperature for 1/2 Inch Grade 55 Plate................ 124

LIST OF TABLES

Table 2.1: Tons Force Required to Punch Typical Grade 36 Steel........................5
Table 2.2: Multiplier Chart for Tons Force Required to Punch.............................6
Table 3.1: Steel Type and Temperature Test Matrix...25
Table 3.2: Hole Size and Plate Thickness Test Matrixes....................................27
Table 3.3: Edge Distance and Preparation Test Matrix (with 15/16 Inch Diameter Holes)..28
Table 3.4: Punching Clearance Test Matrix (1/2 Inch Thickness Plate)..............30
Table 3.5: Die Clearance based on Material Thickness......................................30
Table 3.6: Die Clearance Used for Standard Holes..31
Table 3.7: Punching Operation Test Matrix (15/16 Inch Diameter Holes)..........34
Table 3.8: Cold Tensile Test Thickness Matrix..34
Table 3.9: Galvanizing Test Matrix..35
Table 3.10: Reaming Test Matrix...36
Table 5.1: Results of Chemistry Investigation..63
Table 5.2: Results of ASTM Coupon Tests..65
Table 5.3: Results of ASTM Cold Coupon Tests..66
Table 5.4: Results of Charpy Testing...66
Table 5.5: Steel Type and Temperature Investigation Results (Grade 36, 1/2 Inch Thickness, 15/16 Inch Diameter Hole Size)..69
Table 5.6: Steel Type and Temperature Investigation Results (Grade 50, 1/2 Inch Thickness, 15/16 Inch Diameter Hole Size)..70
Table 5.7: Steel Type and Temperature Investigation Results (Grade 55, 1/2 Inch Thickness, 15/16 Inch Diameter Hole Size)..70
Table 5.8: Steel Type and Temperature Investigation Results Summary (1/2 Inch Thickness, 15/16 Inch Diameter Hole)..71

Table 5.9: Hole Size and Plate Thickness Investigation Results (Grade 36) 81
Table 5.10: Hole Size and Plate Thickness Investigation Results (Grade 50) 81
Table 5.11: Plate Thickness Investigation Summary (11/16, 13/16, and 15/16 Inch Diameter Holes) 82
Table 5.12: Edge Distance and Preparation Investigation Results (Grade 36, 1/2 Inch Thickness, 15/16 Inch Diameter Hole Size) 83
Table 5.13: Edge Distance and Preparation Investigation Results (Grade 50, 1/2 Inch Thickness, 15/16 Inch Diameter Hole Size) 84
Table 5.14: Punching Clearance Investigation Results (Grade 36, 1/2 Inch Thickness) 86
Table 5.15: Punching Clearance Investigation Results (Grade 50, 1/2 Inch Thickness) 86
Table 5.16: Punching Clearance Investigation Summary (1/2 Inch Thickness) ... 86
Table 5.17: Punching Operation Investigation Results (Grade 50, 15/16 Inch Diameter Hole Size) 87
Table 5.18: Punching Operation Investigation Summary (15/16 Inch Diameter Hole, Grade 50) 88
Table 5.19: Cold Tensile Testing Thickness Investigation Results (Grade 36, 15/16 Inch Diameter Hole Size) 88
Table 5.20: Cold Tensile Testing Thickness Investigation Results (Grade 50, 15/16 Inch Diameter Hole Size) 89
Table 5.21: Galvanizing Investigation Results (Grade 36, 3/8 Inch Thickness, 13/16 Inch Diameter Hole Size) 90
Table 5.22: Galvanizing Investigation Results (Grade 50, 3/8 Inch Thickness, 13/16 Inch Diameter Hole Size) 90
Table 5.23: Reaming Investigation Results (Grade 36, 1/2 Inch Thickness, 15/16 Inch Diameter Hole Size) 92

Table 5.24: Reaming Investigation Results (Grade 50, 1/2 Inch Thickness, 15/16 Inch Diameter Hole Size) 92
Table 5.25: Average Strength Ratio and Standard Deviation by Preparation..... 101
Table 5.26: Average Usable Elongation and Standard Deviation by Preparation Type........ 103
Table 5.27: Strength Ratio and Usable Elongation Statistics for Replicate Specimens........ 105
Table A.1: Current Limit States for UIUC Specimen SA........ 112
Table A.2: Current Limit States for UIUC Specimen SB 113
Table A.3: Current Limit States for UIUC Specimen SD........ 114
Table A.4: Current Limit States for UIUC Specimen SE 115

1. INTRODUCTION

A research project entitled "Performance and Effects of Punched Holes and Cold Bending on Steel Bridge Fabrication," sponsored by the Texas Department of Transportation (TxDOT), is currently in progress at The University of Texas at Austin (UT) and Texas A&M University (TAMU). This project includes, but is not limited to, the research work described herein entitled "Tensile and Fatigue Behavior of Punched Structural Plates." This research includes testing and analysis completed primarily at the Ferguson Structural Engineering Laboratory (FSEL).

1.1 BACKGROUND

Punching is a quick, economical, and versatile method utilized in the fabrication of metal. Punching processes may be directly applied to the fabrication of structural steel intended for use in bridges, buildings, and a variety of other assemblies for civil use. Typically, punching is employed in the fabrication of structural elements related to connections, such as members, cross-frames, and gusset plates on bridges.

The American Association of Transportation Officials (AASHTO) steel bridge specifications do not allow full size punched holes in primary load carrying members. The specifications state that holes in these members may be punched and then reamed full size (in order to remove the damaged zone immediately surrounding the hole) or drilled. In members in which punching is currently allowed, AASHTO limits the maximum thickness of punched material to 3/4 inch for grade 36, 5/8 inch for grade 50, and 1/2 inch for grade 70 (AASHTO Construction 11-15). Interestingly enough, no distinction is made between punched and drilled holes in the building specification. This is most likely because structural building elements, relative to structural bridge elements, have fewer fatigue and fracture-critical issues due to less cyclic loading and exposure to varying environmental conditions.

Fabricators generally use punching for connection-related bridge elements that have a small number of holes. Since many fabricators' current practices are to use computer numeric controlled (CNC) drilling for splice plates, this generally leaves gusset plates, connection angles, webs, and any other remaining secondary elements as candidates for punching. Based on recent specification modifications, some areas of possible concern now include the punching of thick gusset plates, as well as the punching of elements such as cross-frames and diaphragms in curved plate structures. Cross-frames and diaphragms are now considered primary members; therefore, if there is any bolting of these elements such as connecting angles to plate diaphragms, punching to full size is prohibited (AASHTO Design 2004).

AASHTO Construction specifications require that punched holes must be sub-punched and reamed to the required diameter when used in members carrying calculated load forces. Holes are required to be sub-punched at least 3/16 inch smaller than the nominal size of the fastener and then reamed to full size (AASHTO Construction 2004). The purpose of reaming is to remove the plastically strained material surrounding the hole and any micro-cracks formed during the punching operation. Nevertheless, the practice of adding a 1/16 inch damage zone to all prepared holes, punched or drilled, is used in all structural steel specifications in the United States.

Since the current specifications only provide general guidelines pertaining to the exclusion and thickness limitations of the punching process, this research investigates the effects of many parameters on punched hole specimens and the punching process while providing a comparison to drilled and reamed holes. The variations imposed on punched hole specimens in this study include a range of steel types, temperatures, hole sizes, plate thicknesses, edge distances and preparation, punch clearance and operation, galvanizing, and reaming. Through tensile and fatigue testing and analysis, this research explores the possible use of punched holes with a reduced connection capacity.

1.2 OBJECTIVE AND SCOPE

As noted in the Background section, the goal of this research work is to determine the influence of punched holes upon the tensile and fatigue capacity of steel connections. In order to do this, a total of 120 punched, drilled, and reamed hole specimens have been tested in tension and fatigue and analyzed at the FSEL. Based on the results of this study, possible modified specification provisions, including guidelines and limits based on material, geometric, and punching variations, for members with punched holes have been recommended.

2. BACKGROUND AND LITERATURE REVIEW WITH ANALYSIS

2.1 THE PUNCHING PROCESS AND RAMIFICATIONS OF PUNCHING

Punching is a rapid method of making holes for bolted connections in steel structures and is done using a punch and an oversize female die in either a hydraulic or mechanical press. Hole punching equipment is often utilized in manufacturing lines which combine two or more processes (e.g. punching and shearing) for efficient fabrication. Many times, punching processes are used to rapidly, and even automatically, produce smaller angle members for cross frames and bracing members.

In the punching process, a hole is produced by shearing the parent material. As shown in Tables 2.1 and 2.2, the force required to punch a hole increases with the thickness of the material, diameter of the hole, and the strength of the steel (Brolund 2004).

Table 2.1: Tons Force Required to Punch Typical Grade 36 Steel

Tons Force Required to Punch ASTM-A36 Structural Steel (60,000 psi Tensile Strength)													
	Material Thickness (in.)												
Hole Dia. (in.)	**1/16 .063**	**1/8 .125**	**3/16 .187**	**1/14 .250**	**5/16 .312**	**3/8 .375**	**1/2 .500**	**5/8 .625**	**3/4 .750**	**7/8 .875**	**1 1.000**	**1-1/8 1.125**	**1-1/4 1.250**
1/4	1.4	3.0	4.4	5.9	7.3	8.8	-	-	-	-	-	-	-
5/16	1.8	3.7	5.5	7.4	9.2	11.0	-	-	-	-	-	-	-
3/8	2.1	4.4	6.6	8.8	11.0	13.3	17.7	-	-	-	-	-	-
7/16	2.5	5.2	7.7	10.3	12.9	15.5	20.6	-	-	-	-	-	-
1/2	2.8	5.9	8.8	11.8	14.7	17.7	23.6	29.5	-	-	-	-	-
9/16	3.2	6.7	9.9	13.2	16.5	19.9	26.5	33.1	-	-	-	-	-
5/8	3.5	7.4	11.0	14.7	18.4	22.1	29.4	37.0	44.2	-	-	-	-
11/16	3.9	8.1	12.1	16.2	20.2	24.3	32.4	40.5	48.6	-	-	-	-
3/4	4.2	8.9	13.2	17.7	22.1	26.5	35.3	44.2	53.0	62.0	-	-	-
13/16	4.6	9.6	14.3	19.1	24.0	28.7	38.3	48.0	57.4	67.0	76.6	-	-
7/8	4.9	10.3	15.4	20.6	25.7	31.0	41.0	51.5	62.0	72.2	82.5	-	-
15/16	5.3	11.1	16.5	22.1	27.6	33.1	44.2	55.2	66.3	77.3	88.3	99.4	-
1	5.6	11.8	17.6	23.6	29.4	35.3	47.1	59.0	70.7	82.5	94.3	106.0	-
1-1/16	6.0	12.5	18.7	25.0	31.3	37.6	50.0	62.6	75.0	87.7	100.0	113.0	125.2
1-1/8	6.3	13.3	19.8	26.5	33.0	39.7	52.9	66.2	79.4	92.7	106.0	119.0	132.5
1-3/16	6.7	14.0	20.9	28.0	34.9	42.0	55.9	69.9	83.9	97.9	111.9	125.9	139.9
1-1/4	7.1	14.7	22.0	29.5	36.8	44.2	58.9	73.7	88.4	103.2	117.9	132.6	147.3
1-5/16	7.4	15.5	23.1	30.9	38.6	46.3	61.8	77.2	92.7	108.1	123.6	139.0	154.6
1-3/8	7.8	16.2	24.2	32.4	40.4	48.6	64.8	81.0	97.2	113.4	129.6	145.8	162.0
1-1/2	8.5	17.7	26.4	35.3	44.1	53.0	70.6	88.3	106.0	123.6	141.3	159.0	176.7
1-3/4	9.9	20.6	30.9	41.2	51.5	61.9	82.5	103.1	123.7	144.3	164.9	185.6	206.2
2	11.3	23.6	35.3	47.1	58.8	70.7	94.3	117.8	141.4	164.9	188.5	212.1	235.6
2-1/4	12.7	26.5	39.7	53.0	66.2	79.5	106.0	132.5	159.0	185.6	212.1	238.6	-
2-1/2	14.2	29.5	44.1	58.9	73.5	88.4	117.8	147.3	-	-	-	-	-
2-3/4	15.6	32.4	48.5	64.8	80.9	97.2	129.6	-	-	-	-	-	-
3	17.0	35.4	52.9	70.7	88.2	106.0	141.4	-	-	-	-	-	-

Table 2.2: Multiplier Chart for Tons Force Required to Punch

Multiplier Chart for Materials Other Than A-36 Structural Steel		
Type of Material	**Tensile Strength (psi)**	**Chart Multiplier**
Aluminum, 1/2 Hard Sheet	19,000	0.32
Copper, Rolled	28,000	0.47
Mild Steel - H.R. Plate 1020	50,000	0.83
Boiler Plate	55,000	0.92
Structural Cor - Ten (ASTM -A242)	66,000	1.10
Structural A572-GR50	70,000	1.17
Steel, 50 Carbon HP Plate	70,000	1.17
Steel, Stainless 302, 304, 316	70,000	1.17
Structural T-1	90,000	1.50

As a general rule, the minimum hole size that may be punched is equal to the material thickness, otherwise the material may compress and/or the surrounding material may be excessively damaged. This limit reduces the range of punch hole sizes that can be used in typical structural connections. For example, standard 15/16 inch holes for 7/8 inch bolts may only be punched in material that is 15/16 inch or less in thickness. For this reason, hole punching is generally only performed on thinner secondary members in bridges.

When compared to drilling, the punching process has a noticeable effect on both the punched hole and parent material. The effects of punching may easily be seen at the macroscopic level as shown in the figures in this section and in following sections of this report. At the microscopic level, strain aging of steel may play a role in the difference between the performance of punched and drilled holes in tension and fatigue.

Particularly, material adjacent to a punched hole may be susceptible to the effects of strain aging. Baird classifies strain aging as a term used to cover a wide variety of effects in which some aging process takes place during or after plastic strain. A load versus elongation curve for a typical steel specimen, analogous to its stress versus strain curve, is shown in Figure 2.1. If a specimen is loaded to point B and then unloaded, a permanent elongation of OD will remain. If the specimen is then immediately reloaded, it will follow curve DBC, which is the normal curve. If instead the reloading is delayed and the specimen remains at room temperature or higher (typically aging is negligible below room temperature and above 212° F), reloading will result in the specimen following curve DBEF (Baird 1963). In this case the specimen is said to have been strain aged, resulting in a higher ultimate tensile strength and decreased ductility.

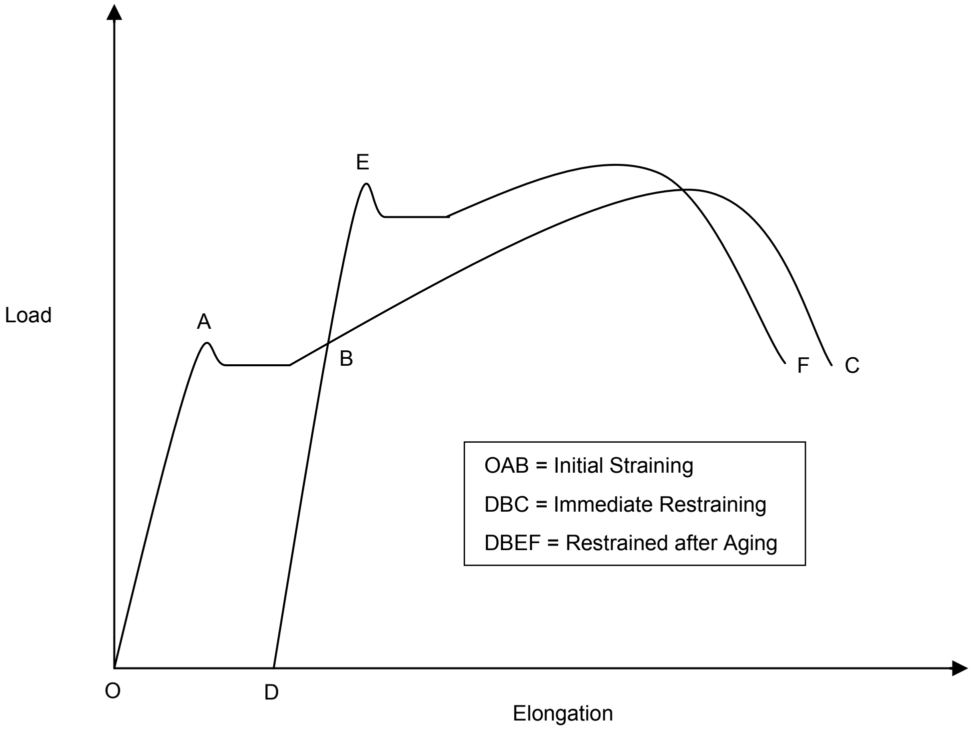

Figure 2.1: Load versus Elongation and Effect of Strain Aging

Hume-Rothery (1954) notes that the cause of strain aging and accompanying increase in strength and decrease in ductility is the desegregation of interstitial carbon and nitrogen solute atoms from the iron crystal lattice within the material. Normally, the carbon and nitrogen solute atoms occupy the interstitial sites in the body-center-cubic iron crystal lattice and create "misfit stresses" in the strain fields of dislocations. When these interstitial atoms are relocated to the core regions of dislocations by heat or stress (e.g. localized punching), the "misfit energy" is lowered, thus causing an increase in hardness and strength and a decrease in ductility.

These material response characteristics play an important role in the aftereffects of the punching process. Brolund (2004) states that since punching material relies on shear cutting action, the process produces four inherent characteristics found on both the surface of the punched hole and the adjacent parent material as illustrated in Figure 2.2.

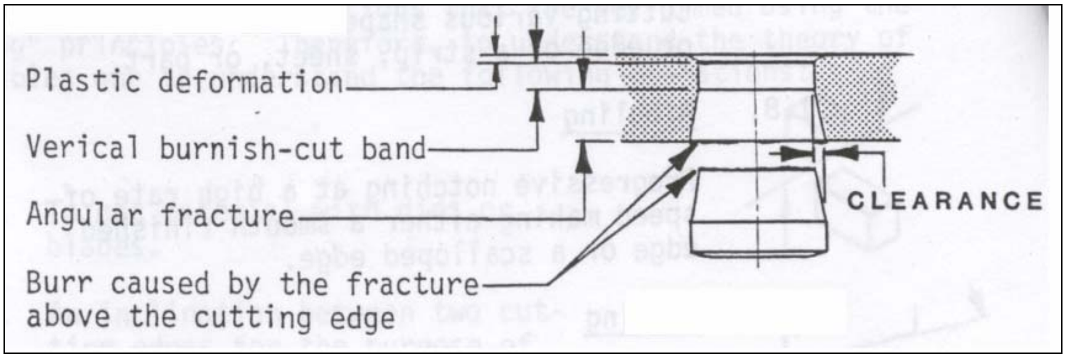

Figure 2.2: Characteristics of Parent Material and Punched Hole (Brolund 2004)

The severity of the characteristics illustrated in Figure 2.2 depends on many variables including, but not limited to, the:

- Thickness of the material

- Type and hardness of the material
- Amount of clearance between the cutting edges
- Condition of the cutting edges
- Support or firmness of material on both sides of the cut
- Diameter of hole in relation to material thickness

Generally, three different zones around the hole are developed during the punching process as illustrated in Figure 2.3. As shown, zone 1 is at the top of the parent material and characterized by low roughness due to shear by contact with the punch. Zone 2, in the middle of the parent material, is characterized by greater surface damage and plasticity from the tearing of the material. Lastly, zone 3 is at the bottom of the parent material and is characterized by low roughness due to shear by contact with the die (Gutierrez-Solana, Pesquera, and Sanchez 2004). These zones of damage are shown on the sample punching progression specimens in Figures 2.4 and 2.5 generated at the FSEL.

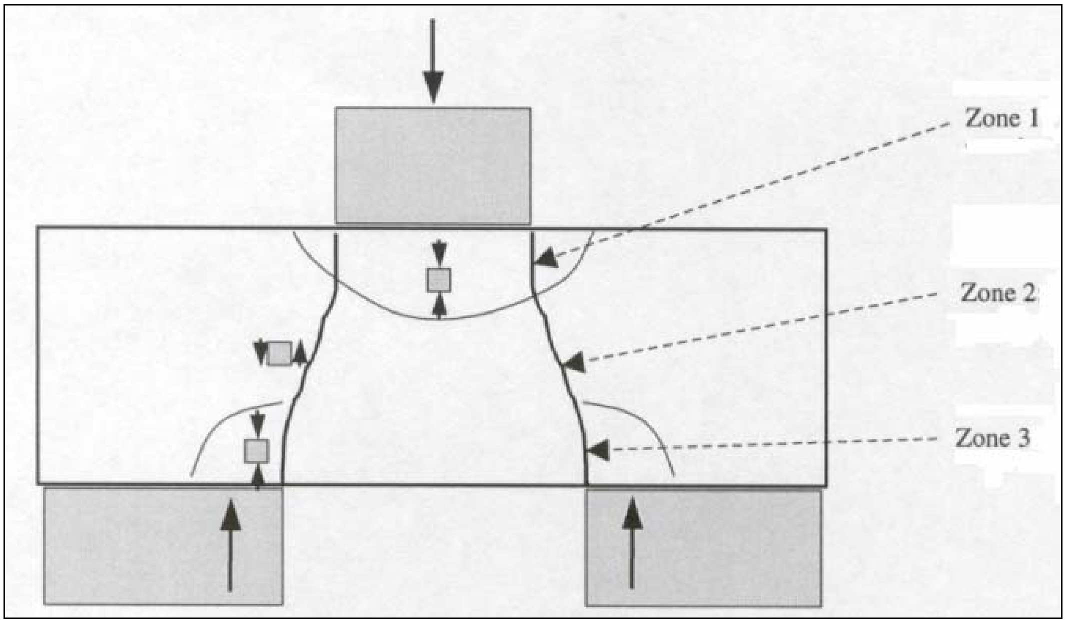

Figure 2.3: Scheme of Three Different Zones around Hole after Punching (Sanchez 2002)

Figure 2.4: Punch Progression at Different Distances through Material (15/16 Inch Diameter Hole in 3/4 Inch Thickness Grade 50 Plate)

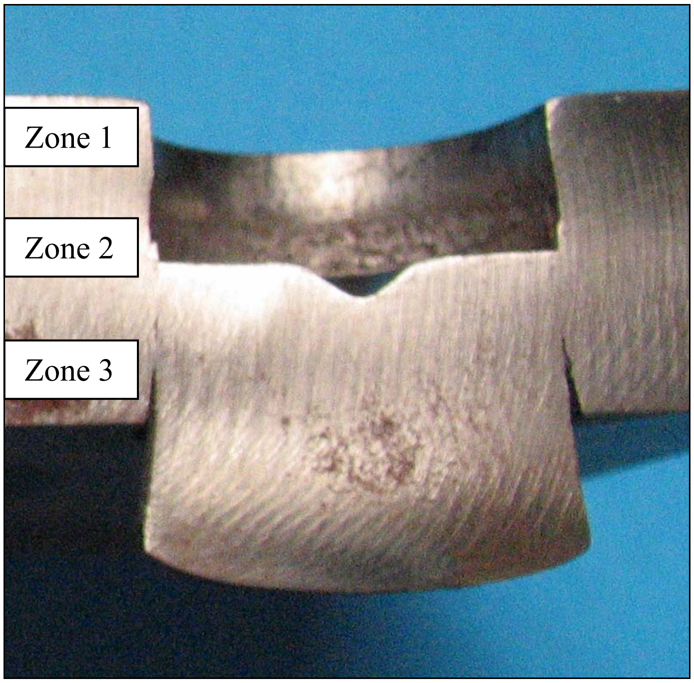

Figure 2.5: Close-Up of Punch Progression (15/16 Inch Diameter Hole in 3/4 Inch Thickness Grade 50 Plate)

Huhn and Valtinat (2004) suggest that the cold-work hardening of the area around a punched hole causes reductions in strength and elongation performance. In their research, Huhn and Valtinat studied parent material hardness in this area around a punched hole as shown in Figure 2.6. As anticipated, the parent material closest to the hole edge had the highest hardness values. Specifically, the greatest amount of work hardening occurred at the zone 2 region where plastic tearing of the material takes place during punching.

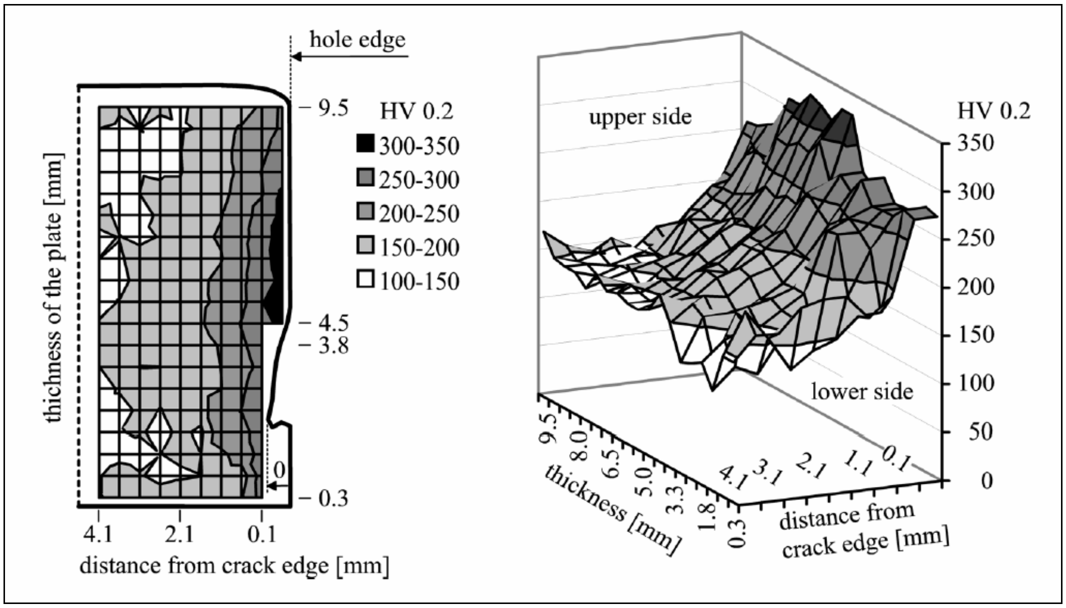

Figure 2.6: Distribution of Hardness around a Punched Hole (Huhn 2004)

Huhn and Valtinat (2004) also studied the strength and elongation performance of micro-tensile test specimens of parent material around a punched hole. Figure 2.7 shows the stress-strain behavior of five specimens at varying distances “x” from the edge of a hole. As one moves toward the edge of a hole, the tensile strength of the material increases and the elongation at fracture decreases rapidly. This loss of ductility was attributed to cold-working and strain aging of the material.

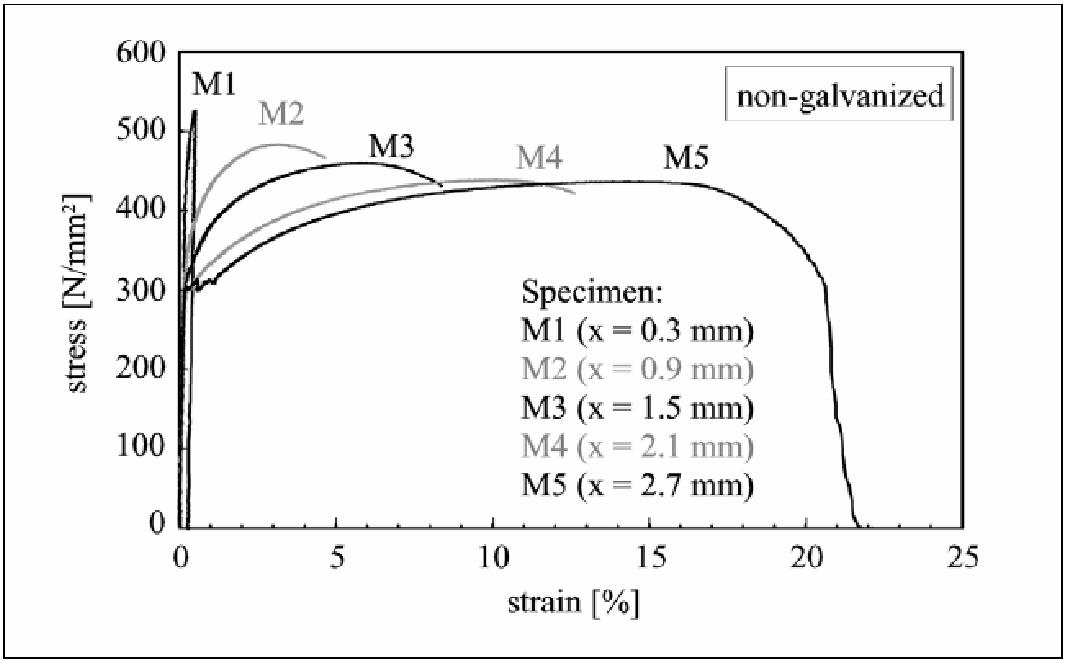

Figure 2.7: Stress-Strain Curves of Micro-Tensile Test Specimens (Huhn 2004)

Gaylord (1972) notes that strains at the edge of a hole are much larger than those located at a distance from a hole, but stress concentrations (K) at holes are usually neglected in structural design. In the case of a tension-only loaded plate with a hole located in the middle of the section:

$$K = \frac{\sigma_{\max}}{\sigma_{applied}} = 3 \tag{5.1}$$

This stress concentration is usually ignored because stress is redistributed by yielding adjacent to the hole. This ductility is shown in Figure 2.8, an illustration of the unloaded and loaded (or stretched) states of a sheet with an orthogonal grid. Note that following hole punching, the hardened material adjacent to a punched hole limits the redistribution of stress, resulting in lower strength and ductility.

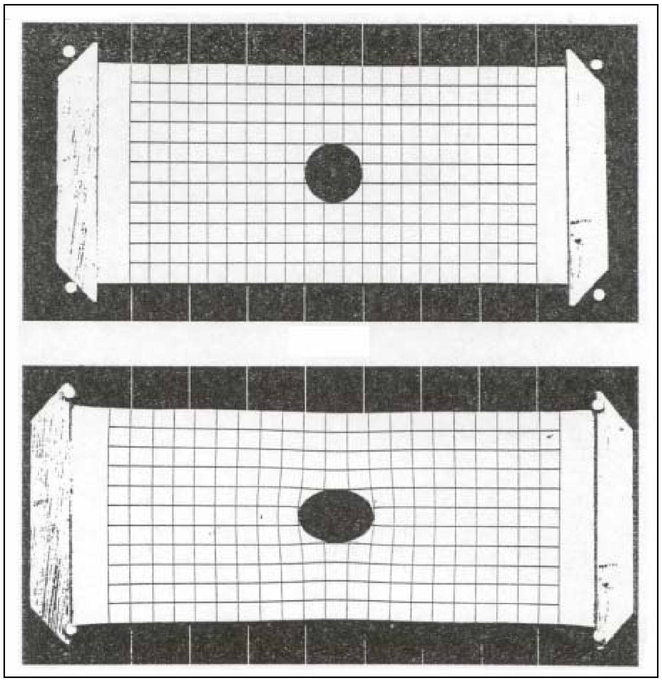

Figure 2.8: Ductility of the Loaded (Stretched) Sheet with Orthogonal Grid (Gaylord 1972)

2.2 EARLY RESEARCH

Some of the earliest published research pertaining to the effects of punching holes in structural metals focused on riveting in the construction of boilers, bridges, and ships during the mid- to late-19th century in Europe. As a result of early fractures from punched holes in ships and boilers, engineers sought to devise rules for the punching, or subpunching and subsequent reaming, of holes in iron and steel plate. Researchers found that although punching holes in plates is an economically cheaper option relative to drilling holes, the punching process caused plastic deformation and micro-cracking in the punched material (de Jong 1945). Research work explored strain aging and embrittlement of punched material during fabrication and service as well as ramifications of this material damage.

Most of this research only explored the effects of hole-making methods on material strength and, qualitatively, on material ductility. Test results comparing punching, punching followed by reaming, and drilling holes varied, but generally showed that punching reduced the strength of plates or connections by 5 to 10 percent relative to drilling (de Jong 1945). Since there was a limited amount of quantitative results available by the beginning of the 20th century, theoretical and experimental research on the punching of holes then expanded throughout Europe, Japan, and the United States.

2.3 UNIVERSITY OF ILLINOIS AT URBANA-CHAMPAIGN RESEARCH

In the 1940s, 1950s, and 1960s, researchers at the University of Illinois at Urbana-Champaign (UIUC) extensively investigated the behavior of structural steel connections. In this time period, at least one hundred and fifty full-size steel connections were tested and over nine hundred previous connection tests completed at other facilities were analyzed. UIUC researchers explored a wide range of variables, from fastener pattern and specimen configuration to plate characteristics, while testing double-strap butt-type and other large truss-type riveted and bolted connections (see Figure 2.9). Following testing and analysis, the method of forming holes was found to be one of the most significant variables affecting joint efficiency in their study.

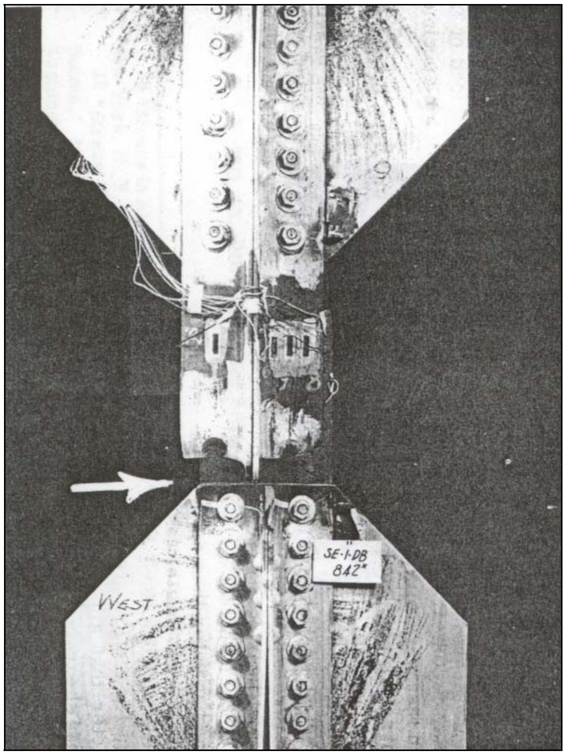

Figure 2.9: Typical Truss-Type Specimen Following Failure (Chesson and Munse, Behavior 1958)

UIUC tests and analysis provided information on the general behavior and ultimate strength of connections and allowed researchers to offer design recommendations for variables such as hole preparation in connections. Chesson and Munse found that tension members with punched holes commonly had a tensile strength that was 10 to 15 percent less than members with drilled holes (Chesson and Munse, Behavior 1958). Schutz similarly reported a 13 to 14 percent value tensile strength difference in his work. In addition, punched specimens generally had smaller deformations than drilled members of the same proportion. Chesson and Munse concluded that punching reduced the net section ductility and produced a depression and a lip at the hole that acted as a shear key to impede deformation relative to drilling. This lower ductility caused the ultimate stress to be reached early near the holes; thus, stress in the more distant material could not be as effectively developed relative to drilled plates (Chesson and Munse, Truss 1963).

Out of the many specimens that were tested and analyzed at the UIUC, twenty have been re-analyzed using current AASHTO Load Resistance Factor Design (LRFD) Bridge Design Specifications. These ten pairs of specimens were all large truss-type connections that were replicates with either punched or drilled holes. Note that all reduction and resistance factors were taken as 1.0 since only the method of hole preparation was being compared. The following current AASHTO LRFD Bridge Design Specifications sections were utilized in analyzing these specimens:

- 6.8.2 Tensile Resistance

$$P_r = \phi_y P_{ny} = \phi_y F_y A_g \tag{2.1}$$

$$P_r = \phi_u P_{nu} = \phi_u F_u A_n U \tag{2.2}$$

where P_{ny} = nominal tensile resistance for yielding in gross section

F_y = yield strength

A_g = gross cross-sectional area of the member

P_{nu} = nominal tensile resistance for fracture in net section

F_u = tensile strength

A_n = net area of the member as specified in Section 6.8.3

U = reduction factor to account for shear lag (taken as 1.0 in this comparison of results)

ϕ_y = resistance factor for yielding of tension members (taken as 1.0 in this comparison of results)

ϕ_u = resistance factor for fracture of tension members (taken as 1.0 in this comparison of results)

- 6.8.3 Net Area

  Net area, A_n, of a member is the sum of the products of thickness and the smallest net width of each element. The width of each standard bolt hole shall be taken as the nominal diameter of the hole plus 1/16 inch.

  The net width for each chain shall be determined by subtracting from the width of the element the sum of the widths of all holes in the chain and adding the quantity $s^2/4g$ for each space between consecutive holes in the chain, where:

  s = pitch of any two consecutive holes
  g = gage of the same two holes

- 6.13.4 Block Shear Rupture Resistance

  If $A_{tn} \geq 0.58\ A_{vn}$, then:

  $$R_r = \phi_{bs}\left(0.58 F_y A_{vg} + F_u A_{tn}\right) \quad (2.3)$$

  otherwise:

  $$R_r = \phi_{bs}\left(0.58 F_u A_{vn} + F_y A_{tg}\right) \quad (2.4)$$

  where A_{vg} = gross area along the plane resisting shear stress
  A_{vn} = net area along the plane resisting shear stress
  A_{tg} = gross area along the plane resisting tension stress
  A_{tn} = net area along the plane resisting tension stress
  F_y = specified minimum yield strength of the connected material
  F_u = specified minimum tensile strength of the connection material

ϕ_{bs} = resistance factor for block shear (not used in order to obtain the most accurate comparisons)

- 6.13.5 Connection Elements

  The factored resistance in tension shall be taken as the least of the values given by Section 6.8.2 for yielding and fracture, respectively, or the block shear rupture resistance specified in Section 6.13.4.

Using these specification details on the UIUC specimens, a current specification limit state was calculated based on a governing tension (yield or fracture) failure or a block shear (shear or tension) failure. Tables A1 through A4 in the Appendix show the limit state calculations for each type of UIUC specimen.

A comparison between the UIUC experimental strength limit state versus the current AASHTO Design specification strength limit state is illustrated in Figure 2.7. The 45 degree line shown in the plot signifies equal experimental and specification limit states. Whereas points above this line indicate experimental results that exceed specification limits, points below this line indicate experimental results that are lower than specification limits. Points falling below this line signify non-conservative specification limit states. As seen in Figure 2.10, the drilled hole variations of each specimen pair performed better than the punched hole variations, some of which fell below the 45 degree line. Most notably, there is a large difference between the performance of punched and drilled holes in the plotted specimen that failed at the highest load in Figure 2.7. Chesson and Munse suggest that this large discrepancy may be due to the effect of punched holes on wide plates with large edge distances (Chesson and Munse, Truss 1963).

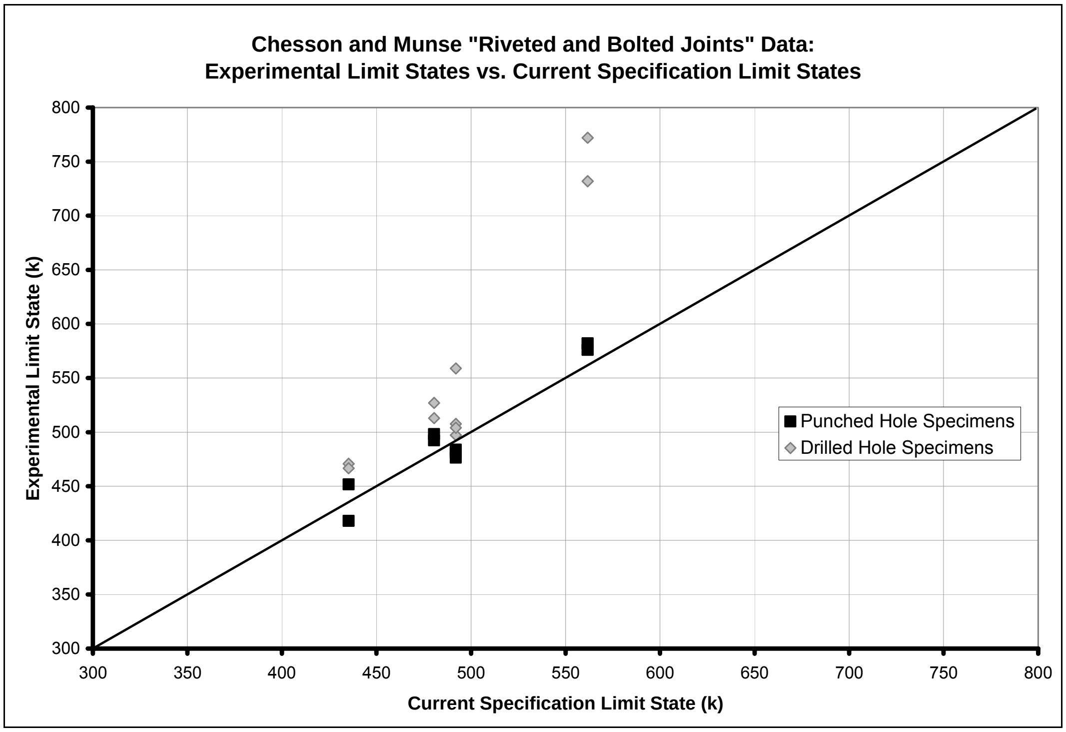

Figure 2.10: Experimental versus Current Specification Limit States for Chesson and Munse Data

In their research, Chesson and Munse noted that no current specifications penalize the punching of holes and recommended modification of rules for analyzing and designing connections (Chesson and Munse, Behavior 1958). They suggested that the allowable stress for members with punched holes be 7/8 (0.875) of the allowable stress for drilled holes. In addition, qualitative recommendations were made regarding a greater differential in allowable stresses for wide punched and drilled plates with large edge distances.

2.4 RECENT RESEARCH

In 2002, Frank (2002) performed a study comparing the tensile behavior of plates prepared with punched and drilled holes. Plate material and thicknesses that may be typically punched, or unintentionally punched full-size, in a state of Texas highway bridge were used. In tests that varied two grades of steel, thicknesses, and temperatures, each drilled hole specimen exhibited greater strength and ductility relative to its punched hole replicate. Specifically, Frank showed the average strength ratio of punched and drilled holes specimens to be 0.98 and 1.16, respectively. His recommendations included the reaming of punched holes in primary tension members and the use of punched holes in secondary connection members. These results closely matched those previously found by Chesson, Munse, and Schutz at the UIUC.

Concurrent research by Rassati, Swanson, and Yuan (2004) at the University of Cincinnati (UC) has been investigating the effects of drilling, punching, and thermal cutting in structural steel. Tensile testing results of bar and tee specimens have shown average strength ratios of 1.05 for punched specimens and 1.11 for drilled and flame cut specimens. This strength difference due to hole preparation is somewhat smaller than those differences previously reported by Frank and the UIUC researchers, but a similar decrease in tensile ductility was found for punched specimens relative to specimens with other methods of hole-forming. Rassati, Swanson, and Yuan reported no well-defined trends with regard to punch-to-thickness ratio, punching workmanship, or the gage of holes in the tee specimens.

Fatigue of punched hole plates is also currently being researched at other universities, both in the United States and in Europe. Rassati, Swanson, and Yuan (UC) are also investigating the efficiency of high-performance grade 70 steel that is punched, sub-punched and reamed, or drilled. UC researchers have found a noticeable reduction in fatigue strength of plates with punched versus drilled holes as illustrated in Figure 2.11. Note that the stress ranges in this plot were based net section areas. According to AASHTO LRFD Bridge Design Specifications (2004), bolted transverse deck plate splices (those replicated by the UC specimens) are considered category B details; thus, the category B curve is highlighted in the figure below. In this study, all punched hole specimens fell below the category B threshold while all drilled and reamed hole specimens fell above this threshold.

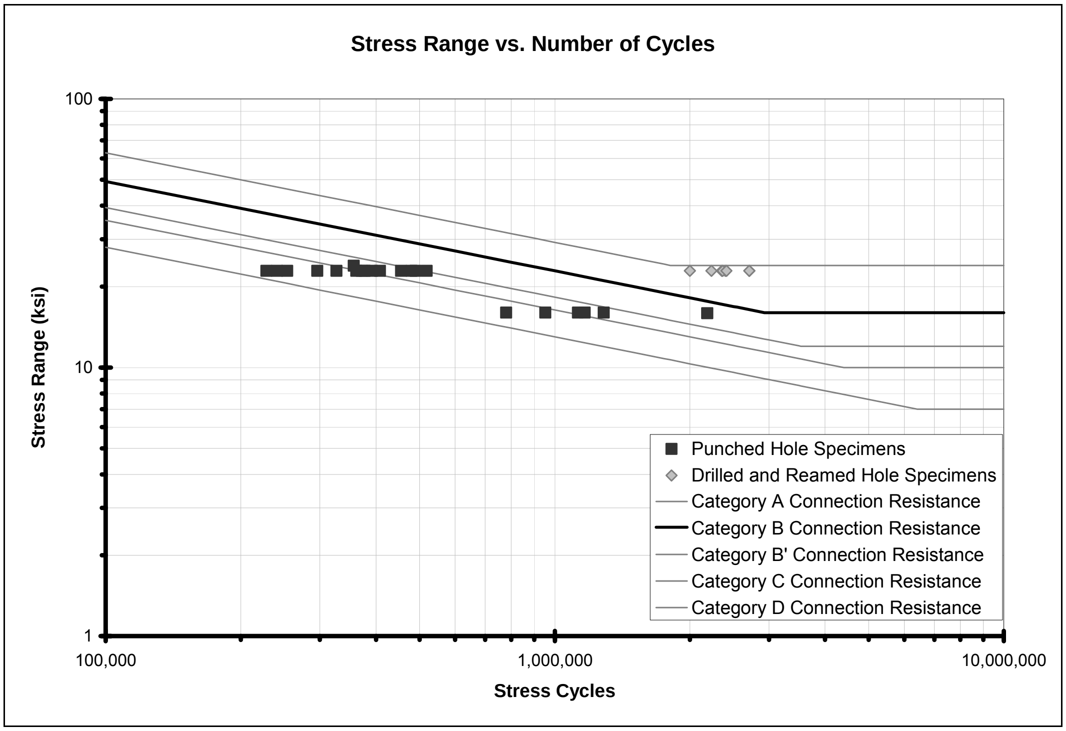

Figure 2.11: Stress Range versus Number of Cycles for UC Data

Fatigue testing in Spain at the University of Cantabria by Gutierrez-Solana, Pesquera, and Sanchez (2004) has shown similar results to the UC study in that punched hole plate specimens failed with fewer fatigue cycles relative to drilled hole plate specimens. Specifically, the average punched to drilled hole ratio of cycles to failure was found to be 0.51 (i.e. drilled specimens had approximately double the fatigue resistance). Solana, Pesquera, and Sanchez found that the fatigue performance of these plates was independent of the steel quality. In addition, their study analyzed local micro-structural damage at fracture surfaces and found punched specimens developing first propagation stages of fracture 10 times faster than replicate drilled specimens.

2.5 USE OF PREVIOUS RESEARCH IN CONJUNCTION WITH CURRENT STUDY

From early research of punched holes and rivets in iron plates to recent tests in Illinois, Ohio, Texas, and Spain, experimental evidence has shown that the tensile and fatigue performance of punched hole specimens is sub par relative to drilled hole specimens. Further testing, as described in this report, considers additional variations including a range of steel types, temperatures, hole sizes, plate thicknesses, edge distances and preparation, punch clearance and operation, galvanizing, and reaming. In combining past research data with multiple sets of current findings, design recommendations may be formulated for the use of members with punched holes. Most importantly, these recommendations may now consider current fabrication practices as well as steels currently used in the bridge industry.

3. EXPERIMENT DESIGN

3.1 PLATE SPECIMENS

The typical plate specimen for the testing investigations described in this chapter is shown in Figure 3.1. All plates had this basic geometry, but plates varied in steel type, hole size, plate thickness, edge distance and preparation, and hole preparation as described in the following section.

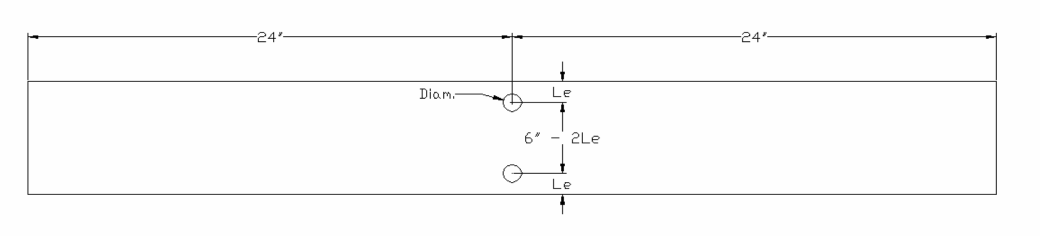

Figure 3.1: Typical Plate Specimen Geometry

3.2 TESTING MATRICES

Since many variables were investigated in this research work, eight tensile testing matrices were used to study a series of variables one at a time. The testing series was as follows:

- Steel Type and Temperature Investigation
- Hole Size and Plate Thickness Investigation
- Edge Distance and Preparation Investigation
- Punching Clearance Investigation
- Punching Operation Investigation
- Cold Temperature Testing Thickness Investigation
- Galvanizing Investigation
- Reaming Investigation

3.2.1 Steel Type and Temperature Investigation

As illustrated in Table 3.1, the Steel Type and Temperature Test Matrix investigates variations in steel type and temperature on the tensile strength of both punched and drilled plate specimens. As shown in tables within this section, all specimen tensile tests appearing in these matrices are designated with a "T." For example, Table 3.1 shows that four tensile tests were completed on grade 36 plates with 15/16 inch diameter holes at room temperature. Note that all similar grade plate in a table row is from the same heat. The steel types studied in this investigation include grade 36, grade 50, and a plate heat designated as "high-carbon grade 55." The high-carbon grade 55 plate was obtained via a shipping mix-up and retained for testing at the FSEL. Temperature conditions in this study included room temperature, cold temperature, aged and room temperature, and aged and cold temperature.

Table 3.1: Steel Type and Temperature Test Matrix

	Test Temp. and Conditions			
Steel Type	**15/16" Hole, Room Temp.**	**15/16" Hole, Aged**	**15/16" Hole, Cold Temp.**	**15/16" Hole, Aged & Cold Temp.**
Grade 36	4-T	2-T	2-T	2-T
Grade 50	4-T	2-T	2-T	2-T
High Carbon Grade 55	2-T	-	-	-

T = Tension Test

Steel type choices were chosen based on those materials most commonly used for connection elements in past and current United States bridge construction. The majority of state of Texas bridges currently in service are constructed with either grade 36 or grade 50 steel. For comparison purposes, a high-carbon grade 55 steel was tested to further demonstrate the effects of different chemical compositions on material performance.

Temperature conditions were chosen to simulate different environmental conditions experienced by state of Texas bridges. Room temperature testing was performed during the spring and summer months indoors at the FSEL. Indoor lab temperatures typically ranged from 70 to 85 degrees Fahrenheit. Cold temperature testing was performed by using the temperature chamber as described later in this report and ranged from zero to five degrees Fahrenheit. Aged plates were stored in an oven at 150 degrees Fahrenheit for 24 hours prior to testing to simulate exposure to summer heat and strain aging that may occur due to this exposure.

3.2.2 Hole Size and Plate Thickness Investigation

As illustrated in Table 3.2, the Hole Size and Plate Thickness Test Matrixes investigates variations in plate thickness and hole size on the tensile strength of both punched and drilled plate specimens. The plate thicknesses studied included 3/8, 1/2, and 3/4 inch dimensions and the hole sizes include 11/16, 13/16, and 15/16 inch diameters.

Table 3.2: Hole Size and Plate Thickness Test Matrixes

	Grade 36, Hole Size (in.)		
Plate Thickness (in.)	**11/16**	**13/16**	**15/16**
3/8	2-T	2-T	2-T
1/2	2-T	2-T	2-T
3/4	-	2-T	2-T

	Grade 50, Hole Size (in.)		
Plate Thickness (in.)	**11/16**	**13/16**	**15/16**
3/8	2-T	2-T	2-T
1/2	2-T	2-T	2-T
3/4	-	2-T	2-T

T = Tension Test

Plate thicknesses were chosen based on typical thicknesses of members and plates that are candidates for punched holes. These thicknesses are based on both current specifications and the capacity of most punch presses. AASHTO Construction (2004) sets maximum thickness limits for punching as 3/4 inch for grade 36 and 5/8 inch for grade 50. Grade 50 plate thicknesses both greater and less than the AASHTO Design limits were tested to examine the validity of these constraints.

Similarly, hole sizes were chosen based on typical connection details using standard size bolts. Since it is common practice to add 1/16 inch to the bolt size to obtain the hole size, hole sizes that correspond to 5/8, 6/8, and 7/8 inch standard bolts were selected. Furthermore, punch press manufacturers recommend only punching hole diameters that are larger than plate thickness. These recommendations were followed as shown in Table 3.2 and excluded the punching of 11/16 inch diameter holes in 3/4 inch plate.

3.2.3 Edge Distance and Preparation Investigation

As illustrated in Table 3.3, the Edge Distance and Preparation Test Matrix investigates variations in edge distance and preparation on the tensile strength of both punched and drilled plate specimens. Plate edges were either flame or shear cut in the fabrication shop and edge spacing varied from AASHTO Design specification minimum to larger distances.

Table 3.3: Edge Distance and Preparation Test Matrix (with 15/16 Inch Diameter Holes)

	Test Condition			
Steel Type and Thickness (in.)	**Sheared Edge, Standard Spacing**	**Flame Cut (Shear Match), Standard Spacing**	**Flame Cut, Standard Spacing**	**Flame Cut, Larger Spacing**
Edge Spacing (in.)	**1-1/2**	**1-1/8**	**1-1/8**	**1-1/4**
A36, 1/2	2-T	2-T	2-T	2-T
Grade 50, 1/2	2-T	2-T	2-T	2-T

T = Tension Test

AASHTO Design specifications do not differentiate between punched and drilled holes when considering edge distance and preparation. Minimum edge distances for flame and shear cut plates with 7/8 inch bolts, and corresponding 15/16 inch diameter holes, are identified as 1-1/8 inch and 1-1/2 inch, respectively (AASHTO Design 2004). Sheared plate edges may lead to more brittle deformation relative to flame cut edges; thus, most bridge specifications require sheared edges to be ground to remove the damaged material. To be conservative, sheared edge specimens were not ground in this investigation. Also note that in this study, the code specified minimum edge distances were used for both flame and shear cut plates.

Edge distances of holes influence the amount of plastic deformation in the material surrounding the punched hole. Large distances constrain the plastic flow around the hole, while smaller ones increase the bulging and plastic deformation on the material between the hole and the edge. Greater plastic deformation reduces the ductility of the material and increases its susceptibility to a more brittle failure (Chesson and Munse, Truss 1963). In the FSEL study, specification minimum flame cut edge distances of 7/8, 1, and 1-1/8 inch were used for 11/16, 13/16, and 15/16 inch hole diameters, respectively (AASHTO Design 2004). To study the change in plastic flow with variance of edge distance, a larger spacing of plus 1/8 inch on each side was used. In these specimens, the distance from the edge to the center-of-hole was set equal to the spacing of the holes.

3.2.4 Punching Clearance Investigation

As illustrated in Table 3.4, the Punching Clearance Test Matrix investigates variations in clearance on the tensile strength of punched plate specimens. To replicate proper and improper, or worn, punch dies, holes were punched at both manufacturer recommended clearance and at larger clearance (plus 1/8 inch), respectively.

Table 3.4: Punching Clearance Test Matrix (1/2 Inch Thickness Plate)

	Hole Size (in.) and Clearance Condition (in.)			
Steel Type and Thickness (in.)	**Large Hole (15/16), Large Clearance (3/32)**	**Large Hole (15/16), Recommended Clearance (1/32)**	**Small Hole (11/16), Large Clearance (3/32)**	**Small Hole (11/16), Recommended Clearance (1/32)**
A36, 1/2	1-T	1-T	1-T	1-T
Grade 50, 1/2	1-T	1-T	1-T	1-T

T = Tension Test

Clearance is defined as the relationship of the larger female die hole size to the male punch size. As shown in Table 3.5, the punch press manufacturer recommends the following die clearances based on material thickness:

Table 3.5: Die Clearance based on Material Thickness

Material Thickness (in.)	**Overall Die Clearance (in.)**
1/8 to 1/4	0.020 over nominal
1/4 to 1/2	1/32 over nominal
7/16 to 13/16	1/16 over nominal
5/8 to 1-1/16	3/32 over nominal
1 to 1-1/4	1/8 over nominal

Based on these recommendations, Table 3.6 displays the thickness, hole size, and die size combinations that were used at the FSEL:

Table 3.6: Die Clearance Used for Standard Holes

Nominal Thickness (in.)	Nominal Hole Size (in.)	Die Size (in.)	Clearance (in.)
3/8	11/16	23/32	1/32
3/8	13/16	27/32	1/32
3/8	15/16	31/32	1/32
1/2	11/16	23/32	1/32
1/2	13/16	27/32	1/32
1/2	15/16	31/32	1/32
3/4	13/16	29/32	3/32
3/4	15/16	1-1/32	3/32

Although recommended clearances are given by the punch press manufacturer, clearances do vary during fabrication due to wear or use of improper die size. Varying clearances may change the performance of the parent material since they may bring about more initial imperfections and cause greater strain hardening. For this reason, AASHTO Construction (2004) specifies that punch clearances must be 1/16 inch or less. To investigate this maximum clearance recommendation, large clearance specimens were fabricated with a 1/8 inch difference between die and punch size.

Brolund defines proper clearance as that which causes no secondary shear and a minimum plastic deformation and burr. As illustrated in Figure 3.2, increasing the clearance between the cutting edges increases the deformation due to the moment arm "A." When this occurs, the material adjacent to the cutting edge is put in tension and stretched excessively. This will cause extra roll-in at the top of the hole and too much burr at the bottom of the hole (Brolund 2004).

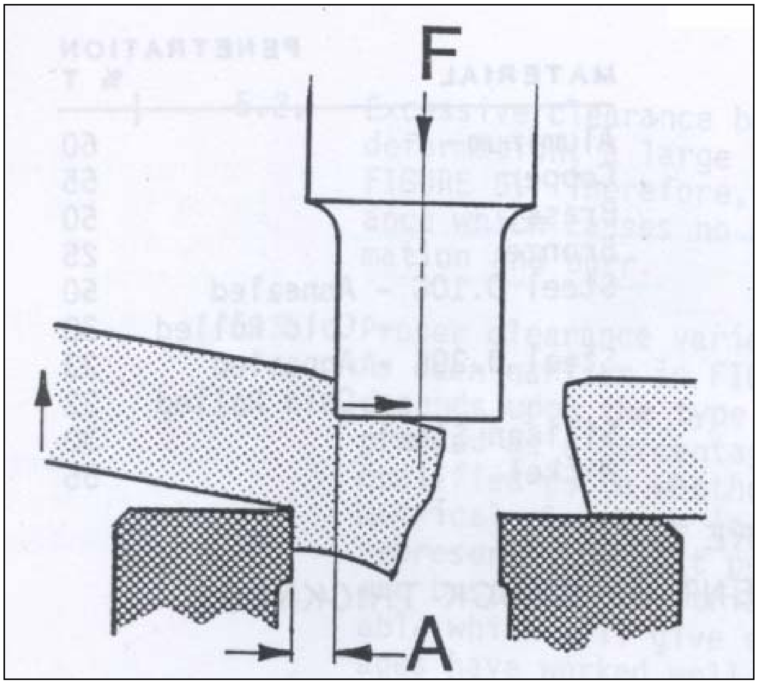

Figure 3.2: Deformation Due to Increasing Clearance (Brolund 2004)

Furthermore, as illustrated in Figure 3.3, a large clearance between the two opposed cutting edges will cause an angular fracture and lower quality of the punched hole. Without proper clearance, the material will not fracture cleanly, causing excessive plastic deformation and a large burr, and may reduce punch life (Brolund 2004).

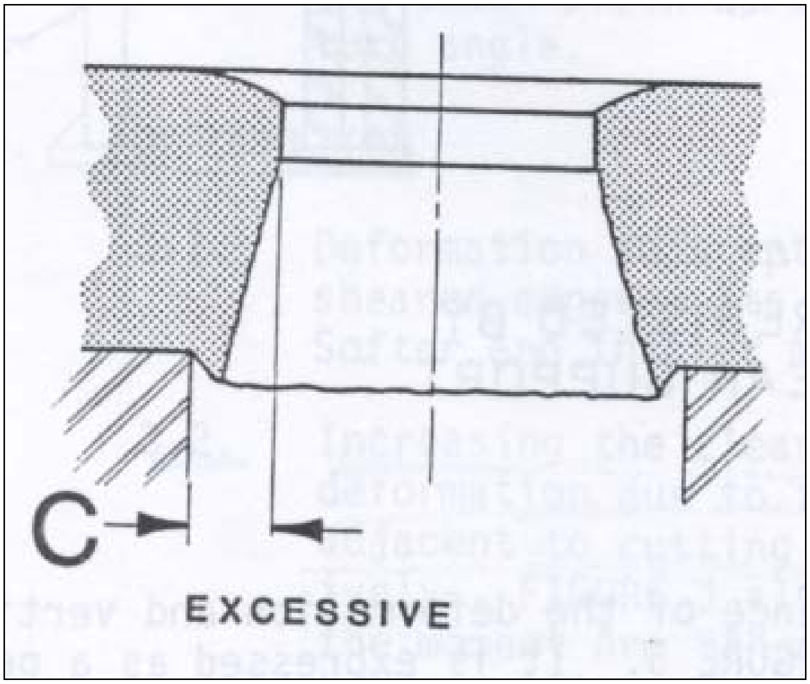

Figure 3.3: Excessive Clearance and Unclean Fracture (Brolund 2004)

3.2.5 Punching Operation Investigation

As illustrated in Table 3.7, the Punching Operation Test Matrix investigates variations in punch press operations on the tensile strength of punched plate specimens. Since most punching was performed at the FSEL with the same punch press, seven plates of three thicknesses were punched at Alamo Iron Works (AIW), a steel fabrication shop in San Antonio, Texas. Grade 50 plates of 3/8, 1/2, and 3/4 inch thicknesses were punched with nominal 15/16 inch holes at AIW as per normal shop procedure (see section 4.1.2) to examine the difference in performance between research lab punched plates and fabrication shop punched plates.

Table 3.7: Punching Operation Test Matrix (15/16 Inch Diameter Holes)

	Temperature Condition	
Location	**Room Temp.**	**Cold Temp.**
UT	3-T	1-T
Alamo	3-T	1-T

T = Tension Test

3.2.6 Cold Tensile Testing Thickness Investigation

As illustrated in Table 3.8, the Cold Tensile Test Thickness Matrix investigates variations in steel type and thickness on the tensile strength of both punched and drilled plate specimens at low temperatures. This testing was completed as a follow-up to the Steel Type and Temperature Test Matrix in which cold temperature specimens performed similarly or better in average strength ratio and average usable elongation relative to room temperature specimens. To further validate these results, three different plate thicknesses were tested under similar cold temperature conditions.

Table 3.8: Cold Tensile Test Thickness Matrix

	Plate Thickness (in.)		
Steel Type	**3/8**	**1/2**	**3/4**
Grade 36	2-T	2-T	2-T
Grade 50	2-T	2-T	2-T

T = Tension Test

3.2.7 Galvanizing Investigation

As illustrated in Table 3.9, the Galvanizing Test Matrix investigates the effect of the galvanizing process after hole preparation on the tensile strength of both punched and drilled plate specimens. Four plates of 3/8 inch thickness were galvanized at Southwest Galvanizing, Inc. (SGI), a hot dip galvanizing company in San Antonio, Texas. Specimens of 3/8 thickness were studied since thin plates such as these are typically candidates for galvanizing and use on traffic signal structures.

Table 3.9: Galvanizing Test Matrix

	Plate Preparation	
Steel Type	**As Received Plate**	**Galvanized Plate**
Grade 36	2-T	2-T
Grade 50	2-T	2-T

T = Tension Test

Previous literature review and research by Huhn and Valtinat (2004) has noted that hot dip galvanizing at high temperatures may promote aging of steel and may have a negative impact of the fatigue behavior of connections. Huhn and Valtinat mention that aging may be especially critical for galvanized connections in which punched holes exist.

3.2.8 Reaming Investigation

As illustrated in Table 3.10, the Reaming Test Matrix investigates variations in reaming and sub-punching in forming a hole. This was done since a varying amount of reaming may occur in a shop during fit-up of elements and connections. AASHTO Construction specifications require that punched holes must be sub-punched and reamed to the required diameter when used in members carrying calculated load forces. Holes are required to be sub-punched at least 3/16 inch smaller than the nominal size of the fastener and then reamed to full size (AASHTO Construction 2004).

Table 3.10: Reaming Test Matrix

	Punch Diameter and Amount of Reaming (in.)		
Steel Type	**3/4 and 3/16**	**13/16 and 2/16**	**7/8 and 1/16**
Grade 36	1-T	1-T	1-T
Grade 50	1-T	1-T	1-T

T = Tension Test

The purpose of reaming is to remove the plastically strained material surrounding the hole and any micro-cracks formed during the punching operation. The holes in all specimens in this test matrix were reamed to 15/16 inch after sub-punching and reaming. Testing began with the evaluation of the AASHTO Construction (2004) lower-bound limit on reaming (3/16 inch) and was followed by subsequent testing of specimens with less reaming to investigate the effects of "inadequate" reaming.

3.2.9 Fatigue Investigation

In addition to the eight tensile testing matrices presented in this section, fatigue testing of replicate specimens with varying parameters was also proposed during this study. In addition to tensile stresses, fatigue stresses also play an important role in the critical loading of bridge elements. Secondary and connection elements such as those that are candidates for punching may not experience high stress levels, but may experience a significant amount of cyclic loading. Unfortunately, technical difficulties with FSEL equipment caused unreliable fatigue cycle data; thus, only qualitative fatigue results are presented within this portion of the study. Fatigue testing is currently in progress at the FSEL.

4. SPECIMEN FABRICATION AND TEST PROCEDURES

4.1 SPECIMEN FABRICATION

Sixty-six (66) plates with punched holes, 46 plates with drilled holes, and 6 plates with sub-punched and reamed holes were tested in the investigations as described in the Experiment Design chapter. Most specimen preparation took place in the FSEL with in-house equipment as described in the following two sections.

4.1.1 Drilled Plates

The drilling process is typically the most common hole-making process in the fabrication of structural steel. Drilled holes are commonly made by forcing a rotating bit into a stationary work-piece. This process is used especially when the material is too thick for punching. All drilled specimens were prepared using one of the two following electromagnetic drills in the FSEL:

- Jancy Heavy-Duty Drill "Slugger" – 375 no load RPM, 10 Amps
- Milwaukee Heavy-Duty Electromagnetic Drill Press – 450 no load RPM, 12.5 Amps (shown in Figures 4.1 and 4.2)

Each drill was hand-operated (i.e. hand-fed) and outfitted with an annular cutter of 11/16, 13/16, or 15/16 inch diameter for hole fabrication. The slug remaining inside the annular cutter following drilling may be seen in Figure 4.2. Drilling time for a typical 15/16 inch diameter hole in a 1/2 inch plate was approximately 15-30 seconds. Additionally, an oil-based lubrication fluid was used during the drilling process. As shown in Figures 4.3 and 4.4, the drilled hole surface is relatively smooth with a series of shallow drill bit grooves. Furthermore, the surface is approximately even with constant texture throughout the depth of the hole.

Figure 4.1: Typical Drilled Hole Preparation (with Slugger)

Figure 4.2: Close-Up of Drill, Bit, Slug, and Specimen during Preparation

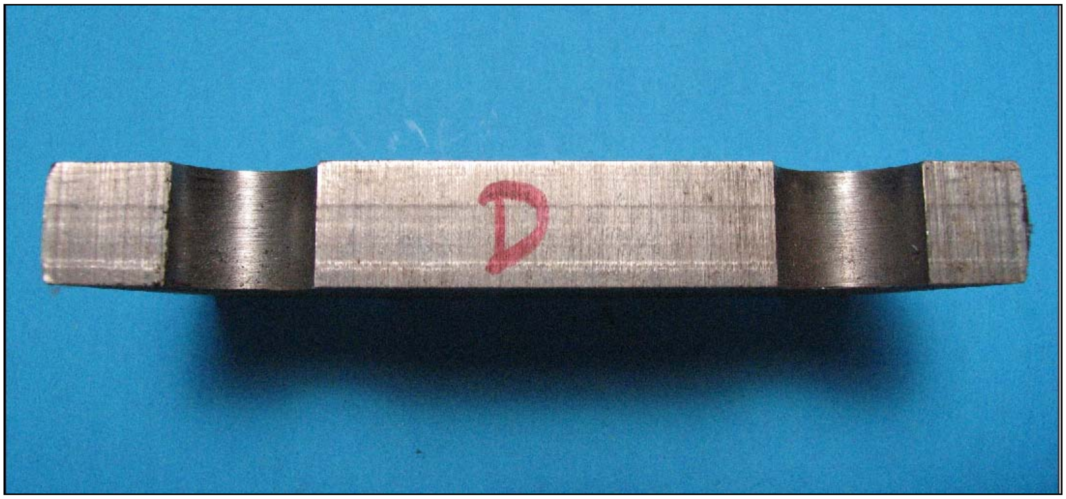

Figure 4.3: Cross-Section of Typical Drilled Hole Specimen (15/16 Inch Diameter Hole in 3/4 Inch Thickness Grade 50 Plate)

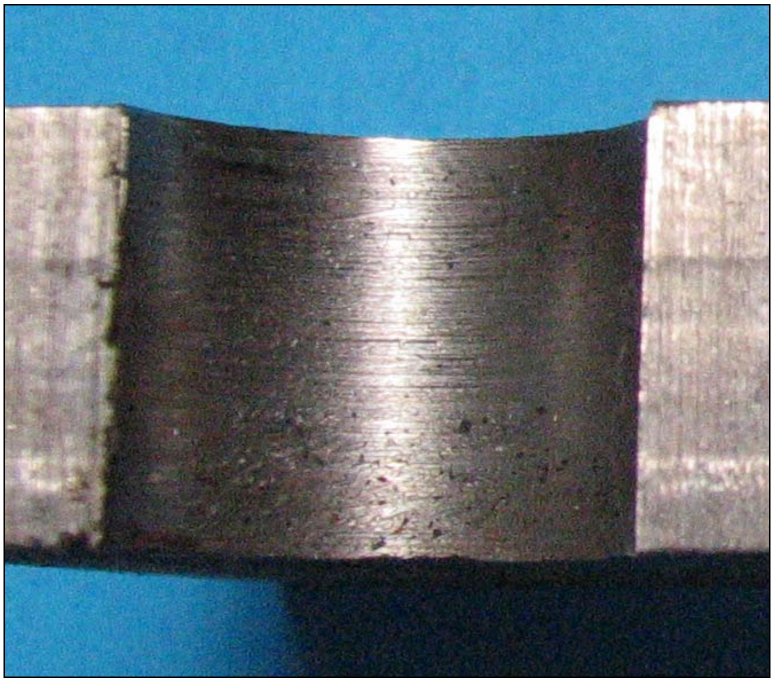

Figure 4.4: Close-Up of Cross-Section of Typical Drilled Hole Specimen (15/16 Inch Diameter Hole in 3/4 Inch Thickness Grade 50 Plate)

4.1.2 Punched Plates

All punched specimens were prepared using a Whitney 790AX6 Portable Flange Press at the FSEL as shown in Figures 4.5 and 4.6. The punch press has a 100 ton capacity and was operated with a 1-1/8 horsepower hydraulic power unit. For all in-house punching, the manufacturer recommended punch and die combination as previously shown in Table 3.6 was used for each particular thickness and hole size combination.

Figure 4.5: Plate Inserted in Punch Press

Figure 4.6: Plate and Punched Holes Following Typical Specimen Preparation

Seven plate specimens were punched at AIW in addition to those punched at the FSEL. The plates were punched using normal operation procedures of the fabrication shop with five of the seven plates (3/8 inch and 1/2 inch thicknesses) punched by the mechanical punch shown in Figure 4.7. The two remaining, larger thickness 3/4 inch plates were punched using a hydraulic punch similar to the FSEL punch press. All plates were punched to form nominal 15/16 inch diameter holes. As per usual AIW shop procedure, a one inch die was used for all of the plate thickness. The most noticeable differences between the two punching operations were the clearance considerations and the faster punching rate at which AIW prepared plates.

Figure 4.7: Mechanical Punch Press at AIW

In general, punched hole surfaces are rougher than those of drilled hole surfaces as shown in Figures 4.8 and 4.9. This was typical of those specimens punched both at the FSEL and at AIW.

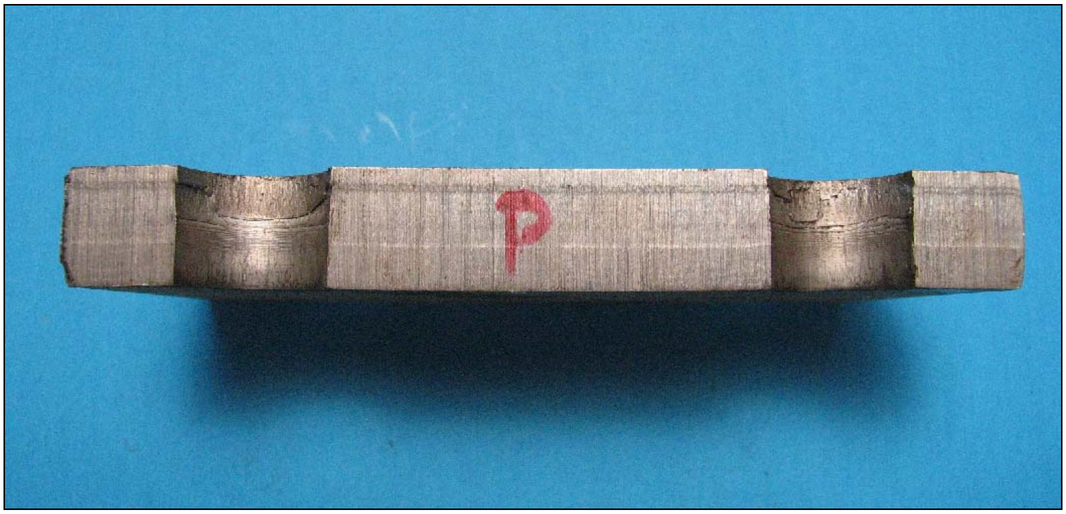

Figure 4.8: Cross-Section of Typical Punched Hole Specimen (15/16 Inch Diameter Hole in 3/4 Inch Thickness Grade 50 Plate)

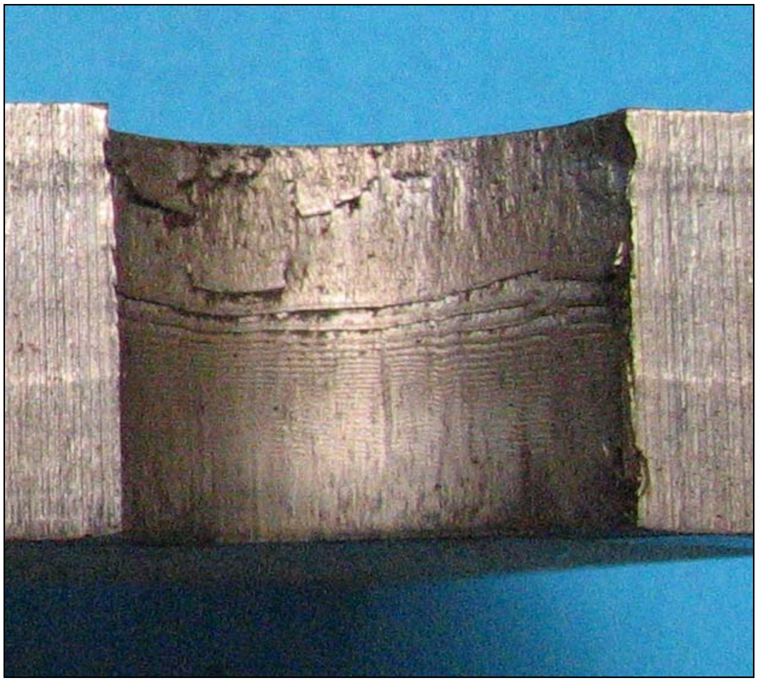

Figure 4.9: Close-Up of Cross-Section of Typical Punched Hole Specimen (15/16 Inch Diameter Hole in 3/4 Inch Thickness Grade 50 Plate)

Similarly, Figures 4.10 and 4.11 show typical punched holes of varying thicknesses and grades of steel. Note that punched holes from both FSEL and AIW fabrication are shown in the figures. The severity of surface damage is dependent on many variables including plate thickness, hole diameter, grade of steel, and punching operation.

Figure 4.10: Typical 15/16 Inch Diameter, 1/2 Inch Thickness and 15/16 Inch Diameter, 3/4 Inch Thickness Punched Holes (Grade 50)

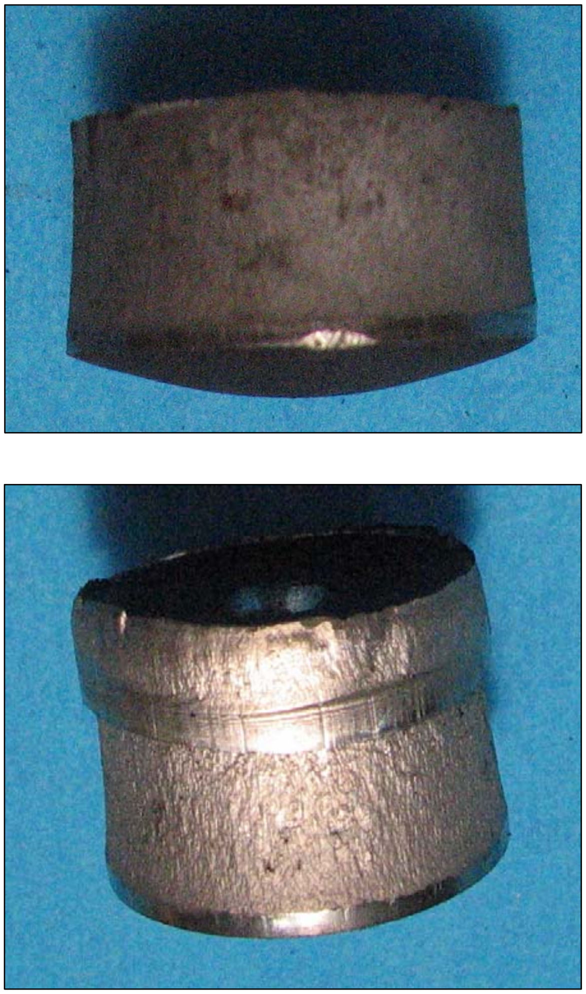

Figure 4.11: AIW Typical 15/16 Inch Diameter, 1/2 Inch Thickness and 15/16 Inch Diameter, 3/4 Inch Thickness Punched Holes (Grade 50)

4.2 GALVANIZING PROCEDURE

Four plate specimens of 3/8 inch thickness were punched at the FSEL and galvanized at SGI in a zinc hot dip. Galvanizing occurred as per normal operation procedures in the shop in an 840 degree Fahrenheit kettle of 99% zinc and no-tin alloy. Prior to galvanizing, the plates were cleaned with a hydrochloric acid solution at the shop and rinsed. These plates were tensile tested until failure approximately one week later.

4.3 REAMING PROCEDURE

Reaming is utilized following the sub-punching, or sub-drilling, of a hole in an element. The reaming of holes removes an additional ring of larger diameter material by forcing a rotating bit into a stationary work-piece with an already existing hole. In general, this process is typical during fit-up of elements that have been sub-punched or sub-drilled. When used after sub-punching, reaming is used as a standard practice to "remove the damaged material" around the exterior of a punched hole. All reamed specimens in this study were sub-punched with the Whitney 790AX6 Portable Flange Press and reamed to full size with a radial drill equipped with a 15/16 inch diameter tapered bridge reamer bit (shown in Figure 4.12) in the FSEL. During the reaming process, the bit was self-centering in that the crosshead of the radial drill was in the unlocked position.

As shown in Figures 4.13 and 4.14, the reamed hole surface is relatively smooth with a series of shallow drill bit grooves. Furthermore, the surface is approximately even with constant wear throughout the thickness of the material as compared to the surface of punched holes.

Figure 4.12: High Speed Radial Drill and Reamer

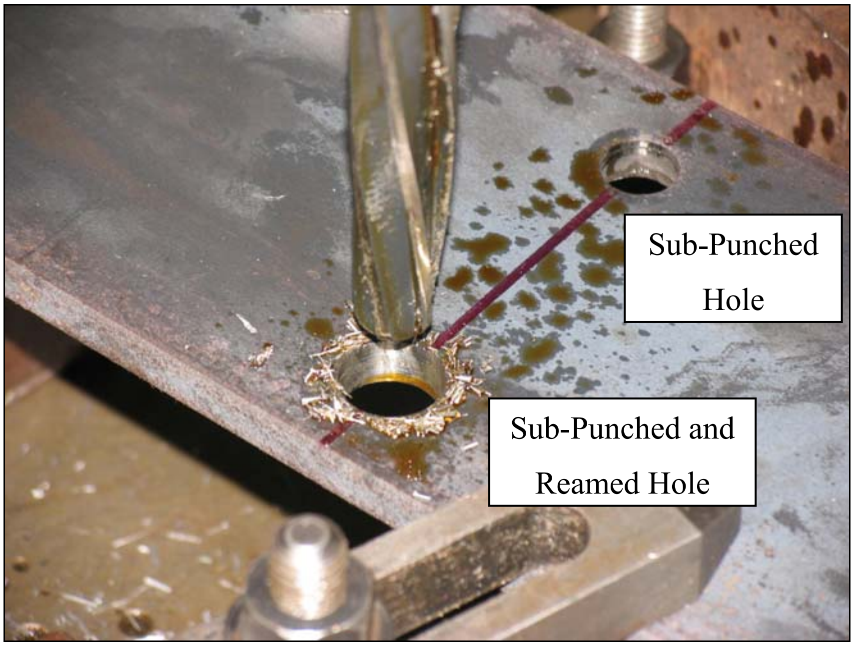

Figure 4.13: Reamer Bit and Finished Hole in Specimen

Figure 4.14: Close-Up of Reamer Bit and Hole in Specimen

4.4 TESTING APPARATUS AND PROCEDURE

4.4.1 Tensile Testing

One-hundred eighteen (118) plate specimens with varying parameters were tensile tested during this investigation at the FSEL. The tensile testing apparatus and general procedure at both room temperature and cold temperature are explained in the following two sections.

4.4.1.1 Room Temperature Tensile Testing

Room temperature tensile testing began with the documentation of plate and hole dimensions prior to testing. Plate width, thickness, and two hole diameters on both sides of the plate were recorded for each specimen. These measurements were all taken with calipers to an accuracy of 0.001 inch. Since the hole diameters varied depending on the hole-making process, an average diameter was used for each hole to calculate the net section area as shown in Equation 3.1. Note that two diameters of each hole were measured on each side of the plate (i.e. four diameter measurements were taken for each hole). Hole diameter variations from one side of the plate to the other ranged from 0.001 to 0.02 inches.

$$A_{net} = \left(w - d_{1,avg} - d_{2,avg}\right) \cdot t \qquad (3.1)$$

where w = width

$d_{1,avg}$ = average diameter of hole 1

$d_{2,avg}$ = average diameter of hole 2

t = thickness

All tensile specimens were tensile tested to failure in the FSEL's 600 kip Universal Testing System (UTS) as shown in Figures 4.15 and 4.16. During each test, the load and cross-head displacement were recorded using a Personal Data Acquisition (PDAQ) system and linear displacement potentiometer as shown in Figures 4.17 and 4.18. During testing, the recorded load and displacement data was taken with an accuracy of 0.1 kip and 0.001 inch, respectively. The average loading rate for the specimens was 0.65-0.85 kips per second, which met the American Society of Testing and Materials (ASTM 2004) E8-04 requirements for standard testing of metallic materials.

Figure 4.15: 600-Kip UTS Used for Tensile Testing

Figure 4.16: Test Specimen in Grips of 600-Kip UTS

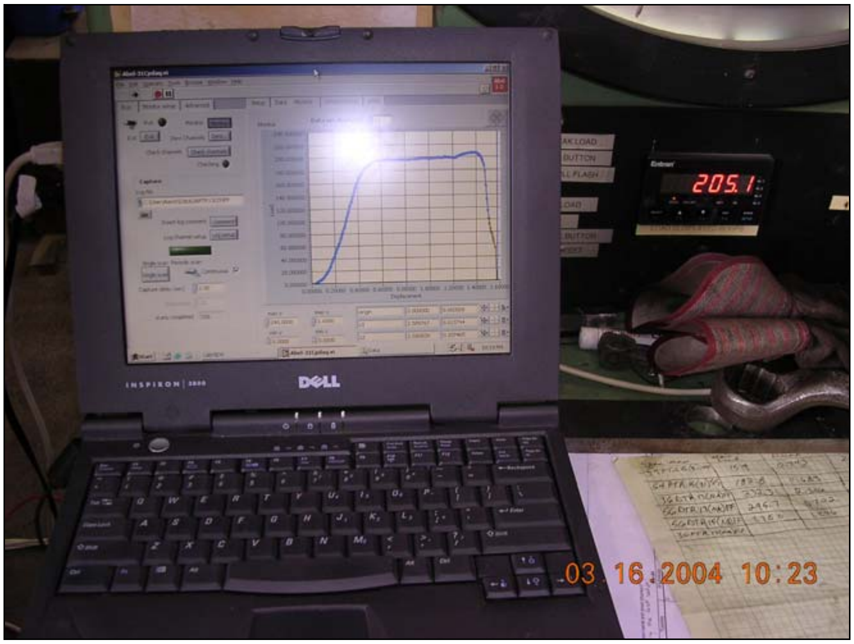

Figure 4.17: PDAQ System Used for Tensile Testing

Figure 4.18: Linear Potentiometer Used for Tensile Testing

4.4.1.2 Cold Temperature Tensile Testing

Tensile testing at a lower temperature was completed to investigate the effects of temperature on specimen performance. Again, specimen geometries were documented and specimens were tensile tested to failure in the 600 kip UTS. Specimens were placed in a Frigidaire 19.7 cubic foot chest freezer for 24 hours prior to testing as shown in Figure 4.19 to allow for total through-thickness temperature equilibrium. The freezer temperature was approximately -13°F, in which a one inch thick plate was found to reach total through-thickness temperature equilibrium in ten hours. This total through thickness cooling duration requirement was found by placing a thermocouple in the center of a one inch plate and comparing its readings to a thermocouple on the surface during cooling.

Figure 4.19: Interior of Freezer Storing Cold Plates

As with the room temperature tests, the load and cross-head displacement were recorded using the PDAQ system and linear displacement potentiometer during the test. In order to duplicate room temperature testing conditions, specimens were again loaded at an average rate of 0.65-0.85 kips per second. Each plate specimen was placed in a temperature chamber once it was removed from the freezer in order to keep the specimen at a constant cold temperature as shown in Figures 4.20 and 4.21. In order to keep the plate at this low temperature, the temperature chamber was outfitted with 1-1/2 inches of insulation as well as shelves on each side that contained dry ice. Test durations typically ranged from five to ten minutes from start to finish (i.e. from removal of specimen from freezer to fracture of plate) and on average remained at a temperature of -13 +/- 5°F. These temperature fluctuations were monitored with thermocouples attached to the plate surfaces.

Figure 4.20: Temperature Chamber Surrounding Specimen in 600-Kip UTS


2004.06.30

Figure 4.21: Open Temperature Chamber Prior to Tensile Test

4.4.2 Fatigue Testing

Fatigue testing of several plate specimens with varying parameters was proposed during this investigation at the FSEL. As with tensile testing, fatigue testing began with documentation of plate and hole dimensions prior to testing. All fatigue specimens were tested to failure in the FSEL's 220 kip Mechanical Testing System (MTS) as shown in Figures 4.22 and 4.23. During each test, the load range and number of cycles were recorded using a Data Acquisition (DAQ) control system as shown in Figure 4.24. The cyclic frequency for the load range for the specimens was 3.5 Hertz.

Although this system was calibrated with a load cell, non-uniform (and unintended) cyclic loads were experienced by specimens during fatigue testing due to issues with the MTS and control electronics. Strain data monitoring confirmed these non-uniform cyclic loading issues; therefore, data could not be considered accurate for this study's fatigue specimen testing. Therefore, two qualitative tests of punched and drilled holes in the same specimen were investigated to understand general specimen behavior in fatigue. As of 2005, the previously proposed testing is currently in progress at the FSEL using a new fatigue system.

Figure 4.22: Profile of 220-Kip MTS Used for Fatigue Testing

Figure 4.23: Typical Specimen in Grips of 220-Kip MTS

Figure 4.24: Control System Used for Fatigue Testing

According to AASHTO Bridge Design Specifications (2004), bolted transverse deck plate splices (those replicated by the specimens tested) are considered category B details; thus, for fatigue considerations:

$$N = \frac{A}{S_R^{\ 3}} \tag{3.2}$$

where N = fatigue life, or number of cycles

$A = 120 \times 10^8$ for detail category B (bolted transverse deck plate splice)

S_R = stress range

In choosing an appropriate stress range for investigation of specimen fatigue failures, two general guidelines were used:

1. It was necessary to keep the net section stress less than the yield stress of the material (Equation 3.3).
2. It was necessary to keep the minimum load greater than zero to investigate stress cycles from tension forces only (Equation 3.4).

$$\frac{P_{\max}}{A_{net}} < \sigma_y \tag{3.3}$$

where P_{max} = maximum load on net section

A_{net} = net area

σ_y = yield strength of material

$$P_{\min} > 0 \tag{3.4}$$

where P_{min} = minimum load on net section

As previously mentioned, issues with the MTS and DAQ did not allow for uniform cyclic loading. The two qualitative punched and drilled specimens were both monitored with strain gages during testing and although they experienced non-uniform cyclic loads, they did meet the guidelines of Equations 3.3 and 3.4.

4.4.3 Chemistry Analysis

Punched hole samples from all nine specimen plate heats were sent to Chicago Spectra Service Lab Inc. in Chicago, Illinois for their standard nine element steel chemistry testing. The chemistry testing determined weight percentages of carbon, manganese, phosphorus, sulfur, silicon, nickel, chromium, molybdenum, and copper in each of the plate types. These chemistry testing results were also used for comparison with chemistry data given in the steel supplier's mill test reports.

4.4.4 ASTM Coupon Testing

Eight inch flat plate-type coupons with reduced sections from all nine specimen plate heats were tensile tested to failure in the FSEL's 600-kip UTS in accordance with ASTM E8-04 standards. During each test, the load and eight inch gage length extensometer readings were recorded using a PDAQ system. Following this testing, the yield strength, ultimate strength, and percent elongation of each plate heat could be derived from the collected data. These coupon testing results were also used for comparison with chemistry data given in the steel supplier's mill test reports.

4.4.5 Charpy V-Notch Testing

Charpy simple-beam impact test specimens from all nine specimen plate heats were impact tested at the FSEL in accordance with ASTM E23-04 standards. During each test, an absorbed energy value was obtained for a specimen at a particular temperature. Following this testing, the temperature values at 15 foot-pounds of energy and at the upper shelf of the energy-temperature curve of each plate heat could be derived from the collected data.

5. TEST RESULTS AND ANALYSIS

5.1 CHEMISTRY INVESTIGATION

Results from Chicago Spectra Service Lab's standard steel chemistry tests for all nine specimen plate heats are shown in Table 5.1. These results may be compared with chemistry data given by the steel supplier's mill test reports as shown by the shaded rows in the table. Additionally, all plate heats met ASTM chemistry requirements for either A36 or A572 Grade 50 steel as shown.

Table 5.1: Results of Chemistry Investigation

Heat Description	C (%)	Mn (%)	P (%)	S (%)	Si (%)	Ni (%)	Cr (%)	Mo (%)	Cu (%)
3/8" Gr. 36	0.15	0.53	0.009	0.038	0.14	0.13	0.15	<0.01	0.59
	0.14	0.64	0.007	0.037	0.18	0.12	0.17	0.03	0.29
1/2" Gr. 36	0.16	0.67	0.011	0.037	0.13	0.11	0.14	<0.01	0.57
	0.15	0.79	0.014	0.044	0.18	0.10	0.14	0.03	0.49
3/4" Gr. 36	0.13	0.61	<0.005	0.052	0.15	0.15	0.13	<0.01	0.45
	0.12	0.77	0.015	0.038	0.23	0.12	0.16	0.04	0.33
1/2" Gr. 36 (S)	0.22	0.68	<0.005	0.012	<0.01	0.01	0.03	<0.01	0.03
	0.21	0.83	0.012	0.010	0.01	-	-	-	0.04
ASTM A36 Req.	0.26 max	-	0.04 max	0.05 max	0.40 max	-	-	-	-
3/8" Gr. 50	0.12	0.88	<0.005	0.022	0.28	0.07	0.44	<0.01	0.37
	0.12	1.00	0.007	0.021	0.32	0.08	0.48	0.02	0.33
1/2" Gr. 50	0.13	0.79	<0.005	0.031	0.23	0.08	0.36	<0.01	0.37
	0.13	1.04	0.008	0.029	0.33	0.09	0.44	0.02	0.32
3/4" Gr. 50	0.12	0.86	<0.005	0.020	0.23	0.09	0.45	<0.01	0.31
	0.12	1.12	0.008	0.018	0.33	0.10	0.56	0.02	0.27
1/2" Gr. 50 (S)	0.05	0.95	<0.005	0.006	0.10	0.13	0.07	<0.01	0.40
	0.05	1.13	0.010	0.006	0.12	0.14	0.07	0.04	0.39
1/2" High C Gr. 55	0.22	0.77	0.006	0.039	0.15	0.13	0.10	<0.01	0.45
	0.20	0.95	0.006	0.042	0.22	0.13	0.09	0.04	0.43
ASTM A572 Req.	0.23 max	1.35 max	0.04 max	0.05 max	0.40 max	-	-	-	-

*Shaded Data from MTRs

*Elements Noted:
C = Carbon
Mn = Manganese
P = Phosphorus
S = Sulfur
Si = Silicon
Ni = Nickel
Cr = Chromium
Mo = Molybdenum
Cu = Copper

*(S) = Shear Cut Heat

5.2 ASTM COUPON TESTING

Tensile results from all nine specimen standard 1-1/2 inch wide by 8 inch long gage length coupons are shown in Table 5.2. These results may be compared with material data given by the steel supplier's mill test reports as shown by the shaded rows in the table. All plate heats met ASTM chemistry requirements for either A36 or A572 Grade 50 steel as shown with the exception of two percent elongation test values. In addition, cold coupons that matched those cold specimens tested during the initial material screening were examined. Note that the cold coupons had a higher strength relative to their room temperature replicates. Tensile results from these cold coupon tests are shown in Table 5.3.

Table 5.2: Results of ASTM Coupon Tests

Heat Description	Yield Strength (ksi)	Ultimate Strength (ksi)	% Elong.
3/8" Gr. 36	47.5	70.9	22.8
	48.6	69.1	26.0
1/2" Gr. 36	47.5	69.9	16.4
	46.4	69.6	23.5
3/4" Gr. 36	42.2	65.7	30.3
	43.9	65.6	23.5
1/2" Gr. 36 (S)	48.0	62.2	26.6
	42.8	67.6	31.5
ASTM A36 Req.	36 min	58-80	20 min
3/8" Gr. 50	55.8	78.4	21.6
	58.6	75.4	28.8
1/2" Gr. 50	53.7	75.5	23.6
	55.8	76.4	27.5
3/4" Gr. 50	60.8	83.3	23.5
	60.7	77.7	27.5
1/2" Gr. 50 (S)	72.8	79.2	16.5
	71.0	81.0	27.0
1/2" High C Gr. 55	60.0	84.8	20.3
	62.2	87.1	20.5
ASTM A572 Req.	50 min	65 min	18 min

*Shaded Data from MTRs

*(S) = Shear Cut Heat

Table 5.3: Results of ASTM Cold Coupon Tests

Heat Description	Yield Strength (ksi)	Ultimate Strength (ksi)	% Elong.
1/2" Gr. 36 (Cold)	50.3	74.6	25.3
1/2" Gr. 50 (Cold)	56.3	77.8	22.9

5.3 CHARPY V-NOTCH TESTING

Final results from the Charpy tests for all nine specimen plate heats are shown in Table 5.4. The temperature at 15 foot-pounds and at the upper shelf was estimated based on energy versus temperature plots for each plate heat, shown in Appendix Figures A1 through A9. Charpy simple-beam impact test specimens of the two 3/8 inch thickness plates were sub-size according to ASTM standards; thus, energy readings for these specimens were factored accordingly to obtain values for full-size specimens (these readings were multiplied by the ratio of standard specimen width to actual specimen width). All plate heats met ASTM toughness requirements of 70°F at 15 foot-pounds for A36 or A572 steel.

Table 5.4: Results of Charpy Testing

Heat Description	Temperature at 15 ft-lbs (F)	Temperature at Upper Shelf (F)
3/8" Gr. 36	-38	70
1/2" Gr. 36	-32	70
3/4" Gr. 36	-40	80
1/2" Gr. 36 (S)	18	90
3/8" Gr. 50	-62	40
1/2" Gr. 50	-44	80
3/4" Gr. 50	0	80
1/2" Gr. 50 (S)	0	80
1/2" High C Gr. 55	-8	70

*(S) = Shear Cut Heat

5.4 NOTES ON CHEMISTRY, COUPON, AND CHARPY INVESTIGATIONS

Although the eight test investigations studied specific parameters such as steel type, plate thickness, and hole size, to name a few, basic material properties may have also played a significant role in the performance of the plates. As previously shown, chemistry, coupon, and Charpy testing was completed for each plate heat used for specimen testing. For each type of material, these tests specifically revealed chemistry composition, yield strength, ultimate strength, percent elongation, and hardness characteristics. In the following three sections, chemistry, coupon tensile strength, and Charpy "outlier" plate heats are noted along with observed performance differences of these plate heats during tensile testing. Note that these tensile testing performance differences may be attributed to these plate heat characteristics or to the specific parameters that were examined during the investigations.

5.4.1 Chemistry Considerations

Whereas chemistry results for six of the nice plate heats were somewhat similar, those for the three remaining plate heats varied to some extent. All plate heats designated as grade 36 or grade 50 met steel chemistry specifications according to both sets of chemistry testing that were completed. The following three plate heats were the chemistry "outliers":

- 1/2 Inch Thickness Grade 36 Sheared
- 1/2 Inch Thickness Grade 50 Sheared
- 1/2 Inch Thickness High Carbon Grade 55

5.4.2 Influence of Coupon Tensile Strength Characteristics

All plate heats designated as grade 36 or grade 50 met steel material specifications according to both sets of testing that were completed. Whereas all plate heats designated as grade 36 showed similar coupon strength performance, one of the plate heats designated as grade 50 differed from the other three grade 50 plate heats in strength performance. The following plate heat was the coupon "outlier":

- 1/2 Inch Thickness Grade 50 Sheared

5.4.3 Influence of Notch Toughness Characteristics

During Charpy testing, four plate heats displayed notably lower notch toughness characteristics relative to the other five plate heats. The following four plate heats were the Charpy "outliers":

- 1/2 Inch Thickness Grade 36 Sheared
- 3/4 Inch Thickness Grade 50
- 1/2 Inch Thickness Grade 50 Sheared
- 1/2 Inch Thickness High Carbon Grade 55

5.5 STEEL TYPE AND TEMPERATURE INVESTIGATION

Tensile results of specimens from the steel type and temperature test matrix are shown in Tables 5.5 through 5.7. Tabular results in the sections that follow are generally separated by punched and drilled hole preparation, and then more specifically separated by specific investigation parameters. Tables 5.5 through 5.7 display test results from room temperature, aged, cold temperature, and aged and cold temperature specimens. Net section stress was determined by dividing the specimen's ultimate load during testing by its measured net area.

Strength ratio was determined by dividing the specimen's net section stress by the specimen heat's ultimate stress as determined by FSEL coupon testing. Neither of these calculations used resistance factors or the addition of an extra 1/16 inch to hole size as in the AASHTO LRFD Bridge Design Specifications (previously discussed in section 2.3). Lastly, usable elongation was determined by finding the specimen's elongation at its ultimate load during testing. The net section stress, strength ratio, and usable elongation values at failure are reported for each specimen as shown.

Table 5.5: Steel Type and Temperature Investigation Results (Grade 36, 1/2 Inch Thickness, 15/16 Inch Diameter Hole Size)

Grade 36 Specimens:

Method	Temperature	Net Section Stress[1] (ksi)	Strength Ratio[2]	Usable Elongation[3] (in.)
Punched	Room	63.8	0.91	0.347
	Room	68.3	0.98	0.349
	Aged	65.3	0.93	0.361
	Cold	66.9	0.96	0.375
	Aged and Cold	68.4	0.98	0.351
Drilled	Room	74.7	1.07	1.576
	Room	74.8	1.07	1.468
	Aged	74.4	1.06	1.508
	Cold	79.7	1.14	1.862
	Aged and Cold	79.7	1.14	1.818

1 - Net Section Stress = $\sigma_{ult} = P_{ult}/A_{net}$
2 - Strength Ratio $S_R = \sigma_{ult}/\sigma_{u,\ coupon}$
3 - Usable Elongation = δ at P_{ult}

Table 5.6: Steel Type and Temperature Investigation Results (Grade 50, 1/2 Inch Thickness, 15/16 Inch Diameter Hole Size)

Grade 50 Specimens:

Method	Temperature	Net Section Stress[1] (ksi)	Strength Ratio[2]	Usable Elongation[3] (in.)
Punched	Room	78.4	1.04	0.586
	Room	80.0	1.06	0.416
	Aged	77.8	1.03	0.484
	Cold	81.7	1.08	0.534
	Aged and Cold	80.8	1.07	0.464
Drilled	Room	82.4	1.09	1.096
	Room	85.2	1.13	1.073
	Aged	83.3	1.10	1.077
	Cold	88.3	1.17	1.339
	Aged and Cold	88.7	1.18	1.635

1 - Net Section Stress = $\sigma_{ult} = P_{ult}/A_{net}$
2 - Strength Ratio $S_R = \sigma_{ult}/\sigma_{u,\ coupon}$
3 - Usable Elongation = δ at P_{ult}

Table 5.7: Steel Type and Temperature Investigation Results (Grade 55, 1/2 Inch Thickness, 15/16 Inch Diameter Hole Size)

High Carbon Grade 55 Specimens:

Method	Temperature	Net Section Stress[1] (ksi)	Strength Ratio[2]	Usable Elongation[3] (in.)
Punched	Room	79.9	0.94	0.362
Drilled	Room	88.5	1.04	1.105

1 - Net Section Stress = $\sigma_{ult} = P_{ult}/A_{net}$
2 - Strength Ratio $S_R = \sigma_{ult}/\sigma_{u,\ coupon}$
3 - Usable Elongation = δ at P_{ult}

A summary of tensile results from the steel type and temperature test matrix is shown in Table 5.8. Tabular summary results in the sections that follow are generally separated by punched and drilled hole preparation, and then more specifically separated by specific investigation parameters. The average strength ratio and average usable elongation values at failure are reported for each set of specimens as shown.

Table 5.8: Steel Type and Temperature Investigation Results Summary (1/2 Inch Thickness, 15/16 Inch Diameter Hole)

Method	Steel Grade	Avg. Strength Ratio[1]	Avg. Usable Elongation[2] (in.)
Punched	36	0.95	0.357
	50	1.06	0.497
	55	0.94	0.362
Drilled	36	1.10	1.646
	50	1.13	1.244
	55	1.04	1.105

1 - Strength Ratio $S_R = \sigma_{ult}/\sigma_{u,\ coupon}$
2 - Usable Elongation = δ at P_{ult}

As shown in Table 5.8, punched hole specimens of each of the three grades of steel tested had a smaller average strength ratio and average usable elongation relative to their drilled hole replicates. The difference between punched and drilled hole performance was most notable in the grade 36 specimens.

The 1/2 inch high carbon grade 55 plate heat differed from other plate heats in that it had a higher carbon composition (0.22%). During testing, the 1/2 inch high carbon grade 55 plate exhibited an equivalent or lower average strength ratio and average usable elongation relative to the 1/2 inch grade 36 plate. This difference was most notable with the drilled hole specimen testing. In addition, the 0.22% carbon 1/2 inch high carbon grade 55 plate exhibited a lower average strength ratio and an equivalent or lower average usable elongation relative to the 0.13% carbon 1/2 inch grade 50 plate. This difference was most notable with both the punched and drilled hole specimen testing.

5.6 ROOM TEMPERATURE TENSILE OBSERVATIONS

These general trends of lower strength and less elongation of punched hole specimens relative to drilled hole replicate specimens may be seen quantitatively in the load versus displacement plot in Figure 5.1. Note that varying amounts of slip occurred at the beginning of the tests; thus, elongations have been adjusted accordingly. These replicate 1/2 inch thickness, 15/16 inch diameter hole, grade 50 punched and drilled specimens fractured at 159.3 kips and 169.2 kips, respectively. Additionally, the usable elongation of these replicate punched and drilled specimens were 0.748 inches and 1.103 inches, respectively.

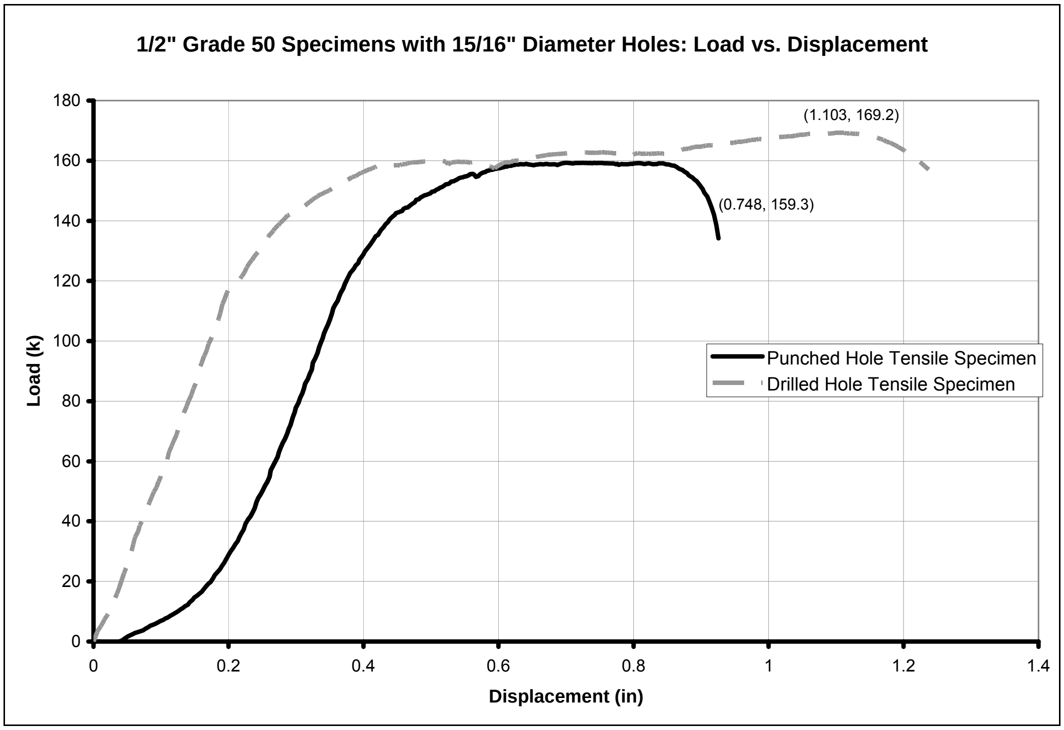

Figure 5.1: Load versus Displacement Comparison of Similar Punched and Drilled Hole Specimens

As shown in Tables 5.5 through 5.7, specimens with punched hole preparation generally failed at a lower net section stress, strength ratio, and usable elongation relative to their drilled hole replicates. A typical start-to-finish progression of a punched hole specimen failing in tension is illustrated in Figures 5.2 through 5.4. First, as shown by a reduction in net area (i.e. thickness reduction, necking of net section) and an elongation of the holes, the specimen would yield at the net section (Figure 5.2). Then as the ultimate load approached, cracking would typically initiate from a hole and continue outward until fracture occurred at the edge (Figure 5.2). After this occurred, fracture generally propagated through the middle of the net section (Figure 5.3) which would result in a complete fracture failure (Figure 5.4). As shown by Figure 5.4, which were replicate 3/4 inch thickness, 15/16 inch diameter hole, grade 50 punched and drilled specimens, it may be seen that typical punched hole specimen failures were less ductile than typical drilled hole specimen failures. Due to this difference in ductility, the punched hole specimen underwent less plastic strain than its drilled hole replicate. Most notably, there was less thickness reduction and necking of the net section in the punched specimens relative to the drilled specimens.

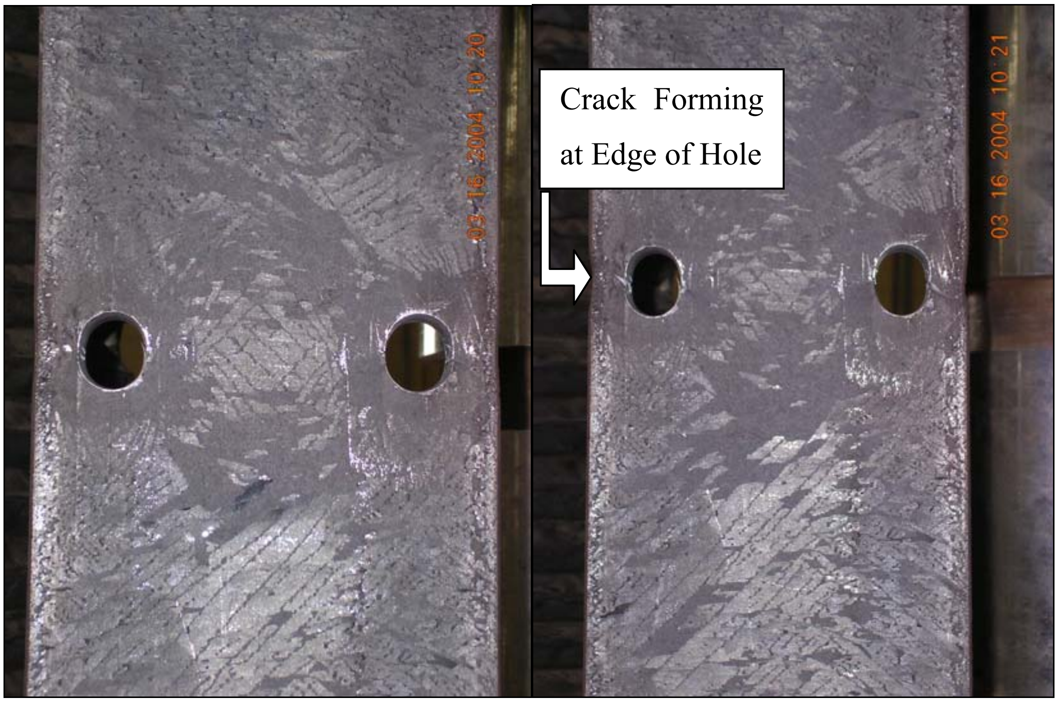

Figure 5.2: Punched Hole Specimen Yielding and Initial Fracture

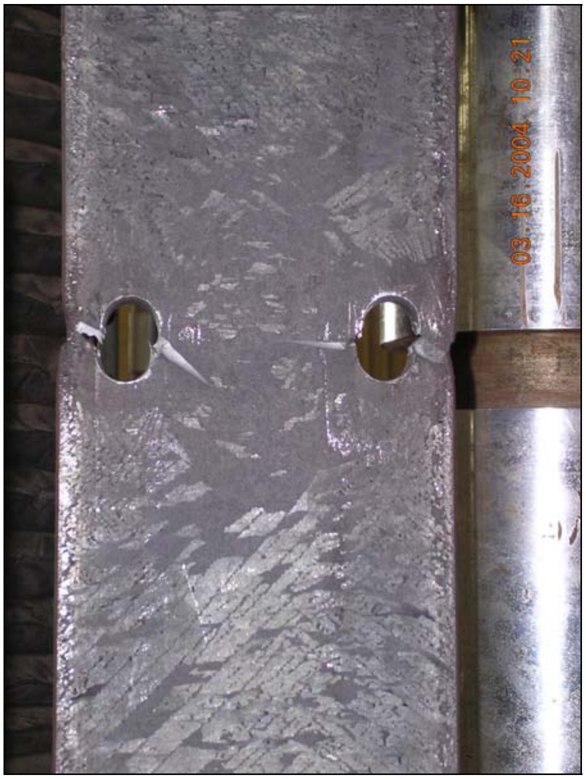

Figure 5.3: Punched Hole Specimen Progression of Fracture

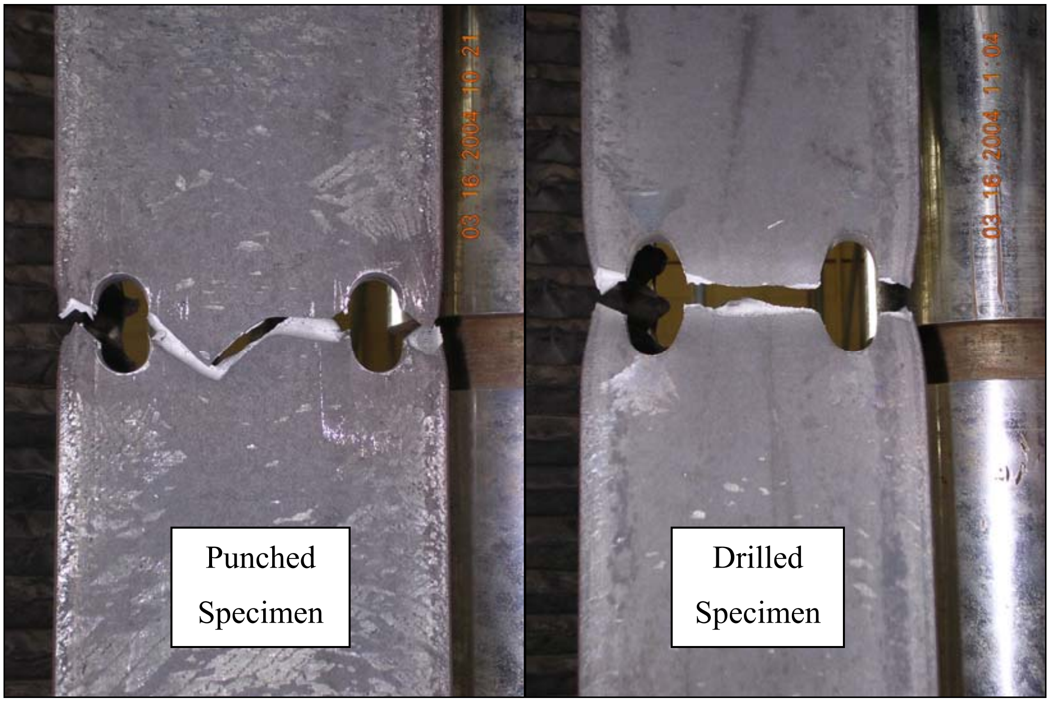

Figure 5.4: Fractured Punched Hole and Drilled Hole Specimens

This difference in ductility is also shown by viewing the fracture surfaces of punched and drilled hole specimens in Figures 5.5 through 5.7. Again, punched hole specimen surfaces had a rougher, more brittle fracture appearance relative to the fracture surfaces of drilled hole specimens. Of note, the fracture surface at the hole is rougher in those specimens with punched holes. These punched hole fracture surfaces did not appear to be influenced by the changes in clearance and punching operations examined in this study. In addition, it may be seen that the drilled hole specimens experienced a visibly noticeable larger reduction in area prior to failure. The cross-sections of those specimens that were prepared with reamed holes appeared very similar to those prepared with drilled holes.

Moreover, Figure 5.5 show replicate 3/4 inch thickness, 15/16 inch diameter hole, grade 50 punched and drilled specimens. The strength ratios for this punched and drilled replicate pair were 1.07 and 1.08, respectively, and the usable elongations were 0.558 and 1.110, respectively. Similarly, Figures 5.6 and 5.7 show replicate 3/8 inch thickness, 15/16 inch diameter hole, grade 50 punched and drilled specimens. The strength ratios for this punched and drilled replicate pair were 0.97 and 1.06, respectively, and the usable elongations were 0.469 and 1.058, respectively.

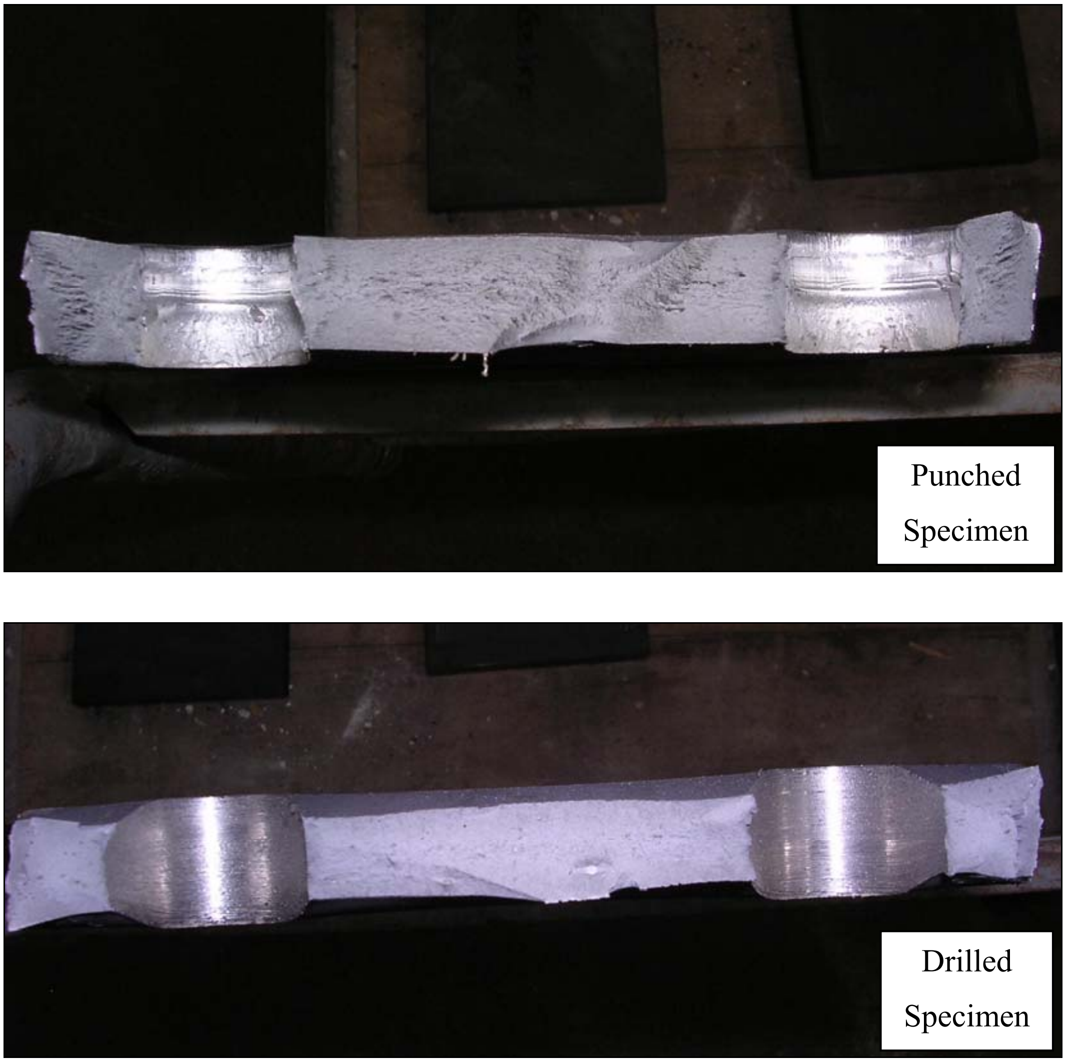

Figure 5.5: Typical Punched and Drilled Hole Fracture Cross-Sections (3/4 Inch Thickness, 15/16 Inch Diameter Hole, Grade 50)

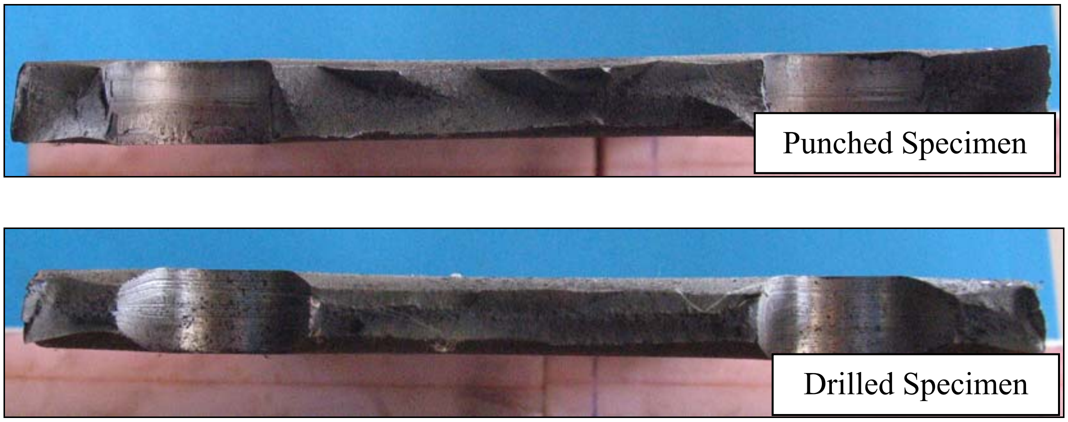

Figure 5.6: Typical Punched and Drilled Hole Fracture Cross-Sections (3/8 Inch Thickness, 15/16 Inch Diameter Hole, Grade 50)

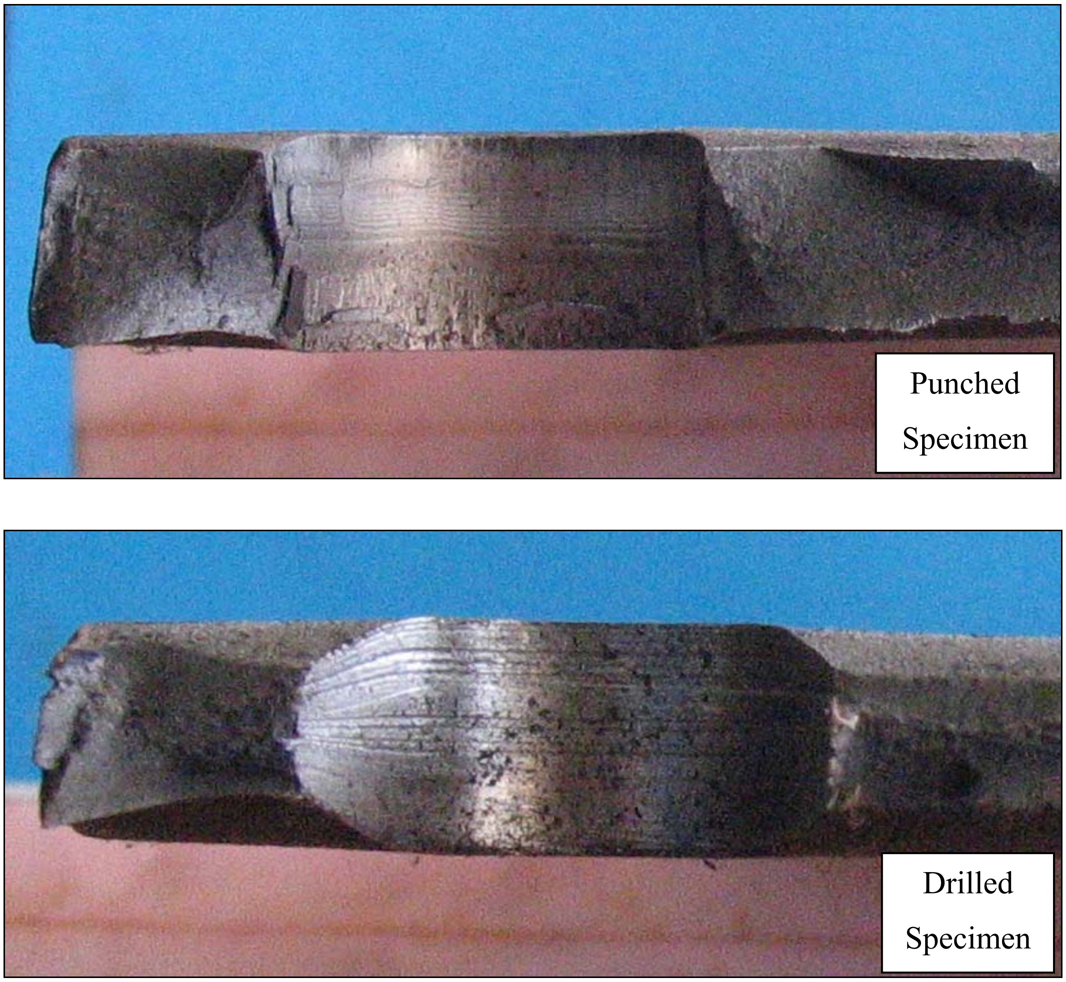

Figure 5.7: Close-Up of Typical Punched and Drilled Hole Fracture Cross-Sections (3/8 Inch Thickness, 15/16 Inch Diameter Hole, Grade 50)

5.7 HOLE SIZE AND PLATE THICKNESS INVESTIGATION

Tensile results of specimens from the hole size and plate thickness test matrix are shown in Tables 5.9 and 5.10. These tables display test results from 3/8, 1/2, and 3/4 inch thickness specimens with either 11/16, 13/16, or 15/16 inch hole sizes. Note that specimens of different thicknesses are from different plate heats and have AASHTO specified minimum edge distances for that particular thickness (e.g. 7/8, 1, and 1-1/8 inch edge distance for 11/16, 13/16, and 15/16 inch diameter holes).

Table 5.9: Hole Size and Plate Thickness Investigation Results (Grade 36)

Grade 36 Specimens:

Method	Thickness (in.)	Hole Size (in.)	Hole Size/ Thickness Ratio	Net Section Stress[1] (ksi)	Strength Ratio[2]	Usable Elongation[3] (in.)
Punched	3/8	11/16	1.83	62.4	0.88	0.405
		13/16	2.17	65.2	0.92	0.365
		15/16	2.50	69.6	0.98	0.404
	1/2	11/16	1.38	61.5	0.88	0.946
		13/16	1.63	63.8	0.91	0.360
		15/16	1.88	63.8	0.91	0.347
	3/4	13/16	1.08	64.5	0.98	1.246
		15/16	1.25	64.6	0.98	0.579
Drilled	3/8	11/16	1.83	74.0	1.04	1.838
		13/16	2.17	75.5	1.07	1.568
		15/16	2.50	75.3	1.06	1.345
	1/2	11/16	1.38	72.2	1.03	1.889
		13/16	1.63	73.7	1.05	1.694
		15/16	1.88	74.7	1.07	1.468
	3/4	13/16	1.08	72.6	1.11	2.013
		15/16	1.25	72.7	1.11	1.774

1 - Net Section Stress = $\sigma_{ult} = P_{ult}/A_{net}$
2 - Strength Ratio $S_R = \sigma_{ult}/\sigma_{u,\ coupon}$
3 - Usable Elongation = δ at P_{ult}

Table 5.10: Hole Size and Plate Thickness Investigation Results (Grade 50)

Grade 50 Specimens:

Method	Thickness (in.)	Hole Size (in.)	Hole Size/ Thickness Ratio	Net Section Stress[1] (ksi)	Strength Ratio[2]	Usable Elongation[3] (in.)
Punched	3/8	11/16	1.83	79.6	1.01	1.198
		13/16	2.17	80.4	1.03	0.940
		15/16	2.50	76.2	0.97	0.469
	1/2	11/16	1.38	76.3	1.01	1.138
		13/16	1.63	75.1	0.99	0.484
		15/16	1.88	78.4	1.04	0.586
	3/4	13/16	1.08	85.3	1.02	1.038
		15/16	1.25	89.0	1.07	0.558
Drilled	3/8	11/16	1.83	81.9	1.04	1.611
		13/16	2.17	81.9	1.04	1.243
		15/16	2.50	83.4	1.06	1.058
	1/2	11/16	1.38	81.8	1.08	1.769
		13/16	1.63	83.9	1.11	1.316
		15/16	1.88	82.4	1.09	1.096
	3/4	13/16	1.08	91.9	1.10	1.254
		15/16	1.25	90.3	1.08	1.110

1 - Net Section Stress = $\sigma_{ult} = P_{ult}/A_{net}$
2 - Strength Ratio $S_R = \sigma_{ult}/\sigma_{u,\ coupon}$
3 - Usable Elongation = δ at P_{ult}

As shown in Tables 5.9 and 5.10, punched hole specimens of various hole size to plate thickness ratios had a smaller strength ratio and usable elongation relative to their drilled hole replicates. This was true for both grades of steel examined. Note that different plate heats were utilized in this investigation for each grade and thickness; thus, there may be performance differences depending on specimen plate heat. In all specimen heats other than the 3/8 inch grade 36 plate, test results showed no correlation between hole size to plate thickness ratio and strength ratio. Test results did show correlation between an increase in hole size to plate thickness ratio and a decrease in usable elongation for both punched and drilled plates.

A summary of tensile test results from the hole size and plate thickness test matrix is shown in Table 5.11, arranged with respect to plate thickness.

Table 5.11: Plate Thickness Investigation Summary (11/16, 13/16, and 15/16 Inch Diameter Holes)

Method	Steel Grade	Thickness (in.)	Hole Sizes (in.)	Avg. Strength Ratio[1]	Avg. Usable Elongation[2] (in.)
Punched	36	3/8	11/16,13/16,15/16	0.93	0.391
		1/2	11/16,13/16,15/16	0.90	0.551
		3/4	13/16,15/16	0.98	0.913
	50	3/8	11/16,13/16,15/16	1.00	0.869
		1/2	11/16,13/16,15/16	1.01	0.736
		3/4	13/16,15/16	1.05	0.798
Drilled	36	3/8	11/16,13/16,15/16	1.06	1.584
		1/2	11/16,13/16,15/16	1.05	1.684
		3/4	13/16,15/16	1.11	1.894
	50	3/8	11/16,13/16,15/16	1.05	1.304
		1/2	11/16,13/16,15/16	1.09	1.394
		3/4	13/16,15/16	1.09	1.182

1 - Strength Ratio $S_R = \sigma_{ult}/\sigma_{u,\ coupon}$
2 - Usable Elongation = δ at P_{ult}

Table 5.11 shows punched hole specimens of each of the three plate thicknesses (with three different hole sizes) tested having a smaller average strength ratio and average usable elongation relative to their drilled hole replicates. This was also true for both grades of steel examined. Test results tended to show a slight correlation between increasing average strength ratio with an increase in plate thickness.

Note that the 3/4 inch grade 50 plate had an equivalent average strength ratio and average usable elongation that was similar to the other thickness grade 50 plates. In comparison, the 3/4 inch grade 36 plate exhibited a higher average strength ratio and average usable elongation relative to the other thickness grade 36 plates.

5.8 EDGE DISTANCE AND PREPARATION INVESTIGATION

Tensile results of specimens from the edge distance and preparation test matrix are shown in Tables 5.12 and 5.13. These tables display test results from flame cut and sheared edge prepared specimens with either standard or larger edge spacing. Note that one of the flame cut, standard spacing specimen sets was fabricated from the same heat as the sheared plate (e.g. shear match, or SM, designation is used for the edge preparation comparison). These matched plates, from the same plate heat, are noted in italics in the tables.

Table 5.12: Edge Distance and Preparation Investigation Results (Grade 36, 1/2 Inch Thickness, 15/16 Inch Diameter Hole Size)

Grade 36 Specimens:

Method	Edge Prep.	Edge Spacing (in.)	Net Section Stress[1] (ksi)	Strength Ratio[2]	Usable Elongation[3] (in.)
Punched	Flame Cut	Standard (1-1/8)	63.8	0.91	0.347
		Larger (1-1/4)	65.8	0.94	0.389
		Standard SM (1-1/8)	62.9	1.01	1.072
	Sheared	*Standard (1-1/2)*	62.8	1.01	1.162
Drilled	Flame Cut	Standard (1-1/8)	74.7	1.07	1.468
		Larger (1-1/4)	72.5	1.04	1.383
		Standard SM (1-1/8)	68.4	1.10	1.485
	Sheared	*Standard (1-1/2)*	67.7	1.09	1.609

1 - Net Section Stress = $\sigma_{ult} = P_{ult}/A_{net}$

2 - Strength Ratio $S_R = \sigma_{ult}/\sigma_{u,\ coupon}$

3 - Usable Elongation = δ at P_{ult}

Note: SM = Shear Match

Table 5.13: Edge Distance and Preparation Investigation Results (Grade 50, 1/2 Inch Thickness, 15/16 Inch Diameter Hole Size)

Grade 50 Specimens:

Method	Edge Prep.	Edge Spacing	Net Section Stress^1 (ksi)	Strength Ratio^2	Usable Elongation^3 (in.)
Punched	Flame Cut	Standard (1-1/8)	78.4	1.04	0.586
		Larger (1-1/4)	79.1	1.05	0.479
		Standard SM (1-1/8)	88.7	1.12	0.334
	Sheared	*Standard (1-1/2)*	88.4	1.12	0.354
Drilled	Flame Cut	Standard (1-1/8)	82.4	1.09	1.096
		Larger (1-1/4)	80.2	1.06	0.521
		Standard SM (1-1/8)	89.3	1.13	0.427
	Sheared	*Standard (1-1/2)*	86.6	1.09	0.375

1 - Net Section Stress = $\sigma_{ult} = P_{ult}/A_{net}$
2 - Strength Ratio $S_R = \sigma_{ult}/\sigma_{u,\ coupon}$
3 - Usable Elongation = δ at P_{ult}

Note: SM = Shear Match

As shown in these tables, punched hole specimens with both standard and larger edge distances had a smaller strength ratio and usable elongation relative to their drilled hole replicates. This was true for both grades of steel examined, even though the grade 36 sheared and shear match plate showed large usable elongation. Again, note that two different plate heats were utilized in this investigation; thus, there may be performance differences depending on specimen plate heat. Test results showed no significant correlation between edge distance and strength ratio or usable elongation.

Furthermore, punched hole specimens with both flame cut and sheared edges had a smaller or equivalent strength ratio and usable elongation when compared to their drilled hole replicates. This was true for both grades of steel examined. Test results tended to show no significant correlation between edge preparation and strength ratio or usable elongation.

The 1/2 inch thickness grade 36 sheared plate heat generally differed from other plate heats in that it had a higher carbon composition (0.22%) and a lower percentage composition of alloys such as silicon (<0.01%), nickel (0.01%), chromium (0.03%), and copper (0.03%). During testing, the 0.22% carbon 1/2 inch grade 36 shear plate with edges flame cut off (i.e. plate designated as "shear match" in edge preparation investigation) exhibited an equivalent or higher average strength ratio and average usable elongation relative to the 0.16% carbon 1/2 inch grade 36 plate. This improvement was most notable with the punched hole specimen testing.

The 1/2 inch thickness grade 50 sheared plate heat generally differed from other plate heats in that it had a lower carbon composition (0.05%) and a lower percentage composition of alloys such as sulfur (0.006%) and chromium (0.07%). During testing, the 0.05% carbon 1/2 inch grade 50 shear plate with edges flame cut off (i.e. plate designated as "shear match" in edge preparation investigation) exhibited a higher average strength ratio and a lower average usable elongation relative to the 0.13% carbon 1/2 inch grade 50 plate. This difference was most notable with the drilled hole specimen testing.

5.9 PUNCHING CLEARANCE INVESTIGATION

Tensile results of specimens from the punching clearance test matrix are shown in Tables 5.14 and 5.15. These tables display test results from 11/16 and 15/16 inch hole size specimens with either recommended or larger clearances. These clearances were obtained by changing the die size (e.g. larger clearance was recommended clearance plus 1/8 inch) while keeping the punch size constant, as discussed in section 3.2.4.

Table 5.14: Punching Clearance Investigation Results (Grade 36, 1/2 Inch Thickness)

Grade 36 Specimens:

Method	Hole Size	Clearance (in.)	Net Section Stress^1 (ksi)	Strength Ratio^2	Usable Elongation^3 (in.)
Punched	11/16	Recommended (1/32)	61.5	0.88	0.946
		Larger (3/32)	60.8	0.87	0.429
	15/16	Recommended (1/32)	63.8	0.91	0.347
		Larger (3/32)	67.2	0.96	0.362

1 - Net Section Stress = $\sigma_{ult} = P_{ult}/A_{net}$

2 - Strength Ratio $S_R = \sigma_{ult}/\sigma_{u,\ coupon}$

3 - Usable Elongation = δ at P_{ult}

Table 5.15: Punching Clearance Investigation Results (Grade 50, 1/2 Inch Thickness)

Grade 50 Specimens:

Method	Hole Size	Clearance	Net Section Stress^1 (ksi)	Strength Ratio^2	Usable Elongation^3 (in.)
Punched	11/16	Recommended (1/32)	76.3	1.01	1.138
		Larger (3/32)	79.1	1.05	1.136
	15/16	Recommended (1/32)	78.4	1.04	0.586
		Larger (3/32)	78.8	1.04	0.452

1 - Net Section Stress = $\sigma_{ult} = P_{ult}/A_{net}$

2 - Strength Ratio $S_R = \sigma_{ult}/\sigma_{u,\ coupon}$

3 - Usable Elongation = δ at P_{ult}

A summary of tensile results from the punching clearance test matrix is shown in Table 5.16.

Table 5.16: Punching Clearance Investigation Summary (1/2 Inch Thickness)

Method	Steel Grade	Clearance (in.)	Avg. Strength Ratio^1	Avg. Usable Elongation^2 (in.)
Punched	36	Recommended (1/32)	0.90	0.647
		Larger (3/32)	0.92	0.396
	50	Recommended (1/32)	1.03	0.862
		Larger (3/32)	1.05	0.794

1 - Strength Ratio $S_R = \sigma_{ult}/\sigma_{u,\ coupon}$

2 - Usable Elongation = δ at P_{ult}

As shown in Table 5.16, test results tended to show no significant correlation between average strength ratio and amount of clearance, but a correlation between decreasing average usable elongation with an increase in clearance. This was true for both grades of steel examined.

5.10 PUNCHING OPERATION INVESTIGATION

Tensile results of specimens from the punching operation test matrix are shown in Table 5.17. This table displays results from FSEL and AIW punched specimens that were tested in either room or cold temperatures.

Table 5.17: Punching Operation Investigation Results (Grade 50, 15/16 Inch Diameter Hole Size)

Grade 50 Specimens:

Method	**Location**	**Temperature**	**Thickness (in.)**	**Net Section Stress[1] (ksi)**	**Strength Ratio[2]**	**Usable Elongation[3] (in.)**
Punched	FSEL	Room	3/8	76.2	0.97	0.469
			1/2	78.4	1.04	0.586
			3/4	89.0	1.07	0.558
		Cold	1/2	81.7	1.08	0.534
	AIW	Room	3/8	81.0	1.03	0.657
			1/2	80.2	1.03	0.454
			3/4	89.4	1.07	0.565
		Cold	1/2	82.3	1.09	0.472

1 - Net Section Stress = $\sigma_{ult} = P_{ult}/A_{net}$
2 - Strength Ratio $S_R = \sigma_{ult}/\sigma_{u,\,coupon}$
3 - Usable Elongation = δ at P_{ult}

A summary of tensile results from the punching operation test matrix is shown in Table 5.18.

Table 5.18: Punching Operation Investigation Summary (15/16 Inch Diameter Hole, Grade 50)

Method	Location	Avg. Strength Ratio[1]	Avg. Usable Elongation[2] (in.)
Punched	FSEL	1.04	0.537
	AIW	1.06	0.537

1 - Strength Ratio $S_R = \sigma_{ult}/\sigma_{u,\ coupon}$
2 - Usable Elongation = δ at P_{ult}

As shown in Table 5.18, test results tended to show no significant correlation between punching operation and average strength ratio or average usable elongation.

5.11 COLD TENSILE TESTING THICKNESS INVESTIGATION

Tensile results of specimens from the cold tensile test thickness matrix are shown in Tables 5.19 and 5.20. These tables display test results from cold temperature 3/8, 1/2 and 3/4 inch thickness specimens.

Table 5.19: Cold Tensile Testing Thickness Investigation Results (Grade 36, 15/16 Inch Diameter Hole Size)

Grade 36 Specimens:

Method	Thickness (in.)	Net Section Stress[1] (ksi)	Strength Ratio[2]	Room Temp. Strength Ratio[2]	Usable Elongation[3] (in.)	Room Temp. Usable Elongation[3] (in.)
Punched	3/8	72.0	1.02	0.98	0.405	0.404
	1/2	66.9	0.96	0.91	0.375	0.347
	3/4	69.3	1.05	0.98	1.174	0.579
Drilled	3/8	78.6	1.11	1.06	1.454	1.345
	1/2	79.7	1.14	1.07	1.862	1.468
	3/4	78.0	1.19	1.11	1.984	1.774

1 - Net Section Stress = $\sigma_{ult} = P_{ult}/A_{net}$
2 - Strength Ratio $S_R = \sigma_{ult}/\sigma_{u,\ coupon}$
3 - Usable Elongation = δ at P_{ult}

Table 5.20: Cold Tensile Testing Thickness Investigation Results (Grade 50, 15/16 Inch Diameter Hole Size)

Grade 50 Specimens:

Method	Thickness (in.)	Net Section Stress[1] (ksi)	Strength Ratio[2]	Room Temp. Strength Ratio[2]	Usable Elongation[3] (in.)	Room Temp. Usable Elongation[3] (in.)
Punched	3/8	83.2	1.06	0.97	0.496	0.469
	1/2	81.7	1.08	1.04	0.534	0.586
	3/4	91.7	1.10	1.07	0.580	0.558
Drilled	3/8	86.0	1.10	1.06	1.160	1.058
	1/2	88.3	1.17	1.09	1.339	1.096
	3/4	94.5	1.13	1.08	1.104	1.110

1 - Net Section Stress = $\sigma_{ult} = P_{ult}/A_{net}$
2 - Strength Ratio $S_R = \sigma_{ult}/\sigma_{u,\ coupon}$
3 - Usable Elongation = δ at P_{ult}

As shown in these tables, cold punched hole specimens of all three plate thicknesses had a smaller strength ratio and usable elongation relative to their drilled hole replicates. This was true for both grades of steel examined. Test results tended to show a slight correlation between increasing strength ratio with an increase in plate thickness.

In addition, cold punched hole specimens of all three plate thicknesses had a similar or larger strength ratio and usable elongation relative to their room temperature replicates. This was true for both grades of steel as shown in Tables 5.19 and 5.20.

5.12 GALVANIZING INVESTIGATION

Tensile results of specimens from the galvanizing test matrix are shown in Tables 5.21 and 5.22. These tables display room temperature test results from as received and galvanized specimens. Figure 5.8 shows a typical galvanized specimen failure with flaking of the galvanizing material on the plate following testing.

Table 5.21: Galvanizing Investigation Results (Grade 36, 3/8 Inch Thickness, 13/16 Inch Diameter Hole Size)

Grade 36 Specimens:

Method	Plate Prep.	Net Section Stress[1] (ksi)	Strength Ratio[2]	Usable Elongation[3] (in.)
Punched	As Received	66.1	0.95	0.348
	Galvanized	66.5	0.94	0.388
Drilled	As Received	74.8	1.07	1.522
	Galvanized	76.1	1.07	1.368

1 - Net Section Stress = $\sigma_{ult} = P_{ult}/A_{net}$

2 - Strength Ratio $S_R = \sigma_{ult}/\sigma_{u,\ coupon}$

3 - Usable Elongation = δ at P_{ult}

Table 5.22: Galvanizing Investigation Results (Grade 50, 3/8 Inch Thickness, 13/16 Inch Diameter Hole Size)

Grade 50 Specimens:

Method	Plate Prep.	Net Section Stress[1] (ksi)	Strength Ratio[2]	Usable Elongation[3] (in.)
Punched	As Received	79.2	1.05	0.501
	Galvanized	80.1	1.02	0.428
Drilled	As Received	83.8	1.11	1.085
	Galvanized	83.8	1.07	1.130

1 - Net Section Stress = $\sigma_{ult} = P_{ult}/A_{net}$

2 - Strength Ratio $S_R = \sigma_{ult}/\sigma_{u,\ coupon}$

3 - Usable Elongation = δ at P_{ult}

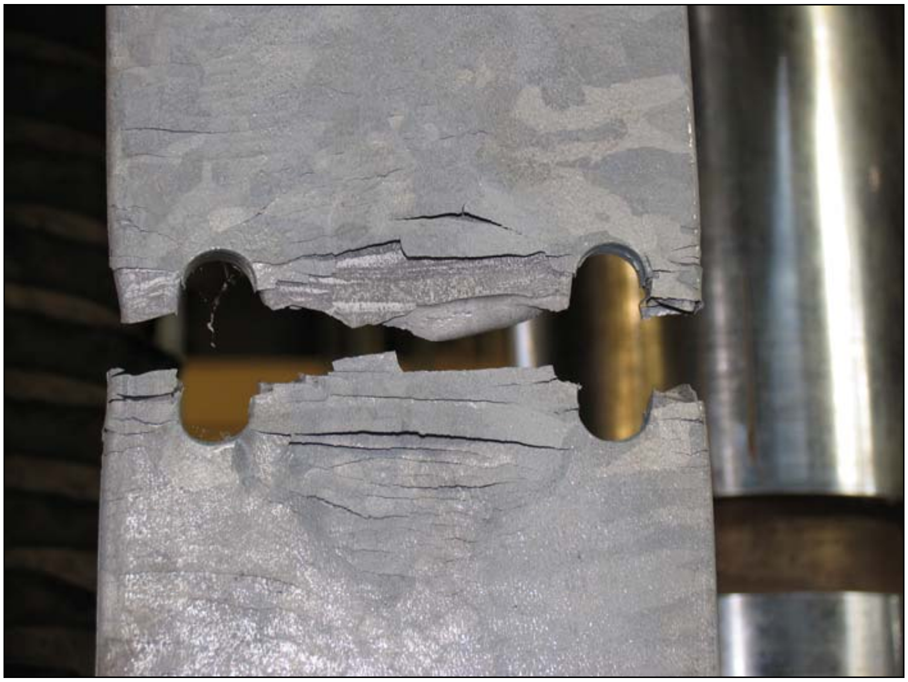

Figure 5.8: Typical Failure of Galvanized Specimen

As shown in Tables 5.21 and 5.22, punched hole specimens of both as received and galvanized plates had a smaller strength ratio and usable elongation relative to their drilled hole replicates. This was true for both grades of steel examined. Test results showed no significant correlation between galvanizing and strength ratio or usable elongation. In addition, galvanized specimens had a similar strength ratio and usable elongation relative to their non-galvanized replicates.

5.13 REAMING INVESTIGATION

Tensile results of specimens from the reaming test matrix are shown in Tables 5.23 and 5.24. These tables display test results from specimens that were reamed 1/16, 2/16, or 3/16 inches following punching. All finished holes had the same diameter of 15/16 inch.

Table 5.23: Reaming Investigation Results (Grade 36, 1/2 Inch Thickness, 15/16 Inch Diameter Hole Size)

Grade 36 Specimens:

Method	Punch Diameter and Amount of Reaming (in.)	Net Section Stress[1] (ksi)	Strength Ratio[2]	Usable Elongation[3] (in.)
Drilled	-	74.8	1.07	1.522
Reamed	3/4 and 3/16	76.6	1.10	1.449
	13/16 and 2/16	76.9	1.10	1.492
	7/8 and 1/16	78.2	1.12	1.521
Punched	-	66.1	0.95	0.348

1 - Net Section Stress = σ_{ult} = P_{ult}/A_{net}
2 - Strength Ratio S_R = $\sigma_{ult}/\sigma_{u,\ coupon}$
3 - Usable Elongation = δ at P_{ult}

Table 5.24: Reaming Investigation Results (Grade 50, 1/2 Inch Thickness, 15/16 Inch Diameter Hole Size)

Grade 50 Specimens:

Method	Punch Diameter and Amount of Reaming (in.)	Net Section Stress[1] (ksi)	Strength Ratio[2]	Usable Elongation[3] (in.)
Drilled	-	83.8	1.11	1.085
Reamed	3/4 and 3/16	86.3	1.14	1.035
	13/16 and 2/16	85.6	1.13	1.030
	7/8 and 1/16	86.1	1.14	1.065
Punched	-	79.2	1.05	0.501

1 - Net Section Stress = σ_{ult} = P_{ult}/A_{net}
2 - Strength Ratio S_R = $\sigma_{ult}/\sigma_{u,\ coupon}$
3 - Usable Elongation = δ at P_{ult}

Test results tended to show no significant correlation between amount of reaming and strength ratio or usable elongation. This was true for both grades of steel examined. Moreover, test results show strength ratio and usable elongation improvements from reaming relative to punching, and even relative to drilling.

5.14 FATIGUE INVESTIGATION

Both qualitative fatigue tests of punched and drilled holes in the same specimen failed through the punched hole net section of the plate. This type of specimen and its typical failure appearance in fatigue is shown in Figures 5.9 and 5.10, respectively. Fracture typically originated at the outside of the hole closest to the plate edge as exhibited in Figure 5.11. Figure 5.12 shows the fracture surface of the plate and a crack emanating from the punched hole damage zone following fatigue fracture failure.

Figure 5.9: Punched and Drilled Fatigue Specimen

Figure 5.10: Typical Failed Fatigue Specimen

Figure 5.11: Profile Close-Up of Fatigue Crack

Figure 5.12: Close-Up of Fatigue Crack Fracture Surface

To further study the effects of punching on fatigue performance, many tests are currently in progress at the FSEL as of 2005. These fatigue tests are investigating the effects of many of those parameters studied in the tensile testing including, but not limited to, grade of steel, plate thickness, hole size, edge preparation and distance, galvanizing, and reaming.

5.15 SUMMARY OF TENSILE TEST RESULTS

Sixty-six (66) plates with punched holes, 46 plates with drilled holes, and 6 plates with punched and reamed holes were tested during this study and the net section stress, strength ratio, and usable elongation values at failure were determined for each specimen. A summary of the tensile strength and usable elongation of these specimens follows.

The following current AASHTO LRFD Bridge Design Specifications sections were utilized in analyzing specimens (note that all reduction and resistance factors were taken as 1.0 since only the method of hole preparation was being compared):

- 6.8.2 Tensile Resistance

$$P_r = \phi_y P_{ny} = \phi_y F_y A_g \tag{6.1}$$

$$P_r = \phi_u P_{nu} = \phi_u F_u A_n U \tag{6.2}$$

where P_{ny} = nominal tensile resistance for yielding in gross section

F_y = yield strength based on coupon tests

A_g = gross cross-sectional area of the member

P_{nu} = nominal tensile resistance for fracture in net section

F_u = tensile strength based on coupon tests

A_n = net area of the member as specified in Section 6.8.3

U = reduction factor to account for shear lag (U = 0.85 for these connections, taken as 1.0 in this comparison of results)

ϕ_y = resistance factor for yielding of tension members (taken as 1.0 in this comparison of results)

ϕ_u = resistance factor for fracture of tension members (taken as 1.0 in this comparison of results)

- 6.8.3 Net Area

  Net area, A_n, of a member is the sum of the products of thickness and the smallest net width of each element. The width of each standard bolt hole shall be taken as the nominal diameter of the hole plus 1/16 inch (taken as actual hole diameter in all net section calculations in this analysis).

  The net width for each chain shall be determined by subtracting from the width of the element the sum of the widths of all holes in the chain and adding the quantity $s^2/4g$ for each space between consecutive holes in the chain, where:

  s = pitch of any two consecutive holes
  g = gage of the same two holes

- 6.13.4 Block Shear Rupture Resistance

  If $A_{tn} \geq 0.58\ A_{vn}$, then:

  $$R_r = \phi_{bs}\left(0.58 F_y A_{vg} + F_u A_{tn}\right) \tag{6.3}$$

  otherwise:

  $$R_r = \phi_{bs}\left(0.58 F_u A_{vn} + F_y A_{tg}\right) \tag{6.4}$$

  where A_{vg} = gross area along the plane resisting shear stress
  A_{vn} = net area along the plane resisting shear stress
  A_{tg} = gross area along the plane resisting tension stress
  A_{tn} = net area along the plane resisting tension stress
  F_y = specified minimum yield strength of the connected material
  F_u = specified minimum tensile strength of the connection material
  ϕ_{bs} = resistance factor for block shear (not used in order to obtain the most accurate comparisons)

- 6.13.5 Connection Elements

  The factored resistance in tension shall be taken as the least of the values given by Section 6.8.2 for yielding and fracture, respectively, or the block shear rupture resistance specified in Section 6.13.4.

Using these specification details on the specimens, a current specification limit state was calculated based on a governing tension (yield or fracture) failure or a block shear (shear or tension) failure. Note that the nominal hole diameter used was that which was measured following hole preparation (i.e. measured hole diameter was used instead of a nominal bolt diameter plus 1/8 inch).

In compiling all test data, a comparison between the FSEL specimen experimental strength limit state versus the current AASHTO Design specification strength limit state is illustrated in Figure 5.13. The 45 degree line shown in the plot signifies equal experimental and specification limit states. Whereas points above this line indicate experimental results that exceed specification limits, points below this line indicate experimental results that are lower than specification limits. Points falling below this line signify non-conservative specification limit states. As seen in Figure 5.13, the drilled and reamed hole specimens generally performed better than the punched hole specimens, 43% of which fell below the 45 degree line.

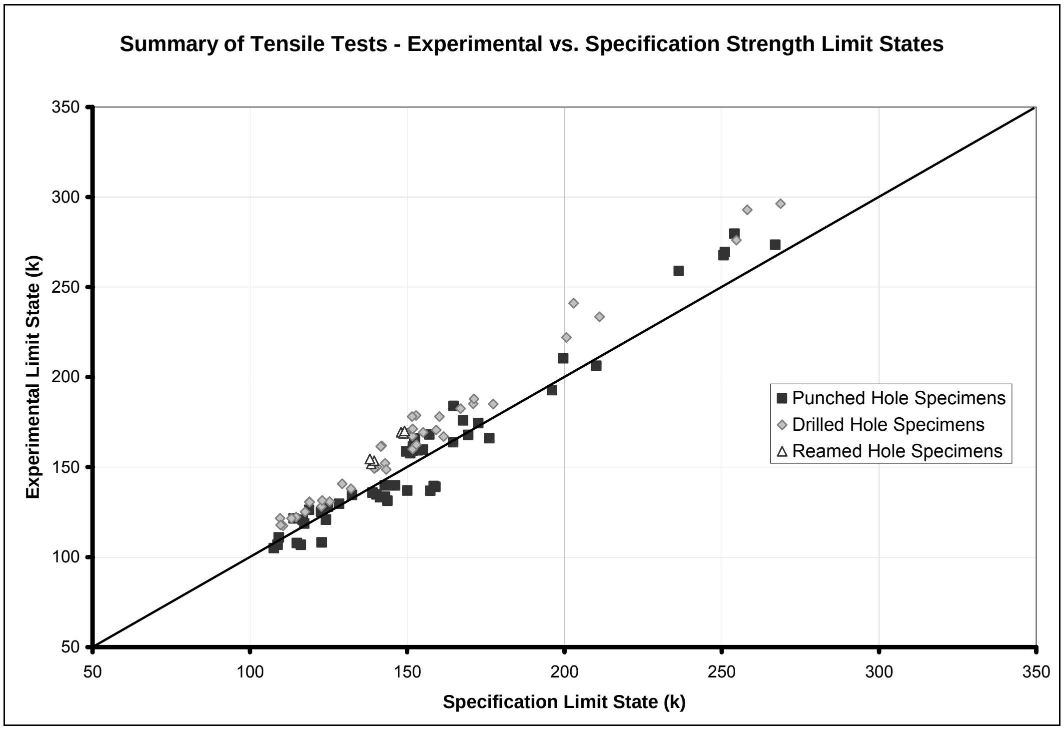

Figure 5.13: Experimental versus Specification Strength Limit State Summary of Tensile Tests

The average strength ratio (i.e. $\sigma_{ult}/\sigma_{u,\ coupon}$) and standard deviation of the strength ratio data for each specimen preparation type is displayed in Table 5.25. It may be seen that in strength performance, reamed specimens had the highest average ratio, followed by drilled and then punched specimens. Similarly, reamed specimens had the lowest variance, or standard deviation, followed by drilled and then punched specimens.

Table 5.25: Average Strength Ratio and Standard Deviation by Preparation

Method	No. of Specimens	Avg. Strength Ratio[1]	Std. Deviation
Punched	66	1.00	0.065
Drilled	46	1.09	0.038
Reamed	6	1.12	0.021

1 - Strength Ratio $S_R = \sigma_{ult}/\sigma_{u,\ coupon}$

A histogram displaying the usable elongations for the specimens tested is shown in Figure 5.14. Note that the plates with punched holes had significantly smaller usable elongations relative to plates with drilled and reamed holes. All usable elongations were measured from similar 48 inch specimens that all had a grip-to-grip length of 24 inches during tensile testing.

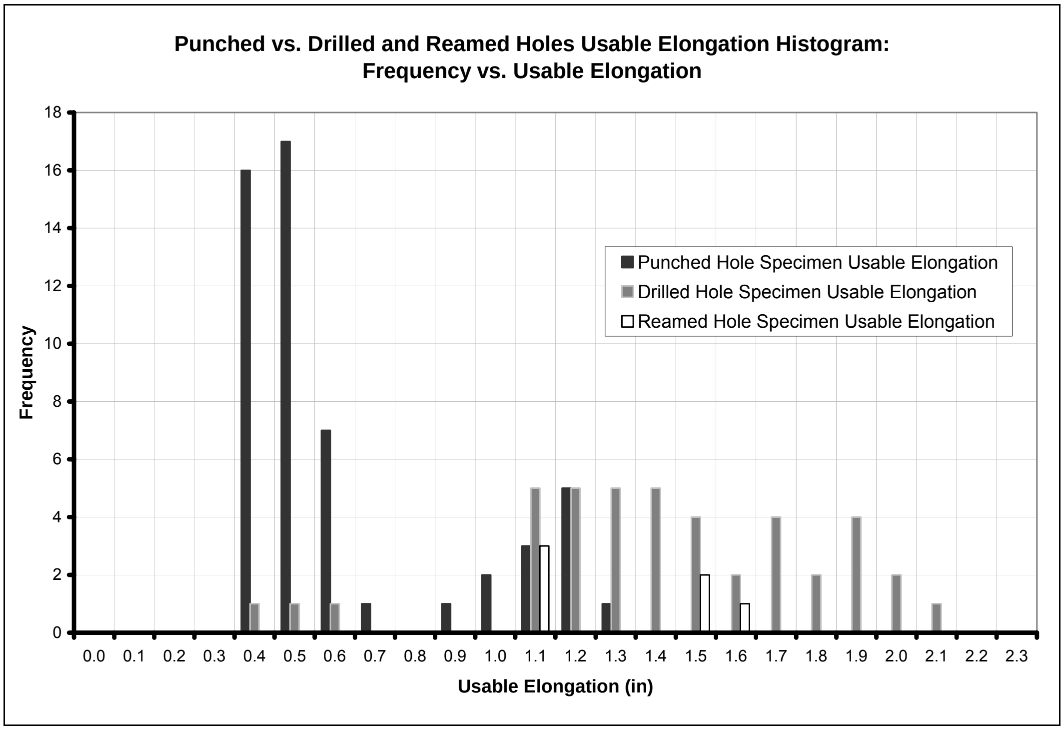

Figure 5.14: Punched versus Drilled and Reamed Holes Usable Elongation Histogram

The average usable elongation (i.e. δ at P_{ult}) and standard deviation of the usable elongation for each specimen preparation type is displayed in Table 5.26. The ductility, as measured by the usable elongation performance, of drilled and reamed specimens had the highest average values, followed by punched specimens. Reamed specimens had the lowest variance, or standard deviation, followed by punched and then drilled specimens.

Table 5.26: Average Usable Elongation and Standard Deviation by Preparation Type

Method	No. of Specimens	Avg. Usable Elongation[2] (in.)	Std. Deviation
Punched	66	0.582	0.285
Drilled	46	1.374	0.390
Reamed	6	1.264	0.243
2 - Usable Elongation = δ at P_{ult}			

Of note, there were 41 replicate pairs of punched and drilled hole plates from similar plate heats that were tensile tested to failure during this study. These replicate specimens allow for a direct comparison of punched and drilled hole specimen performance relative to one another. In these comparisons, the punched strength ratio divided by the drilled strength ratio may be defined as:

$$\left(\frac{P}{D}\right)_{ratio} = \frac{\left(\dfrac{P_{ult,punched}}{A_{net,punched}}\right)}{\left(\dfrac{P_{ult,drilled}}{A_{net,drilled}}\right)} \tag{6.3}$$

Figure 5.15 shows a histogram comparing punched and drilled strength ratios and Figure 5.16 shows a histogram comparing punched and drilled usable elongations.

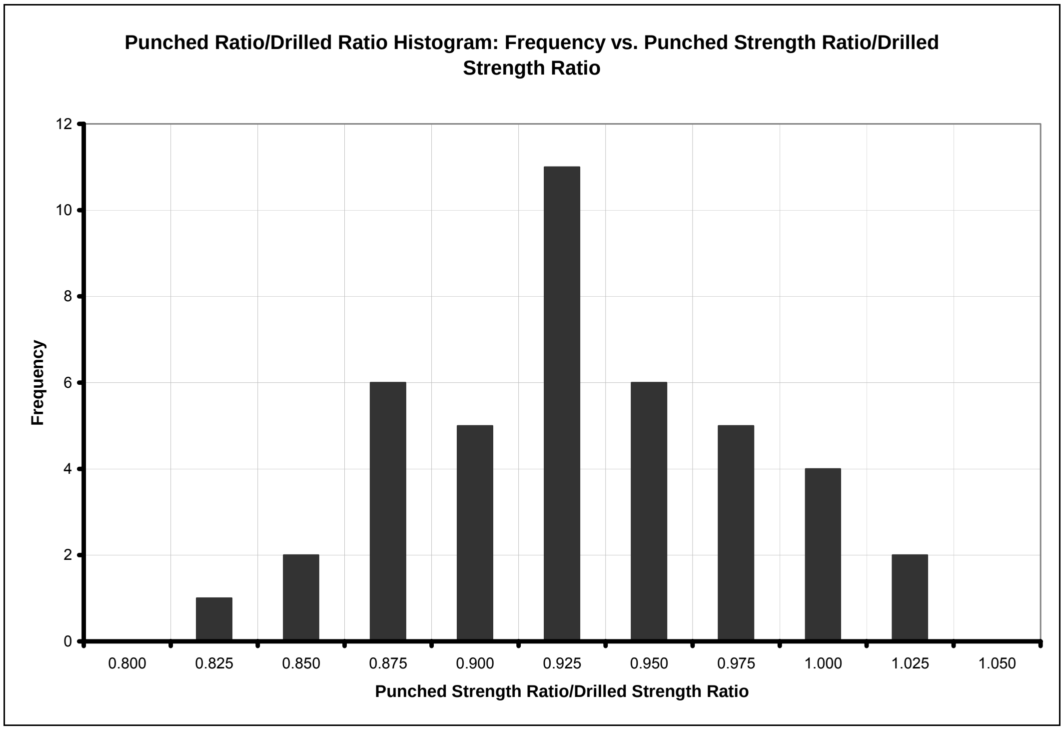

Figure 5.15: Punched Strength Ratio/Drilled Strength Ratio Histogram

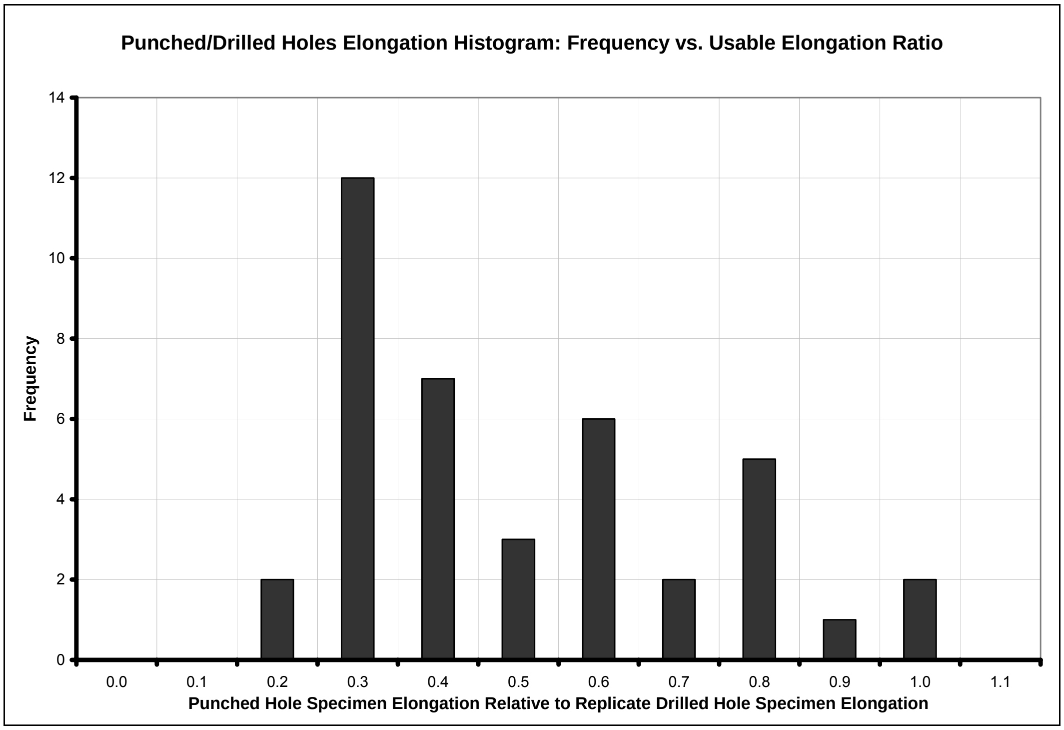

Figure 5.16: Punched/Drilled Holes Usable Elongation Histogram

Table 5.27 shows the average punched to drilled specimen performance ratio for strength and usable elongation for the 41 replicate specimen pairs. As displayed, punched hole specimens on average had a strength ratio of 0.92 and a usable elongation ratio of 0.45 relative to drilled hole specimens. The standard deviation of the replicate strength ratios and usable elongations were 0.048 and 0.218, respectively.

Table 5.27: Strength Ratio and Usable Elongation Statistics for Replicate Specimens

Punched/Drilled Comparison	Average	Std. Deviation
Strength Ratio	0.92	0.048
Usable Elongation	0.45	0.218

Out of the many parameters that were studied in this investigation in addition to the method of hole preparation, only three displayed some influence on the strength ratio and usable elongation of specimens. These parameters include grade of steel, hole size, and plate thickness. In all tests examining these parameters, punched hole specimens had a smaller average strength ratio and average usable elongation relative to their drilled hole replicates. With respect to grade of steel, the difference between punched and drilled hole performance was most notable in the grade 36 specimens (average punched and drilled strength ratios: 0.95 and 1.10, average punched and drilled usable elongation: 0.357 and 1.646). With respect to hole size, test results showed correlation between an increase in hole size to plate thickness ratio with a decrease in average usable elongation (see Tables 5.9 and 5.10). And lastly, with respect to plate thickness, test results showed a slight correlation between increasing average strength ratio with an increase in plate thickness (see Table 5.11).

The remaining parameters studied in this investigation displayed little to no influence on the strength ratio and usable elongation of specimens. These parameters included edge distance and edge preparation, punching clearance, punching operation, galvanizing, and amount of reaming.

Based on the performance of punched holes relative to drilled holes in the qualitative fatigue tests in this study, further fatigue testing is currently in progress at the FSEL.

Furthermore, basic material properties examined in chemistry, coupon, and Charpy testing may have also played a significant role in the performance of some of the plate heats as previously noted.

5.16 ADDITIONAL CONSIDERATIONS

During this investigation's review of previous research, experiment design, and testing and analysis of results, a few additional considerations were brought to the attention of researchers at the FSEL. These considerations include, but are not limited to, investigation of high performance grades of steel, weathering steel, slotted holes, and connections.

Although not frequently used for secondary members due to their large thicknesses, high performance steels may be candidates for punching if leftover, or "scrap," material is used for secondary members during bridge fabrication. For this reason, it may be useful to investigate the tensile and fatigue performance of punched high performance steels such as grade 70 materials that are currently being utilized in hybrid bridge design.

The performance of weathering steel and plate with slotted holes are two additional parameters scheduled for study at the FSEL as of 2005. Since secondary members may be composed of weathering steel or plate with slotted holes, plates with these two parameters are candidates for hole punching.

Ultimately, connections will be tensile and fatigue tested at the FSEL to investigate the performance of bolted double shear lap splice specimens with different types of hole preparation. These tests will serve as a model for studying the influence of hole preparation on connections between secondary members. One interesting consideration may be the friction force of a tightened bolt against a plate and its role in distributing load during tensile and fatigue testing.

6. CONCLUSIONS

Punching is a quick, economical, and versatile method utilized in the fabrication of metal. Punching processes may be directly applied to the fabrication of structural steel intended for use in bridges, buildings, and a variety of structures. Typically, punching is employed in the fabrication of structural elements related to connections, such as members, cross-frames, and gusset plates on bridges.

AASHTO steel bridge specifications do not allow full size punched holes in primary load carrying members. Instead, holes are required to be formed by full-size drilling or reaming following punching. Furthermore, other punching limitations include thickness limits depending on grade of steel.

Previous research has provided information on the general behavior and ultimate strength of connections with variables such as hole preparation. University of Illinois at Urbana-Champaign researchers found that tension members with punched holes commonly had a tensile strength that was 10 to 15 percent less than members with drilled holes. Similarly, strength value differences of 6 to 15 percent were determined during research at both The University of Texas at Austin and the University of Cincinnati.

Sixty-six (66) plates with punched holes, 46 plates with drilled holes, and 6 plates with punched and reamed holes were tensile tested at the FSEL during this study. During testing, the net section stress, strength ratio, and usable elongation values at failure have been determined for each specimen variation. These specimen variations included steel type, temperature, hole size, plate thickness, edge distance, edge preparation, punching clearance, punching operation, galvanizing, and amount of reaming.

Overall, in strength performance, reamed specimens had the highest average strength ratio (1.12), followed by drilled (1.09) and then punched (1.00) specimens. Similarly, reamed specimens had the lowest standard deviation of strength ratios (0.021), followed by drilled (0.038) and then punched specimens (0.065). In usable elongation performance, drilled and reamed specimens had the highest average elongation values (1.374 inches and 1.264 inches), followed by punched specimens (0.582 inches). Again, reamed specimens had the lowest standard deviation of usable elongations (0.243 inches), followed by punched (0.285 inches) and then drilled specimens (0.390 inches).

In order to most directly compare punched and drilled hole preparation, 41 replicate punched and drilled hole plates were tensile tested to failure during this study. Punched hole specimens on average had a strength ratio of 0.92 and a usable elongation ratio of 0.45 relative to drilled hole specimens. The standard deviation of the replicate strength ratios and usable elongations were 0.048 and 0.218, respectively.

Based on the strength performance of punched hole specimens (1.00 average strength ratio, 0.065 standard deviation), and particularly relative to drilled hole specimens (0.92 punched-to-drilled strength ratio, 0.048 standard deviation), a capacity reduction of 0.85 is recommended for punched plate used in steel bridge connections. It is important to consider the strength performance of punched plate relative to specification limit states as well as relative to the performance of drilled plate since current AASHTO specifications for strength performance are calibrated with drilled holes. In using a capacity reduction (ϕ) of 0.85 for punched holes, the strength performance of over 95% of the punched hole specimens in this study is conservative relative to their current specification limit state. Furthermore, the strength performance of over 90% of these specimens is conservative relative to the strength performance of drilled specimens.

During testing, three parameters displayed some influence on the strength ratio and usable elongation of specimens. These parameters included grade of steel, hole size, and plate thickness. In all tests examining these parameters, punched hole specimens had a smaller average strength ratio and average usable elongation relative to their drilled hole replicates. With respect to grade of steel, the difference between punched and drilled hole performance was most notable in the grade 36 specimens (average punched and drilled strength ratios: 0.95 and 1.10, average punched and drilled usable elongation: 0.357 and 1.646). With respect to hole size, test results showed correlation between an increase in hole size to plate thickness ratio with a decrease in average usable elongation (see Tables 5.9 and 5.10). And lastly, with respect to plate thickness, test results showed a slight correlation between increasing average strength ratio with an increase in plate thickness (see Table 5.11).

The parameters studied in this investigation that displayed little to no influence on the strength ratio and usable elongation of specimens included edge distance, edge preparation, punching clearance, punching operation, galvanizing, and amount of reaming.

Based on the performance of punched holes relative to drilled holes in the qualitative fatigue tests in this study, further fatigue testing is currently in progress at the FSEL. Additional considerations in further research include, but are not limited to, investigation of high performance grades of steel, weathering steel, slotted holes, and connections.

APPENDIX

Using current AASHTO specification details on the UIUC specimens described in section 2.3, a limit state was calculated based on a governing tension (yield or fracture) failure or a block shear (shear or tension) failure. Tables A1 through A4 show the limit state calculations for each type of UIUC specimen.

Table A.1: Current Limit States for UIUC Specimen SA

Specimen Type:	SA (4 angles)	
Dimensions:	3.5	
	3.5	
	0.4375	(7/16")
Hole Size (in):	0.8125	(13/16")
Hole Size + 1/16 (in):	0.875	(14/16")
Gross Area (in^2):	11.48	
Net Area (in^2):	8.86	
Net $Area_{modern\ (+1/16\ in.\ hole)}$ (in^2):	8.64	
Net $Area_{w/o\ stagger}$ (in^2):	8.61	
Net $Area_{modern\ w/o\ stagger}$ (in^2):	8.42	

F_y (ksi)	43.1
F_u (ksi)	67.0
x_{bar} (in)	0.41
L (in)	15
$(1-x_{bar}/L)$	0.97
$(1-x_{bar}/L)_{spec}$	0.85
$A_{eff\ net}$ (in^2)	7.53
$A_{eff\ net\ modern}$ (in^2)	7.34
g (in)	1.5
s (in)	17
$\#holes_g$	0.5
$\#holes_s$	6.5

Tensile Limit States:

Yield (k)	494.8
(F_yA_g)	
Fracture (k)	
(F_uA_n)	504.6
$(F_uA_n)_{modern}$	**492.0**

Block Shear Limit States (Fracture):

A_{GT} (in^2)	0.656	
A_{NT} (in^2)	0.479	
$A_{NT\ modern}$ (in^2)	0.465	
A_{GV} (in^2)	7.438	
A_{NV} (in^2)	5.127	
$A_{NV\ modern}$ (in^2)	4.949	
Shear (k)		
$(.6F_uA_{NV} + F_yA_{GT})$		937.6
$(.6F_uA_{NV} + F_yA_{GT})_{modern}$		909.0
Tensile (k)		
$(.6F_yA_{GV} + F_uA_{NT})$		897.6
$(.6F_yA_{GV} + F_uA_{NT})_{modern}$		893.9

Test Results (k):

Punched	**483.8, 476.5, 481.1, 482.0**
Drilled	**507.6, 497.2, 559.0, 504.1**

check:

$.6F_yA_{GV} \leq .6F_uA_{NV}$?		
192.3	199.0	☺

Table A.2: Current Limit States for UIUC Specimen SB

Specimen Type:	SB (4 angles)	
Dimensions:	5	
	3	
	0.375	(3/8")
Hole Size (in):	0.9375	(15/16")
Hole Size + 1/16 (in):	1	(16/16")
Gross Area (in^2):	11.44	
Net Area (in^2):	9.2	
Net Area$_{\text{modern (+1/16 in. hole)}}$ (in^2):	9.02	
Net Area$_{\text{w/o stagger}}$ (in^2):	8.62	
Net Area$_{\text{modern w/o stagger}}$ (in^2):	8.44	

F_y (ksi)	42.0
F_u (ksi)	66.4
x_{bar} (in)	0.7
L (in)	15
$(1-x_{bar}/L)$	0.95
$(1-x_{bar}/L)_{spec}$	0.85
$A_{\text{eff net}}$ (in^2)	7.82
$A_{\text{eff net modern}}$ (in^2)	7.67
g (in)	1.5
s (in)	17
#holes$_g$	0.5
#holes$_s$	5.5

Tensile Limit States:

Yield (k)	**480.5**
(F_yA_g)	
Fracture (k)	
(F_uA_n)	519.2
$(F_uA_n)_{modern}$	**509.1**

Block Shear Limit States (Fracture):

A_{GT} (in^2)	0.563
A_{NT} (in^2)	0.387
$A_{\text{NT modern}}$ (in^2)	0.375
A_{GV} (in^2)	6.375
A_{NV} (in^2)	4.441
$A_{\text{NV modern}}$ (in^2)	4.313

Shear (k)	
$(.6F_uA_{NV} + F_yA_{GT})$	802.3
$(.6F_uA_{NV} + F_yA_{GT})_{modern}$	781.7
Tensile (k)	
$(.6F_yA_{GV} + F_uA_{NT})$	745.3
$(.6F_yA_{GV} + F_uA_{NT})_{modern}$	742.2

Test Results (k):

Punched	**492.4, 498.2**
Drilled	**513.0, 527.0**

check:

$.6F_yA_{GV} \leq .6F_uA_{NV}$?

160.7	171.8	☺

Table A.3: Current Limit States for UIUC Specimen SD

Specimen Type:	SD (4 angles)	
Dimensions:	5	
	3	
	0.375	(3/8")
Hole Size (in):	0.9375	(15/16")
Hole Size + 1/16 (in):	1	(16/16")
Gross Area (in^2):	11.44	
Net Area (in^2):	8.11	
Net Area$_{\text{modern (+1/16 in. hole)}}$ (in^2):	7.83	
Net Area$_{\text{w/o stagger}}$ (in^2):	7.48	
Net Area$_{\text{modern w/o stagger}}$ (in^2):	6.94	

F_y (ksi)	40.5
F_u (ksi)	65.4
x_{bar} (in)	0.41
L (in)	6
$(1-x_{bar}/L)$	0.93
$(1-x_{bar}/L)_{spec}$	0.85
$A_{\text{eff net}}$ (in^2)	6.89
$A_{\text{eff net modern}}$ (in^2)	6.66
g (in)	3.125
s (in)	8
#holes$_g$	1.5
#holes$_s$	2.5

Tensile Limit States:

Yield (k)	463.3
(F_yA_g)	
Fracture (k)	
(F_uA_n)	450.8
$(F_uA_n)_{modern}$	**435.3**

Block Shear Limit States (Fracture):

A_{GT} (in^2)	1.172
A_{NT} (in^2)	0.645
$A_{\text{NT modern}}$ (in^2)	0.609
A_{GV} (in^2)	3.000
A_{NV} (in^2)	2.121
$A_{\text{NV modern}}$ (in^2)	2.063

Shear (k)	
$(.6F_uA_{NV} + F_yA_{GT})$	522.8
$(.6F_uA_{NV} + F_yA_{GT})_{modern}$	513.6
Tensile (k)	
$(.6F_yA_{GV} + F_uA_{NT})$	460.2
$(.6F_yA_{GV} + F_uA_{NT})_{modern}$	451.0

check:

$.6F_yA_{GV} \leq .6F_uA_{NV}$?

72.9	80.9	☺

Test Results (k):

Punched	**451.8, 418.0**
Drilled	**470.7, 466.7**

Table A.4: Current Limit States for UIUC Specimen SE

Specimen Type:	SE (4 angles)	
Dimensions:	5	
	5	
	0.375	(3/8")
Hole Size (in):	0.8125	(13/16")
Hole Size + 1/16 (in):	0.875	(16/16")
Gross Area (in^2):	14.44	
Net Area (in^2):	12.11	
Net $Area_{modern\ (+1/16\ in.\ hole)}$ (in^2):	11.93	
Net $Area_{w/o\ stagger}$ (in^2):	11.94	
Net $Area_{modern\ w/o\ stagger}$ (in^2):	11.81	

F_y (ksi)	38.9
F_u (ksi)	66.7
x_{bar} (in)	1.39
L (in)	22.5
$(1-x_{bar}/L)$	0.94
$(1-x_{bar}/L)_{spec}$	0.85
$A_{eff\ net}$ (in^2)	10.29
$A_{eff\ net\ modern}$ (in^2)	10.14
g (in)	2.375
s (in)	24.5
$\#holes_g$	0.5
$\#holes_s$	9.5

Tensile Limit States:

Yield (k)	**561.7**
(F_yA_g)	
Fracture (k)	
(F_uA_n)	686.6
$(F_uA_n)_{modern}$	**676.4**

Block Shear Limit States (Fracture):

A_{GT} (in^2)	0.891
A_{NT} (in^2)	0.738
$A_{NT\ modern}$ (in^2)	0.727
A_{GV} (in^2)	9.188
A_{NV} (in^2)	6.293
$A_{NV\ modern}$ (in^2)	6.070

Shear (k)	
$(.6F_uA_{NV} + F_yA_{GT})$	1146.0
$(.6F_uA_{NV} + F_yA_{GT})_{modern}$	1110.3
Tensile (k)	
$(.6F_yA_{GV} + F_uA_{NT})$	1054.7
$(.6F_yA_{GV} + F_uA_{NT})_{modern}$	1051.6

check:
$.6F_yA_{GV} \leq .6F_uA_{NV}$?
214.4 242.9 ☺

Test Results (k):

Punched	**576.0, 582.0**
Drilled	**732.0, 772.0**

Final results from the Charpy tests for all nine specimen plate heats were previously shown in Table 5.26. Energy versus temperature plots for each plate heat are shown as follows in Appendix Figures A1 through A9. The four-pointed star designates an approximate 15 foot-pound and temperature correlation.

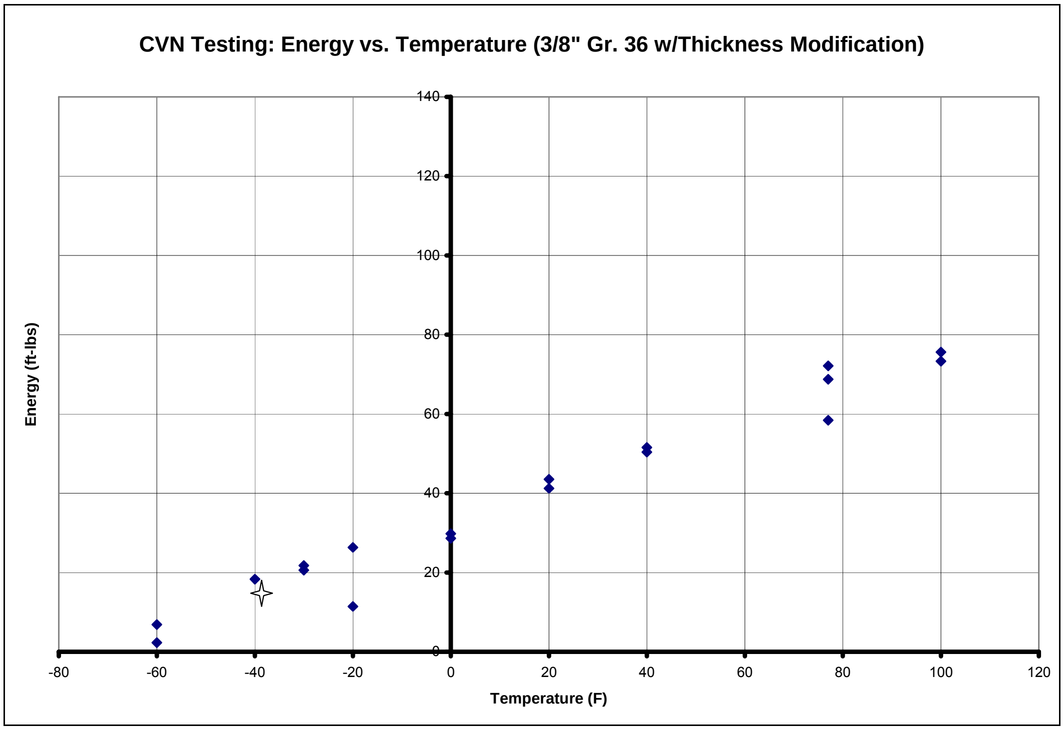

Figure A.1: Energy versus Temperature for 3/8 Inch Grade 36 Plate

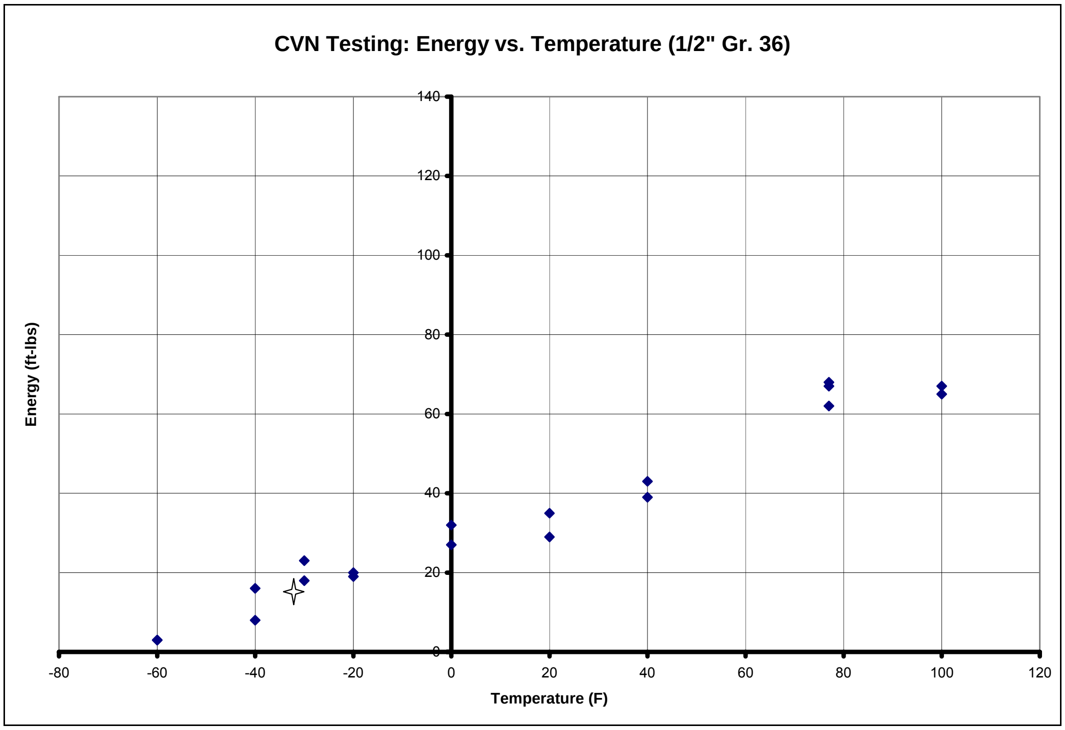

Figure A.2: Energy versus Temperature for 1/2 Inch Grade 36 Plate

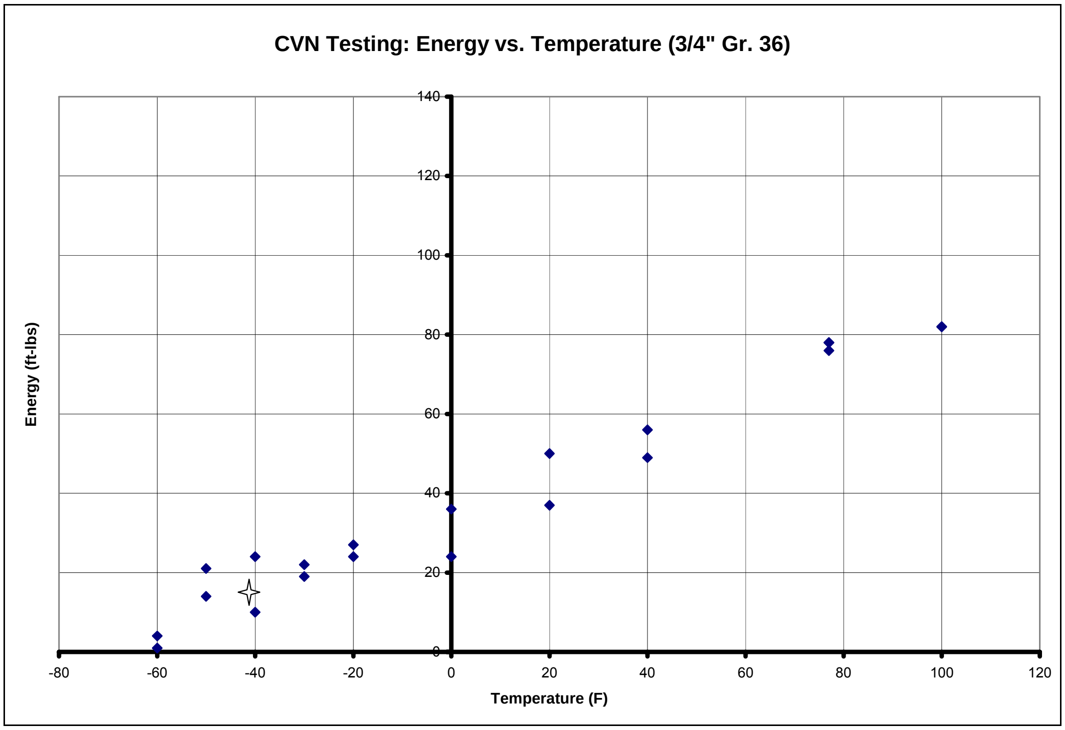

Figure A.3: Energy versus Temperature for 3/4 Inch Grade 36 Plate

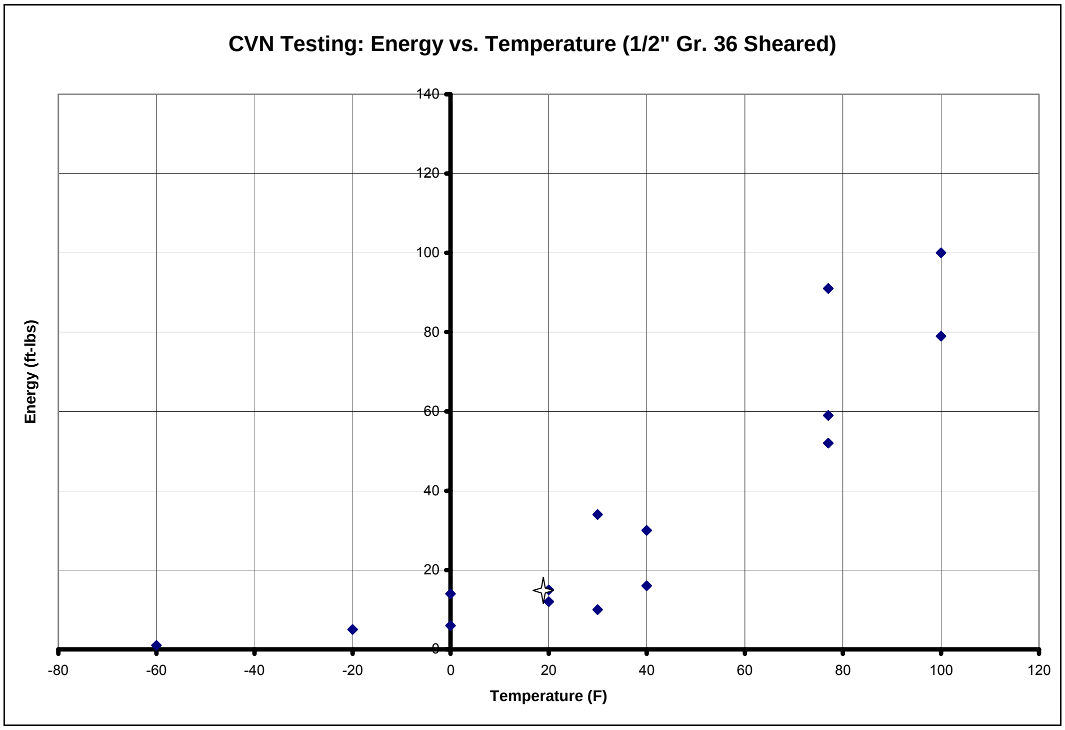

Figure A.4: Energy versus Temperature for 1/2 Inch Grade 36 (Sheared) Plate

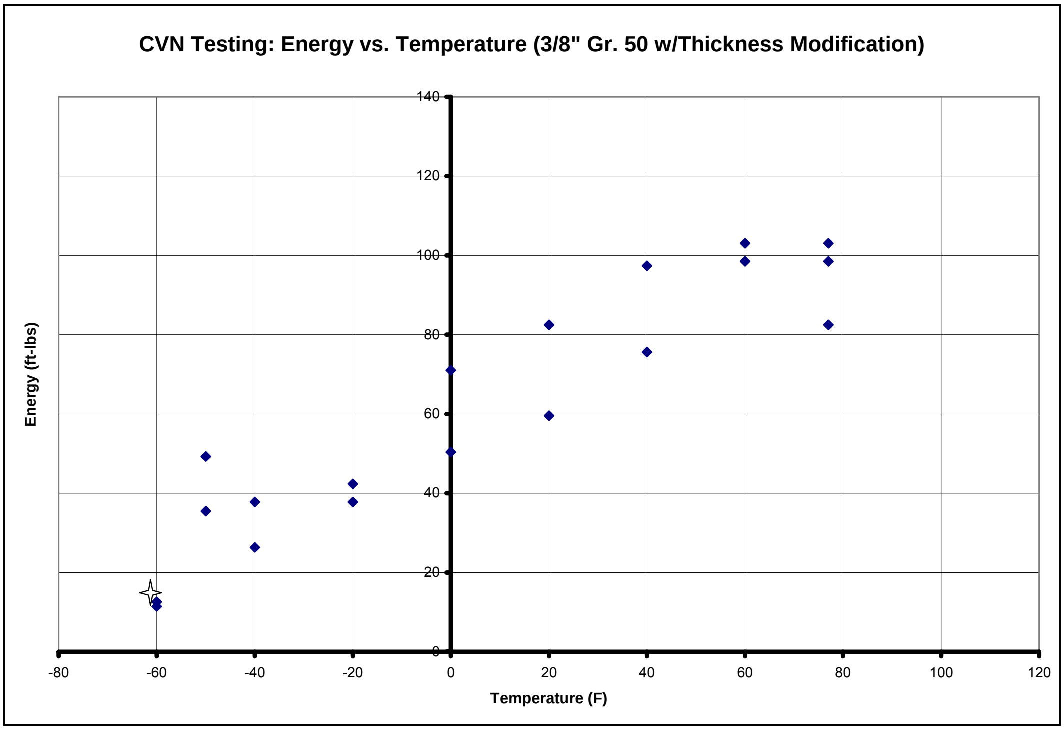

Figure A.5: Energy versus Temperature for 3/8 Inch Grade 50 Plate

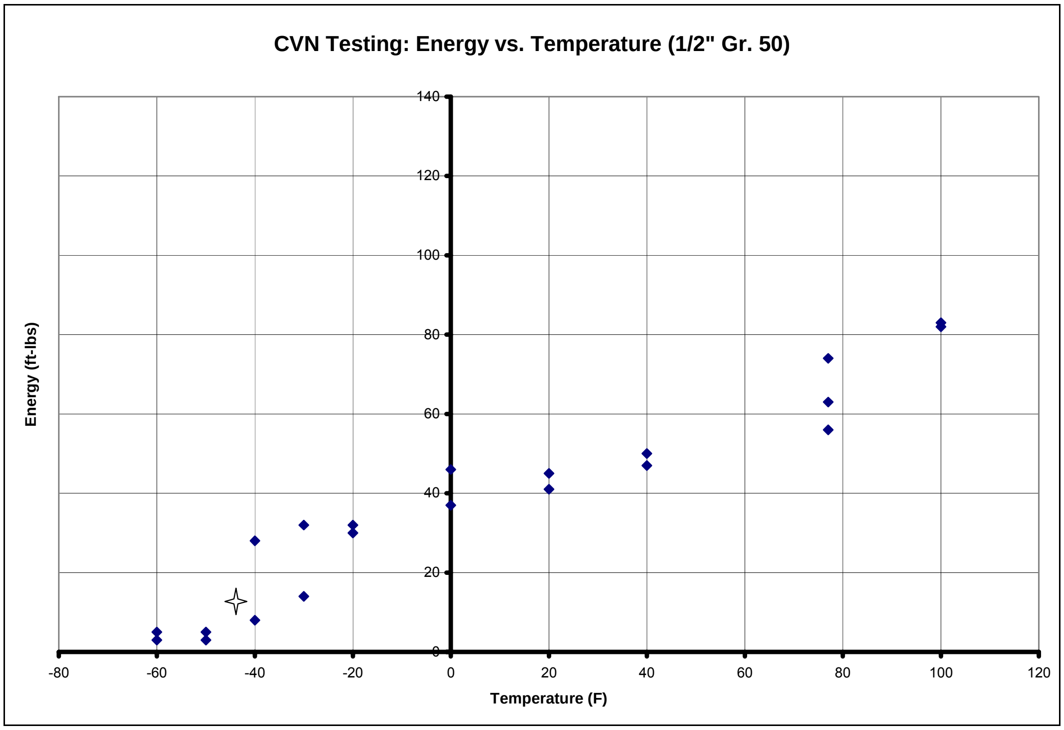

Figure A.6: Energy versus Temperature for 1/2 Inch Grade 50 Plate

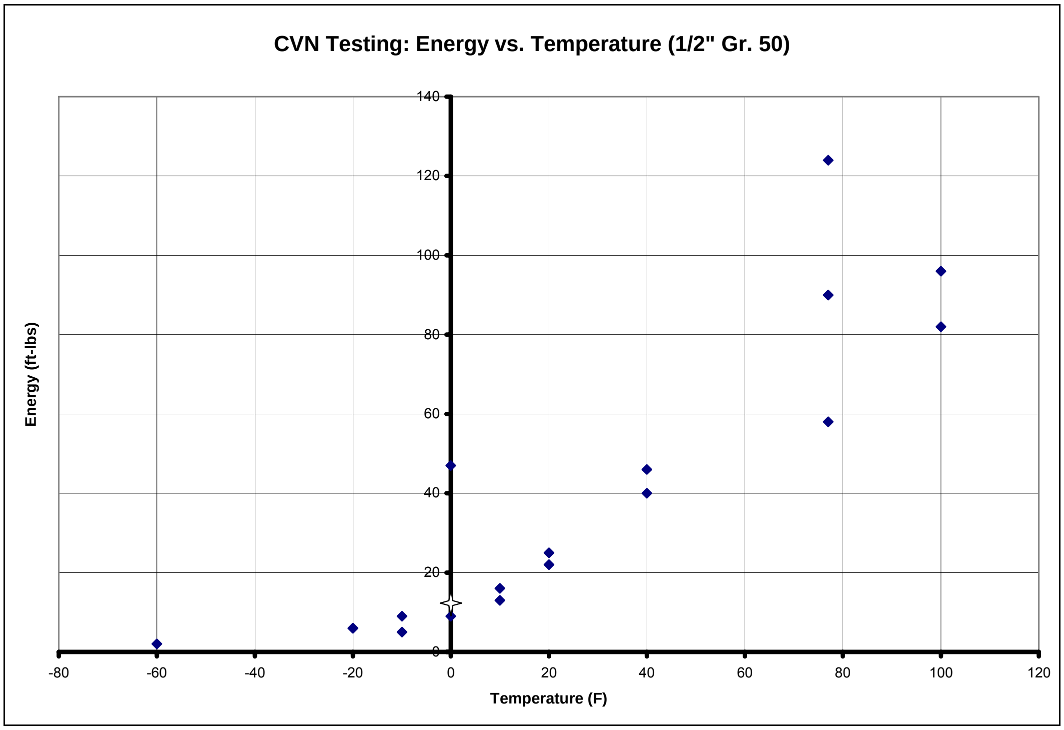

Figure A.7: Energy versus Temperature for 3/4 Inch Grade 50 Plate

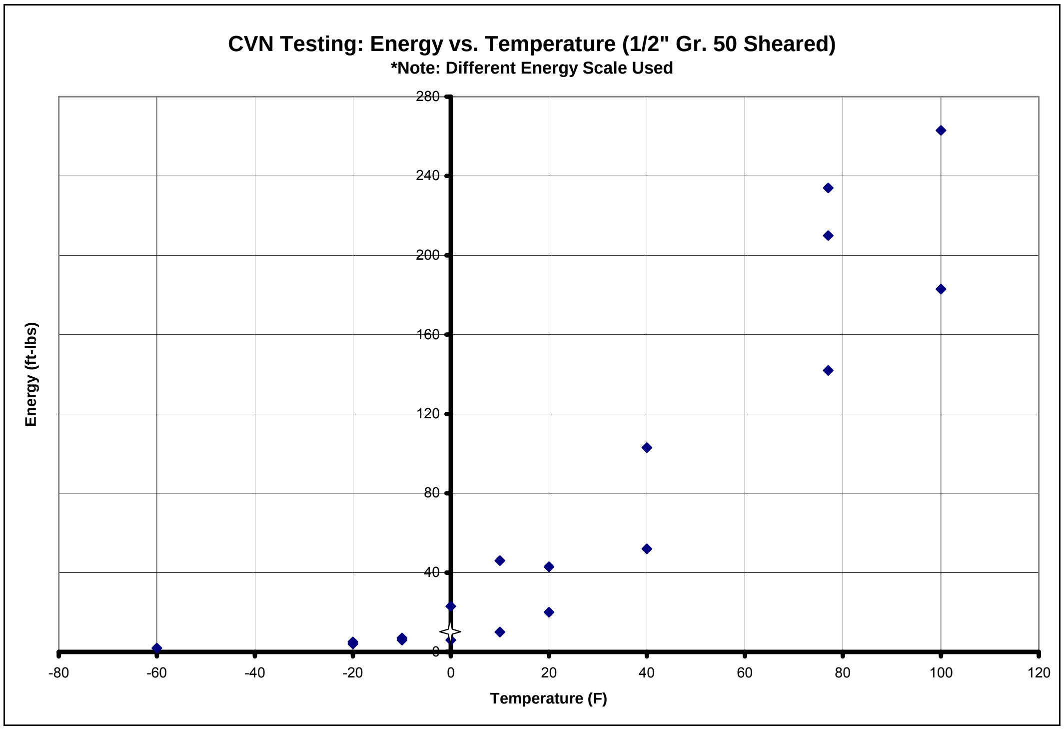

Figure A.8: Energy versus Temperature for 1/2 Inch Grade 50 (Sheared) Plate

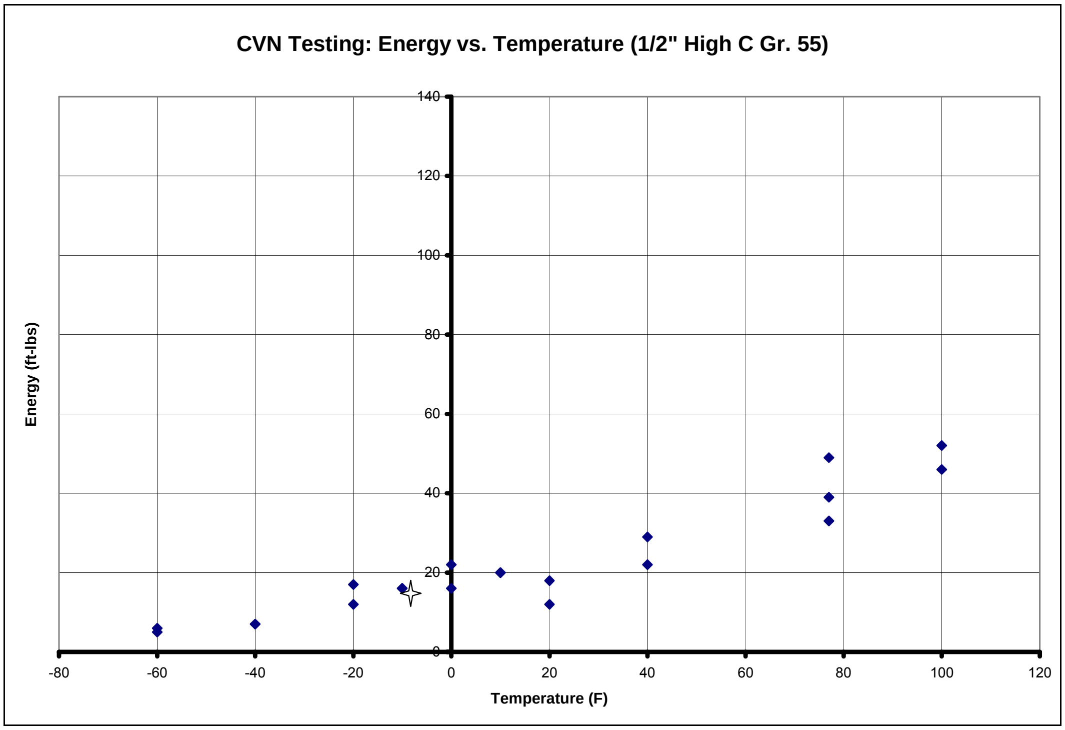

Figure A.9: Energy versus Temperature for 1/2 Inch Grade 55 Plate

BIBLIOGRAPHY

AASHTO LRFD Bridge Construction Guide Specifications – U.S. Units. Washington, DC: American Association of State Highway and Transportation Officials, 2004.

AASHTO LRFD Bridge Design Specifications – U.S. Units. Washington, DC: American Association of State Highway and Transportation Officials, 2004.

Baird, J. D. “Strain Aging of Steel – a Critical Review.” Iron and Steel (May 1963): 186-191.

Brolund, T. F. “Punching and Shearing Science.” W. A. Whitney Portable Press Operations and Maintenance Manual. Rockford: W. A. Whitney Corporation, 2004.

Cayci, M. A., W. H. Munse, and W. M. Wilson. “A Study of the Practical Efficiency under Static Loading of Riveted Joints Connecting Plates.” University of Illinois Engineering Experiment Station Bulletin 402 (January 1953): 1-75.

Chesson, Jr., E., and W. H. Munse. “Riveted and Bolted Joints: Net Section Design.” Journal of the Structural Division: Proceedings of the American Society of Civil Engineers 89 (February 1963): 107-126.

Chesson, Jr., E., and W. H. Munse. “Riveted and Bolted Joints: Truss-Type Tensile Connections.” Journal of the Structural Division: Proceedings of the American Society of Civil Engineers 89 (February 1963): 67-107.

Chesson, Jr., E., and W. H. Munse. “Behavior of Riveted Truss-Type Connections.” Transactions of the American Society of Civil Engineers 123 (1958): 1087-1128.

de Jong, A. E. R. “Riveted Joints: A Critical Review of the Literature Covering Their Development, with Bibliography and Abstracts of the Most Important Articles.” ASME Research Publication (1945): 1-111.

Frank, K.H. “Influence of Hole Making Process upon the Tensile Strength of Steel Plates.” TxDOT Research Publication (May 2002): 1-9.

Gaylord, C. N., and E. H. Gaylord. Design of Steel Structures. New York: McGraw-Hill, 1972.

Gutierrez-Solana, F., D. Pesquera, and L. Sanchez. “Fatigue Behavior of Punched Structural Plates.” Engineering Failure Analysis 11 (2004): 751-764.

Huhn, H. and G. Valtinat. “Bolted Connections with Hot Dip Galvanized Steel Members with Punched Holes.” Proceedings of the ECCS/AISC Workshop, Connections in Steel Structures V: Innovative Steel Connections, June 3-5, 2004. Amsterdam: European Convention for Constructional Steelwork/American Institute of Steel Construction, 2004.

Hume-Rothery, W. The Structure of Metals and Alloys. Suffolk: Richard Clay and Company Limited, 1954.

Iwankiw, N. and T. Schlafly. “Effect of Hole-Making on the Strength of Double Lap Joints.” Engineering Journal of the American Institute of Steel Construction 19 (1982): 170-178.

Peterson, R. E. Stress Concentration Factors. New York: John Wiley and Sons, 1974.

Rassati, G.A., J. A. Swanson, and Q. Yuan. “Investigation of Hole Making Practices in the Fabrication of Structural Steel.” American Institute of Steel Construction (2004).

Schutz, Jr., F. W. The Efficiency of Riveted Structural Joints. Urbana: University of Illinois, 1952.

“Standard Test Methods for Notched Bar Impact Testing of Metallic Materials, ASTM E23-04.” ASTM International Standards for Mechanical Fasteners and Related Standards for Fastener Materials, Coatings, Test Methods, and Quality. West Conshohocken: American Society for Testing and Materials, 2004.

“Standard Test Methods for Tension Testing of Metallic Materials, ASTM E8-04.” ASTM International Standards for Mechanical Fasteners and Related Standards for Fastener Materials, Coatings, Test Methods, and Quality. West Conshohocken: American Society for Testing and Materials, 2004.

VITA

David Jason Lubitz was born on October 11, 1981 in Westminster, Maryland, the son of Robert Myron Lubitz and Linda Joyce Lubitz. After completing his work at South Carroll High School, Sykesville, Maryland, in 1999, he began study at the University of Delaware in Newark, Delaware. During his time at the University of Delaware, David served as a Department of Civil and Environmental Engineering research and teaching assistant and worked as an engineering technician at a local civil engineering consulting firm. In May of 2003, he graduated Magna Cum Laude from the University of Delaware with a Bachelor of Civil Engineering degree. In September of 2003, David began graduate study and employment as a graduate research assistant in the Structural Engineering program at The University of Texas at Austin in pursuit of a Master of Science in Engineering degree.

Permanent Address: 897 Bear Branch Road
P.O. Box 2167
Westminster, MD 21158

This thesis was typed by the author.