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16. Abstract

A large experimental study was undertaken to determine the effect of hole making upon the strength, ductility, and fatigue performance of structural steel plates and connections. The variables included steel strength, plate thickness, hole size, punch to die clearance, galvanizing, temperature, and edge distance. Approximately 300 tension and fatigue tests were performed. The study agreed with the results of previous research that plates with punched holes have lower strength and ductility than ones with drilled holes. The fatigue performance of plates with punched holes was also less than ones with drilled holes. Galvanizing further reduced the fatigue strength of plates with punched holes. The effect upon hole making upon the fatigue strength and to some extent the tensile strength reduced when fully pretensioned bolts were used. Empty holes had a lower fatigue strength then holes used in a bolted connection. The practice of increasing the hole diameter by 1/16 in. when calculating the net section of a tension member did not account for the reduction in strength when the hole was punched. It is recommended that this increase in hole be eliminated and the tension strength of members with punched holes be taken as 90% of normal design values. Due to the low ductility of plates and connection with punched holes, punched holes should only be used in secondary members that do not need the ductility required in main members. The appendix of the report gives the recommended specifications.

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Products

Appendix A of this report contains Product 1 (P1), Specification provisions for details of punched holes and fatigue classification of plates with punched holes.

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Chapter 1. Introduction

This research examined the performance of steel plate and connections with punched and slotted holes. In almost all cases, the performance of specimens with punched was compared with identical specimens with drilled holes. The strength and ductility of the specimens were compared to determine the influence of the hole making technique upon performance. The study of slotted holes was a smaller study that included the behavior of slotted holes made by various thermal cutting techniques.

This report summarizes the work of a three-year research project that consisted of testing hundreds of test specimens. The details of the test methods, fabrication procedures, and other experimental details are contained in references Lubitz (2005), Brown (2006), and Cekov (2006).

1.1 BACKGROUND INFORMATION

Punched holes are commonly used in steel fabrication as a quicker, cleaner, and more cost-effective method of forming holes when compared to other fabrication methods. Holes may also be formed by full-size drilling, sub-punching and reaming to the nominal diameter, and various forms of thermal cutting. Punched holes are often used for secondary tension members, such as angle braces and cross frames in bridges and most members used in buildings. These thinner members are especially suited for mass production using a combination machine that punches holes and shears the ends quickly and efficiently. However, the punching process causes significant damage to the localized area around the hole. This damage has caused concern as to the effects of punching holes on the base material.

While there has been past research investigating the effects of punched holes in various configurations, much of the work is 25 to 50 years old, and may not be applicable to some of the steel types that are currently utilized. Some of this research has been incorporated into specifications in various ways. Current codes are somewhat unclear on how the hole forming method fits in to the design and fabrication process. Specifications do place limits on the thickness of steel that can be punched, as well as limiting the use of punched holes to secondary bridge members. Otherwise, little is mentioned throughout the Specifications.

This project investigated the tensile and fatigue performance of punched holes in structural steel plates and connections using modern bridge steel. This project used a larger and more systematic approach than past research. The primary focus was on tension members, such as braces and cross frames, as they are the most likely to be fabricated with punched holes. For members in compression, the hole forming technique is not relevant. Other connection types, such as the ends of beams, are anticipated to behave in a manner similar to tension members. Before discussing the goals of this project, the method in which modern codes deal with punched holes and tension members is discussed.

1.2 CURRENT CODE PROVISIONS

1.2.1 AASHTO LRFD Bridge Design Specifications 2004

The current American Association of State Highway and Transportation Officials (AASHTO) LRFD Bridge Design Specifications 2004, hereafter referred to as AASHTO Design, give little reference to punched holes. Resistance factors, given in Article 6.5.4.2, do not specify the hole type used for calculations. For tension fracture in the net section, the resistance (phi) factor is ϕ_u=0.80, and tension yielding in the gross section, ϕ_y=0.95. For bolts bearing on material, ϕ_{bb}=0.80 and for block shear resistance, ϕ_{bs}=0.80 (AASHTO Design 2004).

Fatigue categories given in AASHTO Design, as discussed in AASHTO Table 6.6.1.2.3-1 for mechanically fastened connections, make no distinction for different hole types. For the base metal "at gross section of high-strength bolted slip-critical connections, except axially loaded joints in which out-of-plane bending is induced in connected materials," the detail category is given as Category B. For base metal "at net section of high-strength bolted nonslip-critical connection," the detail category is given as Category B as well. For base metal "at net section of riveted connections," the detail category is given as Category D. A bolted deck plate or rib splice is also given as Category B. Examples of these connection types are presented in Figure 1.1 and Figure 1.2, with the exception of the bolted deck plate splices. The descriptions and fatigue categories are similar to those used by the American Institute of Steel Construction (AISC) Steel Construction Manual, Thirteenth Edition (AISC 2005). The fatigue categories for plates and tension connections with punched and drilled holes were investigated in this project.

Bolted joints are designed as either slip-critical connections or bearing-type connections. That is, load is either transferred by bolts bearing on the base metal, or the load is transferred by friction between the connecting parts clamped together by a tightened bolt. Slip-critical connections are important for joints subject to fatigue loadings and joints in axial tension or combined tension and shear. AASHTO allows bearing-type connections only for joints subject to axial compression or joints on bracing members. Article C6.13.2.1.2 states that the failure load of a bearing-type connection is independent of the bolt clamping force. Friction between the faying surfaces of a tightened connection may contribute some percentage to the ultimate load, but that amount is not clear. The effect of pretensioned bolts was also investigated in this project (AASHTO Design 2004).

When determining net area, AASHTO Design Article 6.8.3 states the following: “The width of each standard bolt hole shall be taken as the nominal diameter of the bolt plus 0.125 in. The width deducted for oversize and slotted holes, where permitted in Article 6.13.2.4.1, shall be taken as 0.0625 in. greater than the hole size specified in Article 6.13.2.4.2.” This referenced article lists standard sizes for oversize and slotted holes. The additional width is added to the hole diameter regardless of the hole forming technique. No discussion of hole type is given. As specified in Article 6.10.6.2.1 and 6.10.1.8, flexural members whose tension flanges have holes present also follow this net area requirement. This also includes box-section flexural members, as mentioned in Article 6.11.6.2.1. In Article 6.10.12.2.3, cover plates are designed as slip critical, and the recommended installation procedure for bolted ends, begins with drilling holes. The use of punched holes for cover plates is not specifically mentioned (AASHTO Design 2004).

AASHTO Design Article 6.13.2 is the primary section dealing with bolted connections. This article lists hole sizes for standard bolt diameters (bolt diameter+1/16 in.), edge and end distances, and bolt spacing. When determining the slip load of a connection, distinction is given to hole size (standard, oversize, or slotted), but not to hole fabrication method. Design equations for bearing resistance at bolt holes, Article 6.13.2.9, also make no distinction for hole type. Similarly, Article 6.13.4 does not differentiate the type of hole for block shear rupture resistance. These equations are presented in Section 1.2.5. In determining bearing and block shear resistance, the hole size is determined as the bolt diameter plus 0.125 in. These provisions also apply to bolted splices (AASHTO Design 2004).

1.2.2 AASHTO LRFD Bridge Construction Specifications 2004

The AASHTO LRFD Bridge Construction Specifications 2004, hereafter referred to as AASHTO Construction, presents two guidelines on the use of punched holes where the Design Specifications did not. AASHTO Construction Article 11.4.8 covers bolt holes and their use in bridge fabrication. The first line in Article 11.4.8.1 reads, “All holes shall be either punched or drilled, except as noted herein.” This article then sets the first limit on punched hole use, a thickness limit. The article states:

> “Material forming parts of a member composed of not more than five thicknesses of metal may be punched full-size whenever the thickness of the material is not greater than 0.75 in. (20mm) for structural steel, 0.625 (16mm) for high-strength steel, or 0.5 in. (12mm) for quenched-and-tempered alloy steel, unless subpunching and reaming are required under Article 11.4.8.5. When material is thicker than 0.75 in. (20mm) for structural steel, 0.625 in. (16mm) for high-strength steel, or 0.5 in. (12mm) for quenched-and-tempered alloy-steel, all holes shall either be subdrilled and reamed, or drilled full-size.”

As defined in Article 11.3.1, structural steel is AASHTO M270 (ASTM A709) Grade 36, and High Strength Steels are Grades 50, 50S, 50W, or HPS 50W. Quenched and tempered steels are defined as Grades 70W or HPS 70W. Holes are generally sub-punched 0.1875 in. (3/16 in. or 5mm) smaller than the nominal hole diameter before reaming (AASHTO Construction 2004).

Full-size punched holes are allowed in field connections, but not in connections for primary members. AASHTO Construction Article 11.4.8.5, Preparation of Field Connections, states “Holes in all field connections and field splices of main member of trusses, arches, continuous-beam spans, bents, towers (each face), plate girders, and rigid frames shall be subpunched or subdrilled and subsequently reamed while assembled or drilled full-size through a steel template while assembled.” Though this article does not directly ban the use of punched holes, it implies that punching holes full size in primary members is not allowed. This is a second limit placed on punched hole use, not in primary members. This article also states that holes for floor beams or cross frames can be drilled full-size in the unassembled pieces. As stated in Article 11.4.8.3, Numerically-Controlled (N/C) Drilled Field Splices, the contractor is given the option of drilling or punching holes full-size in unassembled pieces. However, the use of punched holes is limited by Article 11.4.8.1, described previously (AASHTO Construction 2004).

AASHTO Construction Article 11.4.8.1.2, Punched Holes, states,

> “The diameter of the die shall not exceed the diameter of the punch by more than 0.0625 in. (1.5mm). If any holes must be enlarged to admit the bolts, such holes shall be reamed. Holes must be clean-cut without torn or ragged edges. The slightly conical hole that naturally results from punching operations shall be considered acceptable.”

Other guidelines for punched holes are not listed, such as punch and die quality or the type of punch press used. Article 11.4.8.1.4, Accuracy of Holes, lists slotted holes may be prepared by flame cutting, or a combination of drilling or punching and flame cutting. Dimension for slotted holes, and other hole types are listed in the AASHTO Design Specifications. The AASHTO Construction Specifications are not clear on whether these slotted holes made by punching and flame cutting can be used in primary members. The effect of die clearance and method of making slotted holes amounts were investigated in this project.

The TxDOT Standard Specifications for Construction and Maintenance of Highways, Streets, and Bridges 2004, hereafter called TxDOT Construction, follows the provisions set forth in the AASHTO Construction Specifications. TxDOT Construction Section 441.3.C, Bolt Holes, states, "Make holes in primary members full-size (by reaming from a subsize hole, drilling full-size, or punching full-size where permissible) only in assembly unless otherwise approved." Where exactly full-size punched holes are permissible is not listed in the TxDOT Construction Specifications. Primary members are defined in 441.3.A.2. These members include:

- Webs and flanges of plate, tub, and box girders
- Rolled beams and cover plates
- Floor beam webs and flanges
- Arch ribs and arch tie beams or girders
- Truss members
- Diaphragm members for curved plate girders or beams
- Splice plates for primary members
- Any other member designated as "primary" or "main" on the plans

Similar to AASHTO Construction, holes are sub-punched 3/16" smaller than nominal diameter before reaming. Slotted holes can be fabricated by punching or drilling and then thermally cut between holes. Thermal cutting of other holes is permissible only where approved of by the Engineer of Record (TxDOT Construction 2004).

1.2.3 AISC Specifications

The American Institute of Steel Construction (AISC) Manual of Steel Construction, Load and Resistance Factor Design, Third Edition, hereafter referred to as AISC 1999, made little mention of punched holes. The only discussion comes into guidelines for fabrication, Section M2.5, Bolted Construction. This section states,

> "If the thickness of the material is not greater than the nominal diameter of the bolt plus 1/8-in. (3mm), the holes are permitted to be punched. If the thickness of the material is greater than the nominal diameter of the bolt plus 1/8-in. (3mm), the holes shall either be drilled or sub-punched and reamed. The die for all sub-punched holes, and the drill for all sub-drilled holes, shall be at least 1/16-in. (2mm) smaller than the nominal diameter of the bolt. Holes in ASTM 514/A514M steel plates over ½-in. (13mm) thick shall be drilled."

The wording of the amount of reaming, combined with previous provisions, requires sub-drilled holes to be reamed 1/8 in. This implies that punched holes be reamed 3/16 in. This assumes the punch itself has a clearance of 1/16 in. between the die, or a sub-punching diameter of the bolt diameter minus 1/16 in. die size minus an implied 1/16 in. clearance. The recommended clearance amount can vary depending on plate thickness, however. This statement could be confusing, and should likely list a punch size 1/16 in. smaller than bolt diameter, rather than the die size. These provisions are similar to AASHTO Construction provisions discussed previously, with a reaming amount of 3/16 in. The only difference is that AISC does not place limits on where punched holes can be used, such as holes for primary members. Also, the thickness limits do not differentiate for the type of steel used (AISC 1999).

The AISC Steel Construction Manual, Thirteenth Edition (AISC 2005) changes Section M2.5. The new section states, "Bolt holes shall comply with the provisions of the RCSC (Research Council on Structural Connections) Specification for Structural Joints Using ASTM A325 or A490 Bolts, Section 3.3 except that thermally cut holes shall be permitted with a surface roughness profile not exceeding 1,000 micro in. as defined in ASME B46.1. Gouges shall not exceed a depth of 1/16 in." The referenced RCSC Specifications do not mention punched holes. The commentary for this section further states the following,

> "The Specification previously limited the methods used to form holes, based on common practice and equipment capabilities. Fabrication methods have changed and will continue to do so. To reflect these changes, this Specification has been revised to define acceptable quality instead of specifying the method used to form the holes, and specifically to permit thermally cut holes. AWS C4.7, Sample 3, is useful as an indication of the thermally cut profile that is acceptable (AWS, 1977). The use of numerically controlled or mechanically guided equipment is anticipated for the forming of thermally cut holes. To the extent that the previous limits may have been related to safe operation in the fabrication shop, fabricators are referred to equipment manufacturers for equipment and tool operating limits."

Therefore, the current AISC Specifications no longer limit the use of punched holes (AISC 2005).

Like AASHTO, the AISC design process does not differentiate the hole type when selecting ϕ (phi) factors. In addition, Section B3.13b, Net Area, states, "In computing net area for tension and shear, the width of a bolt hole shall be taken as 1/16 in. (2mm) greater than the nominal dimension of the hole." This is repeated in AISC 2005 Section D3.2. The commentary to AISC 2005 Section D3.2 states the following, "The critical net area is based on net width and load transfer at a particular chain. Because of possible damage around a hole during drilling or punching operations, 1/16 in. (1.5mm) is added to the nominal hole diameter when computing the critical net area.” Therefore, punched and drilled holes are treated equally. The addition to the hole size is the same addition as that used by AASHTO Design Specifications, with slightly different wording. AISC 2005 Section J3, Bolts and Threaded Parts, lists required hole spacings, minimum edge and end distances, and nominal hole dimensions. These items are the same as those listed in AASHTO Design specifications as well (AISC 2005).

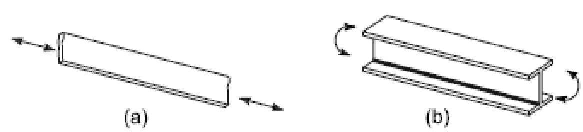
Bearing strength at bolt holes and block shear rupture strength of connections are treated similarly to AASHTO Design equations, though with differences for block shear strength and an additional bearing strength equation. These equations are presented in Section 1.2.5. Both the 1999 and 2005 equations are presented for comparison. The method of hole fabrication does not affect the design calculations for bearing strength and block shear strength. Also, AISC does not mention the hole type when determining slip resistance, Section J3.8. The fatigue categories for mechanically fastened joints used by AISC are identical to those used by AASHTO, discussed in AISC 2005 Appendix 3 and Table A-3.1. These tables are reproduced in Figure 1.1 and Figure 1.2. The descriptions and important parameters are presented, along with illustrative examples for each type. Connections other than mechanically fastened joints are not presented. These descriptions and illustrations are basically identical to those used by AASHTO. A mechanically fastened joint can be a Category B through a Category D connection, depending on the configuration of the joint. The exception item would be the configuration labeled 1.4, a Category C connection. This configuration, for members with light bracing attached, is not listed in AASHTO Design 2004 (AISC 2005). Non-loaded bolted connections occur when secondary members, such as lateral bracing, are attached on primary members or components. The connection transfers the secondary forces through the connection however the primary member carries significant load unrelated to the secondary members. These forces in the components of primary members pass through the bolted attachment and result in stress concentrations around the bolt holes. It is felt that if the bolts are pre-tensioned they will shield the bolt holes from fatigue damage. The compressive stress around the bolt holes is greatest at the ends of the hole and can diminish toward the mid-thickness of the plate. A significant reduction of shielding may occur in thicker plates.

Description	Stress Category	Constant C_f	Threshold F_{TH} ksi (MPa)	Potential Crack Initiation Point
SECTION 1 – PLAIN MATERIAL AWAY FROM ANY WELDING				
1.1 Base metal, except non-coated weathering steel, with rolled or cleaned surface. Flame-cut edges with surface roughness value of 1,000 μin. (25 μm) or less, but without reentrant corners.	A	250×10^8	24 (165)	Away from all welds or structural *connections*
1.2 Non-coated weathering steel base metal with rolled or cleaned surface. Flame-cut edges with surface roughness value of 1,000 μin. (25 μm) or less, but without reentrant corners.	B	120×10^8	16 (110)	Away from all welds or structural *connections*
1.3 Member with drilled or reamed holes. Member with re-entrant corners at *copes*, cuts, block-outs or other geometrical discontinuities made to requirements of Appendix 3.5, except weld access holes.	B	120×10^8	16 (110)	At any external edge or at hole perimeter
1.4 Rolled cross sections with weld access holes made to requirements of Section J1.6 and Appendix 3.5. Members with drilled or reamed holes containing bolts for attachment of light bracing where there is a small longitudinal component of brace *force*.	C	44×10^8	10 (69)	At *reentrant* corner of weld access hole or at any small hole (may contain bolt for minor *connections*)

Illustrative Typical Examples

SECTION 1 – PLAIN MATERIAL AWAY FROM ANY WELDING

1.1 and 1.2



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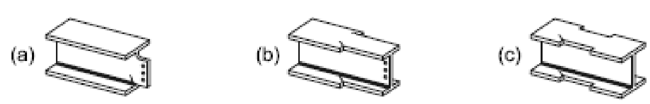

1.4

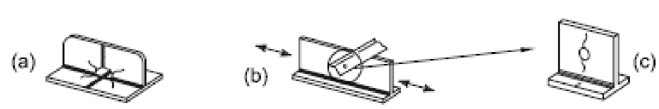

Figure 1.1: AISC Fatigue Design Parameters, 1 of 2 (AISC 2005)

SECTION 2 – CONNECTED MATERIAL IN MECHANICALLY FASTENED JOINTS				
2.1 Gross area of base metal in lap joints connected by high-strength bolts in joints satisfying all requirements for slip-critical connections.	B	120×10^8	16 (110)	Through gross section near hole
2.2 Base metal at net section of high-strength bolted joints, designed on the basis of bearing resistance, but fabricated and installed to all requirements for slip-critical connections.	B	120×10^8	16 (110)	In net section originating at side of hole
2.3 Base metal at the net section of other mechanically fastened joints except eye bars and pin plates.	D	22×10^8	7 (48)	In net section originating at side of hole
2.4 Base metal at net section of *eyebar* head or pin plate.	E	11×10^8	4.5 (31)	In net section originating at side of hole

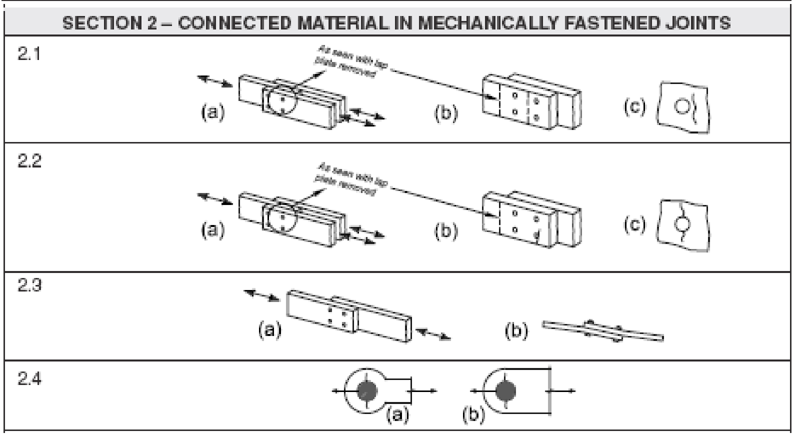

Figure 1.2: AISC Fatigue Design Parameters, 2 of 2 (AISC 2005)

1.2.4 Tension Member Design Equations

The primary focus of this research project was the effect of punched holes on tension members. Therefore, the relevant equations for tension member design from both AASHTO Design 2004 and AISC 2005 are presented. The block shear equations have changed from AISC 1999 to AISC 2005, and both versions are presented for comparison. The relevant section numbers and equation numbers from each reference are given as well. The AASHTO bearing strength equations differ from AISC in that a second equation "When deformation at the bolt hole at service load is not a design consideration" is used by AISC. The forms of the block shear equations are different between AASHTO 2004 and AISC 2005. The AASHTO Design 2004 equations are presented first, followed by the AISC 2005 and AISC 1999 equations.

- **AASHTO Design 2004, 6.8.2: Tensile Resistance**

$P_r = \phi_y P_{ny} = \phi_y F_y A_g$ (6.8.2.1-1)
$P_r = \phi_y Pn_u = \phi_u F_u A_n U$ (6.8.2.1-2)

Where:

P_{ny} = nominal tensile resistance for yielding in gross section (kip)
F_y = specified minimum yield strength (ksi)
A_g = gross cross-sectional area of the member (in.^{2})
P_{nu} = nominal tensile resistance for fracture in net section (kip)
A_n = net area of the member as specified in Article 6.8.3 (in.^{2})
(discussed in Section 1.2.1 of this report)
U = reduction factor to account for shear lag
ϕ_y = resistance factor for yielding of tension members as specified in Article 6.5.4.2 (*ϕ_y = 0.95)*
ϕ_u = resistance factor for fracture of tension members as specified in Article 6.5.4.2 (*ϕ_u = 0.80)*

- **AASHTO Design 2004, 6.13.2.9: Bearing Resistance at Bolt Holes**

For standard holes, oversize holes, short-slotted holes loaded in any direction, and long-slotted holes parallel to the applied bearing force, the nominal resistance of interior and end bolt holes at the strength limit state, R_n, shall be taken as:

With bolts spaced at a clear distance between holes not less than 2.0d and with a clear end distance not less than 2.0d:
$R_n = 2.4dtF_u$ (6.13.2.9-1)

If either the clear distance between holes is less than 2.0d, or the clear end distance is less than 2.0d:
$R_n = 1.2L_ctF_u$ (6.13.2.9-2)

For long-slotted holes perpendicular to the applied bearing force:

With bolts spaced at a clear distance between holes not less than 2.0d and with a clear end distance not less than 2.0d:
$R_n = 2.0dtFu$ (6.13.2.9-3)

If either the clear distance between holes is less than 2.0d, or the clear end distance is less than 2.0d:
$R_n = L_ctF_u$ (6.13.2.9-4)

where:

d = nominal diameter of the bolt (in.)
t = thickness of the connected material (in.)
F_u = tensile strength of the connected material specified in Table 6.4.1-1 (ksi)
L_c = clear distance between holes or between the hole and the end of the member in the direction of the applied bearing force (in.)

- **AASHTO Design 2004, 6.13.4: Block Shear Rupture Resistance**

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

$R_r = \phi_{bs}(0.58F_yA_{vg} + F_uA_{tn})$ (6.13.4-1)

Otherwise:

$R_r = \phi_{bs}(0.58F_uA_{vn} + F_yA_{tg})$ (6.13.4-2)

Where:

A_{vg} = gross area along the plane resisting shear stress (in.^{2})
A_{vn} = net area along the plane resisting shear stress (in.^{2})
A_{tg} = gross area along the plane resisting tension stress (in.^{2})
A_{tn} = net area along the plane resisting tension stress (in.^{2})
F_y = specified minimum yield strength of the connected material (ksi)
F_u = specified minimum tensile strength of the connected material specified in Table 6.4.1-1 (ksi)
ϕ_{bs} = resistance factor for block shear specified in Article 6.5.4.2
(ϕ_{bs} = 0.80)

- **AISC 2005, D2: Tensile Strength**

$P_n = F_yA_g$ (D2-1)
ϕ_t = 0.90 (LRFD)

$P_n = F_uAe$ (D2-2)
ϕ_t = 0.75 (LRFD)

where

A_e = effective net area, in.^{2}
(net area discussed in Section 1.2.4 of this report)
A_g = gross area of member, in.^{2}
Fy = specified minimum yield stress of the type of steel being used, ksi (
F_u = specified minimum tensile strength of the type of steel being used, ksi

- **AISC 2005, J3.10: Bearing Strength at Bolt Holes**

(a) For a bolt in a connection with standard, oversized, and short-slotted holes independent of the direction of loading, or a long-slotted hole with the slot parallel to the direction of the bearing force:

(i) When deformation at the bolt hole at service load is a design consideration:
$R_n = 1.2L_ctF_u \leq 2.4dtF_u$ (J3-6a)
(ii) When deformation at the bolt hole at service load is not a design consideration:
$R_n = 1.5L_ctF_u \leq 3.0dtF_u$ (J3-6b)

(b) For a bolt in a connection with long-slotted holes with the slot perpendicular to the direction of force:

$R_n = 1.0L_c tF_u \leq 2.0dtF_u$ (J3-6c)

Where

$\phi = 0.75$ (LRFD)
d = nominal bolt diameter, in.
F_u = specified minimum tensile strength of the connected material, ksi
L_c = clear distance, in the direction of the force, between the edge of the hole and the edge of the adjacent hole or edge of the material, in.
t = thickness of the connected material, in.

- **AISC 2005, J4.3: Block Shear Strength**

$R_n = 0.6F_uA_{nv} + U_{bs}F_uA_{nt} \leq 0.6F_yA_{gv} + U_{bs}F_uA_{nt}$ (J4-5)

where

$\phi = 0.75$ (LRFD)
A_{gv} = gross area subject to shear, in.^{2}
A_{nt} = net area subject to tension, in.^{2}
A_{nv} = net area subject to shear, in.^{2}
Where the tension stress is uniform, $U_{bs} = 1$; where the tension stress is non-uniform, $U_{bs} = 0.5$.

- **AISC 1999, J4.3: Block Shear Rupture Strength**

(a) When $F_uA_{nt} \geq 0.6F_uA_{nv}$:
$\phi R_n = \phi[0.6F_yA_{gv} + F_uA_{nt}] \leq \phi[0.6F_uA_{nv} + F_uA_{nt}]$ (J4-3a)

(b) When $F_uA_{nt} < 0.6F_uA_{nv}$:
$\phi R_n = \phi[0.6F_uA_{nv} + F_yA_{gt}] \leq \phi[0.6F_uA_{nv} + F_uA_{nt}]$ (J4-3a)

where

$\phi = 0.75$
A_{gv} = gross area subject to shear, in.^{2}
A_{gt} = gross area subject to tension, in.^{2}
A_{nt} = net area subject to tension, in.^{2}
A_{nv} = net area subject to shear, in.^{2}

1.2.5 Practical Limits

Other limits on the use of punched holes exist outside of code provisions as well. The thickness of material that can be punched is often controlled by equipment capacity. The force required to punch a large hole through thick structural steel could potentially exceed the capacity of the punch equipment. These limits are set by punch press manufacturers. This topic is discussed in greater detail in Chapter 2. The general rule to follow on the use of punched holes is that the minimum diameter that can be punched is equal to the thickness of the material. This guideline has been around for many decades in the fabrication industry. For example, for a ½ in. thick plate, the minimum hole diameter that can be punched would be ½ in. This general rule can be violated in certain cases, also discussed in Chapter 2. As mentioned before, AASHTO Construction 2004 does not allow punched holes in material thicker than 0.75 in., 0.625 in., or 0.5 in., depending on steel strength. These limits are likely based on punch press capacity. The AISC 2005 Specifications no longer have any limits on the use of punched holes, however.

These practical guidelines serve as a limit on using punched holes for typical bridge members, except for the thinner webs of girders. Bridge member flanges typically have minimum thicknesses of ¾ in. to 1 in., with thickness often approaching 2 in. to 4 in. These thicker sections cannot be punched. Therefore, punched holes can only be used on thinner members, such as angle braces.

1.3 PROJECT SCOPE

The objective of this project was to quantify the effects of punched holes and slotted holes in structural steel plate material and structural connections. Fatigue tests were also conducted to determine the fatigue characteristics of plates with various types of open holes. Based on the results of the tension and fatigue tests of structural steel plates, simple tension connections were designed and tested to determine the effects of punched holes on bearing strength, block shear strength, deformation capacity, and fatigue life. From these tests, recommendations will be presented on how to account for the possible use of punched holes in the design process. Potential modifications to current AASHTO specifications will also be presented. A study of the effect of hole size, die clearance, plate thickness, and material strength upon the force and energy required to punch holes was undertaken. This work is reported in Cekov (2006) and is not included in this report for brevity.

1.4 REPORT OUTLINE

The important topics of this research project will be reported as follows:

- Chapter 2—Past research into the punch process will be presented. Relevant past research on plates and connections with various hole types will also be discussed.
- Chapter 3—The specimens and test methods used for this project will be discussed. The research project included 118 plates tested in tension, 33 plates

tested in fatigue, 102 double shear lap splice connections tested in tension, and 12 double shear lap splice connections tested in fatigue.

- Chapter 4—The results from the tests will be presented as well as a short description of the relevant specimen fabrication procedures. The data generated in this project as well as results from other researchers are analyzed and compared.
- Chapter 5—A conclusion of this research project will be provided. The tests and results will be summarized, and recommendations and/or possible code changes will be given.
- Appendix A—Lists the recommended specification changes based upon the results of this study.

Chapter 2. Literature Review

2.1 Punch Process

A punched hole is fabricated by a shearing operation resulting from forcing a male punch through the work piece and through a female die. The force required for this operation is related to the hole size to be punched and the thickness and shear strength of the base steel. For example, the force required to punch a hole in various thicknesses of A36 steel is shown in Figure 2.1. These values were taken from a punch press manufacturer, W.A. Whitney. Here, the shear strength of the steel was taken as 60 ksi. The punch force required for other grades of steel can be determined by multiplying the forces shown by the ratio of the new material's shear strength divided by 60 ksi. The ram force presented by Whitney was calculated using an area equal to the hole circumference times plate thickness, multiplied by the 60 ksi shear strength. This shear strength value implies an ultimate strength of about 100 ksi, a high value for A36 steel. The shear strength is likely inflated to cover the fact that the actual properties of a steel member will often be higher than anticipated. This ensures a punch press believed to be capable of punching through certain steel can actually punch through the steel received. Other research has presented an empirical formula for punch force of 0.8 times the ultimate strength times hole circumference times plate thickness ($F=0.8f_u\pi dt$). In the fabrication of specimens for this project, the 0.8 times ultimate strength formula provided a good prediction of the punch force.

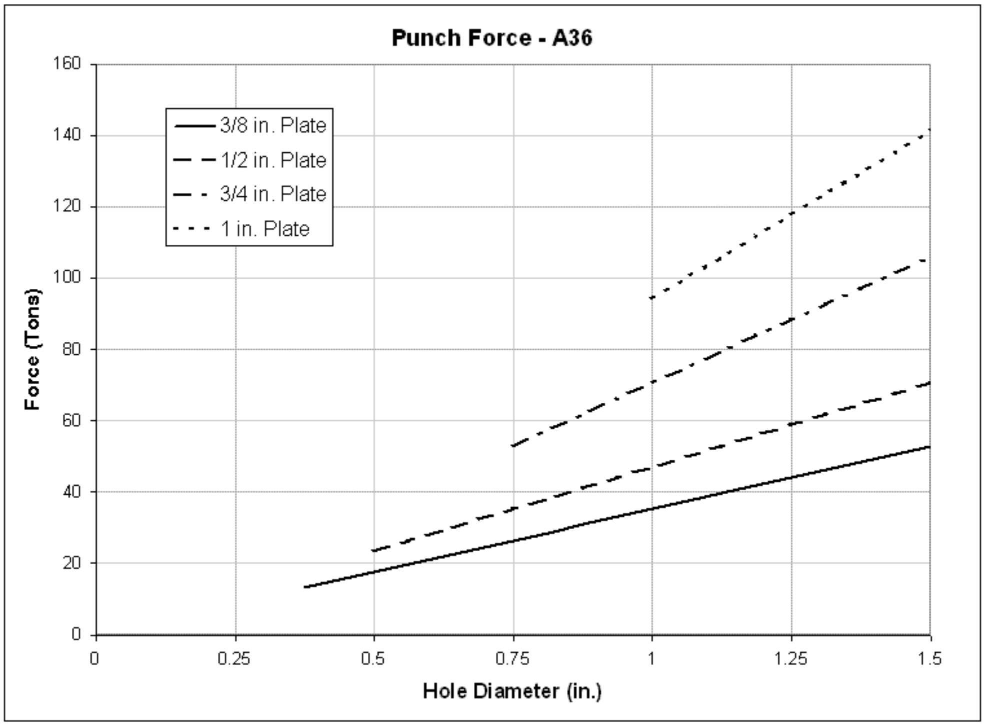

Figure 2.1: Punch Force for A36 Steel (W.A. Whitney)

As mentioned in Chapter 1, there are certain practical limits on the use of punched holes in addition to those allowed by AASHTO and AISC. The punch forces shown in Figure 2.1 reiterate the fact that punched holes can only be used for thinner members, such as angle braces and cross-frames. The force required to punch a 1 in. diameter hole in 1 in. thick material is about 94 tons. If stronger steel than the A36 is used, such as A572 Grade 50, the punch force required might exceed the capacity of a punch press.

In addition, the common recommendation controlling the use of punched holes is that the diameter of hole that can be punched should not be less than the thickness of the base metal. This rule of thumb has been around for many years. This concept can be violated in certain cases, depending on the recommendations of the punch press manufacturer, at the expense of reduced tool life. DeGarmo (1979) stated that smaller holes could be punched, but with difficulty. A punch press manufacturer, W.A. Whitney, stated that damage to both the punch itself and the base metal can often occur if this general rule is ignored. This was especially true for cases when a high-speed mechanical press is used, causing shock forces during the punching process. If hydraulic presses are used, the minimum hole can be of smaller diameter, depending on the shear strength of the material relative to the compressive stress in the punch. As a side investigation in this project, the effect of violating this rule of thumb of the material being punched was determined to be negligible (W.A. Whitney).

The punching process and the associated damage to the base metal have been analyzed in past research. For example, a detailed investigation into the effect of the punching process on the tool life of the punch itself was performed by Luo (1999). The steps used to describe the punching process are displayed in Figures 2.2 through 2.4. Luo categorized the behavior of the base material as it is being punched into three major phases of damage. The first phase involves elastic then plastic deformation of the base metal as it first comes in contact with the punch. Here, the bottom of the base metal starts to bend outward from the force of the punch. The second phase is the punch penetrating into the base metal and material starts to be sheared outward. An initial small amount of the base metal is sheared, and then a crack begins to propagate as the metal is continually forced downward into the die. A shear band is formed at the top of the base metal from the contact with the punch. This is shown in Figure 2.2 as Steps A and B. At some point during the punch penetration, a secondary shear zone develops, as shown in Figure 2.3 as Step C. The metal being forced into the die is sheared by the cutting surface of the die. The location of this secondary zone is dependent on the clearance between the punch and the die and to a small extent on the strength of the base metal. The final phase is the fracture of the slug out of the punched hole. A crack is formed at the top of the base metal due to the shear force caused by the punch, which combines with the fracture crack from the cutting surface of the die. This is shown in Figure 2.3 as Step C and D. The final step shown in Figure 2.4, Step E, where the final hole, and associated slug, is formed (Luo 1999).

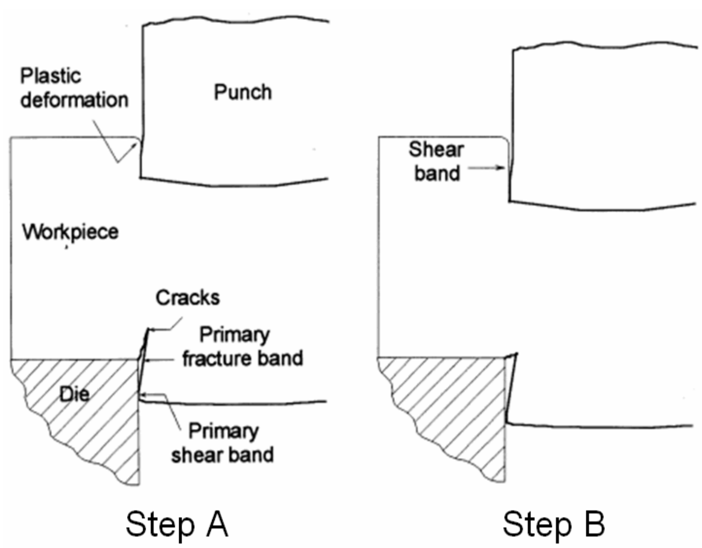

Figure 2.2: Hole Punching Step A and Step B (Luo 1999)

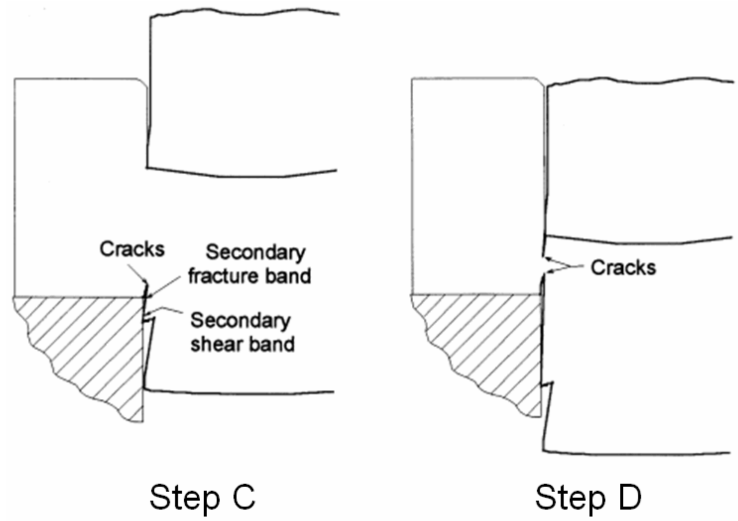

Figure 2.3: Hole Punching Step C and Step D (Luo 1999)

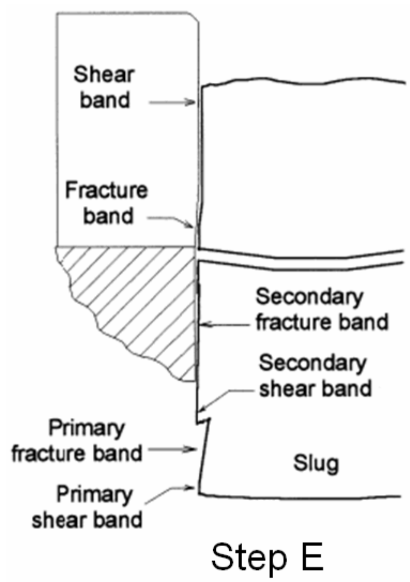

Figure 2.4: Hole Punching Step E (Luo 1999)

The appearance of a punched hole is largely dependent on the clearance between the punch and the die. Die clearance values as recommended by a punch press manufacturer, W.A. Whitney, are shown in Table 2.1. These recommended die clearance values were followed throughout this research project. The values presented also have an overlap between material thicknesses. For example, a ½ in. thick plate is recommended to have a die clearance of either 1/32 in. or 1/16 in.

Table 2.1: Recommended Die Clearance Values (W.A. Whitney)

Material Thickness (in.)	Overall Die Clearance (in.)
1/8 thru 1/4	.020 over nominal (0.020)
1/4 thru 1/2	1/32 over nominal (0.051)
7/16 thru 13/16	1/16 over nominal (0.082)
5/8 thru 1-1/16	3/32 over nominal (0.111)
1 thru 1-1/4	1/8 over nominal (0.145)

A proper die clearance results in a secondary shear band, and limits the deformation and amount of burrs at the bottom of the hole. This is shown in Figure 2.5, taken from a W.A. Whitney Portable Press Catalog. An insufficient die clearance will cause a secondary break. A proper die clearance also minimizes the work required to punch the hole. The work required to punch a hole with insufficient clearance is much larger than with a properly sized die. An excessive die clearance amount results in a larger fracture surface and a large shock when the punch breaks through the material. The shock that results can decrease equipment life and increase maintenance costs. In addition, excessive clearance causes the cutting surface of the punch to breakdown prematurely.

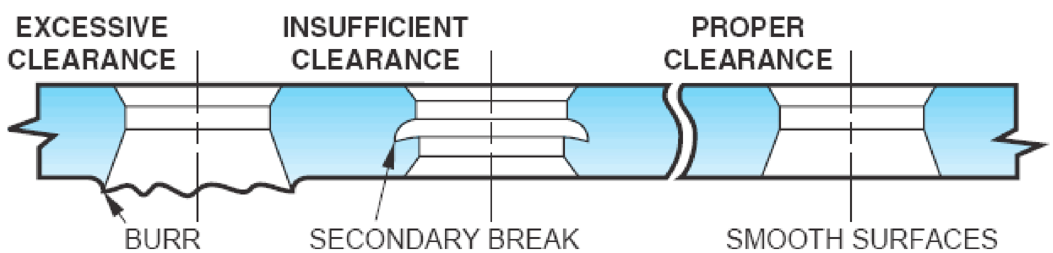

Figure 2.5: Effect of Die Clearance on Punched Hole Appearance (W.A. Whitney)

Examples of the work required to punch multiple hole sizes with various die clearances through multiple thickness and grades of steel were investigated and are presented in Brown (2005). The punch force versus punch displacement values were recorded during the punching process for this project. These figures illustrate that the work required to punch a hole is partially dependent on die clearance. One example is shown in Figure 2.6, for ½ in. A36 steel with a 15/16 in. diameter hole, punched with various die sizes. The recommended die clearance for ½ in. thick steel of 1/32 in. (31/32 in. die) required a slightly higher punch force and greater work, as indicated by the area under the load versus displacement curve, than the other recommended die clearance value of 1/16 in. (32/32 in. die). The predicted force, using the empirical method discussed previously, was 82.3 kips, using 0.8 times the tensile strength of the material, 69.9 ksi, times the hole circumference times plate thickness. The actual maximum punch force was 79.2 kips to 81.6 kips for the three die sizes shown.

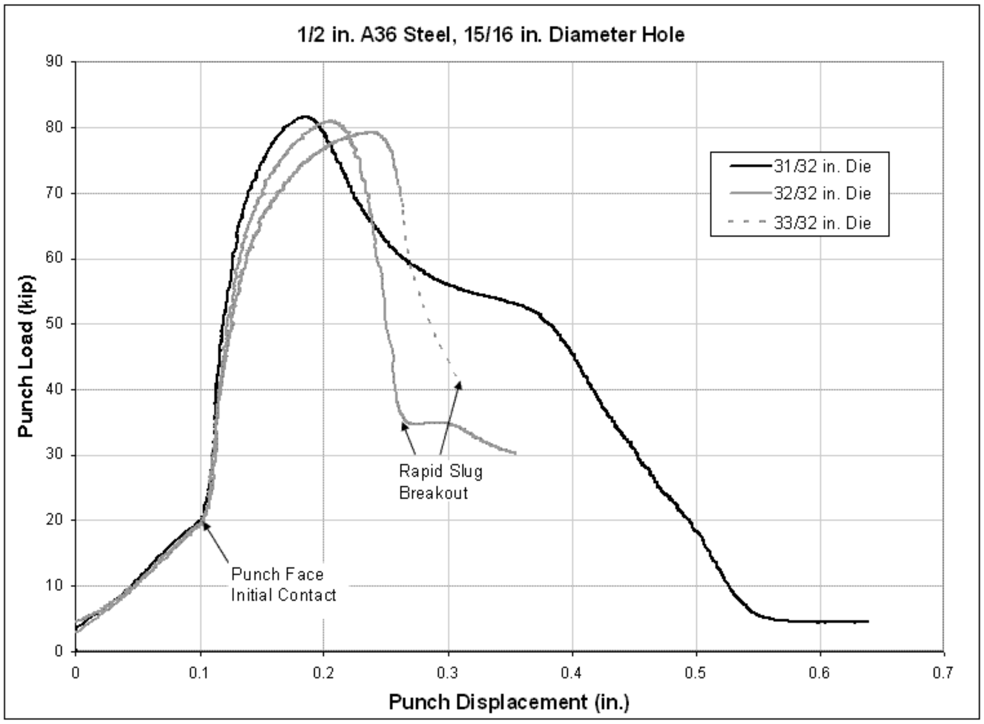

Figure 2.6: Punch Force vs. Displacement—½ in. A36 Steel

Examples of a slug with just a primary shear band and a slug with both a primary and secondary shear band are shown in Figure 2.7. Both slugs are from a ½ in. thick A572 Grade 50 plate. The top slug was made with a 15/16 in. diameter punch with a 31/32 in. die (clearance 1/32 in.), while the bottom slug was made with a 15/16 in. diameter punch with a 33/32 in. die (clearance 3/32 in.). The top slug with the secondary shear band is from a hole punched with a proper sized die, while the bottom slug with just a primary shear band corresponded to a die size that provides an excessive clearance amount, 3/32 in. instead of 1/32 in. or 1/16 in. The associated morphology of the hole is shown in Figure 2.8. The fracture band on the cross section of the hole was much larger when the die clearance is greater than ideal. The shear band in the cross section was related to the amount of penetration from the punch. For the cross section with a small shear band at the top, the punched hole slug was suddenly fractured out of the base material once the fracture crack initiated. Another important fact shown in Figure 2.8 was the larger hole diameter at the bottom of the hole compared to the top, which resulted from the fractured surface propagating at an outward inclined angle, thus increasing the effective diameter of the punched hole. This amount varies with steel grade, material thickness, and die clearance. These figures represent typical punched holes formed during this research project. Die clearance was used as a variable in this research project.

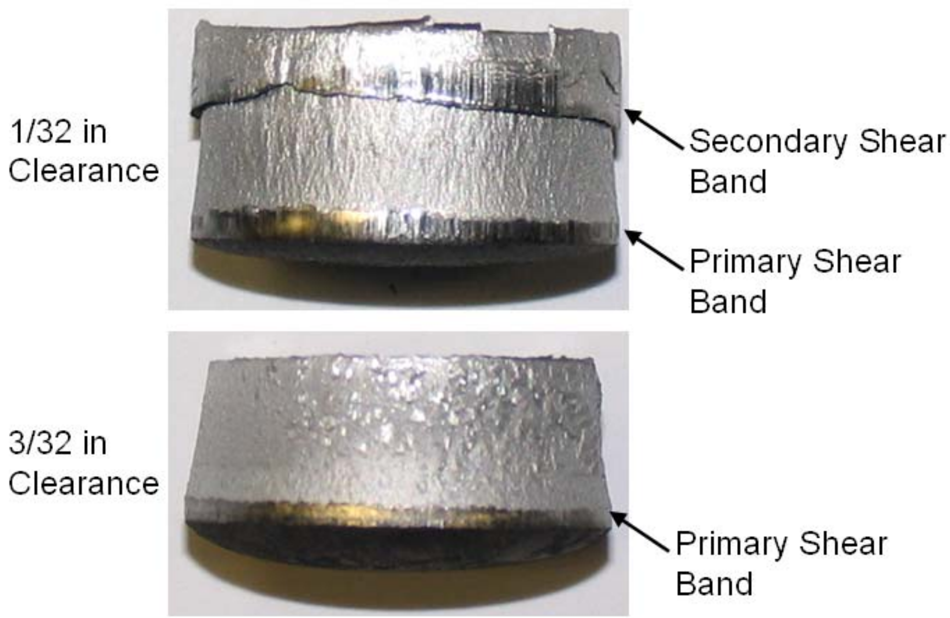

Figure 2.7: Typical Punched Hole Slugs

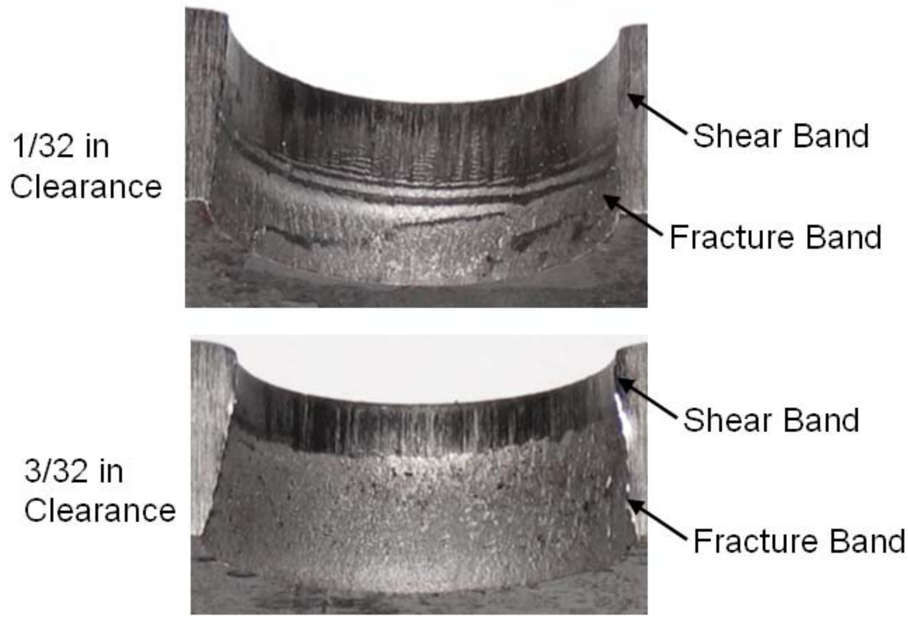

Figure 2.8: Typical Punched Hole Cross Sections

Other research has classified the damage to the base metal in a similar manner. Gutierrez-Solana et al. (2004) defined three main damage regions resulting from a punched hole. These are shown in Figure 2.9. Zone 1, labeled as shear by contact with punch, corresponded to the shear band described previously. Zone 2, labeled as tearing of material, corresponded to the fracture band common to punched holes. Zone 3, labeled as shear by contact with matrix, corresponded to the very tip of the bottom of the base material in contact with the cutting surface of the die. This is shown as Step A in Figure 2.2.

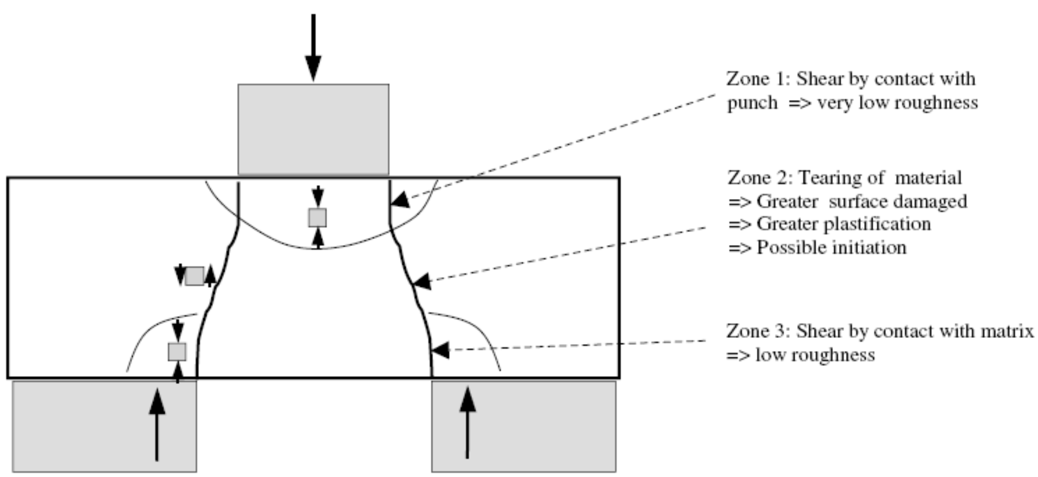

Figure 2.9: Zones of Damage in a Punched Hole (Gutierrez-Solana et al. 2004)

Research by Huhn and Valtinat (2004) further investigated the effects of the punching process on the base material. They reported hardness values in the vicinity of the punched hole, shown in Figure 2.10. The hardness value, in a Vickers hardness scale, increased dramatically towards the edge of the punched hole. These values increased from an unstrained value of 180 to a value of 350 to 400 near the punched holes. In addition, several micro tensile test specimens were tested. The results of these tests are shown in Figure 2.11. The distance outward from the edge of the hole is denoted as 'x' in the figure. This graph demonstrates the dramatic loss of ductitility and increased brittleness due to a form of work hardening as a result of the punching process.

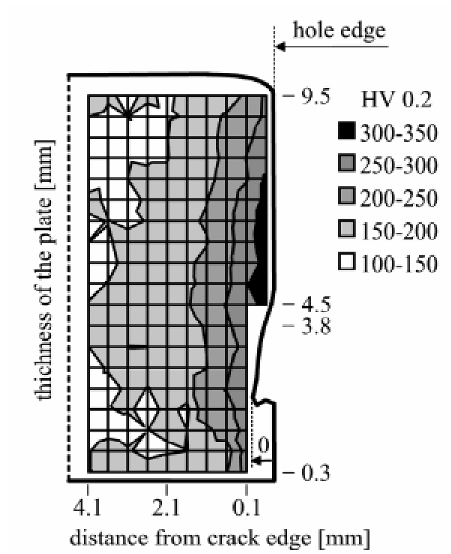

Figure 2.10: Distribution of Hardness around a Punched Hole (Huhn 2004)

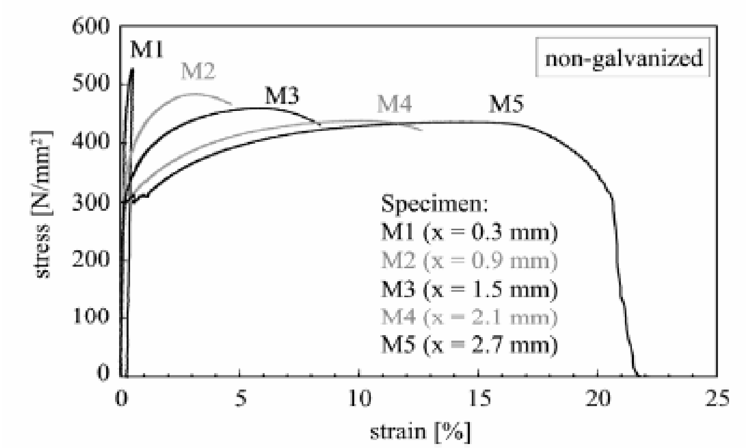

Figure 2.11: Stress-Strain Curves for Area near Punched Hole (Huhn 2004)

Driver et al. (1981) presented additional information on the punching process. The various shear and fracture zones were identified in a similar manner, and increases in hardness values near the edge of a punched hole were nearly identical to those presented previously. The authors also discussed strain ageing, a phenomena that may limit the performance of punched holes. After the initial cold working of the punching process, a decrease in ductility may occur in the surrounding material. While the immediate effects due to cold working are best shown by the previous figures, strain ageing is a time-dependent event. There is a gradual increase in the apparent yield point of the steel after it has been loaded past its initial yield point. If the steel is unloaded and then reloaded after a certain amount of time, the steel has a new, higher yield point and decreased ductility. This was shown by Baird (1963) in a figure similar to that shown in Figure 2.12. Strain ageing can be compounded when a member is hot dip galvanized. Strain ageing can be accelerated by heating steel to certain temperatures for certain period of times. This is often done in research to simulate strain ageing effects. Further discussion on strain ageing can be found in Baird (1963), Driver et al. (1981), Rassati et al. (2004), and Lubitz (2005). Strain ageing was investigated in this project by heating the specimens after punching and then comparing the results with unheated specimens. No significant difference in strength and ductility was found between the heated and unheated specimens.

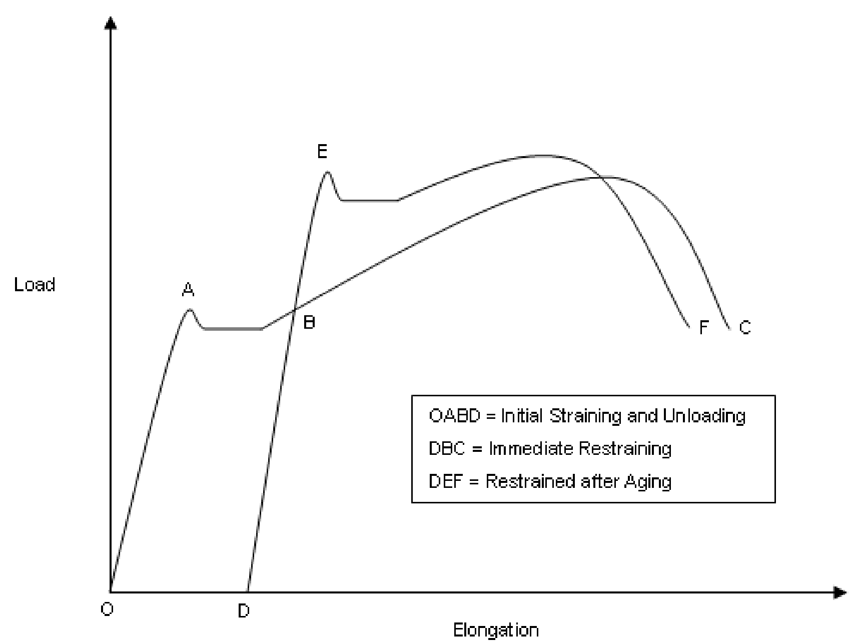

Figure 2.12: Strain Ageing Effect on Load-Elongation Relationship (Lubitz 2005)

Therefore, the punching process itself hardens the material near the hole causing increased hardness values and a loss of ductility, which can compounded by the time dependent effects of strain ageing. From these effects, punched holes cause much more damage to the base material compared to drilled holes.

2.2 PREVIOUS TENSILE TESTS WITH PUNCHED HOLES

In an extensive literature survey published by de Jonge (1945), research into riveted joints was conducted as far back as 1837. Much of the research prior to 1945 dealt with flat plate type joints, commonly used in ships, boilers, and tanks. Towards the end of the 19th century, a series of experiments began on joints used for large buildings and bridges. Of the many tests and conclusions described, de Jonge noted that punched holes in a joint generally resulted in strengths five to ten percent lower than joints with drilled holes.

Early work in the 1950's and 1960's at the University of Illinois at Urbana-Champaign worked to expand on the many factors involved in tension member design. As referenced by Chesson and Munse (1958), the literature survey by de Jonge (1945) provided little test data on full-size tension members. In a series of three papers, Chesson and Munse reported on a large number of experiments dealing with large riveted and bolted truss-type tension connections. The method of hole forming was one of several variables investigated throughout the research. Duplicate specimens with punched and drilled holes were used for many of the truss-type configurations. The angle stock material used had average yield and ultimate strengths of 41 ksi and 66 ksi, respectively. The gusset plate material used had average yield and ultimate strengths of 36 ksi and 60 ksi, respectively. These relatively low yield and ultimate strengths are seldom produced in current structural steel. Based on the results of their tests and analysis, Chesson and Munse (1958, Truss 1963, Net 1963) presented the following conclusions:

- "At a given load, punched members generally had lower deformations than drilled members of the same proportions…Punching reduced the net section ductility."
- "It appears that the lower ductility of the punched members causes the ultimate strain in the gussets to be reached early near the holes so that the more distant material cannot be so effectively developed (because of shear lag) as in the drilled plates."
- "Punching reduces the strength of a tension connection by 10% to 15% below that of a comparable connection with drilled holes."

- “To consider simply the effect of punching, the allowable tensile stress for members with punched holes could be taken as seven-eights of the allowable tensile stress permitted by the design specification for a member fabricated with drilled holes.”

Another key point given was the fact that a designer would have to specify the hole preparation method to be used. While the use of punched holes may be more economical than drilled holes, the 7/8 adjustment for tensile stress could increase the required member sizes. Chesson and Munse also emphasized the importance of using the shear lag factor (U = 1-x/L) in tension member calculations. While this suggestion has survived in modern codes, accounting for the hole fabrication method has not.

Lubitz (2005) compared several specimens tested by Chesson and Munse with predicted design values calculated using the current AASHTO Design equations for tension member design, with all resistance factors taken as 1.0. The results of this comparison are shown in Figure 2.13. In this figure, a 45-degree line represented an experimental load that matched the predicted design load. Therefore, data points above this line represented specimens that exceeded predicted loads, while data points below this line failed prior to reaching their predicted loads. Points above the line therefore indicate conservative predictions of capacity, while points below the line are unconservative. All of the drilled hole specimens were above the line, while many of the punched hole specimens were below the line.

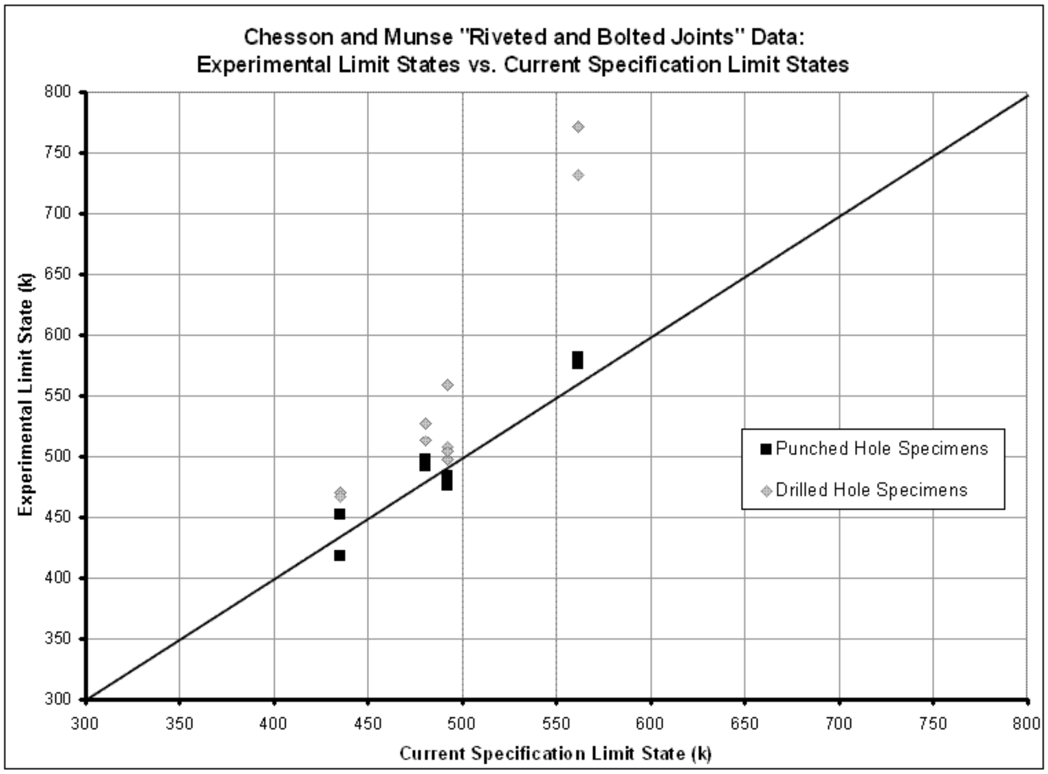

Figure 2.13: Chesson and Munse Test Data Comparison (Lubitz 2005)

Driver et al. (1981) investigated the effects of punched holes in tension connections as well. The test specimens consisted of single bolt specimens in a single or double shear lap splice configuration. The plates were 72 mm (2.83 in.) wide, with 22 mm (0.866 in.) diameter holes with an end distance of 40 mm (1.58 in.) The double shear lap splice specimens with punched holes were made of 2 grades of 10 mm (0.40 in.) thick steel; Gr. 43 with a yield strength of 303 MPa (44 ksi) and an ultimate strength of 445 MPa (64.5 ksi), and Gr. 50 with a yield strength of 453 MPa (65.7 ksi) and an ultimate strength of 560 MPa (81.2 ksi). The drilled hole specimens were tested in a different phase of the project using different steels. The following properties of the steel used were given: Gr. 43 with a yield strength of 232 MPa (33.7 ksi) and an ultimate strength of 391 MPa (56.7 ksi), and Gr. 50 steel with a yield strength of 378 MPa (54.8 ksi) and an ultimate strength of 532 MPa (77.2 ksi). The single shear lap splice specimens were made of 6 mm (0.24 in.) thick steel; Gr. 43 with a yield strength of 296 MPa (43 ksi) and an ultimate strength of 385 MPa (55.8 ksi). The bolts were ‘finger tight’ only. The main conclusions of the Driver et. al tests, though acknowledged with limited experimental information, were:

- “That punching does not generally alter the bearing strength of a bolted connection to any significant degree”
- “That deformations at working load levels with punched holes are likely to be slightly less than with drilled holes”
- “That cracks initiating in the hardened material immediately around the hole will be arrested in the surrounding unhardened material”
- “That the loss of ductility arising from these cracks will probably not impair the performance of a conventional elastically designed structure under static loading”
- “That punched holes should not be permitted in plastically designed structures where deformation capacity may be required of net sections in tension”
- Punched holes should not be permitted in members at low temperatures or subject to fatigue

It is interesting to note that several of the punched hole specimens in the Driver et al. study failed at higher bearing stress values compared to the drilled hole equivalent specimens. The data presented was normalized with ultimate bearing stress divided by the average ultimate tensile strength. Several punched specimens had 10% to 15% higher strengths, while other punched specimens had 10% lower strengths. The authors acknowledged that this trend is in contrast to earlier work. One possible explanation of these results put forth by the authors was that the punched and drilled specimens were compared in different steels, as shown by the different strength values listed previously. A second explanation given by the authors is the use of then modern, 1980’s steel compared to the earlier work.

Driver et al. (1981) presented other past research into the effects of punched holes. Vasarhelyi et al. (1959) tested a double shear lap splice connection with both punched and drilled hole specimens. For specimens that could be compared directly, it was reported there was a reduction in strength of about 10% for punched holes, and a reduction in ductility of about 40%. Wallin (1975) was reported to have tested a single bolt double shear lap splice tension connection with drilled holes and punched holes fabricated with various methods. The results of these tests showed that punched holes had a strength value of approximately 90% of a drilled hole, and ductility values between 50% and 90% of a drilled hole.

Iwankiw and Schlafly (1982) investigated the effects of various hole fabrication techniques on the ultimate strength of bolted connections. Holes were drilled, punched full-size, sub-punched and reamed, flame cut, and flame cut and reamed in 18 separate specimens. The test setup was a single 15/16 in. diameter hole in a double shear lap splice connection with a pretensioned bolt. The specimens were nominally 3 in. wide, with an edge distance of 1-1/2 in. and an end distance of 3 in. The measured yield and ultimate strengths of ½ in. A36 specimens were 53.3 ksi and 82.1 ksi, respectively. The 7/8 in. diameter A325 bolts were pretensioned to approximately 39 kips. Iwankiw and Schlafly stated, "In conclusion, a series of tests has demonstrated that common fabricator hole-making procedures do not significantly affect connection strength and performance under static loads. Furthermore, the prudent utilization of flame-cutting has been shown to be an acceptable alternative." The average deflection at ultimate load for each hole type was remarkably different. The ratio of punched hole specimen deflection to drilled hole specimen deflection was approximately 0.7. Sub-punched and reamed specimens had deflections close to drilled hole specimens.

Several reservations can be reached when examining Iwankiw and Schlafly's data. The authors reported a "safe limit load" of the testing apparatus as 80 kips, and all of the specimen ultimate loads were near or above this safe load. It was reported that 5 of the 18 tests were stopped before reaching this safe load, while others were allowed to go above the limit load and subsequently fracture. Surprisingly, even though the ultimate strength of these 5 specimens was not determined, the load and displacement at which they were stopped was used for comparisons with other failed specimens. Two of these specimens had drilled holes. The drilled hole specimen that did fracture appeared to have remarkably lower strength and deflections than the other specimens that were not stopped. Therefore, the drilled hole specimen average would have been higher had the tests not been stopped, with the increase in average load unknown. In addition, each hole fabrication method was tested in triplicate, but there was a relatively large scatter in some of the test results. There was a 7% difference in ultimate loads for identical specimens. Also, the end distances used were much larger than those that would be used in a structure, 3 in. versus 1.3 in. if 1.5 times the diameter was used. The pretensioned bolts also likely added to the ultimate strength values of each test.

Frank (2002) performed a small study focused on the effects of punched holes in plate material. The specimens were 5-1/2 in. wide with a pair of 1-1/16 in. diameter holes. The tested plates included ½ in. and 1 in. thick A36 steel and 1 in. thick A572 Grade 50 steel. The measured yield strengths of the ½ in. and 1 in. A36 steel were 42.5 ksi and 45.3 ksi, respectively, while the ultimate strengths were 64.7 ksi and 74.1 ksi, respectively. The A572 Grade 50 steel had measured yield and ultimate strengths of 53.6 ksi and 81.7 ksi, respectively. The plates with open holes were tested until fracture occurred on the net section, at both room temperature and a temperature near 0^{o} F. The punched holes had an average strength ratio, or ultimate load divided by tensile strength times net area, of 0.98 and the drilled holes had an average strength ratio of 1.16. The ductility of a punched hole plate was remarkably lower than that of a drilled hole plate.

Bartels et al. (2002) investigated the effects of connection length on the net section rupture strength of tension members with varying connection eccentricities. Duplicate specimens with either punched or drilled holes in WT sections were fabricated with various connection eccentricities and lengths. The WT sections had yield strengths of 58.7 ksi, 61.9 ksi, and 58.7 ksi, with ultimate strengths of 75.1 ksi, 76.3 ksi, and 68.7 ksi, respectively. Snug-tight conditions were used on the bolts. The authors reported an average 7% loss in net section rupture strength due to punched holes. The 1/16" addition to hole diameter, as stated by both AISC and AASHTO, was found to reduce the net section area on average less than 2% for the punched hole specimens used. It was also reported that Kulak and Wu (1997) found this hole diameter addition reduced net area by less than 4% in a range of angle specimens. Furthermore, it was noted that an average increase in hole diameter of 5/16" would reduce the net section capacity by only 7%. Load capacity reductions for specimens with punched holes were as large as 11% compared to drilled specimens in the tests conducted in the report. The 7/8 adjustment to account for punched holes suggested by Chesson and Munse (1963) was therefore described as reasonable. The authors stated, "The deleterious effects of punching, arising from a reduced ductility at the bolt hole due to significant strain hardening and the possible formation of small radial defects, cannot be adequately accounted for by the assumption that the damaged material at the bolt hole is ineffective." It was also acknowledged that the effects of punching became more pronounced as edge distance decreased. This is shown in Figure 2.14.

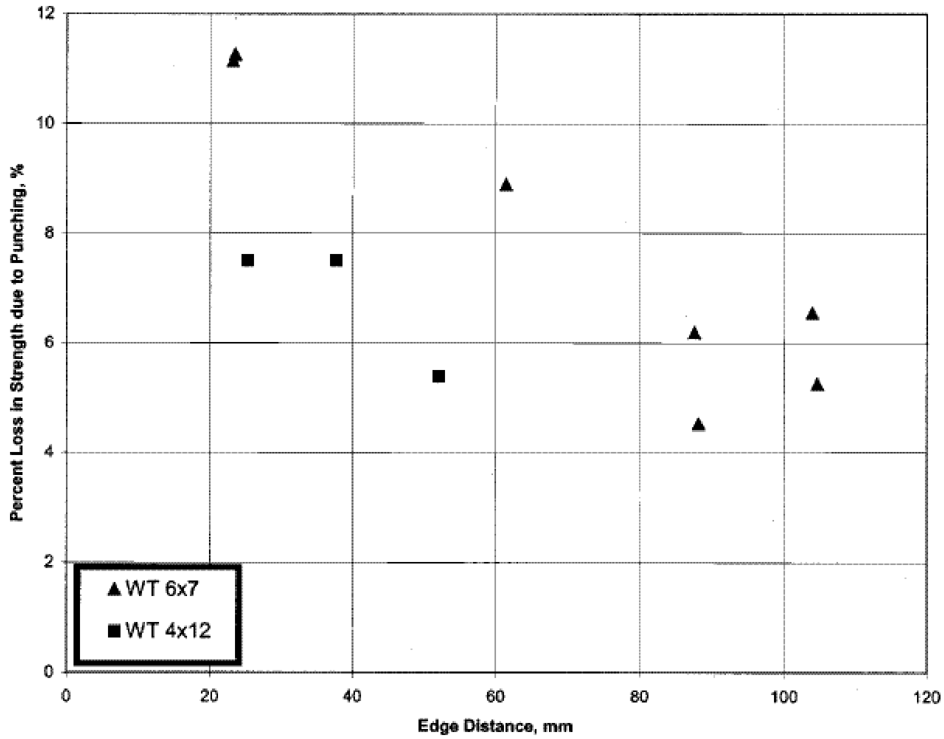

Figure 2.14: Reduction in Net Section Rupture Strength due to Punched Holes (Bartels et al. 2002)

Rassati et al. (2004) investigated several hole fabrication techniques and their effect on flat plate material and material taken from a tee section. Holes were punched, drilled, and flame cut in four grades of steel. The plate specimens consisted of a single hole of various diameters in 3 in. wide, ½ in. thick A36 and A588 steel. The tee specimens were cut down from a W18x40 A992 section, with a single hole of multiple diameters on each flange of the tee section. The A36 steel had measured yield and ultimate strengths of 47.2 ksi and 76.8 ksi, respectively. A heat of A588 steel had measured yield and ultimate strengths of 76.1 ksi and 85.7 ksi, respectively. Two heats of A992 steel had yield strengths of 55.5 ksi and 47.6 ksi, and ultimate strengths of 68.0 ksi and 64.8 ksi, respectively. From the test results, the drilled A36 plate specimens were shown to have an average strength ratio of 1.02, and the punched specimens had an average strength ratio of 0.94. The drilled A588 plate specimens had an average strength ratio of 1.10, and the punched specimens had an average strength ratio of 1.07. These strength ratio values were calculated by the authors including the 1/16 in. addition to hole diameter for the net section area for all hole types. Without this addition, the ratios decrease by approximately 3%. The tests with the A992 tee material showed a strength ratio of 1.16 for drilled specimens, and a strength ratio of 1.09 for punched specimens. In general, strength ratio values were lower for steels with lower tensile to ultimate ratios (f_y/f_u). The A36 plates also yielded in the gross section before fracturing in the net section. The differences in strength are slightly less than those reported by Frank, but a similar difference between hole types was present. Punched holes also showed a lower ductility compared to drilled holes.

Many other research programs have been used in the development of the bearing strength and block shear strength equations used in modern codes. While these investigations did not directly compare punched holes to drilled holes, the test data can be used to further compare results of punched hole experiments. The following research, along with some of the previously presented research data, will be used in Chapter 3 for comparison with test data from this project:

- Lewis (1994)
- Kim (1996)
- Fleischer and Puthli (2000)
- Grondin and Kulak (2002)
- Easterling and Rex (2003)
- Driver, Grondin and Kulak (2006)

2.3 PREVIOUS FATIGUE TESTS WITH PUNCHED HOLES

The type of fatigue failure in a tension connection is dependent on the method of load transfer through the connection. A slip-critical type connection with load transferred through friction between the connected materials fails in either a fretting-type failure at the interface of the connected materials, or in a section between the end of the splice plate and a hole line. A bearing type connection generally fails along the net section of a hole line due to load transferred by shear or bearing from the bolts. These failure types are shown in Figure 2.15. A typical fretting failure is shown in Figure 2.16. This fretting failure initiated in a region between the area of the plates clamped together from the pretensioned bolts and the edge of the connected plates, or between holes. A fretting failure can also occur where indicated in Figure 2.15. A typical net section failure is shown in Figure 2.17. Because of the different failure types, fatigue data is presented with the stress ranges calculated at the net section for bearing type connections, and at the gross range for slip-critical type connections (Fisher et al. 2001).

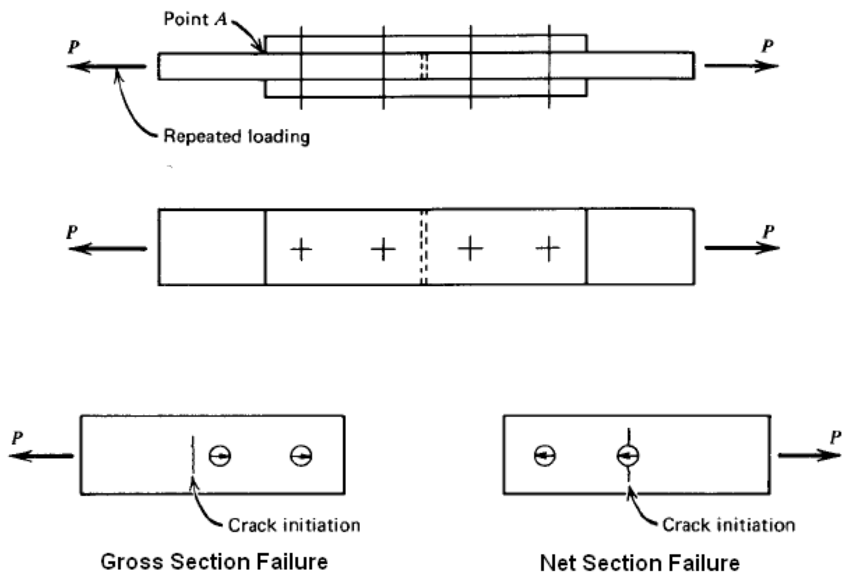

Figure 2.15: Basic Failure Modes (Fisher et al. 2001)

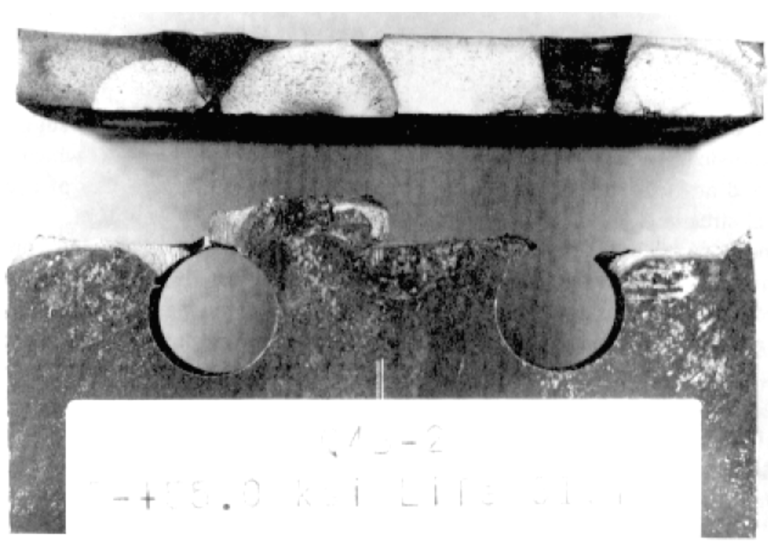

Figure 2.16: Typical Gross Section Fretting Failure (Fisher et al. 2001)

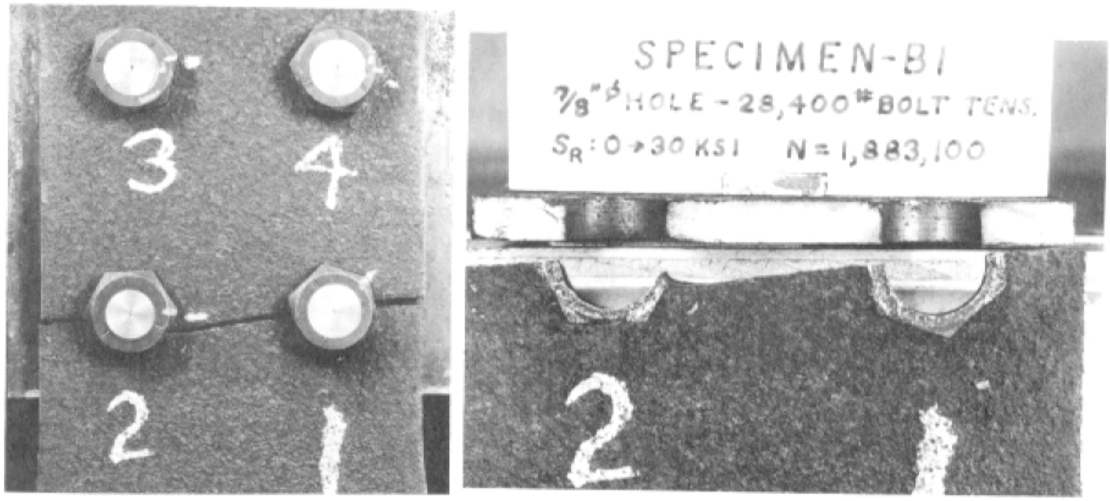

Figure 2.17: Typical Net Section Failure (Fisher et al. 2001)

Huhn and Valtinat (2004) investigated punched holes in combination with hot dip galvanizing in both flat plate specimens and single bolt double shear lap splice specimens. Several fatigue tests were conducted. The connection specimens were tested both with snug bolts and pretensioned bolts, making them bearing type connections and slip-critical type connections, respectively. The results were presented in the form of stress range vs. number of cycle figures. The authors stated that punched holes dramatically reduced the fatigue life of both the plate specimens and the connections. This decrease was compounded if the specimen was hot dip galvanized. The following example was given:

> "This means that a non-galvanized structural member with a drilled hole has the highest fatigue resistance, for example 2M (2 million) cycles at a constant stress range of $\Delta\sigma$ = 80 N/mm^2 (11.6 ksi). If the member has a punched hole or is galvanized, the influence is nearly the same; the fatigue life decreases with a ratio of 2.0. Now the fatigue failure for a stress range $\Delta\sigma$ of 80 N/mm^2 (11.6 ksi) is at 1M cycles. If the member is both punched and galvanized there is an additional effect and the number of load cycles decreases to 500,000."

The authors also noted that the use of pretensioned bolts was found to negate the effects of the punching process as well as the galvanizing process. "This was due to the high pressure under the washers of the bolts. This high pressure gives a certain protection of the area around the hole, so that the stress distribution in the net section became much more favorable, even after slip of the connections." Specimens with just an open hole performed better than the bearing type connections, with the slip-critical type connections performing much better than both plates and bearing type connections. Through the course of testing, it was noted that the fatigue crack initiated in the first zone of the punched holes, the shear zone at the top of the hole. This is shown in Figure 2.18.

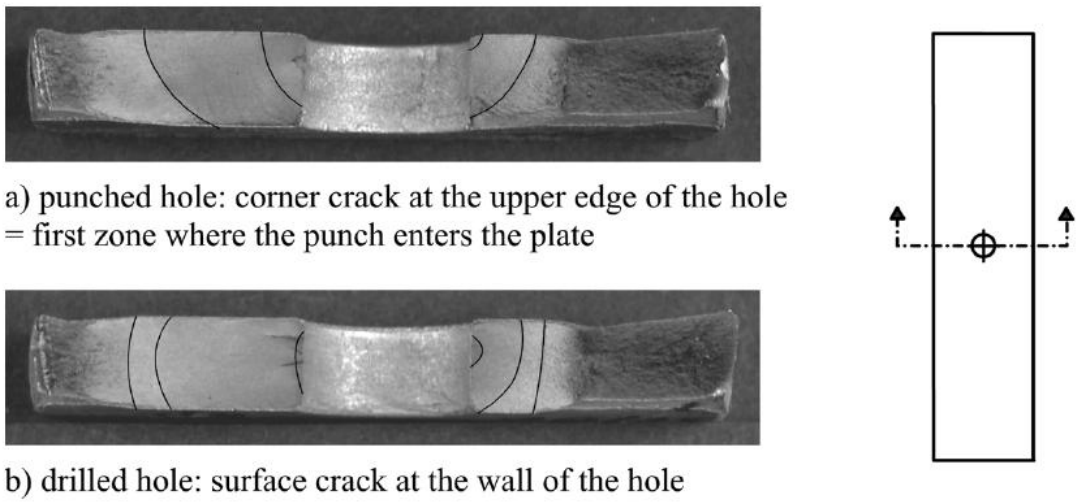

Figure 2.18: Fatigue Crack Initiation Zones (Huhn 2004)

Alegre et al. (2004) conducted a small fatigue study as part of a finite element simulation to predict fatigue behavior of punched plate components. A single 15 mm (0.59 in.) hole in a 45 mm (1.77 in.) wide structural plate was used. The 15 mm (0.59 in.) thick plates were tested at a frequency of 15 Hz, always with tensile loads. The results of these experiments are presented in Figure 2.19, with the stress range calculated on the net section. The AASHTO Design 2004 fatigue Category B and Category D design limits are also shown. The punched hole specimens were shown to have a much lower fatigue life than replicate drilled hole specimens. However, several of the drilled hole specimens fell below the Category B limit. Typical fracture surfaces for both the punched and drilled specimens are shown in Figure 2.20. The fatigue crack for the punched specimens initiated at the transition point between the shear band and the fracture band resulting from the punching process.

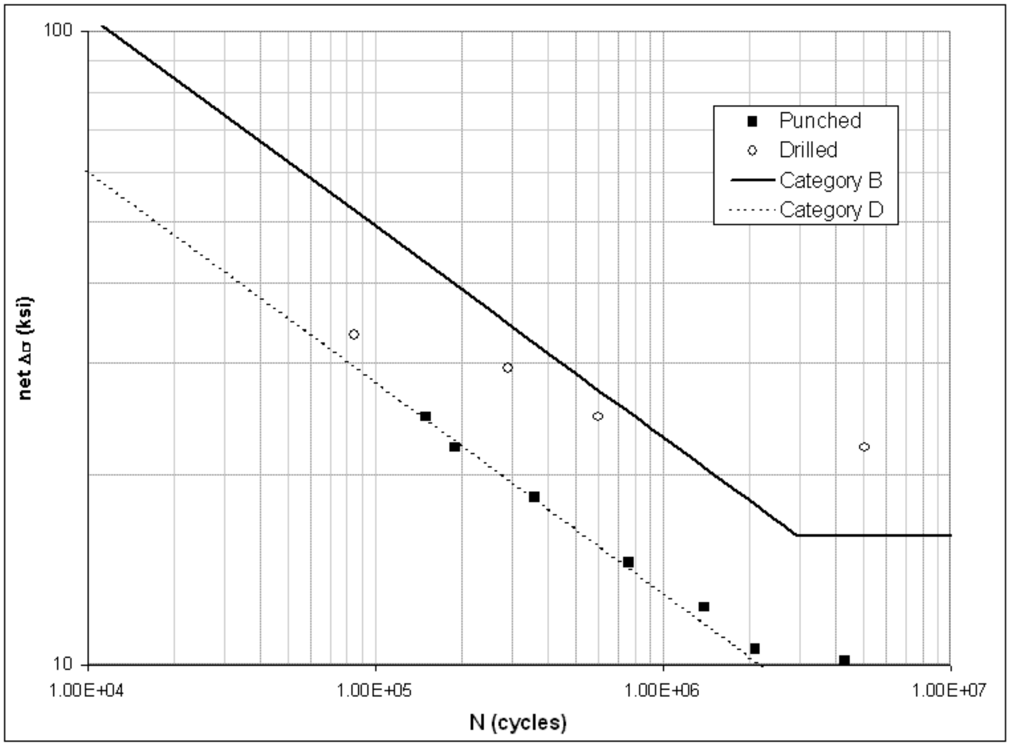

Figure 2.19: Plate Fatigue Specimen Test Results (Alegre et al. 2004)

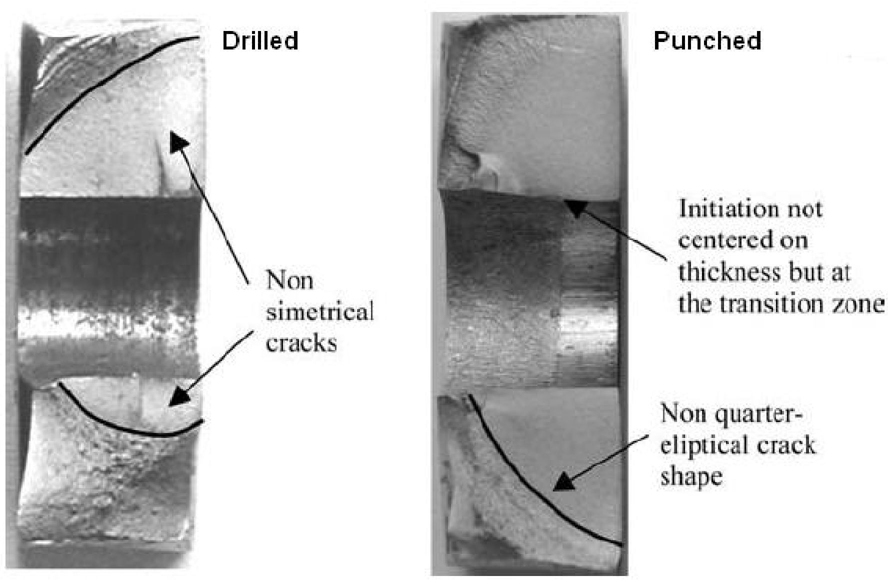

Figure 2.20: Fatigue Failure Surfaces (Alegre et al. 2004)

Gutierrez-Solana et al. (2004) also investigated the fatigue behavior of punched holes in structural plates. A 15 mm (0.59 in.) diameter hole was punched or drilled in a 45 mm (1.77 in.) wide, 15 mm (0.59 in.) thick plate. Three grades of steel were tested at a frequency of 15 Hz, always in tension. The drilled specimens were shown to have twice the fatigue resistance of the punched specimens. The summarized results of the fatigue tests are presented in Figure 2.21, with a net stress range. In this figure, the AASHTO Design 2004 fatigue design limits for Category B and Category D are also presented. All punched specimens are a Category D, while several of the drilled specimens fall below the limit for Category B.

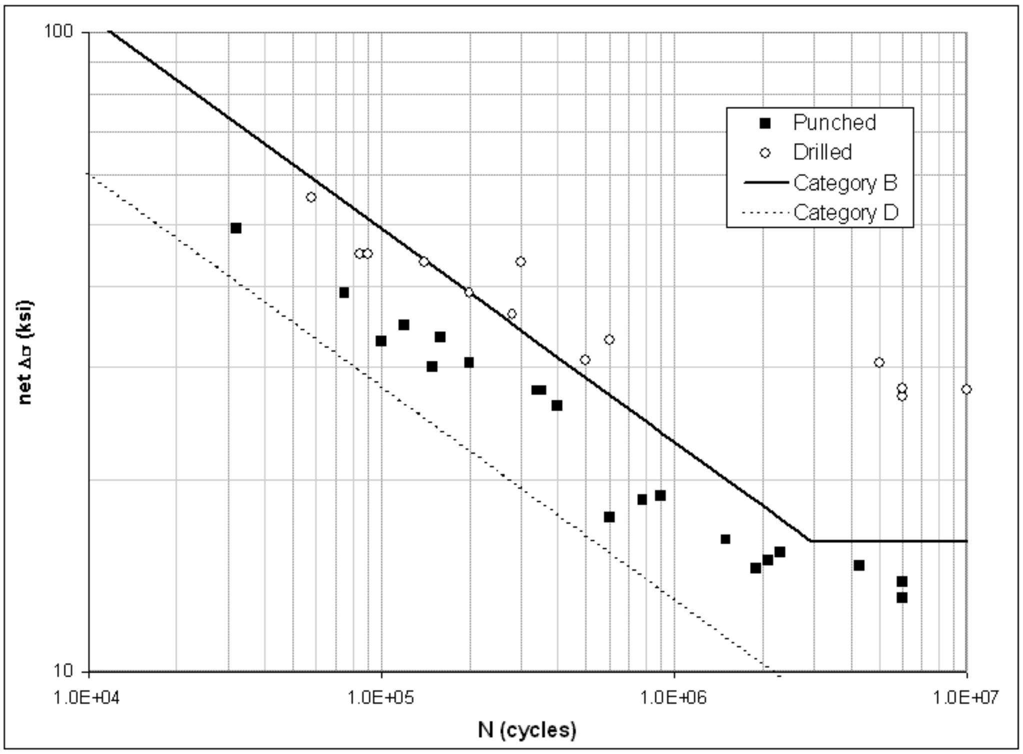

Figure 2.21: Plate Fatigue Specimen Test Results (Gutierrez-Solana et al. 2004)

Several cross sections of failed surfaces from Gutierrez-Solana et al. (2004) were also presented. A failed punched specimen, as shown in Figure 2.22, had the fatigue crack begin "near the transition zone between the cut and the tearing zones due to punching." The crack growth was not symmetrical on both sides of the hole. The fatigue crack on a drilled hole specimen initiated at no clear location, wherever the largest defect from the drilling process was located, as shown in Figure 2.23.

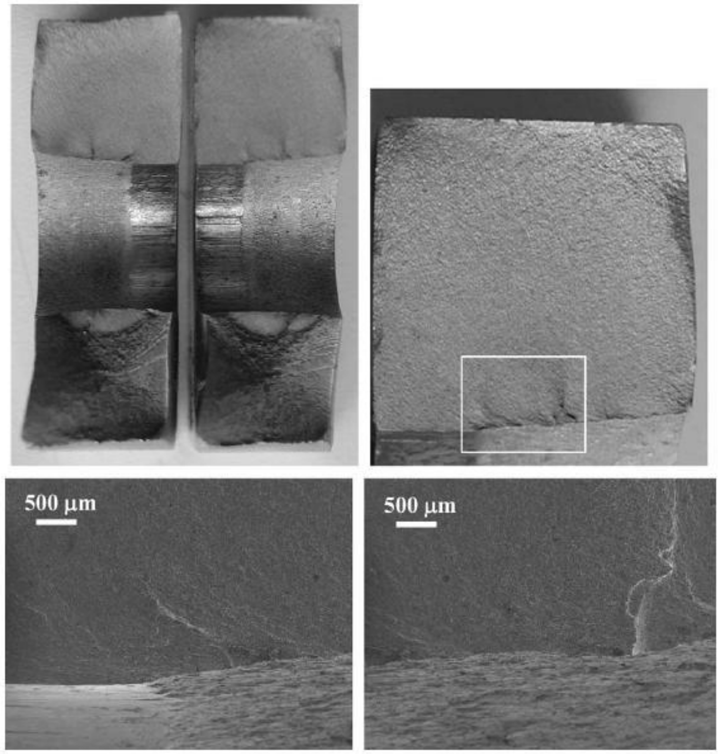

Figure 2.22: Punched Hole Crack Initiation Zone (Gutierrez-Solana et al. 2004)

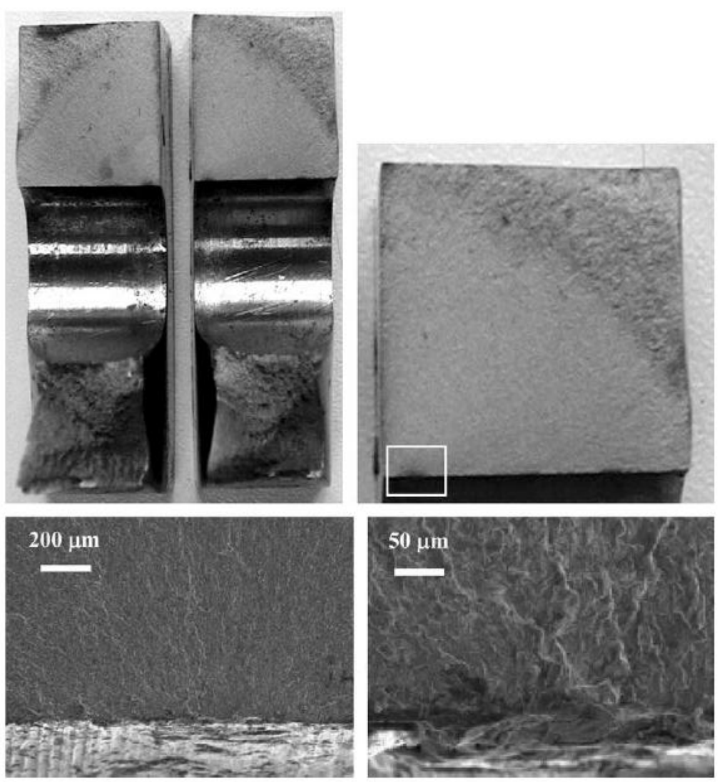

Figure 2.23: Drilled Hole Crack Initiation Zone (Gutierrez-Solana et al. 2004)

Current research by Swanson at the University of Cincinnati has shown a similar trend on the fatigue effects of punched holes. Multiple hole diameters were punched, drilled, or reamed in 3 in. wide flat plate of varying thickness. Shown in Figure 2.24, punched holes had a dramatically lower fatigue life compared to drilled holes. Also shown in this figure are the AASHTO fatigue Category B and Category D limits. All drilled and reamed specimens fell above a Category B design limit, while the punched specimens fell into a Category D.

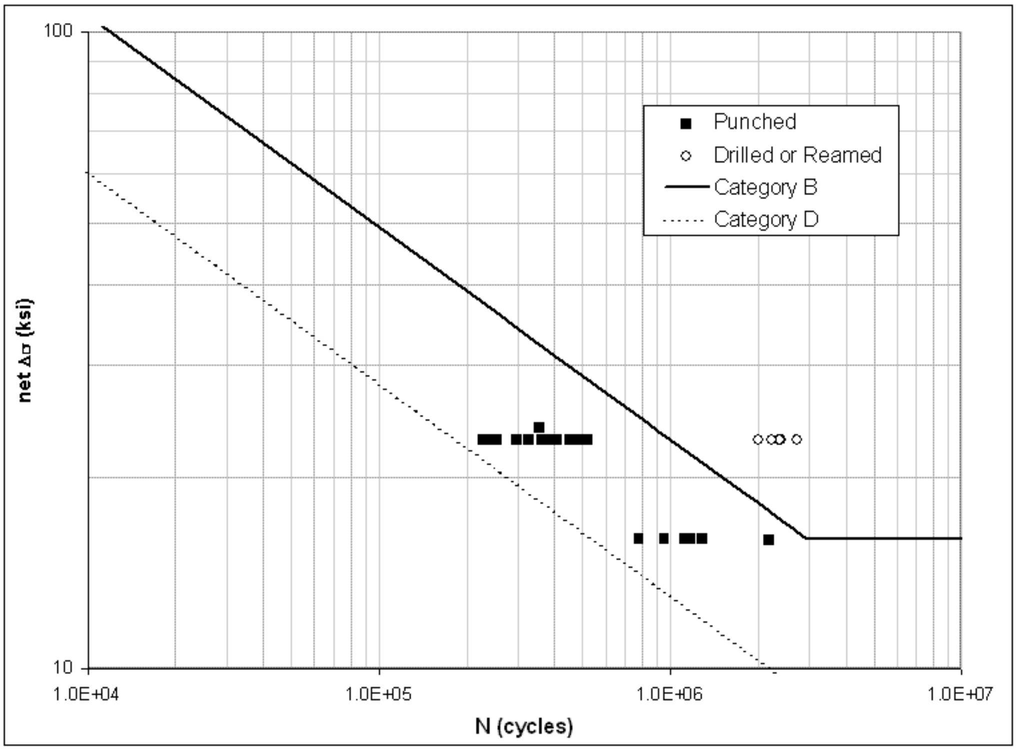

Figure 2.24: Fatigue Test Specimen Results (Swanson)

Other research has investigated fatigue behavior of tension connection, but no direct comparison of hole type was used. The following research, along with the fatigue research data presented previously, will be used in Chapter 3 for comparison with test data from this project:

- Frank and Yura (1981)
- Data compiled by Fisher, Kulak, and Struik (2001)
- Grondin, Josi, and Kulak (2004)

2.3.2 Slotted Holes

The performance of slotted holes was evaluated to complete the study on the effect of hole making upon the performance of structural connections. Slotted holes are used in applications that require greater tolerances than provided by standard size round holes. They are made using one or a combination of techniques. Examples of using a single hole-making technique are shown in Figures 2.25 and 2.26. These techniques include the use of an oxygen-acetylene (oxy-act) torch, laser cutting, and punching.

Figure 2.25: Manual oxygen-acetylene(oxy-act)-cut and laser-cut slotted holes

Figure 2.26: Punched slotted hole

A multi-step process is typically utilized in the fabrication shop. The process usually involves drilling or punching both ends of the slotted holes followed by cutting the remaining material with a plasma or oxy-act torch. The sequence of making slotted holes using this method is shown in Figure 2.27 and Figure 2.28. The holes were tested in the condition shown in Figure 2.28. The AASHTO construction specification does not cover the surface finish of holes. However, the S2.1-2007, Steel Bridge Fabrication Guide Specification in section 4.6.2 says “Thermal-cut holes or portions of slots ground as required to provide maximum surface roughness of ANSI 1000 μin. (25 μm)”. The thermally cut holes tested in this research did not meet this requirement.

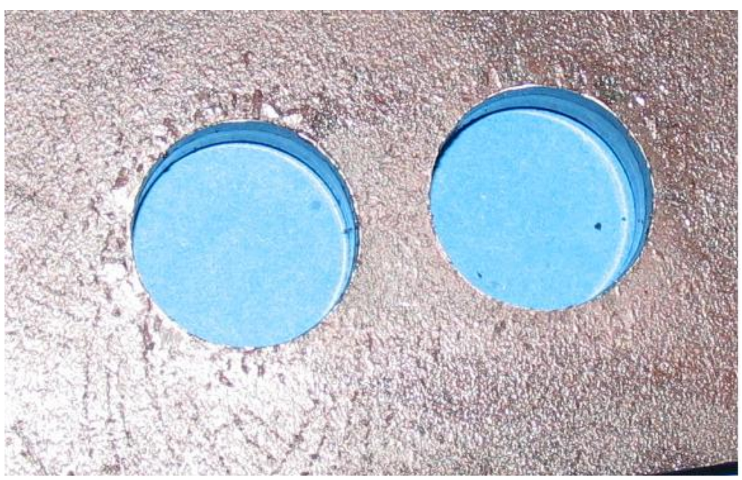

Figure 2.27: Holes punched to form the end of slot

Figure 2.28: Punched holes joined with oxy-act cut

Chapter 3. Test Matrix, Specimen Fabrication and Testing Procedures

This chapter documents an outline of the test matrix utilized to determine the influence of the experimental variables as well as the method of fabricating the specimens, particularly the hole making equipment and procedures. In addition, the chemical and physical properties of the steel used for the test specimens are presented. A brief description of the testing procedures is also included. Lubitz (2005), Brown (2006), and Cekov (2006) contain the details of the testing procedures and documentation of all the test results.

3.1 PLATE TENSION TESTS

When investigating the performance effects of punched holes in structural steel plates, other variables in addition to hole type tend to arise. A number of parameters could influence the ultimate strength and ultimate displacement of a structural member. Each individual variable could interact and consequently skew the results of a single experiment. To limit the influence of each experiment to a single variable, a systematic test method was employed to focus on one parameter at a time. As formulated by Lubitz (2005), the main variables used for the plate material specimens, in addition to punched and drilled holes, were:

- Steel type and testing temperature
- Plate thickness and hole size
- Edge distance and edge fabrication method
- Punched hole and die clearance amounts
- Punching operation
- Cold testing for various plate thickness
- Galvanized specimens
- Sub-punched and reamed holes
- Method of slotting holes

The typical specimen configuration used is shown in Figure 3.1. Various plate thicknesses and steel grades were fabricated to this typical configuration. The types of bridge steel used consisted of A36, A572 Grade 50, and what was called a High Carbon Grade 55. The plate thicknesses tested were 3/8 in., ½ in., and ¾ in. Multiple hole sizes and edge distances were also used. Each specimen was tested to its ultimate tensile capacity, and the corresponding load versus displacement relationship was determined. The results of these experiments will be discussed in Chapter 4.

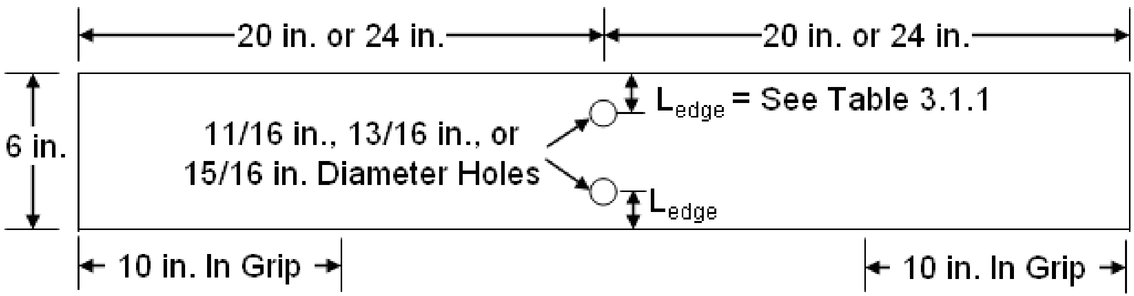

Figure 3.1: Typical Plate Specimen Configuration

As a continuation of the Steel Type and Temperature Matrix set forth by Lubitz (2005), additional plate material was tested using the most common specimen configuration: two holes with a diameter of 15/16 in. and an edge distance to the center of the hole of 1–1/8 in. This configuration also served as a baseline for most comparisons by Lubitz and for additional comparisons from the new tests. The 1-1/8 in. edge distance was given as the minimum edge distance for 7/8 in. bolts (15/16 in. diameter hole) with flame-cut edges, as shown in AASHTO Design 2004 Table 6.13.2.2.6-1: Minimum Edge Distances. The values used for this project are shown in Table 3.1.

Table 3.1: Boundary Distances Used for Plate Specimens

		Edge Distance	
Bolt Diameter (in.)	Hole Diameter (in.)	Flame-Cut Edges (in.)	Sheared Edges (in.)
5/8	11/16	7/8	1-1/8
3/4	13/16	1	1-1/4
7/8	15/16	1-1/8	1-1/2

The new plate material, ½ in. thick, consisted of an additional heat of A572 Grade 50 bridge steel and a heat of A588 bridge steel. As a method of distinguishing the new Grade 50 steel from the Grade 50 steel used previously, the new steel was referred to as ‘Heat Z’. The properties of the new steel are discussed in Section 3.5. For the new specimens, duplicate tests for both punched holes and drilled holes were used. The specimens were tested at room temperature using the same methods as Lubitz (2005). This allowed for a direct comparison to the previous data from Lubitz. The hole fabrication methods and testing procedures are described in Sections 3.6 and 3.7, respectively.

A slightly modified specimen configuration was also used to investigate the effect of net area on the performance effects of punched and drilled holes. It was noted that some of the previous tests yielded in the gross section before fracturing in the net section. This was especially true in the A36 plate material used, due to its low ratio of yield strength over ultimate strength (f_y/f_u). The ratios of the yield to ultimate strength of the steel types used are tabulated later in this chapter. To investigate this variable, the net area was decreased to ensure net section fracture before the gross section yielded in all steel grades. To decrease the net area, an additional 11/16 in. diameter hole was added to the center of the two typical 15/16 in. holes. The modified plate specimen configuration is shown in Figure 3.2. The three holes in each specimen were either all drilled or all punched.

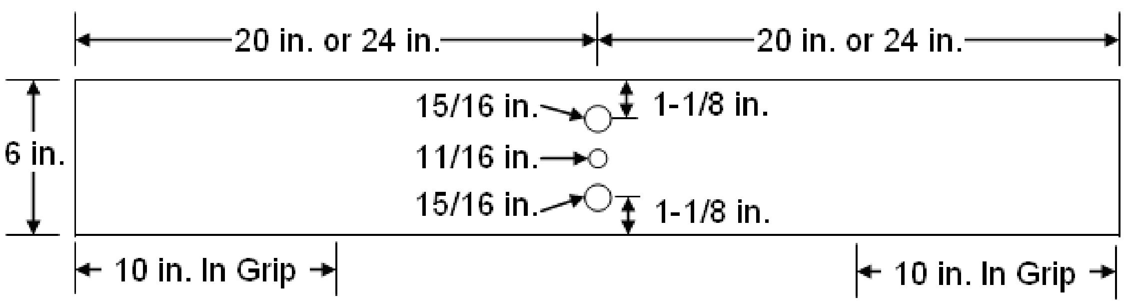

Figure 3.2: Modified Plate Specimen Configuration

Duplicate punched and drilled hole tests using the modified plate specimen configuration were performed. The test matrix for the additional plate tests is shown in Table 3.2. In this table, the symbol “T” is used to represent tension tests and the number 2 represents replicate specimens.

Table 3.2: Additional Plate Tension Test Matrix

	1/2 in. Thick Plate Material			
	15/16 in. Holes		Reduced Net Area	
Steel Type	Punched Holes	Drilled Holes	Punched Holes	Drilled Holes
A36	--	--	2-T	2-T
A572 Gr. 50 Heat Z	2-T	2-T	2-T	2-T
A588	2-T	2-T	2-T	2-T

T = Tension Test

In addition to the main variables discussed previously, another variable was discovered during fatigue testing. While it was assumed that the quality of a drilled hole would have no effect on performance, this turned out to not be the case. Holes drilled with a new bit were found to have better fatigue performance than specimens fabricated with an older, used drill bit. Therefore, in addition to the tests listed in Table 3.2, an extra test on ½ in. A572 Grade 50 Heat Z plate was performed utilizing a set of drilled holes fabricated with the worn drill bit. The results of this test showed no difference in the ultimate strength and displacement between the two drilled hole types. A discussion on the fabrication of the drilled holes is presented in Section 3.6.2.

For this phase of the project, an additional 21 plate tension specimens were tested. This data will be compared to the 97 plate tension tests performed by Lubitz (2005) in Chapter 4, and results of all investigations will be presented.

The slotted holes making techniques studied were:

- Punch full size
- Both ends punched, then thermally cut with oxy-act torch between the punched holes
- Both ends punched, then thermally cut with plasma torch between the punched holes
- Both ends drilled, then thermally cut with oxy-act torch between the drilled holes
- Both ends drilled, then thermally cut with plasma torch between the drilled holes
- Thermally cut with oxy-act torch full size

- Thermally cut with plasma torch full size
- Laser cut full size

Figure 3.3 and Figure 3.4 show the stages of fabrication of a slotted hole with both ends punched and oxy-act cut between them.

Figure 3.3: Phase 1 of making slotted holes

Figure 3.4: Phase 2 of making of slotted holes

In addition, short slotted holes specimens were made and, for reference, drilled round holes specimens. Figure 3.5, Figure 3.6, and Figure 3.7 show the geometry of the specimens.

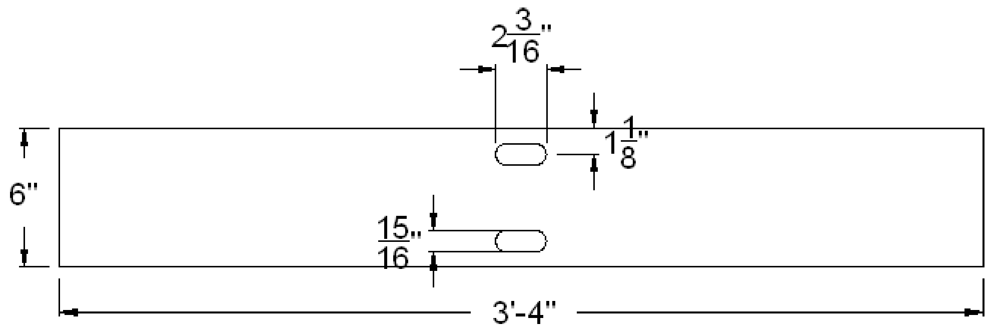

Figure 3.5: Long slotted holes specimen

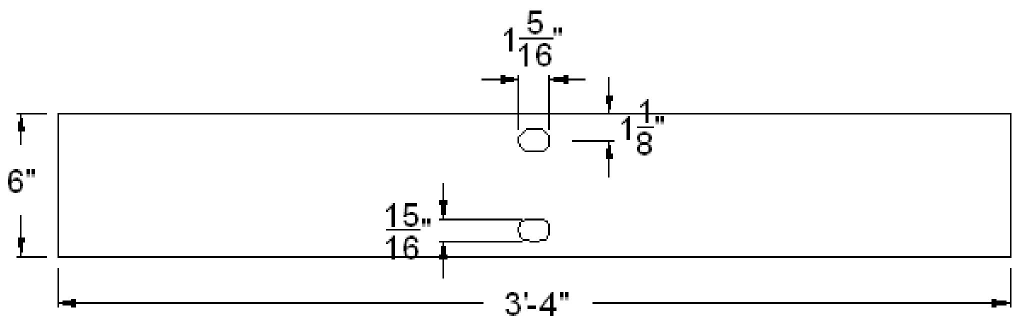

Figure 3.6: Short slotted holes specimen

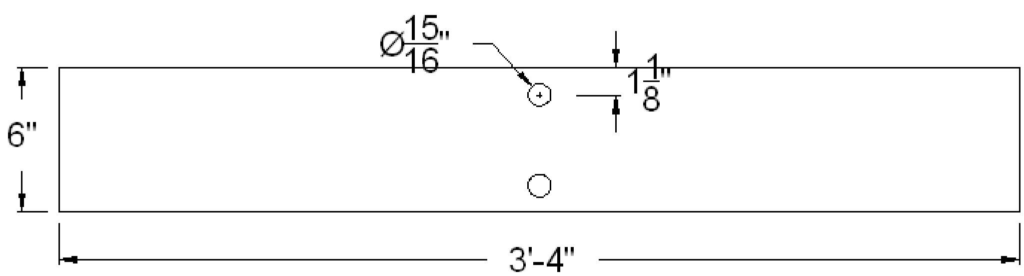

Figure 3.7: Conventional holes specimen

In addition to the specimens prepared at Ferguson Structural Engineering Laboratory (FSEL), nine specimens were prepared by a fabricator to make a comparison between the techniques used at FSEL and the bridge fabricator. Duplicate test for all available techniques were performed. The test matrices of the specimens that were made in the Ferguson lab are shown in Table 3.3, Table 3.4, and Table 3.5. The test matrix for the fabricators specimens is shown in Table 3.6.

Table 3.3: Test matrix A36 steel

Thickness	Holes type (2 specimens of each)	
	round controls	Slotted
3/4" plate	drilled	punched - short slotted
		drilled ends + plasma
		drilled ends + oxy -act
	punched	punched ends + oxy -act
		punched end + plasma
		cut full size plasma
		cut full size oxy

Total specimens: 18

Table 3.4: Test matrix Grade 50 steel 3/8" thickness

Thickness	Holes type (2 specimens of each)	
	round controls	Slotted
3/8" plate	drilled	punched short slotted
		drilled ends + plasma
		drilled ends + oxy -act
	punched	punched ends + oxy -act
		punched end + plasma
		cut full size plasma
		cut full size oxy

Total specimens: 18

Table 3.5: Test matrix Grade 50 steel 3/4" thickness

Thickness	Holes type (2 specimens of each)	
	round controls	Slotted
3/4" plate	drilled	punched short slotted
		drilled ends + plasma
		drilled ends + oxy -act
	punched	punched ends + oxy -act
		punched end + plasma
		cut full size plasma
		cut full size oxy
	Total specimens:	18

Table 3.6: Test matrix of the specimens made fabricators

Steel type	Short/Long	Thickness
A36	Short Slotted	3/4"
	Laser-Cut Long	3/4"
	Long Slotted	3/4"
grade 50	Short Slotted	3/8" and 3/4"
	Laser Cut Long	3/8" and 3/4"
	Long Slotted	3/8 and 3/4"
	Total specimens:	9

3.2 PLATE FATIGUE TESTS

While determining the influence of punched holes on the ultimate strength and ultimate displacement of plate material was important, it was also necessary to investigate the effects of hole type on the fatigue life of the same plate material. As discussed in Chapter 2, it has been shown that punched holes in a plate resulted in a dramatically lower fatigue life compared to drilled holes. To further investigate fatigue performance, identical specimen configurations and several of the variables from the plate tension tests were used. By using the same setup and fabrication methods, a more accurate correlation between tension and fatigue tests was possible. The configuration used in these tests was shown in Figure 3.1.

The first fatigue test matrix used for this project is shown in Table 3.7. In this table, 'F' was used to represent a fatigue test, while the number represents the quantity of replicate specimens. Duplicate test specimens were used to quantify the inherent scatter in fatigue results. This investigation comprised the largest portion of the plate fatigue testing. Multiple hole fabrication techniques were used to determine their effects on the fatigue life of plate material. The fabrication of each hole type is described in Section 3.6. The configuration for each specimen consisted of ½ in. thick plate, a pair of 15/16 in. diameter holes, and an edge distance of 1-1/8 in. For all specimens, a single stress range of 25 ksi based off the net section was used. The use of one stress range eliminated multiple stress ranges as a possible variable. The minimum stress level was 3 ksi.

Table 3.7: Steel Type Test Matrix

	Hole Fabrication Method					
Steel Type	Punched	Worn Drill Bit	New Drill Bit	Sub-Punched and Reamed	Fabricator Punched	2 Sets of Drilled Holes
A36	3-F	3-F	1-F	3-F	--	--
A572 Gr. 50	1-F	1-F	--	--	1-F	--
A572 Gr. 50 Heat Z	2-F	1-F	2-F	3-F	--	1-F
A588	2-F	--	2-F	--	--	1-F
	Typical Specimen: 1/2 in. Thick, 15/16 in. Holes, 1-1/8 in. Edge Distance					

F = Fatigue Test

The hole type labeled 'Sub-Punched and Reamed' in Table 3.7 was punched smaller than the nominal diameter by three different amounts and then reamed to the full-size diameter of 15/16 in. As stated previously, AASHTO requires a hole be sub-punched 3/16 in. smaller than the nominal diameter, then reamed full-size. To investigate the effect of the reaming amount, holes were sub-punched 1/16 in., 1/8 in., and 3/16 in. smaller than the nominal diameter of 15/16 in, then reamed full-size. The holes labeled 'Fabricator Punched' were punched by a local fabrication shop. These holes were similar in appearance to those fabricated at FSEL. As briefly discussed previously, an extra variable in the form of a hole drilled with a worn drill bit was added to the test plan. Through the course of testing, drilled holes made by various methods had remarkably different fatigue lives. Therefore, along with punched, drilled, and sub-punched and reamed holes, this additional drilled hole type became an important variable to investigate.

Also shown in Table 3.7 is a column dealing with 2 sets of drilled holes. These specimens were fabricated with two sets of drilled holes: one set drilled with a new drill bit, and one set drilled with a worn bit. The configuration used is shown in Figure 3.8. Both sets of holes were 15/16 in. diameter in the ½ in. thick material. With this setup, both sets of holes experienced the same stress range, and a direct comparison on fatigue life between the drilled hole types was made.

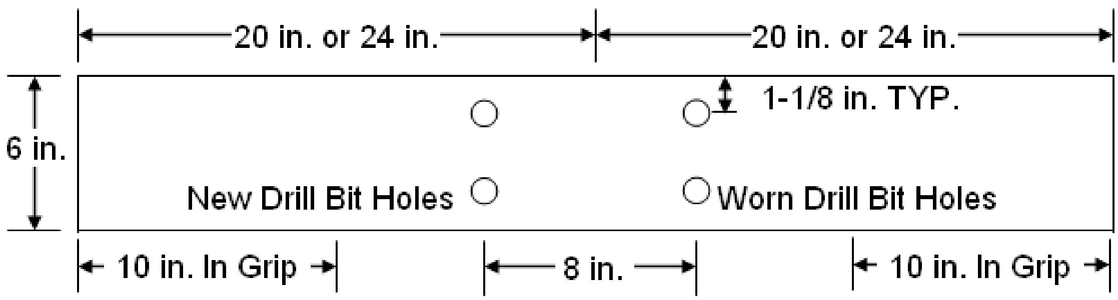

Figure 3.8: Plate Specimen with Two Sets of 15/16 in. Drilled Holes

An investigation into the effect of hole size on the fatigue life of plates was also performed. The hole sizes used were 11/16 in., 13/16 in., and 15/16 in. As discussed in Chapter 1, the design and construction specifications state that the diameter of a hole should be equal to the bolt diameter plus 1/16 in. Therefore, these hole sizes corresponded to 5/8 in., ¾ in., and 7/8 in. bolts, respectively.

In addition to hole size, various plate thicknesses in multiple grades of steel were also investigated. The test matrix for this investigation is shown in Table 3.8 for Grade A36, Table 3.9 for the initial heat of A572 Grade 50, and Table 3.10 for A572 Grade 50 Heat Z. As noted in Chapter 1 and Chapter 2, one common recommendation on the use of punched holes is that the diameter of the punched hole should be equal to or greater than the thickness of the base metal. Therefore, punching an 11/16 in. hole in ¾ in. plate is not recommended. As a result, this configuration was not used. For these test matrices, each configuration was tested with either holes punched with a normal die size or holes drilled with a worn drill bit.

Table 3.8: Hole Size and Plate Thickness Test Matrix, A36 Steel

	Hole Size (in.)					
	11/16		13/16		15/16	
Plate Thick. (in.)	Punched	Drilled	Punched	Drilled	Punched	Drilled
3/8	1-F	1-F	1-F	1-F	1-F	1-F
1/2	1-F	1-F	1-F	1-F	--	--
3/4	--	--	1-F	1-F	1-F	1-F

F = Fatigue Test

Table 3.9: Hole Size and Plate Thickness Test Matrix, A572 Grade 50 Steel

	Hole Size (in.)					
	11/16		13/16		15/16	
Plate Thick. (in.)	Punched	Drilled	Punched	Drilled	Punched	Drilled
3/8	--	--	1-F	--	--	--
1/2	1-F	--	1-F	--	--	--
3/4	--	--	1-F	1-F	1-F	1-F

F = Fatigue Test

Table 3.10: Hole Size and Plate Thickness Test Matrix, A572 Grade 50 Heat Z Steel

	Hole Size (in.)					
	11/16		13/16		15/16	
Plate Thick. (in.)	Punched	Drilled	Punched	Drilled	Punched	Drilled
3/8	--	--	--	--	--	--
1/2	1-F	1-F	1-F	1-F	--	--
3/4	--	--	--	--	--	--

F = Fatigue Test

The edge distance between the center of a hole and the edge of a plate was important, as well as the method of edge fabrication. Therefore, a separate test matrix was developed to investigate edge distance and edge preparation and their effects on fatigue life. This matrix is shown in Table 3.11. The larger edge distance corresponded to a 1/8 in. increase over the standard edge distances listed in Table 3.1. The specimens labeled 'Sheared' had their edges sheared rather than flame cut, but these specimens were from a different heat of steel than the other flame-cut specimens. Therefore, one set of specimens from the same heat of steel as the 'Sheared' specimens had edges flame cut from sheared edge specimens, called 'Flame Cut—Shear Match'.

Table 3.11: Edge Distance and Edge Preparation Test Matrix

	Edge Preparation					
	Sheared		Flame Cut - Shear Match		Larger Edge Distance	
Steel Type	Punched	Drilled	Punched	Drilled	Punched	Drilled
A36	1-F	1-F	1-F	1-F	1-F	1-F
A572 Gr. 50 Heat Z	--	--	--	--	1-F	1-F
	Typical Specimen: 1/2 in. Thick, 15/16 in. Holes					

F = Fatigue Test

Another factor that could affect the performance of punched holes in fatigue is the clearance amount between the male punch and the female die. The punched holes can have different appearances based on clearance amounts. The limit given in AASHTO Construction 2004 Article 11.4.8.1.2 is the diameter of the die shall not exceed the diameter of the punch by more than 1/16 in. To investigate the results of violating this provision, a larger die clearance was used. The punch and die sizes used throughout this project are shown in Table 3.12. The normal die size was used to punch the standard punched holes. The die sizes used to investigate larger clearance effects are also shown. The recommended die clearance values, from punch press manufacturer W.A. Whitney, for each punch size and plate thickness are also presented. Other punch manufacturers, such as American Punch, also recommend the clearance values shown.

Table 3.12: Punch and Die Sizes Used Throughout Project

Plate Thickness (in.)	Punch Size (in.)	Normal Die Size (in.)	Clearance Amount (in.)	Larger Die Size (in.)	Clearance Amount (in.)	Manufacturer Recommended Die Size (in.)
3/8	11/16	23/32	1/32	--	--	1/32
3/8	13/16	27/32	1/32	--	--	1/32
3/8	15/16	31/32	1/32	--	--	1/32
1/2	11/16	23/32	1/32	25/32	3/32	1/32 or 1/16
1/2	13/16	27/32	1/32	--	--	1/32 or 1/16
1/2	15/16	31/32	1/32	33/32	3/32	1/32 or 1/16
3/4	13/16	29/32	3/32	--	--	3/32
3/4	15/16	33/32	3/32	--	--	3/32

The test matrix to evaluate larger die clearances is shown in Table 3.13. The edge distances used are the standard flame-cut edge distances for the respective bolt diameters.

Table 3.13: Punch and Excessive Die Clearance Test Matrix

	Small Hole		Larger Hole	
	Hole Size (in.)	Die Size (in.)	Hole Size (in.)	Die Size (in.)
Steel Type	11/16	25/32	15/16	33/32
A36	1-F		1-F	
A572 Gr. 50 Heat Z	1-F		1-F	
	Typical Specimen: 1/2 in. Thick			

F = Fatigue Test

Punched holes are often used for members that are galvanized afterwards, such as traffic signal structures. As mentioned in Chapter 2, the galvanizing process may strain age the steel due to the high temperatures involved. This could significantly affect the fatigue life of the specimen. For this investigation, 13/16 in. diameter holes were first punched or drilled into 3/8 in. thick A36 steel or the first heat of A572 Grade 50 steel. The plates were then hot-dip galvanized at a nearby company. The test matrix used for the fatigue testing is shown in Table 3.14. Duplicate specimens with punched holes were also used in both types of steel.

Table 3.14: Galvanized Plate Test Matrix

	Hole Type	
Steel Type	Punched	Drilled
A36	2-F	1-F
A572 Gr. 50	2-F	1-F

F = Fatigue Test

In total, there were 70 plate fatigue specimens proposed for testing during this phase of the project. However, due to time and equipment constraints, only 33 of these specimens were tested. The results of the fatigue tests will be presented in Chapter 4.

3.3 CONNECTION TENSION TESTS

AASHTO limits the use of punched holes to secondary members. Secondary members often consist of tension members used in cross-frames and braces. The use of punched holes in these secondary members has the potential to be more cost effective than drilled holes. Therefore, it was desirable to perform a thorough research study into the effects of punched holes in tension members and connections. The important variables chosen to investigate were based on the results of the plate tension tests. These variables may have a different result on the performance of a connection compared to the net section behavior of the plate tests.

Several failure mechanisms must be accounted for when calculating the capacity of a tension member. Both AASHTO and AISC present similar equations for the required strength checks: gross section yielding, net section fracture, bearing strength, and block shear strength. These equations from both Specifications were presented in Chapter 1. The interaction between hole type and net section fracture was determined using the plate tests described previously. The relationship between punched holes and their effect on bearing strength and block shear strength was investigated. To accomplish this, a double shear lap splice type tension connection was used.

Several thicknesses common to secondary members were used in the connection investigation. The plate material was kept constant throughout the investigation, and was the same steel used in both the current and previous plate tests. This included ½ in. and ¾ in. A36 steel and ½ in. and ¾ in. A572 Grade 50 steel. The ½ in. Grade 50 material was the steel labeled as Heat Z. The majority of the specimens were made from the ½ in. thick material.

The hole types tested were a punched hole with the recommended die, a punched hole with a larger die, a hole drilled by a new drill bit, and a hole drilled by a worn drill bit. These hole types were fabricated in an identical manner as those holes used for the plate specimens. A single hole size of 15/16 in. corresponding to a bolt diameter of 7/8 in. was used for all specimens. The die sizes used were the recommended 31/32 in. and a larger size of 33/32 in. for the ½ in. thick plates. For the ¾ in. thick plates, the recommended die size of 33/32 in. was used.

The influence of pretensioned bolts on the bearing strength and block shear strength of a tension member is relatively unknown. A pretensioned bolt is used in connections that are required to be designed as slip-critical. That is, the load in the tension member is transferred through the connection by friction between the connecting materials caused by the pretension in the bolt. Members in bridges subjected to reversed loads are required to be designed as slip critical, as is the case for many secondary members. As stated in Chapter 1, AASHTO allows only joints in compression and joints for bracing members to be designed as bearing-type connections. Also, AASHTO mentions that the failure load of a bearing connection is independent of the bolt clamping force. However, the friction force between the connected materials might in fact contribute an uncertain amount to the ultimate strength of a connection. This friction force may also affect how the hole behaves as it deforms from bearing against the bolt. The tension force in the bolt, and the subsequent normal force from the washers clamping down on the material, may act to confine the deformation at the edge of a hole as it is compressed by the bolt. This confinement could strengthen the surrounding material. To investigate these possibilities, connections with snug tight bolts and connections with pretensioned bolts were tested.

To develop a connection that was controlled by either block shear strength or bearing strength, a two-bolt pattern was chosen. The plate material used, 6 in. wide, was designed with 2 gage distances between the bolts, located at 2 different end distances. The gage distance, g, was defined as the distance from the center of one hole to the center of the other. The end distance, L_e, was defined as the distance from the end of the plate to the center of the hole. The failure type was also dependent on the strength of the material used. The effect of varying the gage distance on failure mode is shown in Figure 3.9 and Figure 3.10. Increasing the gage distance from 2-1/3 in. to 3 in. increased the tension area that can be mobilized on the net section, which caused the joint capacity to be controlled by bearing rather than block shear.

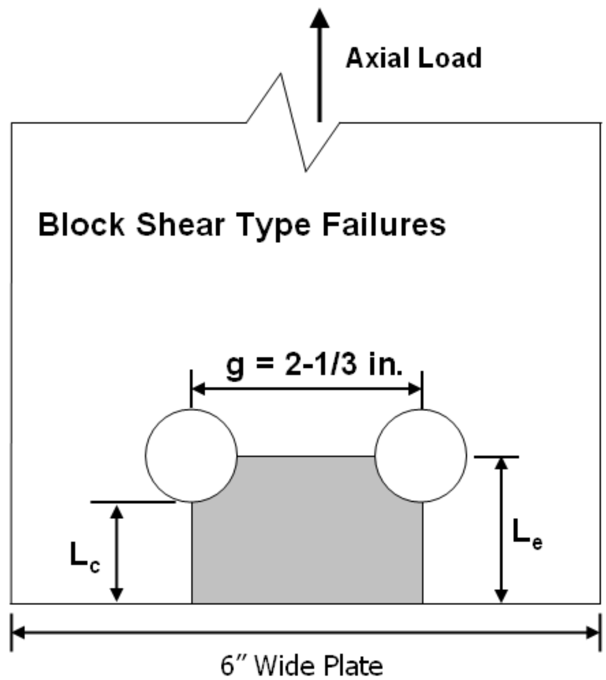

Figure 3.9: Block Shear Type Failure

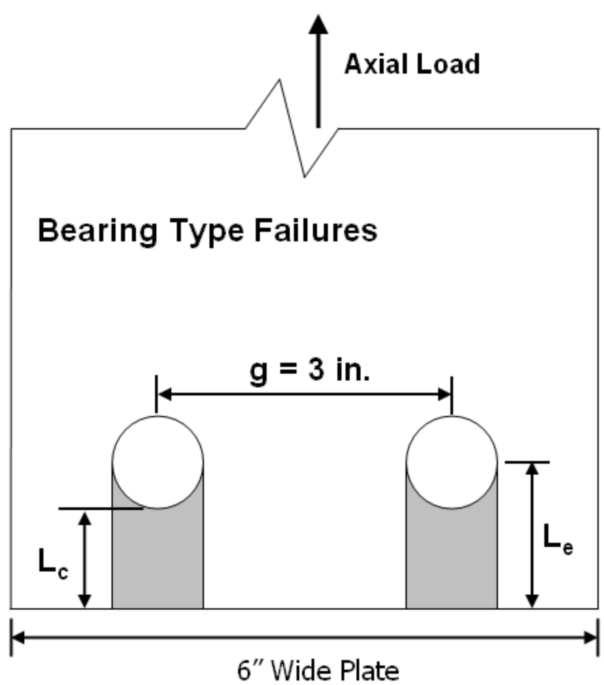

Figure 3.10: Bearing Type Failure

Gage distances used were 2-1/3 in. and 3 in., and the end distances were 1-1/2 in. and 2 in. The 2-1/3 in. gage distance corresponded to the minimum allowed spacing of 2-2/3 times the diameter of the fastener, and the 3 in. gage distance is larger than the preferred 3 times the diameter of the fastener, as stated by AASHTO and AISC. For the 7/8 in. bolts used, the typical spacing of 3d would be 2-5/8 in. In addition to a 2 bolt pattern, a single bolt in the center of the plate at the 2 end distance values was used to directly determine the bearing strength. A specimen configuration was also chosen that included a staggered pair of bolts.

The final test matrices used for the connection tension tests are presented in Table 3.15 through Table 3.18. The tables represent both specimens with snug bolts and specimens with pretensioned bolts. In each table, the number 2 represents duplicate test specimens. The predicted failure type of each specimen is also given. Nominal dimensions of each specimen configuration are shown in Figure 3.11 through Figure 3.13.

Table 3.15: Single Bolt Bearing Connections—Snug Bolts

				Hole Type			
Steel Grade	Predicted Failure Type	Thickness (in.)	L_e (in.)	Punched Normal Die	Punched Larger Die	New Drill Bit	Worn Drill Bit
A36	Bearing	1/2	1-1/2	1-T	2-T	1-T	2-T
			2	1-T	1-T	1-T	1-T
		3/4	1-1/2	1-T	--	1-T	--
			2	1-T	--	1-T	--
A572 Gr. 50 Heat Z	Bearing	1/2	1-1/2	1-T	2-T	1-T	2-T
			2	1-T	1-T	1-T	1-T
		3/4	1-1/2	1-T	--	1-T	--
			2	N/A	--	N/A	--

T = Tension
N/A = Bolts Shear Before Specimen Failure

Table 3.16: Single Bolt Bearing Connections—Pretensioned Bolts

				Hole Type	
Steel Grade	Predicted Failure Type	Thickness (in.)	L_e (in.)	Punched Normal Die	New Drill Bit
A572 Gr. 50 Heat Z	Bearing	1/2	1-1/2	1-T	1-T
			2	1-T	1-T

T = Tension

Table 3.17: Two Bolt Connections—Snug Bolts

					Hole Type			
Steel Grade	Predicted Failure Type	Thick. (in.)	L_e (in.)	g (in.)	Punched Normal Die	Punched Larger Die	New Drill Bit	Worn Drill Bit
A36	Bearing	1/2	1-1/2	2-1/3	1-T	2-T	1-T	2-T
	Bearing			3	1-T	2-T	1-T	2-T
	Block Shear		2	2-1/3	1-T	2-T	1-T	2-T
	Bearing			3	1-T	1-T	1-T	1-T
	Bearing		Staggered		1-T	1-T	1-T	1-T
	Bearing	3/4	1-1/2	2-1/3	1-T	--	1-T	--
	Bearing			3	1-T	--	1-T	--
	Block Shear		2	2-1/3	1-T	--	1-T	--
	Block Shear			3	1-T	--	1-T	--
A572 Gr. 50 Heat Z	Bearing	1/2	1-1/2	2-1/3	1-T	2-T	1-T	2-T
	Bearing			3	1-T	2-T	1-T	2-T
	Block Shear		2	2-1/3	1-T	2-T	1-T	2-T
	Bearing			3	1-T	1-T	1-T	1-T
	Bearing		Staggered		1-T	1-T	1-T	1-T
	Bearing	3/4	1-1/2	2-1/3	1-T	--	1-T	--
	Bearing			3	1-T	--	1-T	--
	N/A		2	2-1/3	N/A	--	N/A	--
	N/A			3	N/A	--	N/A	--

T = Tension
N/A = Bolts Shear Before Specimen Failure

Table 3.18: Two Bolt Connections—Pretensioned Bolts

					Hole Type	
Steel Grade	Predicted Failure Type	Thickness (in.)	L_e (in.)	g (in.)	Punched Normal Die	New Drill Bit
A572 Gr. 50 Heat Z	Bearing	1/2	1-1/2	2-1/3	1-T	1-T
	Bearing			3	1-T	1-T
	Block Shear		2	2-1/3	1-T	1-T
	Bearing			3	1-T	1-T

T = Tension

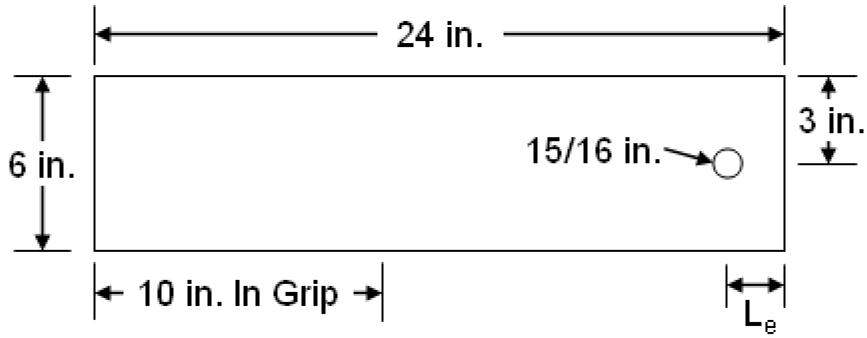

Figure 3.11: Single Bolt Bearing Specimen, L_e = 1-1/2 in. or 2 in.

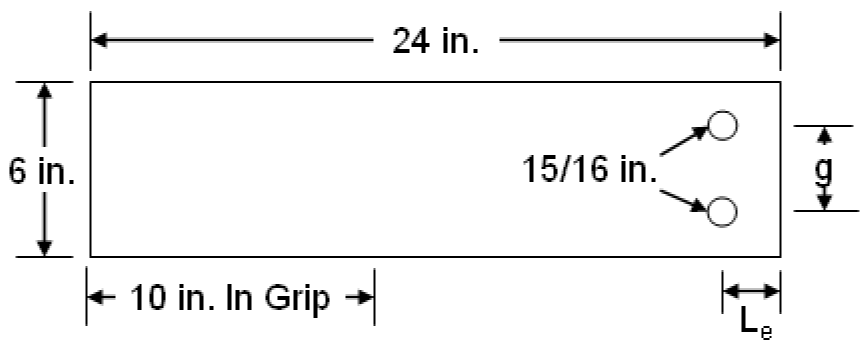

Figure 3.12: Double Bolt Block Shear or Bearing Specimen, L_e = 1-1/2 in. or 2 in., and g = 2-1/3 in. or 3 in.

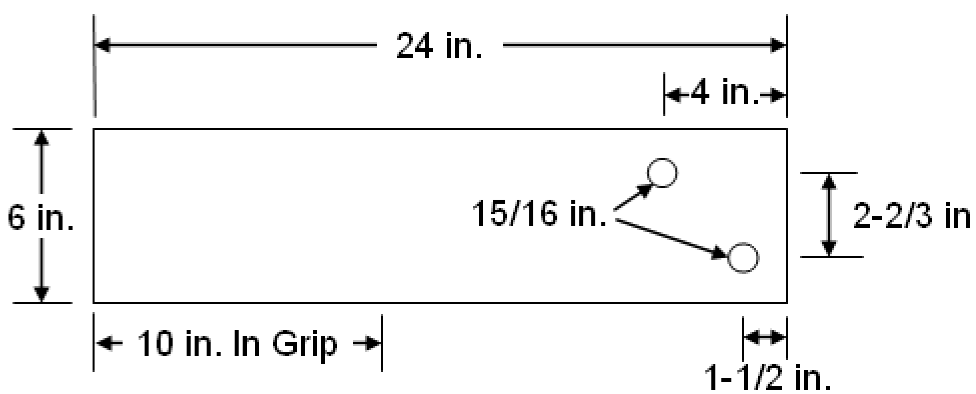

Figure 3.13: Double Bolt Staggered Hole Specimen

Many of the specimens were tested in duplicate to determine the scatter in the test data. Some of the specimens could not be duplicated due to limited amounts of steel. Also, the initial planned test matrix changed as testing progressed. This was especially true after the behavior of a hole drilled with a worn bit was discovered from fatigue test results. In addition, the punched hole made with a larger die had a distinctly different appearance. It was decided to investigate the effect of hole appearance on performance of the connections. Therefore, the larger die size was used for more of the punched specimens and the worn drill bit was used for more of the drilled specimens.

It is likely that holes in real connections will be slightly misaligned, even though the fasteners may pass cleanly through all of the holes. Therefore, the holes for the tension connections were not match-drilled in the connection assembly to simulate real life fabrication issues. Also, no template was used. The hole dimensions were marked by hand, and the holes were fabricated to these markings. Some slight hole misalignment inevitably resulted in the connections, though a bolt passed cleanly through the plies of steel at all times.

In total, there were 102 double shear lap splice connection specimens tested. The results of the tension connection tests are presented in Chapter 4 as well, along with various observations and comments. Comparisons with other research data will be presented.

3.4 CONNECTION FATIGUE TESTS

AASHTO requires that joints subject to fatigue loadings be designed as slip-critical type connections. As many secondary members have the potential to be loaded in fatigue, the use of punched holes and their effect on the fatigue life of tension members was investigated. To accomplish this, a double shear lap slice connection with pretensioned bolts was used. The connection was similar to the configuration used for the tension connection tests. The type of hole remained unchanged as the main parameter investigated. Hole types that were included were holes drilled with a new drill bit and punched holes using the normal size die. A single hole diameter of 15/16 in. was used corresponding to 7/8 in. bolts. The hole making procedures were the same as those used for the plate and connection specimens. For this investigation, one steel grade and one plate thickness was used: ½ in. thick A572 Grade 50 Heat Z.

The slip-critical type joints were tested at 2 different stress ranges, 20 ksi and 30 ksi, with a minimum stress of 3 ksi. As presented in Chapter 2, the relevant stress range for a slip-critical type joint is based off the gross section properties. Specimens at each stress range were duplicated to account for the inherent scatter in fatigue test results. A 4-bolt pattern was used, as opposed to the 2-bolt pattern used in the tension connection tests. The 4-bolt pattern was needed to ensure that the connection remained below the slip load at the stress ranges tested. The design slip load, using AASHTO 2004 Section 6.13.2.8 and the actual bolt pretension, was determined to be 150.5 kips, while the maximum load applied to the fatigue connection was 105 kips for the 30 ksi stress range and 72 kips for the 20 ksi stress range.

The test matrix for pretensioned bolts is shown in Table 3.19. The spacing between bolts was chosen as the recommended value of 3 times the bolt diameter, or 2-5/8 in., for both the transverse (gage) and longitudinal (pitch) directions. The end distance chosen was 1-1/2 times the diameter of the bolt, or 1-15/16 in. The specimen is shown in Figure 3.14.

Table 3.19: Connection Fatigue Test Matrix—Pretensioned Bolts

						Hole Type	
Steel Grade	Thickness (in.)	L_e (in.)	Pitch (in.)	Gage (in.)	Stress Range (ksi)	Punched Normal Die	New Drill Bit
A572 Gr. 50 Heat Z	1/2	1-5/16	2-5/8	2-5/8	20	2-F	2-F
					30	2-F	2-F

F = Fatigue

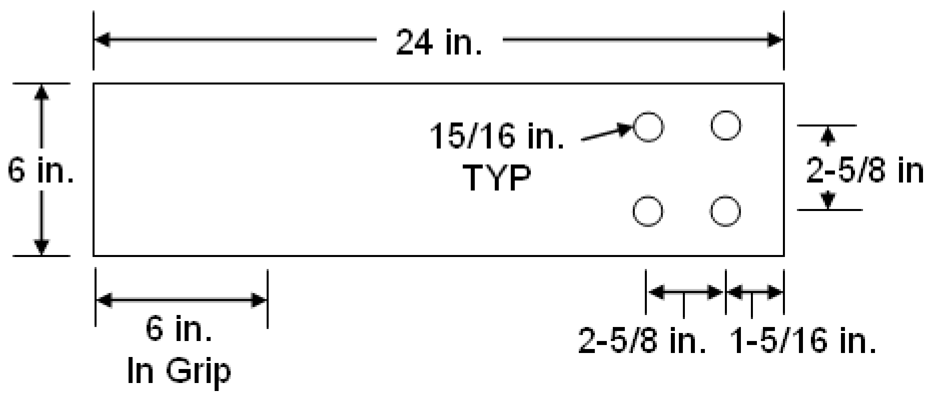

Figure 3.14: 4-Bolt Connection Fatigue Specimen

In addition to slip-critical type joints, connections with snug bolts were also used to simulate bearing-type connections subjected to fatigue loading. AASHTO allows bearing-type connections for joints on bracing members. The same 4-bolt pattern was used. These connections also had replicate specimens tested. A single stress range of 20 ksi on the gross section was used to allow for direct comparison to the stress ranges used for the pretensioned fatigue tests. The equivalent net section stress range was 29.1 ksi. The 4-bolt specimen is shown in Figure 3.14. In addition, a 2-bolt pattern at a lower stress range of 15 ksi on the gross area was used to simulate a connection similar to the one used for the tension connection tests. The equivalent net section stress range was 21.8 ksi. The 2-bolt specimen with snug bolts is shown in Figure 3.15. The proposed test matrix for snug bolts is shown in Table 3.16. It should be noted that AASHTO does not allow tension members subjected to fatigue loadings to be designed as bearing-type connections, except on bracing members. Therefore, this investigation was a worse-case scenario for bridge members, but is a common occurrence for the building industry.

Table 3.20: Connection Fatigue Test Matrix—Snug Bolts

						Hole Type	
Steel Grade	Thickness (in.)	L_e (in.)	Pitch (in.)	Gage (in.)	Stress Range (ksi)	Punched Normal Die	New Drill Bit
A572 Gr. 50 Heat Z	1/2	1-5/16	2-5/8	2-5/8	20	2-F	2-F
		3	--	2-5/8	15	1-F	1-F

F = Fatigue

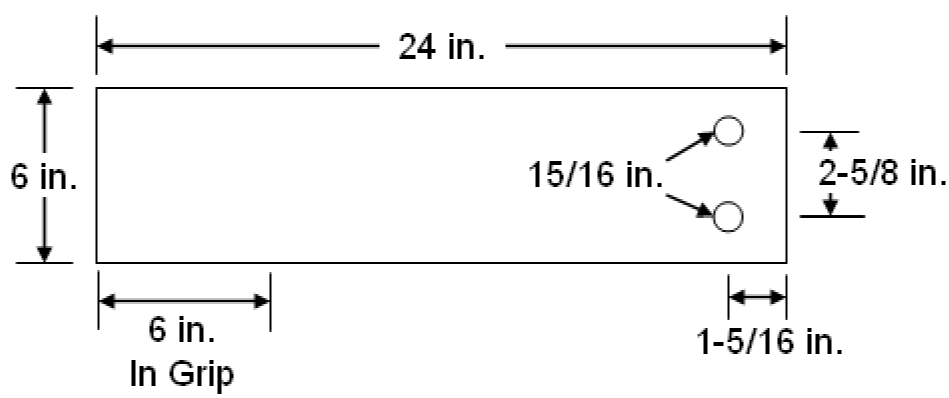

Figure 3.15: 2-Bolt Connection Fatigue Specimen

During testing of the 4-bolt fatigue specimens with snug bolts, some of the specimens failed at locations where the plate stress was theoretically lower than other locations. The failures occurred at the bolt line closest to the unloaded end of the plate, which should have a stress range one-half that of the second bolt line. Assuming each of the four bolts carried the same shear force, P/4, the tensile force in the last row of holes should be P/2, as shown in Figure 3.16. The failure at this theoretically lower stress area was caused by slight hole misalignments from the fabrication process. As was done for the tension connection tests, the holes in the specimens were not made in assembly or with a template. The bolts at the line closest to the unloaded end of the plate may have been in bearing before all other bolts came in to bearing. This would increase the stress on the base material at that bolt line. Since the loads were not large enough to deform the holes, all bolts might not have come into bearing initially. Therefore, the 2-bolt pattern shown in Figure 3.15 was also used to ensure better alignment of holes.

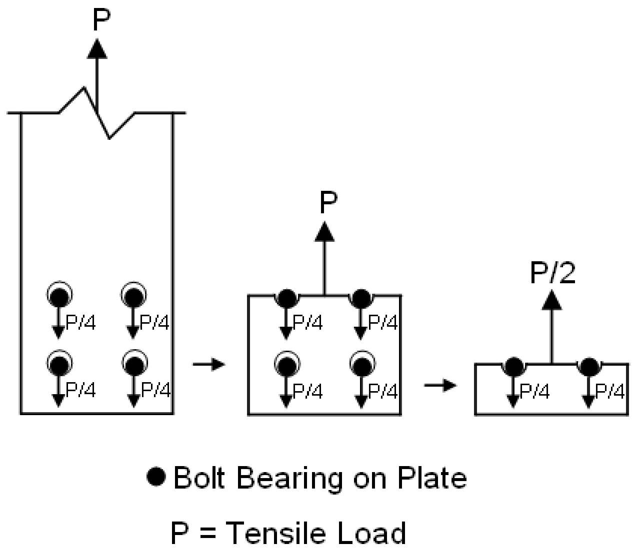

Figure 3.16: FBD Showing Force Level at Each Bolt Line

In total, there were 14 double shear lap slice connection fatigue tests proposed for testing during the project. Due to time and equipment constraints, 12 of these connections were tested. The results from these fatigue tests will be presented in Chapter 4. Comparisons with past research data as well as the plate fatigue tests will be given.

3.5 NON LOAD CARRYING ATTACHMENT TESTS

A total of 32 plate specimens were fatigue-tested. The specimens were 6 inches wide by 60 inches long. Plate thicknesses for the specimens ranged from 0.5 inches to 2.0 inches at 0.25-inch increments to 1.5 inches. This range provided six different plate thicknesses, covering typical flange plate thicknesses used in highway girder construction. While thicker plates are used, it was hypothesized that the reduced shielding effect from the bolt clamping would be noticeable with thicknesses 2.0 inches or less and specimens of greater thickness would yield similar results to those of the 2.0-inch plate thickness.

Mill certifications were obtained for all plates. Material used for a given plate thickness was from the same heat of steel and was either A572 Grade I or II.

Each specimen had a set of four bolt holes spaced at 3 inches along a longitudinal gage line. The gage line was located in the middle of the plate width. All hole diameters were 15/16 inch. The holes were either punched or drilled. Twenty six of the specimens were tested with bolted gusset plates, while the remaining specimens were tested with open holes. The gusset plates were 3/8 inch by 6 inches wide by 12 inches long with punched holes. A single gusset plate was used on a given specimen. A325, 7/8-inch diameter high-strength bolts attached the gusset plate to the specimen. The head of the bolt was installed on the opposite side of the gusset plate. A hardened washer was used under the nut. The bolts were pre-tensioned through the turn-of-the-nut method. Pre-tensioning was first performed on the two inner bolts, followed by the outer two bolts. Figure 3.17 shows a specimen with the attached gusset plate.

Figure 3.17: Specimen with Bolted Gusset Plate

All specimens were cycled at a frequency of 3 Hz under constant-amplitude loading in a 1500 kips capacity load frame. The nominal stress range (based on the gross area cross section) was 25 ksi. Assuming a net hole diameter of 1 inch for the 7/8-inch diameter bolts, the stress range based on the net cross-sectional area was 30 ksi. The strains in several specimens were measured by strain gauge to verify that the applied load ranges were correct. A minimum load of approximately 10 kips was used for each specimen. Each specimen was cycled to until a fatigue crack developed at a hole or for a maximum of approximately 3 million cycles.

The length of each specimen was 5 feet. This length allowed for a 12-inch grip length at either end of the specimen and a 36-inch gage length. The specimens did not have a reduced cross section in the gauge length in an effort to reduce specimen cost. This led to fatigue failure of several specimens within the gripped cross section. However, these specimens (B-7 and C-4) were repaired by grinding and welding the two sides of the fatigue fracture back together. As a result of these grip region failures, specimens that exceeded 500,000 cycles were periodically re-gripped, decreasing the overall gauge length by 1.0 inch at either end of the specimen. This helped force any crack developing in the grip region to re-initiate at a new location, thereby delaying crack propagation.

3.6 MATERIAL PROPERTIES

The same heat of steel was used throughout the project for the respective steel thicknesses and grades. In total, there were 11 different steel heats used. Standard 8 in. gage length tension coupons conforming to ASTM A370-05 were cut and machined from each thickness and grade of steel. The coupons were tested using a 600-kip Universal Testing Machine. The same machine and general loading rate used for coupon testing was also used for plate and connection tension testing. The displacement during testing was monitored by an extensometer attached to the 8 in. gage length section. The load versus displacement relation was recording using a digital data acquisition system (DAQ). This data was in turn used to determine the stress-strain relationship for each type of steel. The tensile properties of each of the initial 9 steel types, reported by Lubitz (2005), are repeated in Table 3.21.

Along with the initial nine steel types, two additional steels were ordered for use throughout this phase of the project: a second heat of A572 Grade 50 steel and a heat of A588 steel. To differentiate the two heats of A572 steel, the new heat was identified as ‘Heat Z’ for all tests. These steel heats are also listed in Table 3.21. Enough steel was ordered to cover plate tension and fatigue tests, as well as the connection tension and fatigue tests. Three coupons were tested from each of the two new heats. The coupons were taken from various locations throughout the steel in order to determine average properties for the entire heat. The ratio of yield stress over ultimate stress (f_y/f_u) is also listed for comparison. The steel supplier’s mill test report (MTR) values are presented as well, with the exception of the ½ in. A572 Grade 50 Heat Z, which was delivered with the incorrect report.

Table 3.21: Tensile Properties of Steel

Heat Description	Yield Strength (ksi)	Ultimate Strength (ksi)	% Elong.	f_y/f_u
3/8" Gr. 36	47.5	70.9	22.8	0.670
	48.6	*69.1*	*26.0*	*0.703*
1/2" Gr. 36	47.5	69.9	16.4	0.680
	46.4	*69.6*	*23.5*	*0.667*
3/4" Gr. 36	42.2	65.7	30.3	0.642
	43.9	*65.6*	*23.5*	*0.669*
1/2" Gr. 36 (S)	48.0	62.2	26.6	0.772
	42.8	*67.6*	*31.5*	*0.633*
3/8" Gr. 50	55.8	78.4	21.6	0.712
	58.6	*75.4*	*28.8*	*0.777*
1/2" Gr. 50	53.7	75.5	23.6	0.711
	55.8	*76.4*	*27.5*	*0.730*
3/4" Gr. 50	60.8	83.3	23.5	0.730
	60.7	*77.7*	*27.5*	*0.781*
1/2" Gr. 50 (S)	72.8	79.2	16.5	0.919
	71.0	*81.0*	*27.0*	*0.877*
1/2" High C Gr. 55	60.0	84.8	20.3	0.708
	62.2	*87.1*	*20.5*	*0.714*
1/2" Gr. 50 Heat Z	54.0	71.5	23.9	0.756
	N/A	*N/A*	*N/A*	*N/A*
1/2" A588	62.6	86.5	21.8	0.724
	65.0	*86.2*	*16.6*	*0.754*

MTR values listed in italics
(S) = Shear cut
N/A = Not Available
*Z = Second Heat of A572 Gr. 50

In addition to the tensile properties of all the steel types, the chemical composition of each steel heat was determined. These are shown in Table 3.22. The last two steel types listed were the new steel ordered for this phase of the project.

Table 3.22: Chemical Composition of Steel

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
1/2" Gr. 36	0.16	0.67	0.011	0.037	0.13	0.11	0.14	<0.01	0.57
3/4" Gr. 36	0.13	0.61	<0.005	0.052	0.15	0.15	0.13	<0.01	0.45
1/2" Gr. 36 (S)	0.22	0.68	<0.005	0.012	<0.01	0.01	0.03	<0.01	0.03
3/8" Gr. 50	0.12	0.88	<0.005	0.022	0.28	0.07	0.44	<0.01	0.37
1/2" Gr. 50	0.13	0.79	<0.005	0.031	0.23	0.08	0.36	<0.01	0.37
3/4" Gr. 50	0.12	0.86	<0.005	0.020	0.23	0.09	0.45	<0.01	0.31
1/2" Gr. 50 (S)	0.05	0.95	<0.005	0.006	0.10	0.13	0.07	<0.01	0.40
1/2" High C Gr. 55	0.22	0.77	0.006	0.039	0.15	0.13	0.10	<0.01	0.45
1/2" Gr. 50Z	0.16	0.81	0.018	0.021	0.15	0.04	0.02	<0.01	0.02
1/2" A588	0.14	1.15	0.013	<0.005	0.40	0.17	0.56	0.02	0.30

(S) = Shear cut

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

3.7 SPECIMEN FABRICATION METHODS

3.7.1 Plate Preparation

The plates were flame cut to the 6 in. wide strips by a steel supplier before delivery to the FSEL. All of the specimens except for the specimens made from ½ in. A36 and ½ in. A572 Grade 50 plate designated by 'S' in Table 3.21 had flame-cut edges. The plates labeled by 'S' had sheared edges. Most of the strips arrived in 20 ft. long sections, with the exception of the ½ in. A588 plate that was only available in 10 ft. long sections. The strips were then saw cut to 4 ft. lengths as needed, except for the A588 strips that were saw cut to 3 ft. 4 in. lengths. The materials used for the connection tests were also prepared in a similar manner, saw cut to the appropriate length.

3.7.2 Drilled Holes

The drilled holes were formed using an annular drill bit powered by a 12.5 Amp Milwaukee Magnetic Drill Press, shown in Figure 3.18. The image shown in Figure 3.18 is courtesy of www.milwaukeetool.com. This drill press was used for all drilled hole sizes, 11/16 in., 13/16 in., and 15/16 in. diameters. During the drilling process, oil lubrication was used to cool the drill bit and base metal, as well as aid in the drilling process.

Figure 3.18: FSEL Magnetic Drill Press

As mentioned before, the quality of a drilled hole was discovered to have a major impact on fatigue life. While it was not initially known why the drilled specimens were behaving well below the expected life, it became apparent that the quality of the drilled hole was the cause of the poor fatigue life. The problem was caused by the use of an annular drill bit without lubrication and at a fast feed rate for approximately 100 to 150 holes during the previous phase of the project. As a result, the older bit produced holes with grooves, as well as a general rough appearance. The drill bit itself also showed damage in the form of discoloration at the end of the bit and nicks out of the cutting surfaces. Holes drilled with this bit and procedure were labeled as a hole drilled with a worn bit. The worn drill bit is shown in Figure 3.19. A typical hole formed using this worn drill bit without cutting oil is shown in Figure 3.20. The relatively deep grooves formed in the steel, as well as the general rough appearance of the hole are evident.

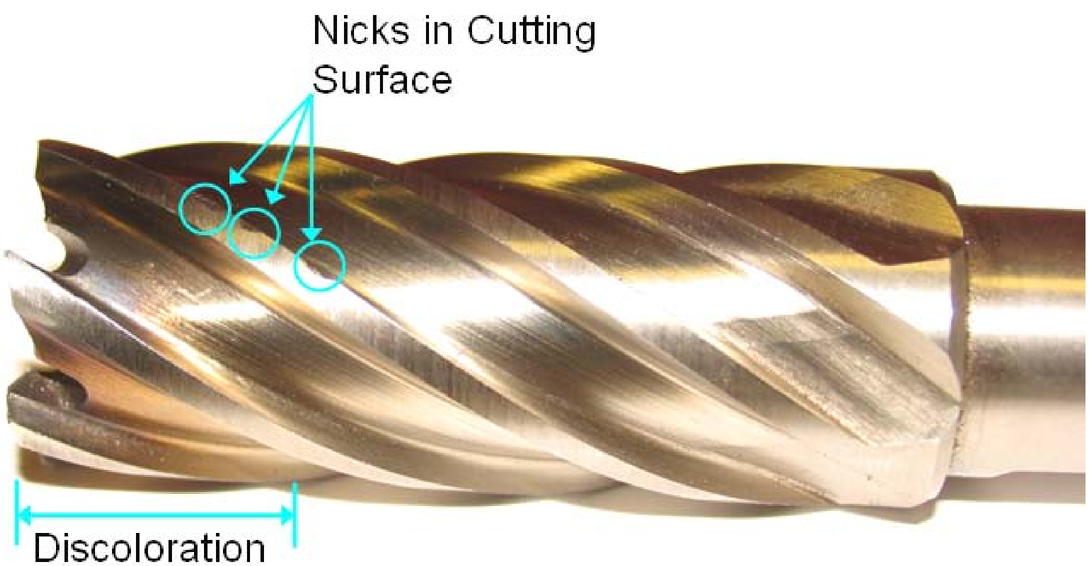

Figure 3.19: Worn Drill Bit

Figure 3.20: Typical Hole Drilled with Worn Bit

The worn drill bit can be related to a drill bit used by a fabrication shop for too long without sharpening or replacement. Therefore, it is likely that a drilled hole used in a bridge or building could have a similar appearance to Figure 3.20. Once discovered, a new drill bit was used in conjunction with oil lubrication for the remaining drilled holes. The quality of this type of hole was remarkably improved. A photograph of the new drill bit, taken at the end of the project, is shown in Figure 3.21. The drill bit showed no sign of discoloration or damage to the cutting surfaces. A typical hole formed using this new drill bit is shown in Figure 3.22. The smoother appearance when compared to the hole fabricated with a worn drill bit is evident. A standard drill was used to make the holes in the non load carrying attachment specimens.

Figure 3.21: New Drill Bit

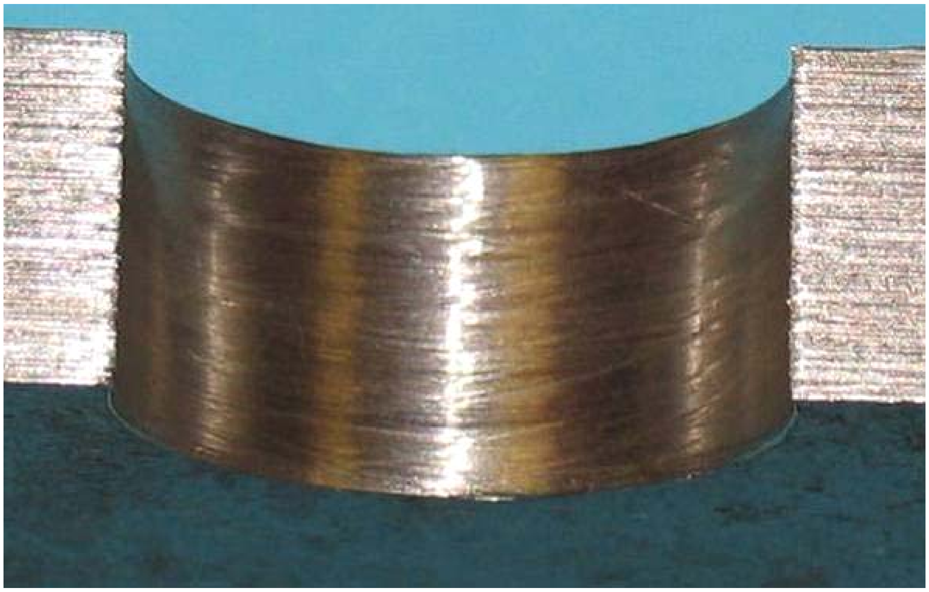

Figure 3.22: Typical Hole Drilled with New Bit

3.7.3 Punched Holes

The punched holes were formed using a W.A. Whitney 790AX6 Portable Flange Press. The press had a 90-ton capacity and was powered by a 0.24 gpm, 1-1/8 hp, 12,000 rpm electric hydraulic pump. The hydraulic pump used was small by fabrication shop standards, which resulted in a slower punch process. For example, the average time to punch a 15/16 in. diameter hole through ½ in. thick steel was 8 sec. to 16 sec., depending on the die clearance. The average time to punch a 15/16 in. diameter hole through ¾ in. plate was 18 sec. to 24 sec., depending on the die clearance used. The slow hole forming did not affect the quality or performance of the punched hole. The FSEL Punch Press is shown in Figure 3.23. A portable flange press is often hung from a spring to allow for easy movement around the work piece. Since this project only used relatively light and easily moved plate material, the press was bolted to a table, and the work piece was moved to the press.

Figure 3.23: FSEL W.A. Whitney Flange Punch Press

New punches and dies were used for the project. Figure 3.24 shows the punch and die used for the largest number of holes, a 15/16 in. diameter punch with the associated 31/32 in. diameter die. Other punches and dies have a similar appearance.

Figure 3.24: 15/16 in. Punch with 31/32 in. Die (At End of Testing)

The quality and appearance of a punched hole is based on a combination of the strength of the material, the size of the hole relative to plate thickness, and the clearance between the male punch and the female die. As discussed previously, plate thickness, hole size, and die clearance were all parameters investigated in this project. A typical punched hole is shown in

Figure 3.25 for a 15/16 in. diameter hole with 31/32 in. die Holes punched with a larger than recommended clearance value require less work to punch, but a large flare will result at the exit side of the hole. More on the punching process and the results of die clearance can be found in Chapter 2. The same die used was for ½ to 1 inch thick plates in the specimens with non load carrying gusset tests. The die used in the punching of these holes was 1/32 in. larger than the punch.

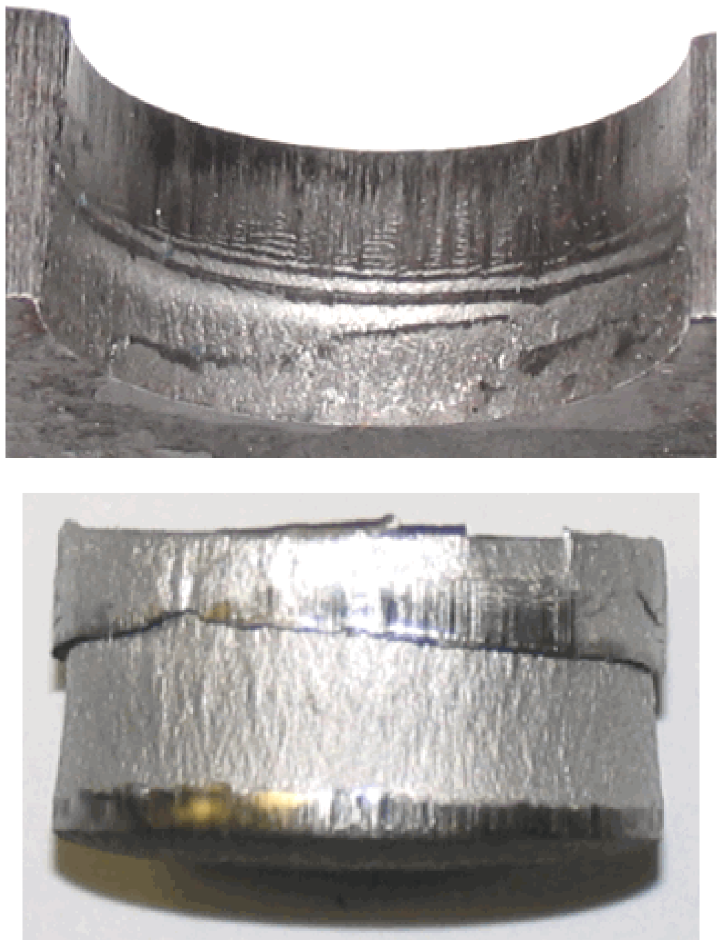

Figure 3.25: Typical Punched Hole and Slug, 15/16 in. with 31/32 in. Die

3.7.4 Sub-Punched and Reamed Holes

Holes required to be formed by sub-punching and subsequently reamed to the full-size diameter were also fabricated at the FSEL. For a full-size hole of 15/16 in., the hole was sub-punched by the AASHTO required amount of 3/16 in. Also, for additional investigations, this sub-punching amount was reduced to 1/8 in. and 1/16 in. The holes were then reamed using a tapered bridge reamer, shown in Figure 3.26, using a radial drill press.

Figure 3.26: FSEL Tapered Bridge Reamer

The quality of the surface of the hole resulting from the sub-punching and reaming process was equal to or better than the appearance of a drilled hole. A typical example of a reamed hole is shown in Figure 3.27.

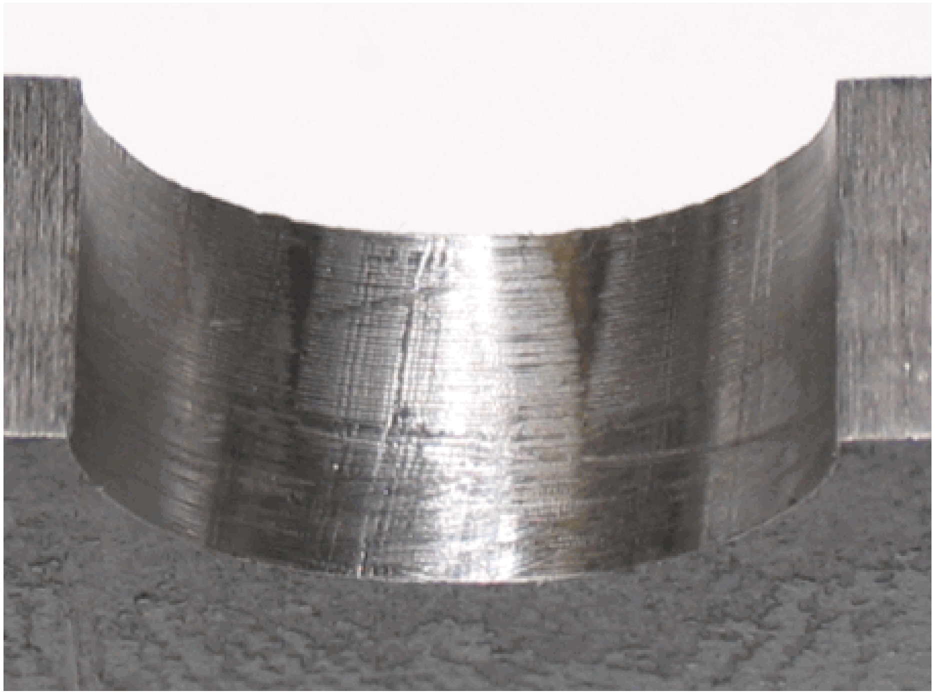

Figure 3.27: Typical Sub-Punched and Reamed Hole

3.8 PLATE TESTING PROCEDURES

3.8.1 Tension Tests

For all of the experiments performed in this project, the actual fabricated specimen dimensions were measured and used to calculate the stress level in each specimen. All of the dimensions were measured to an accuracy of 0.001 in. The width and thickness of the specimen at the net area line were measured. The holes were measured to determine their as-fabricated diameter at the top and bottom of the hole, and an average was used. However, for punched holes, the angular fracture at the bottom of the hole in certain specimens was determined to increase the average diameter of the hole by a large enough value to affect the predicted design ultimate strength. Therefore, the use of the average hole diameter of a punched hole was changed to using the diameter at the top of the hole only. For comparison, experimental results of punched hole specimens will be related to both methods of presenting hole diameter. The bottom of holes punched through the ¾ in. thick material had a noticeable change, while the holes punched in the 3/8 in. and ½ in. thick material did not show a noticeable difference.

All of the plate specimens were tested using a 600 kip Universal Testing Machine (UTM). The UTM with a typical plate specimen is shown in Figure 3.28. For scale, the specimen visible between the grips is approximately 2 ft. long. A close up view of a specimen in the wedge grips is shown in Figure 3.29. The displacement of the crosshead of the machine was measured using a Linear Potentiometer (Linear Pot) at the base of the machine, shown in Figure 3.30. Each specimen was tested at or below the suggested loading rates from ASTM A370-05. The loading rates for the coupon tests and the plate tension tests were approximately equal. A digital data acquisition system (DAQ) was used to record the load from the UTM and the displacement readings from the Linear Pot. The load and displacement readings were taken at 1-second intervals. Each specimen was tested until fracture. The ultimate load and corresponding displacement at ultimate load were determined.

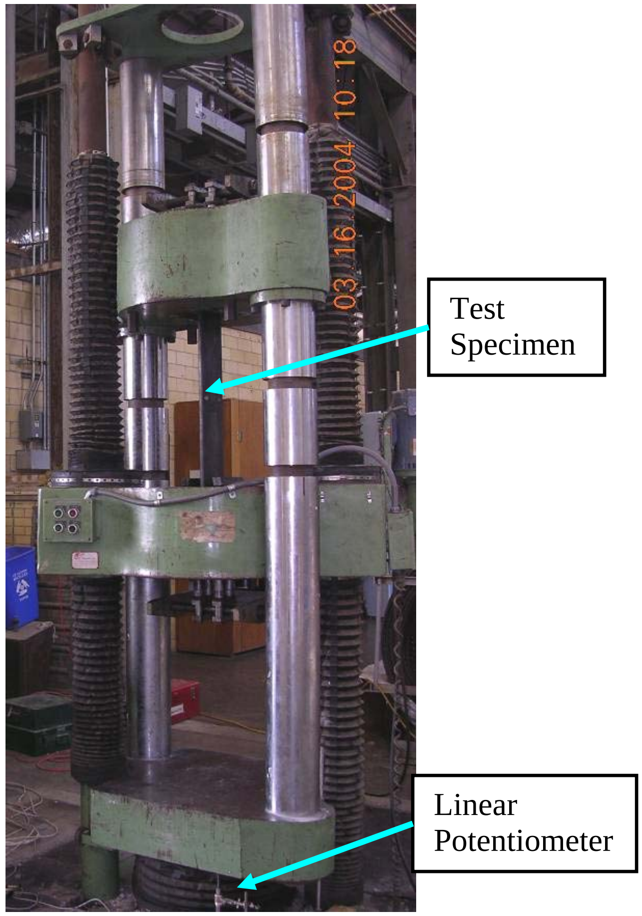

Figure 3.28: FSEL 600 kip Universal Testing Machine with Plate Specimen

Figure 3.29: Typical Plate Specimen in Universal Testing Machine

Figure 3.30: Linear Potentiometer at Base of UTM

3.8.2 Fatigue Tests

The fatigue tests of the plate specimens were performed using a 220-kip MTS Systems Corp. (MTS) load frame. The frame is shown in Figure 3.31. For scale, the connection shown is approximately 4 ft. long, with 3 ft. visible between the grips. The system was controlled by an MTS FlexTest SE controller, which was also used for data acquisition. Before testing, the system was calibrated using an external load cell.

Figure 3.31: FSEL 220-kip MTS Load Frame, Shown with Connection Specimen

Each of the plate specimens was tested at a tensile stress range of 25 ksi on the net section. The minimum stress was kept at 3 ksi in tension to ensure the loads never dropped into compression. The maximum load was well below the net section yield stress of the material. The corresponding load range was computed using the as-fabricated dimensions. Each test was run at a cyclic rate of 3.5 Hz.

Using a system of axial force error amounts and system error measurements, the system was stopped when certain limits were exceeded. The error limits were set to stop the test when a crack formed from the edge of a hole to the edge of the plate, and from the other edge of a hole to approximately 25% to 50% of the distance between the two holes. A typical example of the extent of cracking at the end of a test is shown in Figure 3.32. Here the crack is highlighted with a line.

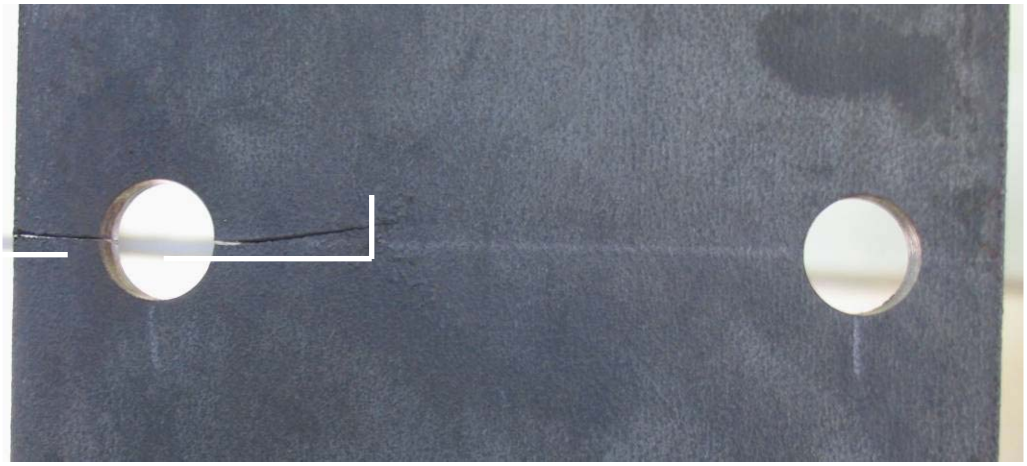

Figure 3.32: Typical Plate Fatigue Failure

If a specimen did not fail by a certain cycle count, the test was stopped prematurely and the specimen was labeled a runout test. The number of cycles considered adequate was above 2 million, well into the range of that required for a Category B specimen at a stress range of 25 ksi. The lower limit for a Category B at a stress range of 25 ksi is 770,000 cycles.

3.9 CONNECTION TESTING PROCEDURES

3.9.1 Tension Tests

A reusable double shear lap splice pull assembly was used to run multiple tests for the snug bolt connection specimens. This pull assembly consisted of two splice plates fillet welded to a single middle plate. The weld was designed to be much stronger than the maximum expected load. The test assembly remained in the upper grips of the Universal Testing Machine, allowing for the test specimens to be interchanged with minimal effort. The pull assembly dimensions are shown in Figure 3.33. The center plate was long enough to cover the required weld length, 10 in. in the upper grips, and extra space for a total length of 24 in. A typical completed pull assembly with test specimen is shown in Figure 3.34.

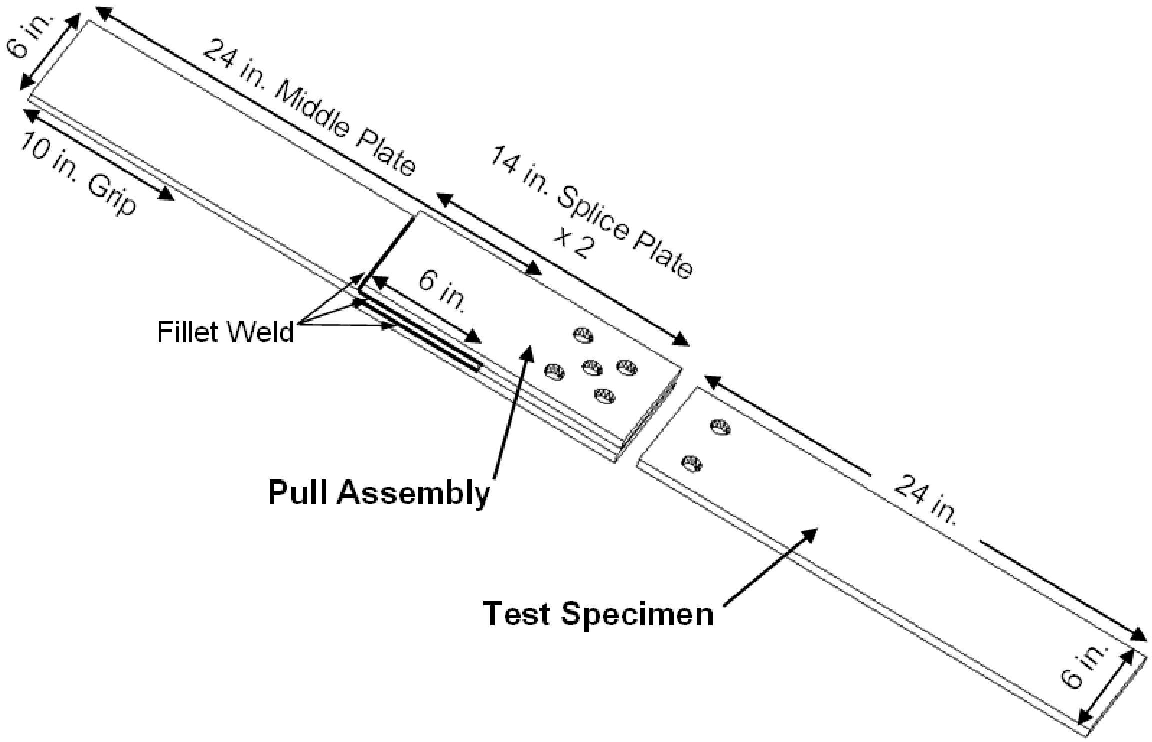

Figure 3.33: Pull Assembly Dimensions

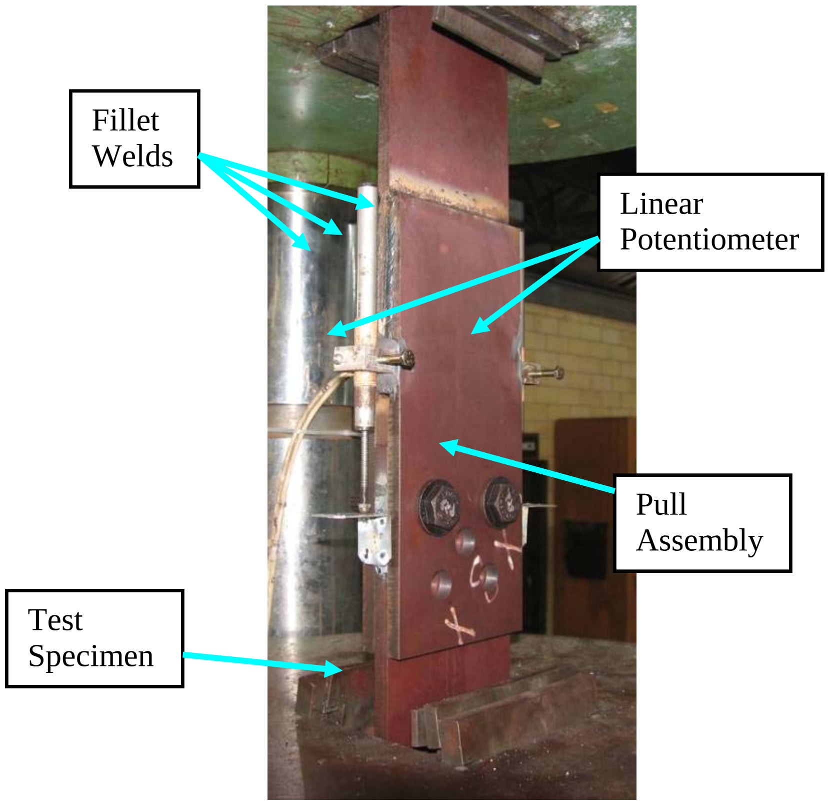

Figure 3.34: Pull Assembly with Test Specimen

The inner plate of the test pull assembly was made of the same thickness of steel as the test specimen, either ½ in. thick A572 Grade 50 Heat Z, or ¾ in. thick A572 Grade 50. The splice plates were made of either ½ in. thick A588 steel or ¾ in. thick A572 Grade 50 steel. With this assembly, the center pull plate was designed to remain elastic before the ultimate load of the test specimen was reached. The two splice plates combined had twice the area of the test specimen, therefore half the stress on each bolt hole. In addition, the ½ in. A588 steel was stronger than the ½ in. A572 Grade 50 steel used in the specimens. With half the stress and stronger steel for the splice plates, little to no hole deformation occurred in the test pull assembly. The test assembly was replaced if a noticeable amount of hole deformation had occurred.

As mentioned in Section 3.3, test specimens had gage distances between the two holes of 2-1/3 in. or 3 in., and end distances of 1-1/2 in. or 2 in. In addition, single bolt specimens with two end distances were tested. A 5-hole pattern was drilled or sub-punched and reamed into the 2 splice plates to allow for both spacings to be used with the same pull assembly, as well as the single bolt tests. The staggered bolt pattern specimen was chosen to fit into the holes used for the different spacings. The dimensions of the splice plates used are shown in Figure 3.35. The various orientations of the test specimens used with the pull assembly are shown in Figure 3.36.

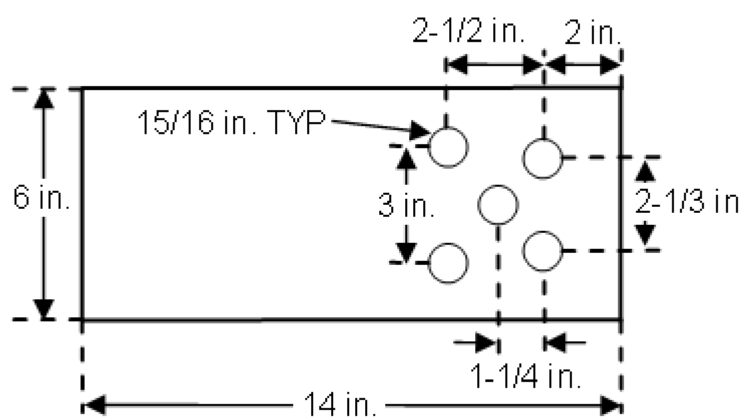

Figure 3.35: Pull Assembly Splice Plate Dimensions

Figure 3.36: Orientations of Test Specimens in Pull Assembly

Prior to welding the center pull plate to the splice plates, a typical plate specimen and a set of thin shims were placed into the pull assembly before welding. The gap caused by the shims ensured that the specimens would fit easily into the test assembly each time. There was also a gap of 1 in. or more left between the bottom of the center plate in the welded test assembly and the top of the test specimen. This allowed the splice plates to bend outward to accommodate expansion of the specimen plate holes due to the bolt bearing forces. Few, if any, tests caused the plates to bend outward by a noticeable amount.

The same pull assembly configuration for the snug bolt tests was also used for the pretensioned tests. As the pull assembly was left in the testing machine for multiple specimens, the surface of the pull assembly was only new for the first test at each gage distance. To determine if this had any effect on the test results, two new pull assemblies were made to each allow two single bolt specimens to be tested, for four single bolt specimens tested with pretensioned bolts. Each friction surface was therefore new for each test. The fact that the surface was slightly worn for the repeated 2-bolt tests was determined to have little effect on the remaining pretensioned tests. The dimensions of the modified splice plates used for the single bolt pretensioned pull assembly are shown in Figure 3.37. These modified splice plates were also welded to a center pull plate and inserted into the upper grips of the test machine. The completed modified pull assembly is shown in Figure 3.38.

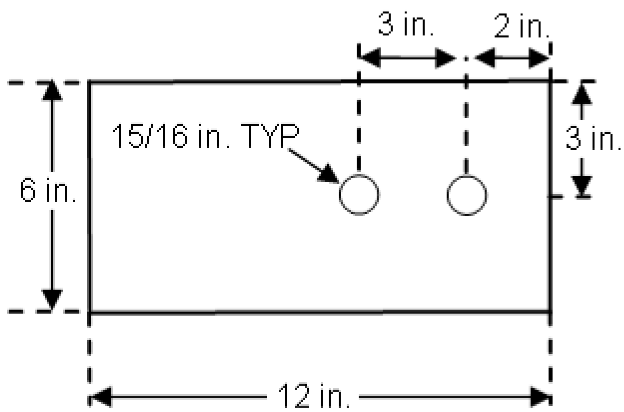

Figure 3.37: Modified Single Bolt Pull Assembly Splice Plate Dimensions, ½ in. Thick Steel

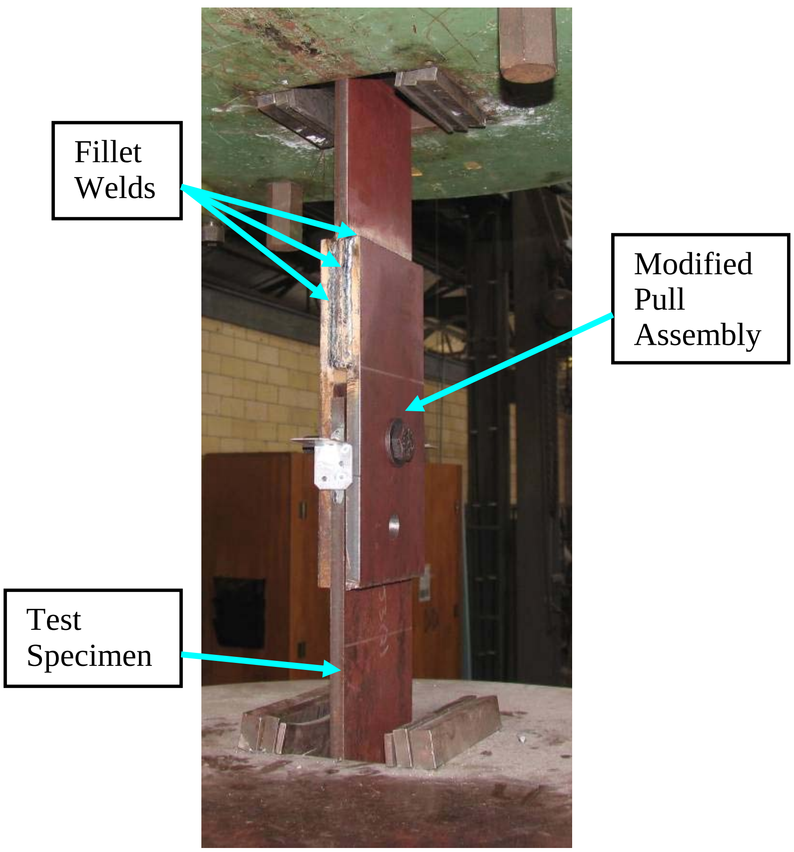

Figure 3.38 Typical Modified Pull Assembly with Test Specimen

The specimens tested with pretensioned bolts were assembled to ensure that the slip could occur after the frictional capacity was exceeded. The specimen was inserted into the pull assembly such that the bottom of the specimen holes were in bearing with the bolts, and thus the bolts in bearing with the top of the splice plate holes. Once the bottom of the specimen holes were in bearing, the bolts were tightened. During testing, the specimen first had to slip into bearing on the tops of the holes before the load would start to increase past the initial slip load. Using this method, the slip load and displacement was clearly evident and recorded.

The bolts used for the connection tests, both tension and fatigue, were 7/8 in. diameter A490 twist-off-type tension-control bolt assemblies supplied by Lohr Structural Fasteners. The twist-off type bolts ensured that the proper tension force would develop in each bolt, thus the bolt tension force would not be a variable in the pretensioned bolt test specimens. Three proof tests were performed using a Skidmore-Wilhelm Tension Calibrator to determine the tension in the bolt when the end of the bolt twisted off. The loads ranged from 57 kips to 58 kips, with an average tensile load of 57.3 kips. The minimum bolt pretension specified in both AISC and AASHTO for 7/8 in. bolts is 49 kips. A typical bolt used in the experiments is shown in Figure 3.39. The surface of the twist off portion of the bolt is also shown in the same figure.

Figure 3.39: 7/8 in. A490 Twist-Off Type Bolt Used for Tests

The connection tension tests were performed using the same 600 kip Universal Testing Machine (UTM) used for the plate tension tests. The load during testing from the UTM was record by a digital data acquisition system (DAQ) system, also the same as that used for the plate tests. However, rather than the single Linear Pot used to measure crosshead displacement during testing, a pair of Linear Pots was attached to the specimens and pull assembly to measure bolt hole elongation. This configuration was shown previously in Figures 3.34 and 3.36, and is shown again in Figure 3.40. The hole elongation gave a better indication into the behavior of the connection compared to the total crosshead displacement. A Linear Pot was attached to both sides of the connection to determine the approximate rotation in the connection and an average hole elongation amount. The rotation was related to the alignment of the two holes, as one hole higher than the other slightly misaligns the connection. The average of the two displacement readings from the Linear Pots was determined and used for test results. As mentioned, the pull assembly itself was designed to remain undeformed at the hole lines when in bearing and in the gross area of the upper plate. The area of the splice plates was twice that of the test specimen (combined 1 in. thick vs. ½ in. thick), and the splice plates were also made of a higher strength steel. This ensured that the only deformation measured by the Linear Pots was from the test specimen itself, not the pull assembly. The Linear Pots were attached to the pull assembly with an aluminum block glued to both sides, which allowed the Linear Pots to be removed while inserting the test specimens. Small angles were tack welded to the sides of each test specimen to serve as contact points for the Linear Pots. The small weld bead had no effect on the test results, as the location of the failure planes were near the bolts holes, not the edge of the plates. The small contact angles appear in Figure 3.34, Figure 3.36, Figure 3.38, and Figure 3.40.

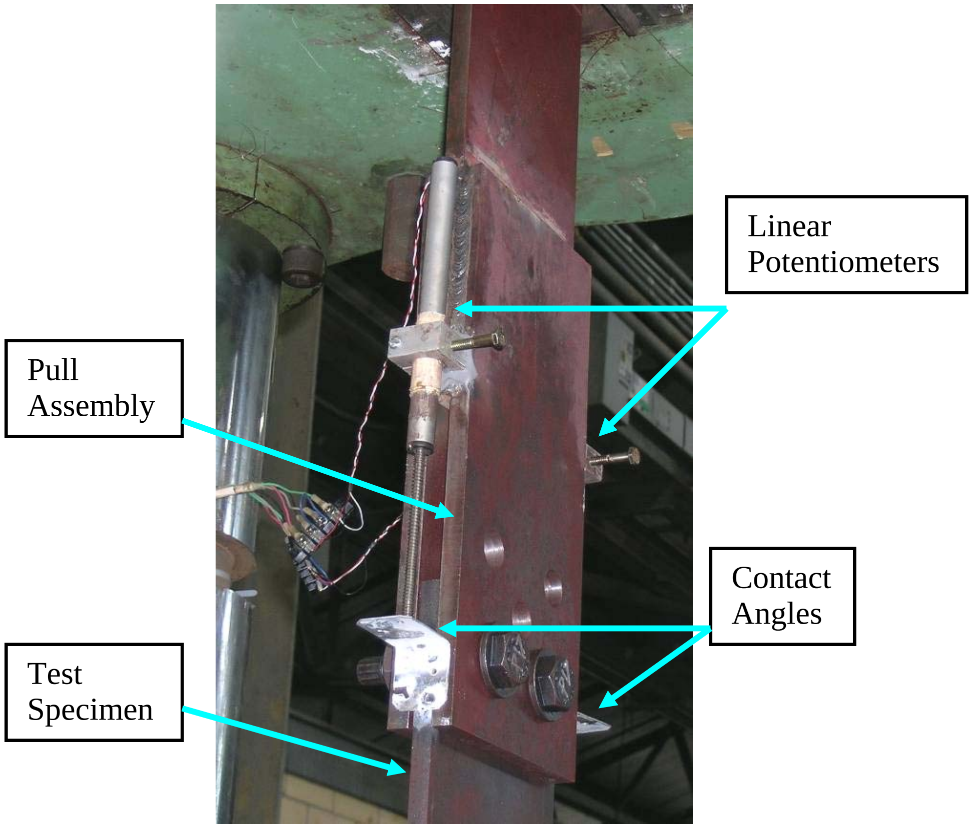

Figure 3.40: Linear Pot Configuration with Contact Angles on Test Specimen.

3.9.2 Fatigue Tests

To test the connection fatigue specimens in a double shear lap splice configuration, two splice plates were used to connect two test specimens at once. Each set of specimens represented a single test. The connection was designed to fail in the center plates, representing the test specimens. The failure of either center plate constituted the failure of the specimen configuration. That is, the specimen in the set that did not fail was not reused. Each specimen configuration of hole type, stress range, and bolt pretension was duplicated. As shown previously in Figure 3.14 and Figure 3.15, both a 4-bolt pattern and a 2-bolt pattern were used.

The splice plates consisted of the same 4-bolt pattern as shown in Figure 3.14, mirrored to an 8-bolt pattern to connect two specimen plates together. The splice plates were made out of ½ in. A572 Grade 50 Heat Z steel, as were the test specimens. A ½ in. gap was left between the upper and lower plates before attaching the splice plates. The same splice plate configuration was used for the 4-bolt test specimens and the 2-bolt test specimens, with both snug and pretensioned bolts. The splice plates were reused for multiple experiments, as no hole elongation or damage occurred during the tests. The outer splice plates were the same thickness as the specimens, which resulted in the splice plate area being twice that of the test specimen (combined 1 in. thick vs. ½ in. thick). Since the load ranges were well below slip loads during testing, little to no friction damage occurred to the splice plates as well. The minimum stress was kept at 3 ksi in tension. The specimens were cycled at 3 Hz. The same twist-off type bolts used for the tension connection tests were used for the fatigue connection tests. A typical 4-bolt assembled connection is shown in Figure 3.41. The view of a connection fatigue specimen with the twist-off type bolts pretensioned is shown in Figure 3.42.

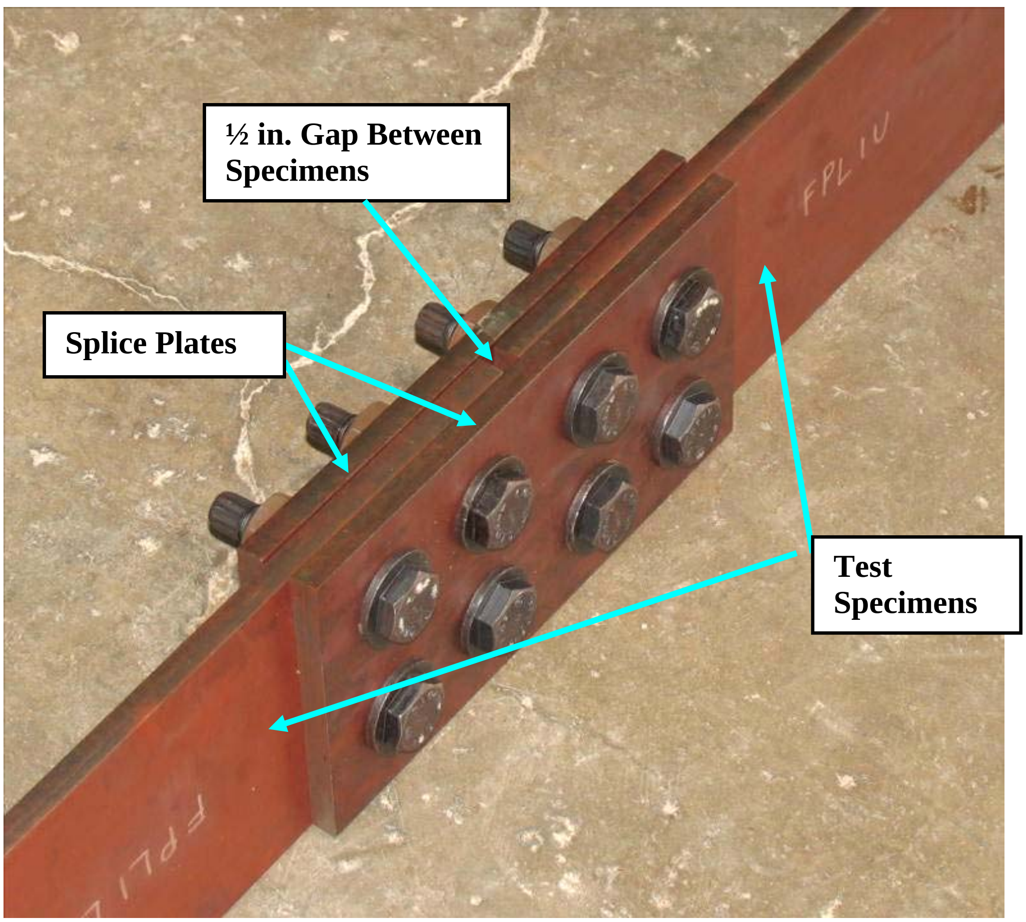

Figure 3.41: Typical Assembled 4-Bolt Fatigue Connection

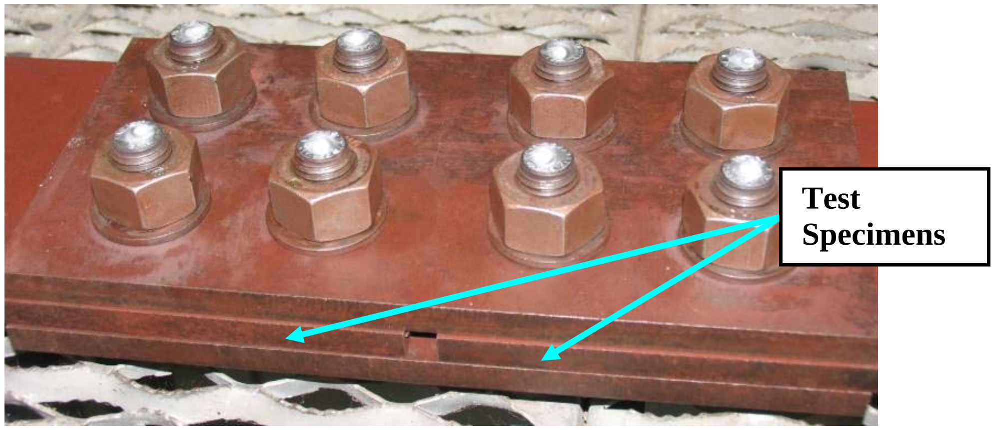

Figure 3.42: Twist-off Type Bolts Pretensioned

The connection fatigue specimens were cycled using the same FSEL 220 kip MTS load frame used for the plate fatigue specimens. The 220 kip machine was shown in Figure 3.30, with a typical connection specimen being tested. In addition to the MTS load frame at the FSEL, the project involved testing using a 550 kip MTS load frame at the TxDOT Construction Division's Materials and Pavements Section. This MTS system was run in a similar manner to the FSEL MTS system. The software used to control the system was identical. The TxDOT MTS system is shown in Figure 3.43. For scale, the connection is approximately 4 ft. long, with 3 ft. shown between the grips.

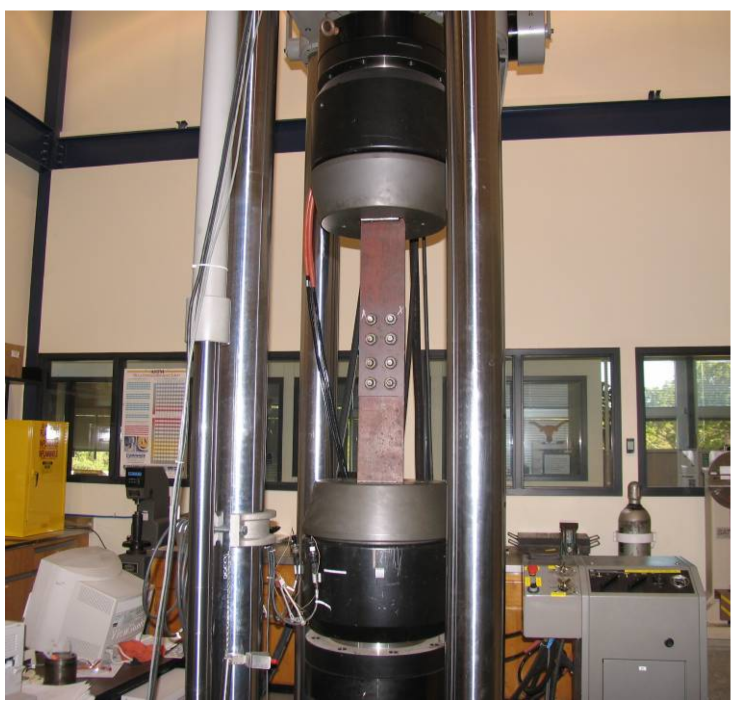

Figure 3.43: TxDOT 550 kip MTS Load Frame, Shown with Connection Specimen

The MTS software limits on axial force and axial error were set in a similar manner to the plate specimens to ensure that the amount of cracking at the end of each test was similar for all of the specimens. The limits used to control the stopping point of any failed specimens were kept the same between the two testing locations. This failure amount consisted of a crack from the edge of a hole to the edge of the plate, and a crack from the edge of a hole to about 25% to 50% of the distance between the two holes. If no crack had formed, the tests were stopped after either 2 million or 4 million cycles, depending on the stress range. These values corresponded to a specimen falling well above a Category B design curve at the appropriate stress range.

Chapter 4. Test Results and Analysis

As presented in Chapter 3, the effects of punched holes in structural steel members was investigated by performing tensile and fatigue tests on both plate material and in a double shear lap splice configuration. The results and analysis of these tests will be presented in the following order:

- Plate tension tests results
- Plate fatigue test results
- Connection tension test results
- Connection fatigue test results
- Comparisons with past research data

4.1 PLATE TENSION TEST RESULTS

The results of all tension tests on plate material are presented in this section. These include both the tests performed by Lubitz (2005) and the tests conducted during this phase of the project. Each specimen consisted of 6 in. wide plate with two holes of the indicated diameter, unless noted otherwise. The thickness of the plate specimen depended on the test being performed. When calculating the net section stress, the ultimate load was divided by the actual as-fabricated net area. The strength ratio was determined by dividing the net section stress by the ultimate strength determined from the coupon tests, listed in Table 3.17. A strength ratio value less than 1.0 signifies a specimen that did not reach the measured ultimate strength. A strength ratio value greater than 1.0 signifies an ultimate strength greater than the measured ultimate strength. The elongation was taken as the displacement at the maximum load. The net section stresses for both the punched and drilled specimens did not include the 1/16 in. addition to hole diameter required by both AASHTO and AISC, as discussed in Chapter 1. This addition is analyzed in Section 4.2.

The data presented in this section represented the average results of each investigation, where applicable. The net area for punched hole specimens was first determined using the average hole diameter and then compared to just using the diameter of the top of the hole. For punched holes that had a large flare at the bottom of the hole, the averaging process was found to benefit punched holes by decreasing the net area, thus increasing the ratio of experimental strength to predicted strength. This change most affected the ¾ in. specimens and specimens with large die clearance values. Therefore, the results presented in this section for punched hole specimens have net areas calculated from the diameter of the top of the hole only.

4.1.1 Steel Type and Temperature Investigation

The average results of the steel type and temperature investigation are shown in Table 4.1. This data included results performed during the previous phase of the project by Lubitz (2005), as well as the additional tests in this phase of the project. Each specimen was fabricated with a pair of 15/16 in. diameter holes.

Table 4.1: Steel Type and Temperature Investigation Average Results, ½ in. Plate Material

Method	Steel Grade	Number of Specimens	Avg. Strength Ratio	Average Elongation (in.)
Punched	36	5	0.95	0.36
	50	5	1.05	0.50
	55	1	0.94	0.36
	50Z	*2*	*1.04*	*0.35*
	A588	*2*	*1.05*	*0.67*
Drilled	36	5	1.10	1.65
	50	5	1.13	1.24
	55	1	1.04	1.11
	50Z	*2*	*1.09*	*0.52*
	A588	*2*	*1.08*	*0.80*

Note: New Results in Italics

From the results of the additional tension tests, the new steel types, A572 Grade 50 Heat Z and A588, were shown to have similar results to the steels used previously. The difference between the punched and drilled specimens was smaller in these new heats of steel compared to the previous heats. As indicated by the average results, punched holes had a lower average strength ratio in all grades of steel compared to drilled holes. The average elongation for punched holes was also lower than drilled holes for each grade of steel. It is interesting to note that the elongation of the new drilled specimens were noticeably lower than the previous drilled specimens. However, there was still a significant difference between the punched and drilled specimens. The largest difference between hole types was in the A36 material, while the smallest difference was in the A572 Grade 50 Heat Z and A588 steel. More information on the results of the steel type and temperature investigation can be found in Lubitz (2005).

A typical failed specimen with drilled holes is shown in Figure 4.1. A typical failed specimen with punched holes is shown in Figure 4.2. The specimens shown are ½ in. thick A588 steel with a pair of 15/16 in. diameter holes. Notice the yielded areas around the net section line indicated by the flaking of the mill scale during testing. Attention should also be paid to the difference in necking amounts at the net section showing the increased ductility in drilled hole specimens.

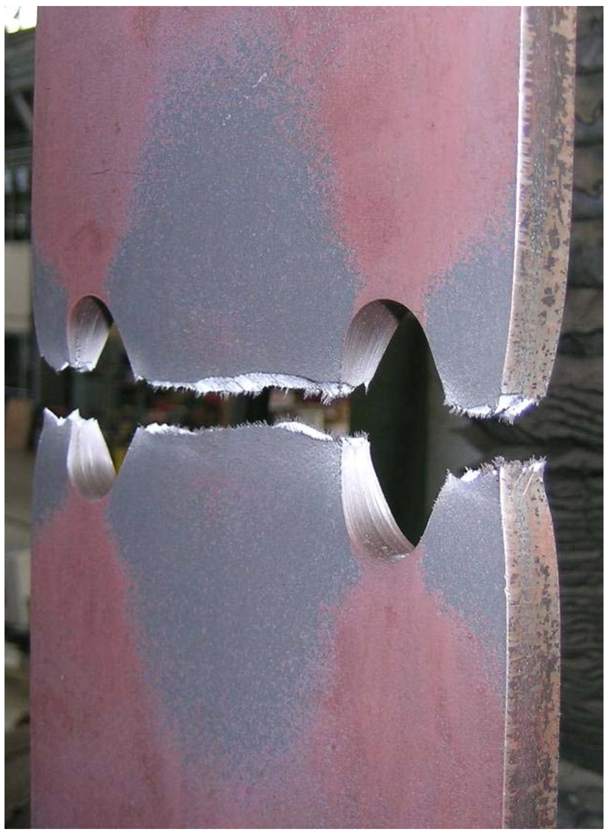

Figure 4.1: Typical Failed Drilled Hole Plate Specimen

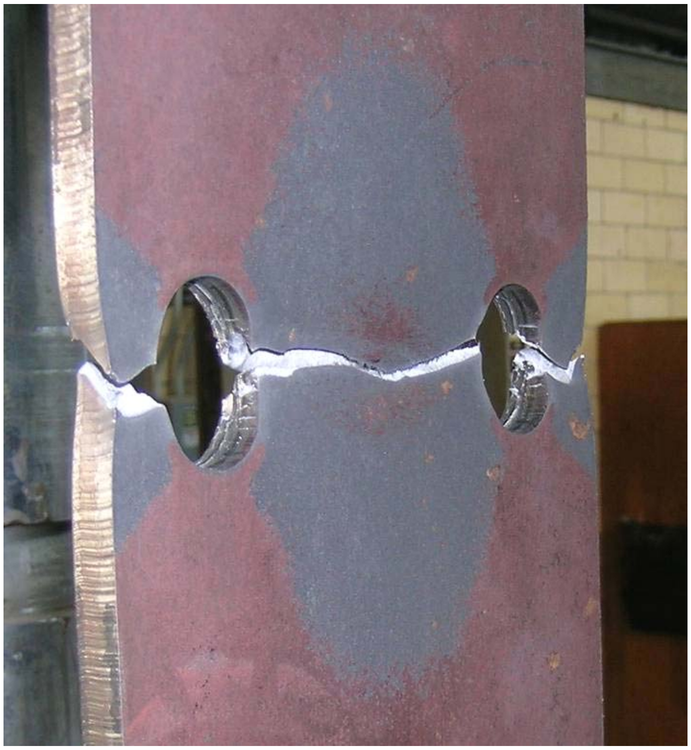

Figure 4.2: Typical Failed Punched Hole Plate Specimen

The average results of the tension tests on specimens with a reduced net area in three grades of steel are shown in Table 4.2. Here, an additional 11/16 in. diameter hole was either punched or drilled in the center of the plate, between a pair of 15/16 in. diameter punched or drilled holes. Each specimen was tested at room temperature.

Table 4.2: Reduced Net Area Test Average Results, ½ in. Plate Material

Method	Steel Grade	Number of Specimens	Avg. Strength Ratio	Average Elongation (in.)
Punched	36	2	1.01	0.28
	50Z	2	1.09	0.27
	A588	2	1.09	0.33
Drilled (New Bit)	36	2	1.09	0.44
	50Z	2	1.13	0.34
	A588	2	1.08	0.36

The results of the reduced net area investigation showed a similar trend to the specimens with the normal net area. Comparing Table 4.2 with Table 4.1 shows the punched specimen's strength ratio increased in these reduced net area tests. The increase in average strength ratio was greatest in the A36 specimens. In the previous tests, the A36 specimens yielded in the gross section prior to fracturing in the net section. For the reduced net area specimens, this did not occur. In the drilled specimens, the average strength ratio remained approximately the same. In the specimens with a reduced net area, the A588 punched hole specimens had approximately equal strength ratios with the drilled hole specimens. A direct comparison of elongation between the two specimens with different net areas was not possible. However, the same trend of punched holes having lower deformation values was still present, though the difference between hole types was smaller in the reduced net area specimens.

Typical failed specimens with a reduced net area are shown in Figure 4.3 for drilled holes, and Figure 4.4 for punched holes. These specimens were fabricated of ½ in. A36 steel, with a pair of 15/16 in. diameter holes and a single 11/16 in. diameter hole. Notice the greater necking at the net section in the drilled hole specimen, which indicated the increased ductility allowed by drilled holes. Also noticeable in the figures are the yield lines shown by the flaking of the mill scale.

Figure 4.3: Reduced Net Area Plate Specimen Failure—Drilled Holes

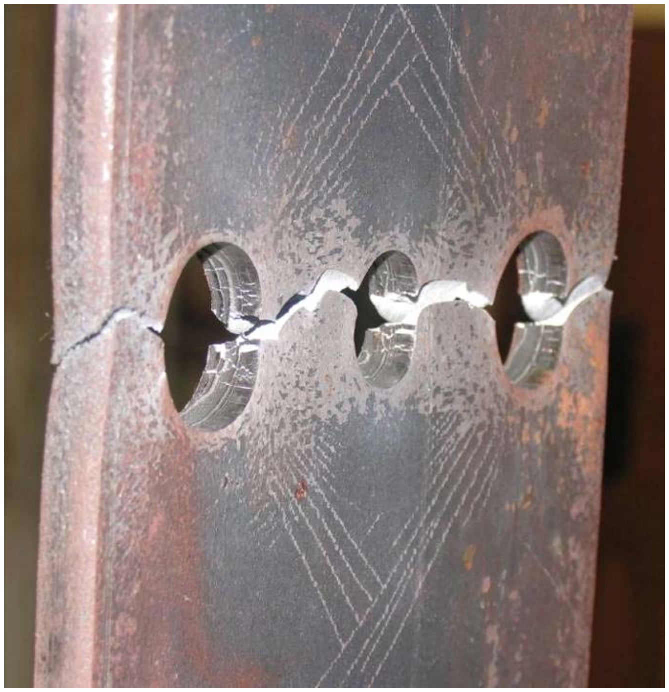

Figure 4.4: Reduced Net Area Plate Specimen Failure—Punched Holes

4.1.2 Plate Thickness and Hole Size Investigation

The average results of the plate thickness and hole size investigation are shown in Table 4.3. The plate thicknesses and nominal hole sizes used for each specimen are indicated, as well as the associated hole size to plate thickness ratio. A pair of holes was used for each specimen, as indicated. For each hole size, the appropriate edge distances as specified by AASHTO and AISC were used.

Table 4.3: Plate Thickness Investigation Average Results

Method	Steel Grade	Number of Specimens	Thick. (in.)	Hole Sizes (in.)	Avg. Strength Ratio	Average Elongation (in.)
Punched	36	3	3/8	11/16,13/16,15/16	0.92	0.39
		3	1/2	11/16,13/16,15/16	0.90	0.55
		2	3/4	13/16,15/16	0.96	0.91
	50	3	3/8	11/16,13/16,15/16	1.00	0.87
		3	1/2	11/16,13/16,15/16	1.01	0.74
		2	3/4	13/16,15/16	1.03	0.80
Drilled	36	3	3/8	11/16,13/16,15/16	1.06	1.58
		3	1/2	11/16,13/16,15/16	1.05	1.68
		2	3/4	13/16,15/16	1.11	1.89
	50	3	3/8	11/16,13/16,15/16	1.05	1.30
		3	1/2	11/16,13/16,15/16	1.09	1.39
		2	3/4	13/16,15/16	1.09	1.18

A comparison between the different thicknesses within each grade of steel is not possible due to the fact that each thickness is from a different heat of steel. However, in general, as with the steel type and temperature investigation, the hole size and plate thickness investigation showed that punched hole specimens had a noticeable reduction in strength ratio compared to drilled hole specimens. The difference was again larger in A36 specimens than in A572 Grade 50 specimens. Within each steel grade, there was a slight increase in average strength ratio as the plate thickness increased. Two of the A572 Grade 50 punched hole specimens had strength ratios less than 1.0. All of the A36 punched hole specimens in this investigation had strength ratios less than 1.0. The 3/8 in. thick A36 punched specimens exhibited an increase in net section stress with an increase in hole size to thickness ratio. There was no noticeable effect in the other thicknesses and grades of steel used. Elongation decreased as hole size to thickness ratio increased, but this is as expected due to the reduction in net area. Again, there was a noticeable decrease in punched hole elongation compared to drilled hole elongation.

4.1.3 Edge Distance and Edge Preparation Investigation

The results of the edge distance and edge preparation investigation are shown in Table 4.4 and Table 4.5. The larger edge distances used represented a 1/8 in. increase over the values specified by AASHTO and AISC. Each specimen was fabricated with a pair of 15/16 in. diameter holes. The 'Flame Cut–Shear Match' specimens had edges flame cut from a sheared edge specimen. This meant that 'Flame Cut–Standard' and 'Flame Cut–Larger' were from the same heat of steel, while 'Flame Cut–Shear Match' and 'Sheared–Standard' were from a different heat of steel. The standard flame-cut specimen results are listed for reference.

Table 4.4: Edge Distance and Edge Prep. Results—½ in. A36 Plate

Method	Edge Prep.	Edge Spacing (in.)	Net Section Stress (ksi)	Strength Ratio	Elongation (in.)
Punched	Flame Cut	Standard (1-1/8)	63.7	0.91	0.35
		Larger (1-1/4)	65.6	0.94	0.39
		Standard SM (1-1/8)	62.8	1.01	1.07
	Sheared	Standard (1-1/2)	62.6	1.01	1.16
Drilled	Flame Cut	Standard (1-1/8)	74.7	1.07	1.47
		Larger (1-1/4)	72.5	1.04	1.38
		Standard SM (1-1/8)	68.4	1.10	1.49
	Sheared	Standard (1-1/2)	67.7	1.09	1.61

Note: SM = Shear Match

Table 4.5: Edge Distance and Edge Prep. Results—½ in. A572 Grade 50 Plate

Method	Edge Prep.	Edge Spacing	Net Section Stress (ksi)	Strength Ratio	Elongation (in.)
Punched	Flame Cut	Standard (1-1/8)	78.1	1.03	0.59
		Larger (1-1/4)	78.8	1.04	0.48
		Standard SM (1-1/8)	88.3	1.12	0.33
	Sheared	*Standard (1-1/2)*	88.1	1.11	0.35
Drilled	Flame Cut	Standard (1-1/8)	82.4	1.09	1.10
		Larger (1-1/4)	80.2	1.06	0.52
		Standard SM (1-1/8)	89.3	1.13	0.43
	Sheared	*Standard (1-1/2)*	86.6	1.09	0.38

Note: SM = Shear Match

This investigation again showed that punched hole specimens had a lower strength ratio compared to the equivalent drilled hole specimen, with the exception of the A572 Grade 50 'Sheared' specimens. The difference was again larger in A36 material than in A572 Grade 50 material. The sheared plate results behaved comparably to the ‘Flame Cut–Shear Match’ specimen, which were from the same heat of steel as the ‘Sheared–Standard’ specimens. Overall, the investigation results showed that there was little correlation between edge distance and strength ratio. However, the test results showed a slight decrease in elongation as edge distance increased, with a large decrease in the drilled A572 Grade 50 specimens. The results may change if edge distances below specification minimums are used.

4.1.4 Punch and Die Clearance Investigation

The results of the punch and die clearance investigation are shown in Table 4.6 and Table 4.7. The larger clearance values are a 1/16 in. increase over the manufacturer recommended amounts, discussed in Chapter 2 and Chapter 3. Each specimen was fabricated with a pair of 15/16 in. diameter holes. The specimens with holes punched with the recommended die size are listed again for reference.

Table 4.6: Punch and Die Clearance Results—½ in. A36 Plate

Method	Hole Size (in.)	Clearance (in.)	Net Section Stress (ksi)	Strength Ratio	Elongation (in.)
Punched	11/16	Recommended (1/32)	61.3	0.88	0.95
		Larger (3/32)	59.9	0.86	0.43
	15/16	Recommended (1/32)	63.7	0.91	0.35
		Larger (3/32)	66.1	0.95	0.36

Table 4.7: Punch and Die Clearance Results—½ in. A572 Grade 50 Plate

Method	Hole Size (in.)	Clearance (in.)	Net Section Stress (ksi)	Strength Ratio	Elongation (in.)
Punched	11/16	Recommended (1/32)	75.9	1.01	1.14
		Larger (3/32)	77.8	1.03	1.14
	15/16	Recommended (1/32)	78.1	1.03	0.59
		Larger (3/32)	77.5	1.03	0.45

The punch and die clearance investigation showed no significant relationship between die clearance and strength ratio. The test results showed a slight decrease in elongation as die clearance increased. The average strength ratio for both clearance values was lower for A36 plate specimens compared to the A572 Grade 50 specimens.

As mentioned in Chapter 1 and Chapter 2, the rule of thumb on the use of punched holes is that the diameter of the punched hole should not be less than the thickness of the material. A series of plate tension tests were performed during this project to investigate the effect of violating this rule of thumb on the material being punched. The results are shown in Table 4.8. The specimens consisted of 1 in. thick A572 Grade 50 material punched with a pair of 11/16 in. diameter holes. Multiple die clearance values were used—1/32 in., 1/16 in., and 1/8 in.—and compared to a specimen with drilled holes. The recommended die clearance for 1 in. thick plate was either 3/32 in. or 1/8 in. Results are presented comparing the punched hole specimen maximum loads to the drilled hole specimen maximum load.

Table 4.8: Punch and Die Clearance Results—1 in. A572 Grade 50 Plate

Method	Hole Size (in.)	Clearance (in.)	Punch Force (k)	Ultimate Load (k)	Punched Load / Drilled Load	Elongation (in.)
Punched	11/16	Smaller 1/32	117.5	311.5	0.97	1.37
		Smaller 1/16	104.0	288.4	0.89	1.56
		Recom. 1/8	103.0	286.3	0.89	1.51
Drilled	11/16	--		322.4	--	2.47

Similar behavior was observed in the punched hole plate specimens regardless of die clearance, with the exception of the small clearance amount of 1/32 in. However, all punched hole specimens still had lower average strength ratios and elongation amounts compared to the drilled hole specimen. The differences between punched and drilled holes were of a similar magnitude as the other plate tension tests. There was also a relatively large increase in the force required to punch the hole with a smaller die clearance, corresponding to an increase in the work required. Therefore, violating the rule of thumb showed little effect on the material being punched over the normal effects of punching holes, but damage to the punch itself is likely.

4.1.5 Punching Operation Investigation

The results of the punching operation investigation are shown in Table 4.9. Each specimen was made with a pair of 15/16 in. diameter holes. Holes were punched by a local fabricator and compared with equivalent punched hole specimens made at the FSEL, listed again for reference. Several ½ in. specimens made from both locations were tested at a cold temperature of -13 +/- 5^{o} F as well.

Table 4.9: Punching Operation Results—½ in. A572 Grade 50 Plate

Method	Location	Temperature	Thick. (in.)	Net Section Stress (ksi)	Strength Ratio	Elongation (in.)
Punched	FSEL	Room	3/8	75.9	0.97	0.47
			1/2	78.1	1.03	0.59
			3/4	87.5	1.05	0.56
		Cold	1/2	81.4	1.08	0.53
	Fabricator Punched	Room	3/8	80.1	1.02	0.66
			1/2	79.5	1.05	0.45
			3/4	88.4	1.06	0.57
		Cold	1/2	81.6	1.08	0.47

Note: Strength Ratio Based Off Room Temp f_u

The results of this investigation showed that, on average, specimens with holes punched at FSEL behaved similarly to specimens with holes punched at a fabrication shop.

4.1.6 Cold Temperature Plate Thickness Investigation

The results of the cold temperature plate thickness investigation are shown in Table 4.10 and Table 4.11. The various thicknesses and grades of steel were each fabricated to the standard specimen configuration, with a pair of 15/16 in. diameter holes. The results of the room temperature tensile tests are presented again for reference. The cold temperature was -13 +/- 5^{o} F.

Table 4.10: Cold Temperature Plate Thickness Results—A36 Plate

Metho	Thick. (in.)	Cold Net Section Stress (ksi)	Cold Strength Ratio	Cold Elongation (in.)	Room Temp. Strength Ratio	Room Temp. Elongation (in.)
Punched	3/8	71.9	1.01	0.41	0.98	0.40
	1/2	66.7	0.95	0.38	0.91	0.35
	3/4	67.9	1.03	1.17	0.96	0.58
Drilled	3/8	78.6	1.11	1.45	1.06	1.35
	1/2	79.7	1.14	1.86	1.07	1.47
	3/4	78.0	1.19	1.98	1.11	1.77

Note: Strength Ratio Based Off Room Temp f_u

Table 4.11: Cold Temperature Plate Thickness Results—A572 Grade 50 Plate

Method	Thick. (in.)	Cold Net Section Stress (ksi)	Cold Strength Ratio	Cold Elongation (in.)	Room Temp. Strength Ratio	Room Temp. Elongation (in.)
Punched	3/8	82.9	1.06	0.50	0.97	0.47
	1/2	81.4	1.08	0.53	1.03	0.59
	3/4	90.2	1.08	0.58	1.05	0.56
Drilled	3/8	86.0	1.10	1.16	1.06	1.06
	1/2	88.3	1.17	1.34	1.09	1.10
	3/4	94.5	1.13	1.10	1.08	1.11

Note: Strength Ratio Based Off Room Temp f_u

The results of this investigation again showed that punched holes had lower strength ratios compared to the drilled hole equivalent. The difference in strength ratio was again larger in A36 material. The cold temperature tests showed higher strength ratios for both drilled and punched holes compared to the equivalent room temperature tests, though the ultimate strengths were compared to the room temperature coupon strengths. The cold temperature elongations were similar or slightly larger than the room temperature elongations.

4.1.7 Galvanizing Investigation

The results of the galvanizing investigation are shown in Table 4.12 and Table 4.13. The specimens were fabricated in 3/8 in. thick plate with a pair of 13/16 in. diameter holes with the recommended edge distances and die clearance values. The non-galvanized replicate specimens are presented again for comparison.

Table 4.12: Galvanizing Results—3/8 in. A36 Plate

Method	Plate Prep.	Net Section Stress (ksi)	Strength Ratio	Elongation (in.)
Punched	As Received	64.9	0.92	0.37
	Galvanized	66.2	0.93	0.39
Drilled	As Received	75.5	1.06	1.57
	Galvanized	76.1	1.07	1.37

Table 4.13: Galvanizing Results—3/8 in. A572 Grade 50 Plate

Method	Plate Prep.	Net Section Stress (ksi)	Strength Ratio	Elongation (in.)
Punched	As Received	80.0	1.02	0.94
	Galvanized	79.9	1.02	0.43
Drilled	As Received	81.9	1.04	1.24
	Galvanized	83.8	1.07	1.13

This investigation continued to the show that punched hole specimens had lower strength ratios than the drilled hole equivalent, with the difference larger in A36 steel than A572 Grade 50 steel. The test results showed little noticeable effect on strength ratio due to the galvanizing process, though several specimens showed lower elongation values.

4.1.8 Sub-Punch and Reaming Investigation

The results of the sub-punch and reaming investigation are shown in Table 4.14 and Table 4.15. Each specimen had two holes sub-punched by the indicated amount and subsequently reamed to a nominal diameter of 15/16 in. The final reamed holes were measured to calculate net section stress, using the average diameter at the top and bottom of the hole. The results for the specimens drilled or punched full-size are shown for comparison.

Table 4.14: Sub-Punch and Reaming Results—½ in. A36 Plate

Method	Punch Diameter and Amount of Reaming (in.)	Net Section Stress (ksi)	Strength Ratio	Elongation (in.)
Drilled	-	74.7	1.07	1.47
Reamed	3/4 and 3/16	76.6	1.10	1.45
	13/16 and 2/16	76.9	1.10	1.49
	7/8 and 1/16	78.2	1.12	1.52
Punched	-	63.7	0.91	0.35

Table 4.15: Sub-Punch and Reaming Results—½ in. A572 Grade 50 Plate

Method	Punch Diameter and Amount of Reaming (in.)	Net Section Stress (ksi)	Strength Ratio	Elongation (in.)
Drilled	-	82.4	1.09	1.10
Reamed	3/4 and 3/16	86.3	1.14	1.04
	13/16 and 2/16	85.6	1.13	1.03
	7/8 and 1/16	86.1	1.14	1.07
Punched	-	78.1	1.03	0.59

The results of this investigation showed that the performance of the sub-punched and reamed hole specimens were equal to or greater than the drilled hole specimens. The amount of reaming was found to have little to no effect on strength ratio or elongation values.

4.2 Plate Tension Test Summary and Analysis

In total, 51 drilled hole specimens, 61 punched hole specimens, and 6 sub-punched and reamed plate specimens were tested in tension. Of these specimens, Lubitz (2005) tested 40 of the drilled hole specimens, 51 of the punched hole specimens, and the 6 sub-punched and reamed specimens. The remaining specimens were the new tests conducted during this phase of the project. The test data from each investigation reported in Section 4.1 will be compiled and presented in this section.

From the various investigations performed on plate specimens, a consistent trend appeared in the form of punched hole specimens having a lower strength ratio and lower elongation at ultimate load compared to equivalent drilled hole specimens. The differences were larger in A36 steel than A572 Grade 50 steel. Sub-punching and reaming a hole produced behavior similar to a drilled hole. The remaining variables that were investigated, die clearance, punching operation, edge distance, edge fabrication method, hole size, plate thickness, and galvanizing, did not show a significant influence on the behavior of punched hole specimens.

The effect of steel grade on the strength ratio of the plate tension test specimens is shown in Figure 4.5 and Figure 4.6. Figure 4.5 presents the A36 specimens, while Figure 4.6 presents the A572 Grade 50, High Carbon Grade 55, A572 Grade 50 Heat Z, and A588 specimens. In these figures, the 45-degree line represents the case when the experimental load and predicted loads are equal. The predicted loads were determined using the AASHTO and AISC tensile strength equations presented in Chapter 1, with resistance factors taken as 1.0 and the as-fabricated net areas used. For the plate tension tests, the relevant equations were net section fracture strength and gross section yielding, identical for AASHTO and AISC. Therefore, data points above this line represented specimens that exceeded predicted loads, while data points below this line failed prior to reaching their predicted loads. Points above the line are considered conservative, while points below the line are unconservative. Specimens with a strength ratio greater than 1.0 are above the 45-degree line.

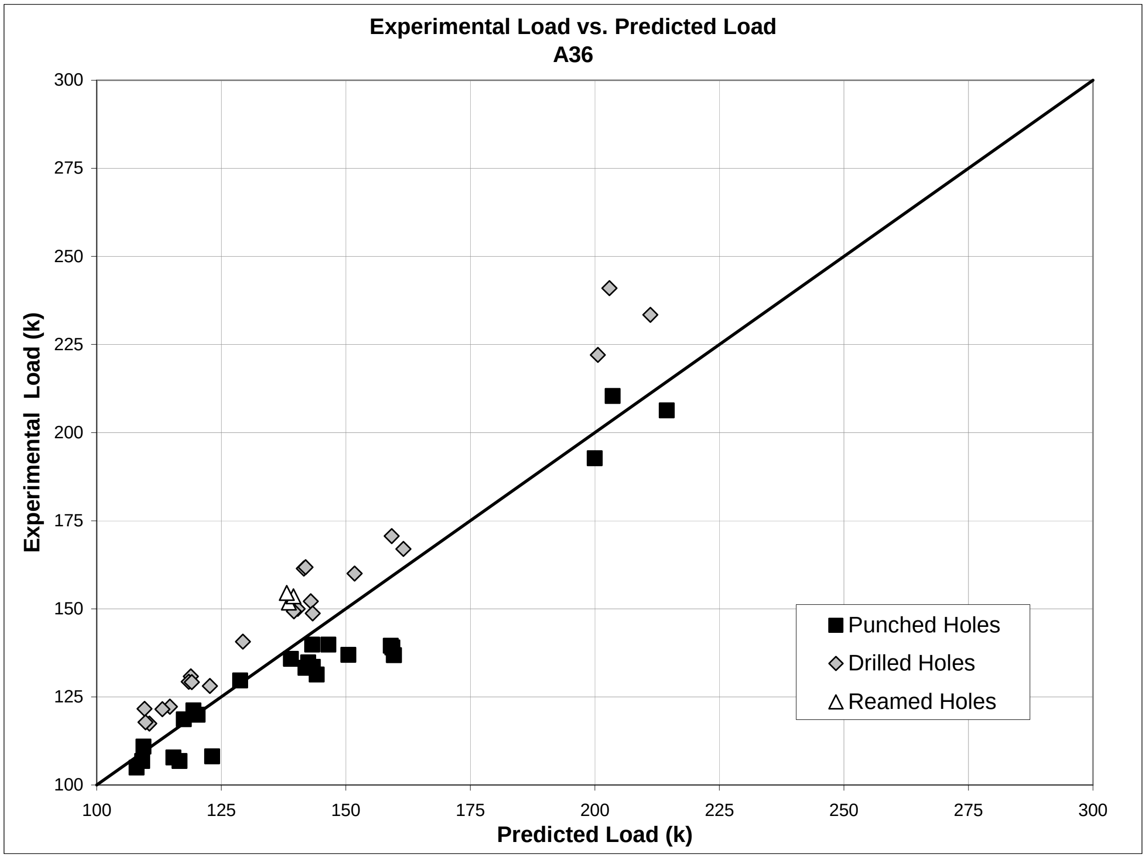

Figure 4.5: Plate Tension Test Data Comparison—A36 Steel

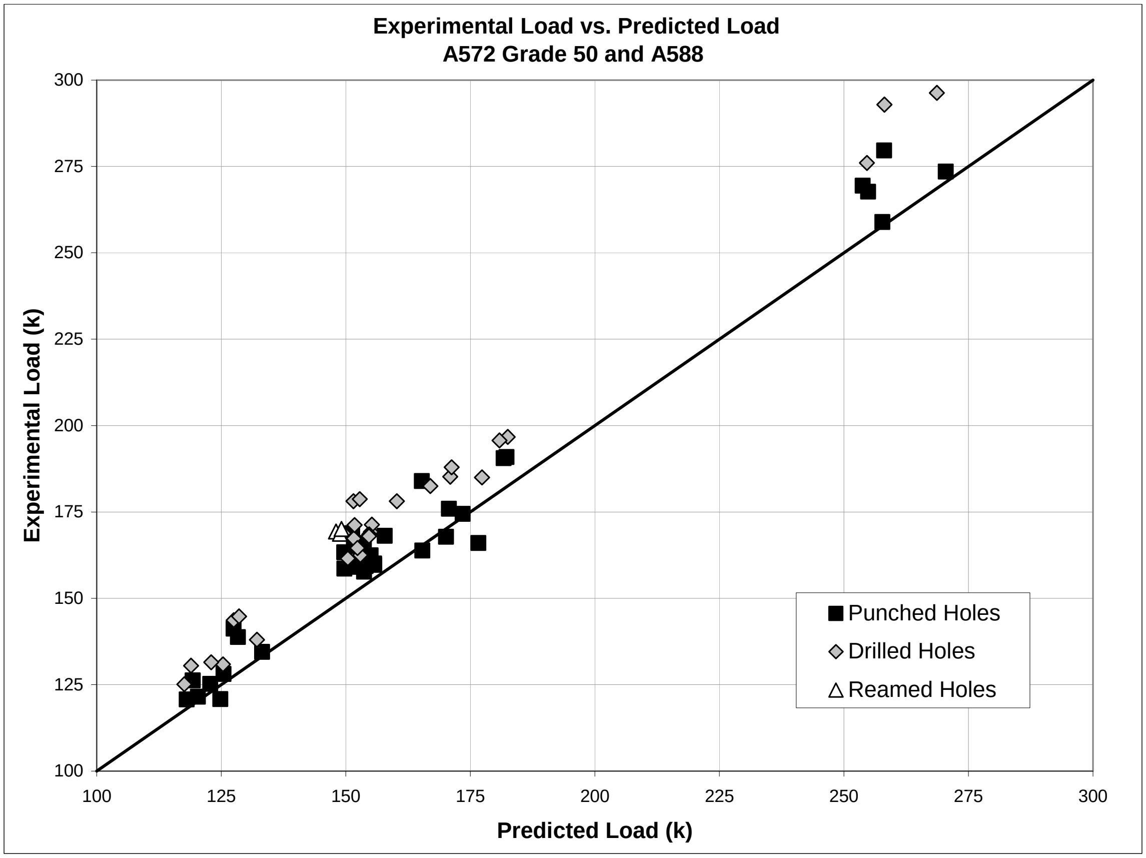

Figure 4.6: Plate Tension Test Data Comparison—A572 Grade 50 and A588 Steel

All of the drilled hole specimens in both grades of steel were above the line, with a minimum strength ratio of 1.03. All of the reamed hole specimens were also above the 45-degree line, with a minimum strength ratio of 1.10. However, many of the punched hole specimens in A36 steel were below the 45-degree line, with a minimum strength ratio of 0.86. The minimum A572 Grade 50 or A588 strength ratio was 0.94. In total, 38% of the punched hole specimens were below the 45-degree line with strength ratios less than 1.0.

The average strength ratio for each hole type is presented in Table 4.16. Again, average strength ratio was the experimental ultimate strength divided by the predicted design strength. The standard deviation of each hole type is also presented. The standard deviation was largest for the punched hole specimens, indicating the larger variability in results caused by the punched holes. This table shows that, on average, there was an approximate 8% reduction in the strength ratio for punched holes. However, due to the large standard deviation for punched hole, this difference was often larger.

Table 4.16: Average Strength Ratio for Hole Fabrication Method

Fabrication Method	# of Specimens	Average Strength Ratio	Standard Deviation
Drilled	51	1.09	0.035
Punched	61	1.01	0.062
Reamed	6	1.12	0.021

From the various investigations, there were 50 replicate punched and drilled hole specimens. That is, there were specimens that had an identical configuration with either punched holes or drilled holes. Items such as steel grade, plate thickness, hole size, and edge distance were identical between the replicates. These replicate specimens allowed a direct comparison between punched hole performance and drilled hole performance. A histogram showing how the punched hole specimen strength ratio compared to the drilled hole specimen strength ratio is shown in Figure 4.7. In this figure, if a punched hole specimen and a drilled hole specimen behaved identically, the ratio would be 1.0. This figure again indicated that the difference between strength ratios of punched and drilled hole specimens was larger in A36 steel than in A572 Grade 50 steel.

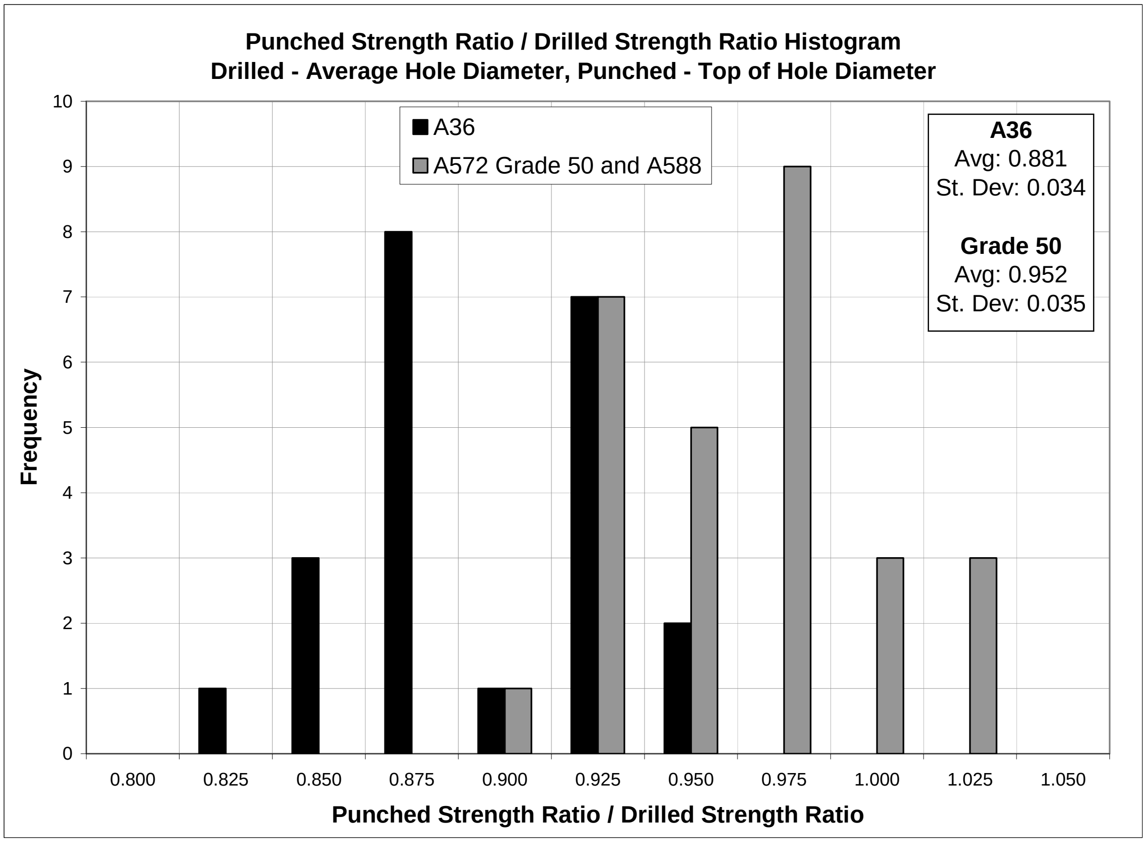

Figure 4.7: Punched Strength Ratio / Drilled Strength Ratio Histogram

The compiled elongation values at ultimate load for the plate tension tests are presented in Figure 4.8. As indicated by the histogram in Figure 4.8, punched holes generally showed a lower elongation value at ultimate load compared to drilled holes and sub-punched and reamed holes.

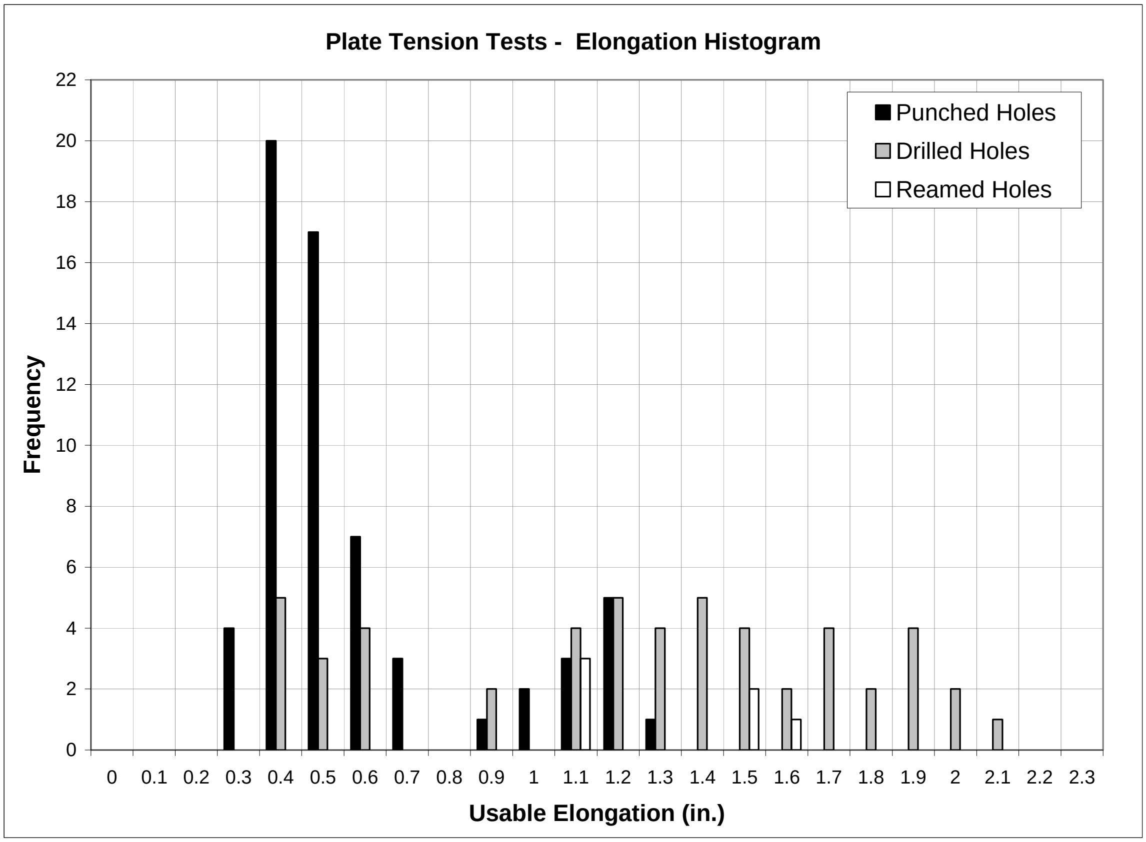

Figure 4.8: Plate Specimen Elongation Histogram

Average values of elongation at ultimate load for each hole type are shown in Table 4.17. These average values again show that punched holes had a lower ductility than drilled holes. However, each hole type did have a large standard deviation, which can also be seen in the histogram shown in Figure 4.8. These values did not include the reduced net area plate tension tests.

Table 4.17: Average Elongation for Hole Fabrication Method

Fabrication Method	# of Specimens	Average Elongation (in.)	Standard Deviation
Drilled	45	1.30	0.445
Punched	55	0.58	0.278
Reamed	6	1.26	0.243

The average elongation values for the specimens with a reduced net area are shown in Table 4.18. The average elongations are lower than those shown in Table 4.17, but this is expected with the reduced net area. However, the similar trend of punched hole specimens having lower elongations was still present.

Table 4.18: Average Elongation—Reduced Net Area

Fabrication Method	# of Specimens	Average Elongation (in.)	Standard Deviation
Drilled - Reduced Net Area	6	0.38	0.046
Punched - Reduced Net Area	6	0.30	0.029

A similar comparison between the 50 replicate punched hole and drilled hole specimens was also made for the useable elongation values at ultimate load. The histogram shown in Figure 4.9 represents a punched hole specimen's elongation divided by the replicate drilled hole specimen's elongation. Here, a ratio of 1.0 would again represent a punched hole specimen that behaved identically to a drilled hole specimen. The difference between punched hole displacement and drilled hole displacement was larger in A36 steel compared to A572 Grade 50 steel.

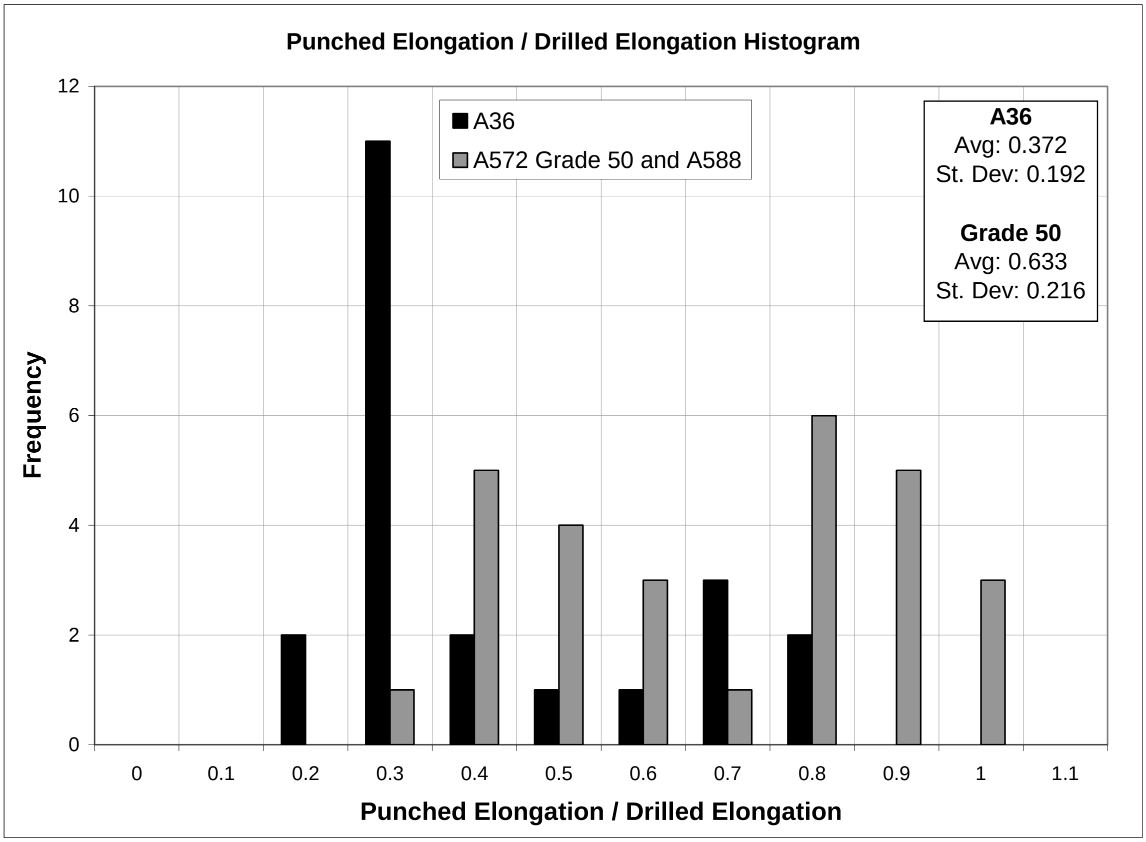

Figure 4.9: Punched Elongation / Drilled Elongation Histogram

As mentioned in Chapter 1, both AASHTO and AISC require a 1/16 in. addition to the nominal hole diameter when calculating net area. The data presented previously did not use this addition. The addition to the hole diameter will decrease the net area and decrease the predicted ultimate load. Taking the experimental ultimate load divided by this new and lower predicted load will increase the strength ratio values listed in the previous tables.

From the experimental results, the strength ratio for drilled hole specimens never fell below 1.0. Therefore, the hole size addition was determined to be unnecessary for drilled hole specimens. However, the punched hole experimental results might benefit from a hole size additional, thus increasing the strength ratio. The effect on strength ratio of punched hole specimens from two different additions to the hole diameter are shown in Table 4.19. The first hole diameter increase, 1/16 in., corresponds to the requirements of both AASHTO and AISC. This adjustment is approximately a 9.1% increase in hole diameter for a 11/16 in. hole. For a 13/16 in. diameter hole, this 1/16 in. addition is a 7.7% increase, and for a 15/16 in. diameter hole, the addition decreases to 6.7%. To determine if a consistent hole size adjustment is beneficial, a 10% increase in hole diameter was also evaluated and is shown in Table 4.19. Strength ratios above 1.0 indicate a conservative estimate of the ultimate load of the specimen.

Table 4.19: Effect of Increasing Punched Hole Size on Strength Ratio

			% With Strength Ratio > 1.0		
Steel Grade	Hole Size	No. of Tests	None	1/16"	10%
A36	11/16"	4	0.0	0.0	0.0
	13/16"	4	75.0	100.0	100.0
	15/16"	14	28.6	57.1	64.3
A572 Grade 50	11/16"	4	75.0	100.0	100.0
	13/16"	4	75.0	100.0	100.0
	15/16"	20	95.0	95.0	100.0
		Average:	62.3	73.8	77.0

The effect of the hole diameter adjustments on the minimum strength ratio of punched specimens from the test data is also shown in Table 4.20.

Table 4.20: Effect of Increasing Punched Hole Size on Minimum Strength Ratio

Steel Grade	Hole Size (in.)	None	1/16 in.	10%
A36	11/16	0.86	0.88	0.88
	13/16	0.91	0.94	0.94
	15/16	0.91	0.94	0.95
A572 Gr. 50	11/16	0.99	1.01	1.02
	13/16	0.99	1.02	1.03
	15/16	0.94	0.97	0.98

With the exception of the A36 specimens, the 1/16 in. or 10% addition to hole diameter increased the percentage of punched hole specimens that had experimental loads greater than the predicted loads. Using a 10% addition increased the number of specimens with strength ratios greater than 1.0 more than the 1/16 in. addition. The 10% addition slightly increased the minimum strength ratio in both grades of steel. To get all punched hole data points above a strength ratio of 1.0, the hole size adjustment required is 41.5% using an average hole diameter. Using just the diameter of the top of the hole, the hole size adjustment required is 48.1%. This emphasizes that the hole size adjustment must be large to account for the few low strength punched specimens that were not covered by the 10% increase. Bartels et al. (2002) came to a similar conclusion in that a 5/16 in. addition to hole diameter was found to reduce net section capacity by only 7%.

From the results of the experiments, drilled hole specimens did not require any addition to hole diameter, as all strength ratio values were above 1.0. A recommendation could be made to change the 1/16 in. addition to hole diameter to a 10% increase in hole diameter for punched holes, as the 10% increase is a more consistent value for various hole diameters. To further compensate for the possible use of punched holes, an addition of larger than 10% could also be recommended. The different hole size adjustments will also be used to analyze data from the connection tests performed during this project, discussed in Section 4.5.

4.3 PLATE FATIGUE TEST RESULTS

Of the original 70 plate fatigue tests proposed in Section 3.2, 33 were completed. Due to time and equipment constraints, the remaining specimens could not be tested. However, the specimens that were tested in fatigue provided a fairly clear indication into the performance of punched holes, drilled holes, and sub-punched and reamed holes in plate material. Each specimen was made of 6 in. wide plate with a pair of holes, as indicated. The thickness of the plate depended on the test being performed. Each plate specimen was tested at a stress range of 25 ksi. The minimum stress was 3 ksi. The stress ranges were based off the net section, which was calculated from the measured dimensions of each specimen. The cycle counts for the fatigue specimens presented were the cycle count at failure or the cycle count when the test was stopped if no failure occurred above 2 million cycles. The specimens that did not fail were considered runout specimens.

4.3.1 Steel Type Investigation

The results of the steel type investigation are shown in Table 4.21. The specimens were ½ in. thick plates of the indicated steel types, with a pair of 15/16 in. diameter holes fabricated with the indicated method. The edge distance was the recommended value of 1-1/8 in. The proposed tests that were not completed are listed as N/T, not tested.

Table 4.21: Steel Type Fatigue Results

	Hole Fabrication Method					
Steel Type	Punched	Fabricator Punched	Worn Drill Bit	New Drill Bit	Sub-Punched and Reamed	2 Sets of Drilled Holes
A36	531,961	--	526,598	1,121,119	2,708,672**	--
	426,238	--	536,836	--	1,041,915	--
	497,182	--	513,820	--	708,133	--
A572 Grade 50	550,643	481,571	684,630	--	--	--
A572 Grade 50 Heat Z	400,608	--	N/T	2,092,372**	2,192,053**	944,892
	N/T	--	--	N/T	N/T	--
	--	--	--	--	N/T	--
A588	414,480	--	--	3,920,364**	--	710,415
	431,073	--	--	2,088,164**	--	--

Note: N/T = Specimen Not Tested, ** Runout Specimen

From the results of this investigation, it was discovered that holes drilled with a worn drill bit had a remarkably lower fatigue life compared to holes drilled with a new drill bit. The holes drilled with a new drill bit had a similar fatigue life to sub-punched and reamed holes. Two million cycles was chosen to stop the tests to save time. Specimens that did not fail are indicated as runout tests. At the 25 ksi net stress ranged used, 2 million cycles was beyond the Category B design curve. The specimens with holes drilled with a worn drill bit and the punched hole specimens had fatigue lives well below a Category B design curve, 770,000 cycles at a stress range of 25 ksi.

Also presented in this investigation were specimens with two sets of drilled holes. On the same specimen, one pair of holes was drilled with a worn drill bit, while the other pair of holes was drilled with a new drill bit. This configuration was used to apply identical stress ranges to the holes drilled with different methods on the same specimen. From the test results, the specimens formed fatigue cracks at the location of the holes drilled with the worn drill bit, while the area near the holes drilled with a new drill bit remained uncracked. This was true for both grades of steel used.

The amount of reaming appeared to have an effect on the fatigue performance of the sub-punched and reamed specimens. The A36 runout specimen, 2,708,672+ cycles, was reamed 3/16 in. The other two specimens were reamed 1/8 in. and 1/16 in. for the cycle counts of 1,041,915 and 708,133 respectively. However, the A572 Grade 50 specimen, also a runout specimen stopped at 2,192,053+ cycles, was reamed only 1/16 in. From these results, it appeared that the amount of reaming increased the fatigue life, but the result was not consistent.

The cycle counts at failure between hole types did not show any significant variance between grades of steel. This indicated that steel grade was not an important parameter in fatigue tests results. For each grade of steel, punched hole specimens and specimens with holes drilled with a worn bit had much lower fatigue lives than specimens with holes drilled with a new bit. The results of this investigation and the other fatigue investigations will be summarized in Section 4.4.

Typical failed specimens from the plate fatigue tests are shown in Figure 4.10 through Figure 4.14. The first crack usually initiated at the edge of the hole closest to the edge of the plate where the stress concentration factor was the largest, Point A in Figure 4.10. A crack then propagated towards the edge of the plate. During the propagation of the first crack or after the first crack reached the edge of the plate, a second crack would initiate at the other edge of the hole, Point B, and propagate towards the middle of the plate, as shown in Figure 4.10. The tests were stopped when approximately 50% of the cross-section was cracked. The failure point was kept relatively constant between each specimen. When each test was stopped, the specimen was pulled apart in tension to observe the failure cross-section. Therefore, the remainder of the cross-section that was not cracked in fatigue had the appearance of a tensile failure surface.

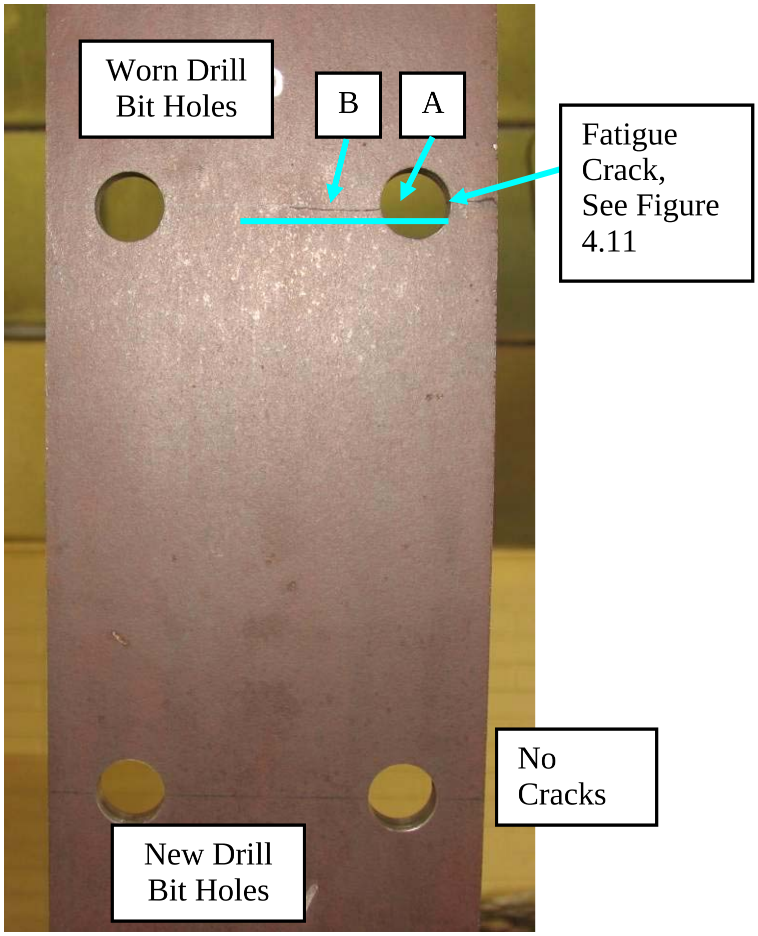

Figure 4.10: A588—2 Sets of Drilled Holes Specimen at Failure, N=710,415

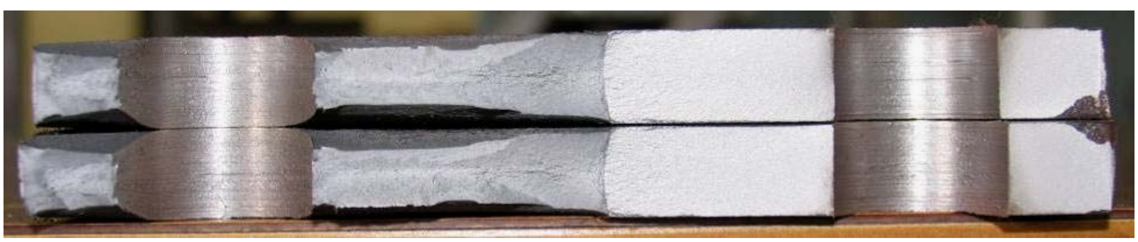

Figure 4.11: Cross-Section of A588—2 Sets of Drilled Holes Specimen at Failure; Worn Drill Bit Hole Line, N=710,415

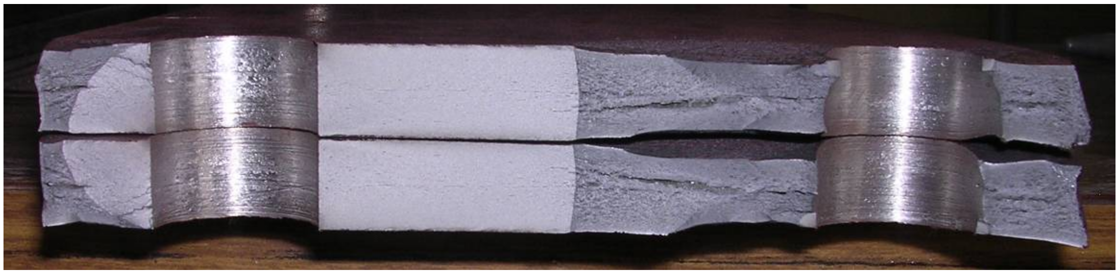

Figure 4.12: Cross-Section of A572 Grade 50 Heat Z—2 Sets of Drilled Holes Specimen at Failure; Worn Drill Bit Hole Line, N=944,892

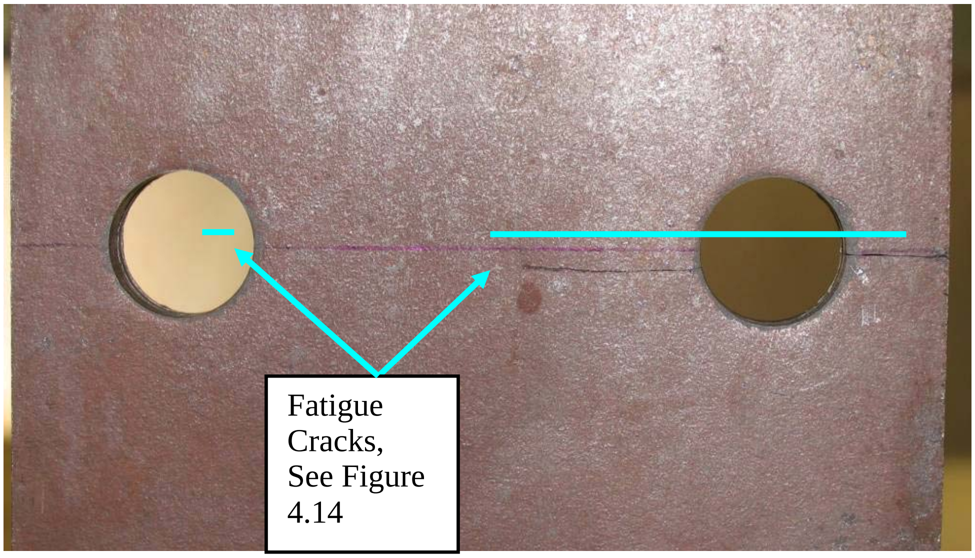

Figure 4.13: A588—Punched Hole Specimen at Failure, N=414,480

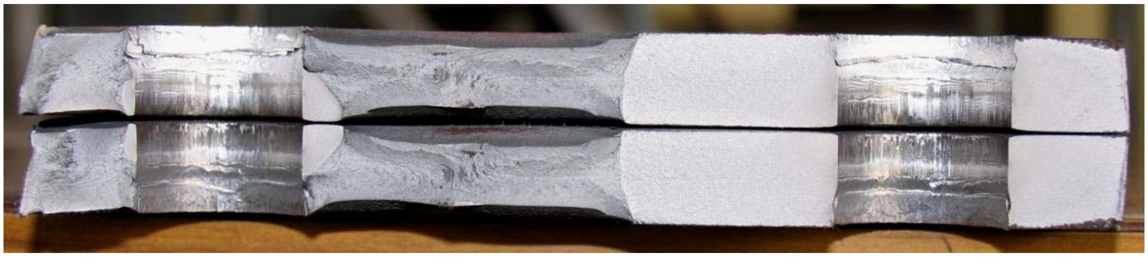

Figure 4.14: Cross-Section of A588—Punched Hole Specimen at Failure, N=414,480

4.3.2 Hole Size and Plate Thickness Investigation

The results of the hole size and plate thickness investigation are shown in Table 4.22 and Table 4.23. The type of steel used is indicated in each table. The specimens varied in plate thickness and hole diameter. The holes were punched with a normal size die or drilled with a worn drill bit. The edge distances were the recommended values for each hole size. As noted in the tables, only ½ and 1 in. thick plate material was tested due to time and equipment constraints.

The stress range was kept constant at 25 ksi on the measured net section, with a minimum stress of 3 ksi. The 1 inch plates with a 11/16 in. hole violate the adage that holes smaller than the plate thickness should not be punched.

Table 4.22: Hole Size and Plate Thickness Fatigue Results, A36 Steel

	Hole Size (in.)			
	11/16		13/16	
Plate Thick. (in.)	Punched	Drilled	Punched	Drilled
1/2	582,286	768,176	662,744	777,653
1*	2,100,640** 2,004,129**	759,178	--	--

Note: * Punched holes with 3/32 and 1/32 in. die clearance
** Runout Specimen

Table 4.23: Hole Size and Plate Thickness Fatigue Results, A572 Grade 50 Steel

	Hole Size (in.)			
	11/16		13/16	
Plate Thick. (in.)	Punched	Drilled	Punched	Drilled
1/2	2,059,758**	--	508,491	--

Note: ** Runout Specimen

From the limited results of the hole size and plate thickness investigation, hole size appeared to have little effect on the fatigue life of plate holes. However, the 11/16 in. punched holes in A572 Grade 50 steel was a runout specimen at over 2 million cycles. The other punched hole specimens failed at similar cycle counts to the 15/16 in. punched hole specimens listed previously. The drilled hole specimens failed at cycle counts slightly higher than the 15/16 in. diameter drilled hole specimens drilled with a worn drill bit.

The 1 in. plate results are surprising since the punched holes specimens had longer fatigue than the plates with drilled holes. The results are surprising since these specimens were specifically tested to violate the limit that the hole size exceed the plate thickness. One possible explanation for their enhanced fatigue performance may be the residual compressive stresses around the hole created by punching operation.

Figure 4.15 shows the bulge at the edge of the plate caused by the punching of the hole. The plastic deformed material adjacent to the hole would create a residual compressive stresses after punching which maybe the cause of the enhanced fatigue performance.

Figure 4.15: Example of bulging from hole punching

4.3.3 Edge Distance and Edge Preparation Investigation

The results of the edge distance and edge preparation investigation are shown in Table 4.24. The specimens were made from ½ in. thick steel with a pair of 15/16 in. diameter holes. The four proposed specimens to investigate edge preparation (flame cut versus sheared) were not tested. The edge distances used were the recommended amounts specified by AASHTO and AISC, with the larger edge distance specimens having a 1/8 in. increase over the recommended amounts. The holes were punched with a normal size die or drilled with a worn drill bit. The stress range was 25 ksi on the measured net section. The average fatigue lives of specimens with a normal edge distance are given for comparison.

Table 4.24: Edge Distance and Edge Preparation Fatigue Results

	Larger Edge Distance		Normal Edge Distance, Average Results	
Steel Type	Punched	Drilled	Punched	Drilled
A36	690,426	904,274	485,127	525,751
A572 Gr. 50 Heat Z	N/T	N/T	400,608	N/T

Note: N/T = Specimen Not Tested

The specimens with a larger edge distance had slightly improved fatigue lives over the specimens with normal edge distance. The specimen with holes made from a worn drill bit in this investigation still failed well below the specimens made with a new drill bit presented previously. The specimens with a large edge distance did have a slightly lower stress concentration factor, K, than the normal edge distance values, 3.29 versus 3.52. However, while the punched hole specimen also has a slightly increased cycle count, there was not a significant difference between the two edge distances. As noted, the edge preparation specimens could not be tested.

4.3.4 Punch and Die Clearance Investigation

The results of the punch and die clearance investigation are shown in Table 4.25. The larger die size was a 1/16 in. increase over the manufacturer recommended punch and die clearance. The specimens were made from ½ in. thick plates of the steel type indicated. The edge distances were the recommended values for the hole size used. The stress range used was 25 ksi on the measured net section. The average fatigue lives of the punched specimens using the normal die size (23/32 in. and 31/32 in.) are presented for comparison.

Table 4.25: Punch and Die Clearance Fatigue Results

	Small Hole		Larger Hole	
	Hole Size (Die Size) (in.)	Hole Size (Die Size) (in.)	Hole Size (Die Size) (in.)	Hole Size (Die Size) (in.)
Steel Type	11/16 (25/32)	11/16 (23/32)	15/16 (33/32)	15/16 (31/32)
A36	755,750	582,286	461,497	485,127
A572 Gr. 50 Heat Z	N/T	N/T	323,903	400,608

Note: N/T = Specimen Not Tested

The use of a larger die size did not show a significant influence on the fatigue life of the punched hole specimens.

4.3.5 Galvanizing Investigation

Of the six proposed fatigue tests on galvanized specimens, none were completed. Other research, as presented in Chapter 2, has shown that the galvanizing process will further reduce the fatigue life of a specimen with punched holes. Huhn (2004) gave the following example:

> "This means that a non-galvanized structural member with a drilled hole has the highest fatigue resistance, for example 2M (2 million) cycles at a constant stress range of $\Delta\sigma$ = 80 N/mm^2 (11.6 ksi). If the member has a punched hole or is galvanized, the influence is nearly the same; the fatigue life decreases with a ratio of 2.0. Now the fatigue failure for a stress range $\Delta\sigma$ of 80 N/mm^2 (11.6 ksi) is at 1M cycles. If the member is both punched and galvanized there is an additional effect and the number of load cycles decreases to 500,000."

The geometry of the galvanized specimens fabricated from 3/8 in. plate and galvanized after the holes were formed. The results of the fatigue tests are shown in Table 4.26 and are compared with results from tests of non galvanized ½" thick specimens with the same geometry.

Table 4.26: Galvanized specimens investigation

Steel	Specimen	Galvanized 3/8” plates	½” plates
Grade 50	Drilled	737,002	2,059,758**
	Punched 1	206,754	508,491
	Punched 2	183,716	na
A36	Drilled	*	777,653
	Punched 1	170,678	662,744
	Punched 2	122,637	na

* - galvanized drilled A36 specimen failed in tension from an overload before the test
** - run out specimen

The investigation of the galvanized specimens shows that the drilled galvanized specimens have a higher endurance than the punched galvanized specimens. Also, the fatigue life of the galvanized specimens was less than the ungalvanized specimens for both drilled and punched holes. The reduction in fatigue life is in agreement with the investigation made by Valtinat and Huhn (2004). They gave the following example:

> “This means that a non-galvanized structural member with a drilled hole has the highest fatigue resistance, for example 2M (2 million) cycles at a constant stress range of $\Delta\sigma$ = 80 N/mm^2 (11.6 ksi). If the member has a punched hole or is galvanized, the influence is nearly the same; the fatigue life decreases with a ratio of 2.0. Now the fatigue failure for a stress range $\Delta\sigma$ of 80 N/mm^2 (11.6 ksi) is at 1M cycles. If the member is both punched and galvanized there is an additional effect and the number of load cycles decreases to 500,000.”

The reduction in fatigue life due to galvanizing was not as severe in the present study, the reduction was about 3 in fatigue life.

4.3.6 Slotted holes investigation

Two punched–oxy-act holes specimens were tested in fatigue. The results are shown in Table 4.27 and are compared with 13/16” holes, ½” thick plate specimens.

Table 4.27: Slotted holes investigation

Specimen	Fatigue life (cycles)
Drilled A36	777,653
Punched A36	662,744
Punched Gr50	508,491
Slotted 1	415,992
Slotted 2	312,389

Drilled and punched round hole specimens were superior to the slotted holes. The lower endurance of the slotted holes probably is due to the combination of damage from punching plus the residual stress and notches from the flame cutting However, the reduction is not as large as the galvanized specimens.

4.4 PLATE FATIGUE TEST SUMMARY

The summarized results of the plate fatigue test specimens are shown in Figure 4.16. This figure, a stress range versus number of cycles to failure curve (S-N), compares the punched hole specimens with the drilled and sub-punched and reamed specimens as well as the galvanized and 1 in. plate data. The AASHTO fatigue detail Categories B, C, and D are presented as a reference in the figure.

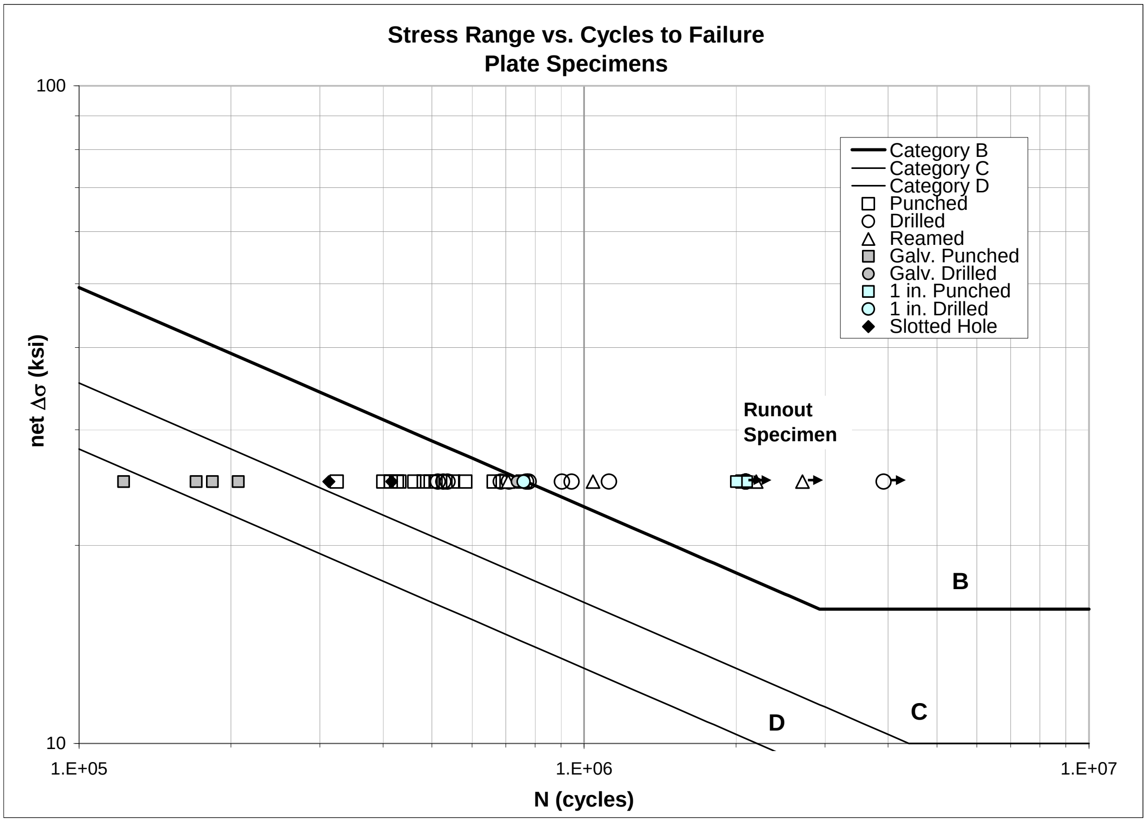

Figure 4.16: Plate Fatigue Test Results

From Figure 4.16, it was evident that fatigue testing produced an amount of scatter in the results that often was equal to differences between test variables. This was especially true for the sub-punched and reamed specimens. Each reamed hole had a very similar appearance but noticeably different fatigue lives, which would indicate that identical specimens can have a large variance in fatigue life. However, hole quality appeared to be the main variable influencing the fatigue life of a plate specimen. Based off the test results, punched hole specimens had a lower fatigue life than drilled specimens and sub-punched and reamed specimens. The sub-punched and reamed specimens had the highest fatigue life, comparable to specimens drilled with a new drill bit. The specimens drilled with a worn drill bit had fatigue lives approximately equal to many of the punched hole specimens. The slotted holes formed by punching the ends and cutting with oxy-act torch had a fatigue strength near the lower bound of the punched holes. The galvanized punched specimens produced much shorter fatigue lives then the other specimens. The galvanized specimen with drilled holes had a fatigue performance comparable to the ungalvanized specimens. Other variables found to not significantly influence the fatigue results were hole size, punch and die clearance, plate thickness relative to hole size, and edge distance.

The plate fatigue test results will be used for comparison with the connection fatigue test results in Section 4.9. Other research data will also be presented.

4.5 CONNECTION TENSION TEST RESULTS

The configurations used for the connection tension tests were presented in Chapter 3. The specimens consisted of two grades of steel, A36 and A572 Grade 50 Heat Z. The average measured thickness and width of each plate type are listed in Table 4.28. The coupon test results of each plate type are listed again for reference. The test plates were either nominally ½ in. thick or ¾ in. thick and 6 in. wide.

Table 4.28: Average Measured Properties of Specimens

	Average Measured Values		Coupon Test Results		
Steel Type	Thickness (in.)	Width (in.)	f_y (ksi)	f_u (ksi)	f_y / f_u
A36 - 1/2 in.	0.49	6.01	47.5	69.9	0.68
A36 - 3/4 in.	0.75	5.97	42.2	65.7	0.64
A572 Grade 50 - 1/2 in.	0.52	6.04	54.0	71.5	0.76
A572 Grade 50 - 3/4 in.	0.75	6.00	60.8	83.3	0.73

Each specimen was fabricated with either one or two 15/16 in. nominal diameter holes. As mentioned previously, the hole diameters were determined by averaging the measured diameter at the top and bottom of the hole. For punched holes that had a large flare at the bottom of the hole, this process was found to benefit punched holes by decreasing the predicted design loads, thus increasing the load ratio (ultimate load divided by predicted design load). To compensate for this, the diameter at the top of the punched hole was used in place of the average top and bottom hole diameter. This change most affected the ¾ in. specimens and the ½ in. specimens with the larger die clearance values. The average hole diameters appear in Table 4.29. A clearance of 1/32 in. is the recommended value for ½ in. thick plate, while the 3/32 in. clearance is excessive. The recommended clearance for ¾ in. thick material is 3/32 in. The as-fabricated hole dimensions for punched holes were therefore based on the diameter at the top of the hole for the results used in this section.

Table 4.29: Average Hole Diameters Using Different Methods

	Average Top and Bottom Hole Diameter (in.)			Average with Top of Hole Diameter Only (in.)	
Steel Type	Drilled Hole	Punched: Normal Clearance	Punched: Excessive Clearance	Punched: Normal Clearance	Punched: Excessive Clearance
A36 - 1/2 in.	0.938	0.940	0.984	0.938	0.939
A36 - 3/4 in.	0.939	0.970	--	0.939	--
A572 Grade 50 - 1/2 in.	0.937	0.941	0.982	0.938	0.938
A572 Grade 50 - 3/4 in.	0.939	0.981	--	0.939	--

The predicted design loads of each specimen, as well as the numbering system used to refer to each specimen, are listed in Table 4.30 through Table 4.34. Table 4.34 represents the specimens with pretensioned bolts, while the other tables represent specimens with snug bolts. For the specimen naming, ‘P’ referred to a punched hole specimen, and ‘D’ referred to a drilled hole specimen. The nominal plate thickness, nominal gage distance, and nominal end distance are also presented for reference. The specimens are grouped by a common configuration of end distance and gage distance, with varying hole type as indicated. For the ½ in. thick specimens, the column labeled ‘Hole Type’ refers to a 15/16 in. diameter hole drilled with a new drill bit, a 15/16 in. hole drilled with a worn drill bit, a 15/16 in. hole punched with a 31/32 in. die (1/32 in. clearance), or a 15/16 in. hole punched with a 33/32 in. die (3/32 in. clearance). For the ¾ in. thick specimens, all holes were drilled with a new bit, and the die size was 33/32 in. (3/32 in. clearance).

When calculating the predicted design loads, the current equations from both AASHTO and AISC were used, as presented in Chapter 1. These equations included gross section yield, net section fracture, bearing resistance, and block shear resistance. The specimens were designed to have either a bearing type failure, or a block shear type failure. Gross section yield and net section fracture did not control the calculated strengths. The controlling failure load is shown in bold text for calculations based off the AISC 2005 equations. For the specimens with staggered holes, the net width and block shear areas were determined using the ‘$s^2/4g$’ addition. Resistance factors were taken as 1.0 for all calculations. Since AASHTO and AISC have different equations for block shear, both predicted design block shear ultimate loads are listed. Both Specifications have the same equation for bearing strength, if using the smaller AISC equation “When deformation at the bolt hole at service load is a design consideration” ($R_n=1.2L_ctf_u \leq 2.4dtF_u$).

The clear end distance L_c was less than 2d for all of the specimens, thus the upper limit ($2.4dtF_u$) did not control any of the bearing strength values. The use of the larger AISC bearing equation "When deformation at the bolt hole at service load is not a design consideration" ($R_n=1.5L_ctf_u \leq 3.0dtF_u$) and further discussion into the block shear equations will be analyzed and discussed in Section 4.6. The hole diameters used for calculations, for both the punched and drilled specimens, did not include the 1/16 in. addition to hole diameter required by both AASHTO and AISC. This addition will also be analyzed in Section 4.6.

Table 4.30: ½ in. A572 Grade 50 Connection Specimen Predicted Design Loads—Snug Bolts

						AISC 2005	AASHTO 2004
Specimen	Nom. Thick. (in)	Nom. g (in)	Nom. L_e (in)	Hole Type	Bearing (k)	Block Shear (k)	Block Shear (k)
P1	0.50	2.33	1.5	31/32	**94.9**	100.2	102.7
D1	0.50	2.33	1.5	New Bit	**93.6**	101.1	103.8
P2	0.50	2.33	1.5	33/32	**93.3**	99.6	102.3
D2	0.50	2.33	1.5	Worn Bit	**92.3**	99.0	101.8
P3	0.50	2.33	1.5	33/32	**92.9**	99.9	102.6
D3	0.50	2.33	1.5	Worn Bit	**91.0**	97.7	100.7
P4	0.50	3.00	1.5	31/32	**92.9**	122.0	124.8
D4	0.50	3.00	1.5	New Bit	**89.5**	122.1	125.3
P5	0.50	3.00	1.5	33/32	**94.9**	125.6	128.2
D5	0.50	3.00	1.5	Worn Bit	**91.7**	124.3	127.2
P6	0.50	3.00	1.5	33/32	**93.2**	125.5	128.2
D6	0.50	3.00	1.5	Worn Bit	**92.3**	120.7	123.5
P7	0.50	2.33	2.0	31/32	138.8	**121.5**	133.7
D7	0.50	2.33	2.0	New Bit	131.9	**118.8**	130.4
P8	0.50	2.33	2.0	33/32	137.8	**118.0**	130.8
D8	0.50	2.33	2.0	Worn Bit	132.6	**117.8**	129.5
P9	0.50	2.33	2.0	33/32	137.4	**119.4**	131.7
D9	0.50	2.33	2.0	Worn Bit	135.2	**119.0**	130.9
P10	0.50	3.00	2.0	31/32	**136.7**	144.7	142.4
D10	0.50	3.00	2.0	New Bit	**137.6**	147.9	145.6
P11	0.50	3.00	2.0	33/32	**138.3**	144.0	141.7
D11	0.50	3.00	2.0	Worn Bit	**135.6**	143.5	141.2
P12	0.50	2.67	1.5 / 4.0	31/32	**125.2**	162.4	163.7
D12	0.50	2.67	1.5 / 4.0	New Bit	**124.7**	161.6	163.0
P13	0.50	2.67	1.5 / 4.0	33/32	**124.0**	160.3	161.6
D13	0.50	2.67	1.5 / 4.0	Worn Bit	**122.3**	159.4	161.1
P14	0.50	--	1.5	31/32	**46.9**	--	--
D14	0.50	--	1.5	New Bit	**46.2**	--	--
P15	0.50	--	1.5	33/32	**46.5**	--	--
D15	0.50	--	1.5	Worn Bit	**45.4**	--	--
P16	0.50	--	1.5	33/32	**46.1**	--	--
D16	0.50	--	1.5	Worn Bit	**45.0**	--	--
P17	0.50	--	2.0	31/32	**67.7**	--	--
D17	0.50	--	2.0	New Bit	**68.5**	--	--
P18	0.50	--	2.0	33/32	**68.8**	--	--
D18	0.50	--	2.0	Worn Bit	**67.6**	--	--

Table 4.31: ½ in. A36 Connection Specimen Predicted Design Loads—Snug Bolts

Specimen	Nom. Thick. (in)	Nom. g (in)	Nom. L_e (in)	Hole Type	Bearing (k)	AISC 2005 Block Shear (k)	AASHTO 2004 Block Shear (k)
P19	0.50	2.33	1.5	31/32	**85.4**	90.7	89.3
D19	0.50	2.33	1.5	New Bit	**84.7**	90.1	88.7
P20	0.50	2.33	1.5	33/32	**86.1**	88.8	87.4
D20	0.50	2.33	1.5	Worn Bit	**85.2**	89.9	88.5
P21	0.50	2.33	1.5	33/32	**86.4**	90.1	88.7
D21	0.50	2.33	1.5	Worn Bit	**85.4**	89.8	88.4
P22	0.50	3.00	1.5	31/32	**86.6**	113.7	112.3
D22	0.50	3.00	1.5	New Bit	**83.2**	113.0	111.6
P23	0.50	3.00	1.5	33/32	**87.0**	113.2	111.8
D23	0.50	3.00	1.5	Worn Bit	**86.1**	112.6	111.2
P24	0.50	3.00	1.5	33/32	**85.2**	112.5	111.1
D24	0.50	3.00	1.5	Worn Bit	**86.6**	115.9	114.5
P25	0.50	2.33	2.0	31/32	125.7	**104.8**	115.9
D25	0.50	2.33	2.0	New Bit	125.1	**105.9**	116.7
P26	0.50	2.33	2.0	33/32	125.5	**104.8**	116.0
D26	0.50	2.33	2.0	Worn Bit	128.7	**105.7**	117.3
P27	0.50	2.33	2.0	33/32	128.6	**104.0**	116.1
D27	0.50	2.33	2.0	Worn Bit	126.4	**106.0**	117.0
P28	0.50	3.00	2.0	31/32	**125.9**	127.0	125.2
D28	0.50	3.00	2.0	New Bit	**125.2**	126.4	124.6
P29	0.50	3.00	2.0	33/32	**126.3**	126.4	124.5
D29	0.50	3.00	2.0	Worn Bit	**127.9**	128.2	125.3
P30	0.50	2.67	1.5 / 4.0	31/32	**115.5**	147.3	146.6
D30	0.50	2.67	1.5 / 4.0	New Bit	**115.1**	146.8	146.1
P31	0.50	2.67	1.5 / 4.0	33/32	**116.4**	148.4	147.7
D31	0.50	2.67	1.5 / 4.0	Worn Bit	**116.8**	149.1	148.4
P32	0.50	--	1.5	31/32	**43.2**	--	--
D32	0.50	--	1.5	New Bit	**41.9**	--	--
P33	0.50	--	1.5	33/32	**43.2**	--	--
D33	0.50	--	1.5	Worn Bit	**43.8**	--	--
P34	0.50	--	1.5	33/32	**43.4**	--	--
D34	0.50	--	1.5	Worn Bit	**42.4**	--	--
P35	0.50	--	2.0	31/32	**63.1**	--	--
D35	0.50	--	2.0	New Bit	**63.0**	--	--
P36	0.50	--	2.0	33/32	**64.7**	--	--
D36	0.50	--	2.0	Worn Bit	**64.4**	--	--

*¾ in. A572 Grade 50 Connection Specimen Predicted Design Loads—
Snug Bolts*

						AISC 2005	AASHTO 2004
Specimen	Nom. Thick. (in)	Nom. g (in)	Nom. L_e (in)	Hole Type	Bearing (k)	Block Shear (k)	Block Shear (k)
P37	0.75	2.33	1.5	33/32	**142.9**	164.3	166.2
D37	0.75	2.33	1.5	New Bit	**140.0**	163.0	165.3
P38	0.75	3.00	1.5	33/32	**140.7**	206.2	208.3
D38	0.75	3.00	1.5	New Bit	**143.1**	209.6	211.3
P39	0.75	--	1.5	33/32	**75.5**	--	--
D39	0.75	--	1.5	New Bit	**75.3**	--	--

Table 4.32: ¾ in. A36 Connection Specimen Predicted Design Loads—Snug Bolts

						AISC 2005	AASHTO 2004
Specimen	Nom. Thick. (in)	Nom. g (in)	Nom. L_e (in)	Hole Type	Bearing (k)	Block Shear (k)	Block Shear (k)
P40	0.75	2.33	1.5	33/32	**125.6**	126.9	125.0
D40	0.75	2.33	1.5	New Bit	**121.8**	123.4	121.5
P41	0.75	3.00	1.5	33/32	**126.2**	160.1	158.2
D41	0.75	3.00	1.5	New Bit	**122.6**	157.3	155.5
P42	0.75	2.33	2.0	33/32	183.6	**143.1**	159.4
D42	0.75	2.33	2.0	New Bit	183.3	**143.9**	159.9
P43	0.75	3.00	2.0	33/32	187.5	**178.9**	176.3
D43	0.75	3.00	2.0	New Bit	184.3	**175.9**	173.4
P44	0.75	--	1.5	33/32	**60.9**	--	--
D44	0.75	--	1.5	New Bit	**59.7**	--	--
P45	0.75	--	2.0	33/32	**89.6**	--	--
D45	0.75	--	2.0	New Bit	**89.6**	--	--

Table 4.33: ½ in. A572 Grade 50 Connection Specimen Predicted Design Loads—Pretensioned Bolts

						AISC 2005	AASHTO 2004
Specimen	Nom. Thick. (in)	Nom. g (in)	Nom. L_e (in)	Hole Type	Bearing (k)	Block Shear (k)	Block Shear (k)
P46	0.50	2.33	1.5	31/32	**93.3**	98.2	100.9
D46	0.50	2.33	1.5	New Bit	**90.3**	96.2	99.2
P47	0.50	3.00	1.5	31/32	**91.7**	122.4	125.3
D47	0.50	3.00	1.5	New Bit	**90.7**	121.6	124.6
P48	0.50	2.33	2.0	31/32	135.3	**118.1**	130.2
D48	0.50	2.33	2.0	New Bit	133.9	**118.9**	130.6
P49	0.50	3.00	2.0	31/32	**133.8**	141.7	139.4
D49	0.50	3.00	2.0	New Bit	**136.0**	143.7	141.5
P50	0.50	--	1.5	31/32	**46.2**	--	--
D50	0.50	--	1.5	New Bit	**45.8**	--	--
P51	0.50	--	2.0	31/32	**68.9**	--	--
D51	0.50	--	2.0	New Bit	**66.7**	--	--

Each of the 102 connection specimens listed were tested to ultimate load. The procedures used were given in Chapter 3. During testing, the load versus displacement behavior was recorded. Four examples of these curves are presented as follows: Figure 4.17 represented a typical specimen with two snug bolts, Figure 4.18 represented a typical specimen with a single snug bolt, Figure 4.19 represented a typical specimen with two staggered snug bolts, and Figure 4.20 represents a typical specimen with two pretensioned bolts. In each figure, both the punched hole specimen and drilled hole specimen with an identical configuration are shown for comparison. The configuration of each specimen is given for reference. Photographs of the failed specimens are also presented.

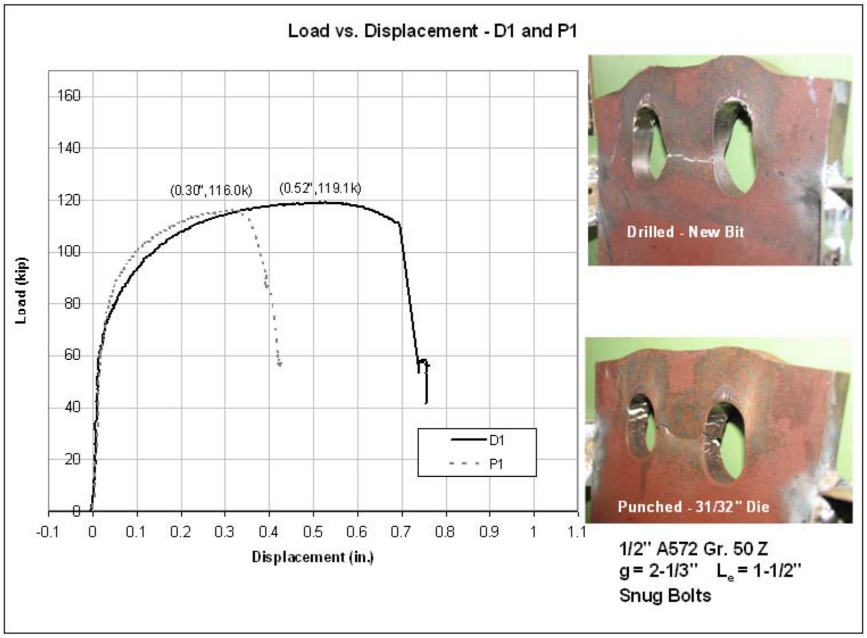

Figure 4.17: Typical Load vs. Displacement Curve—Specimen with 2 Snug Bolts

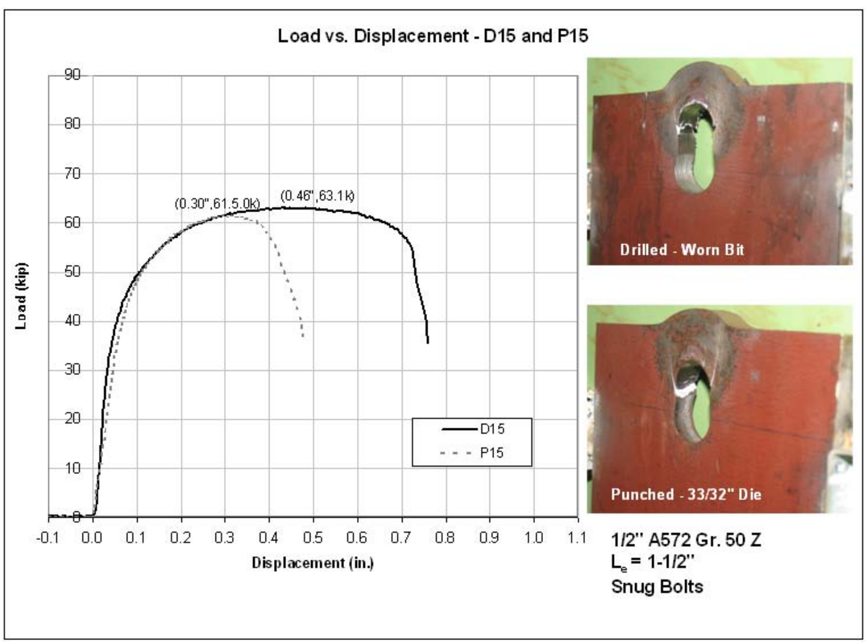

Figure 4.18: Typical Load vs. Displacement Curve—Specimen with 1 Snug Bolt

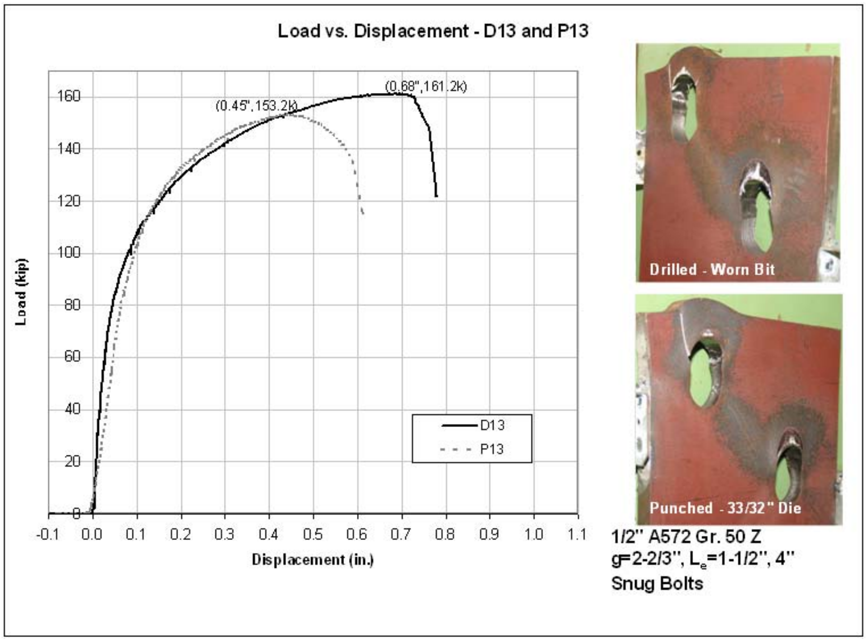

Figure 4.19: Typical Load vs. Displacement Curve—Specimen with 2 Staggered Snug Bolts

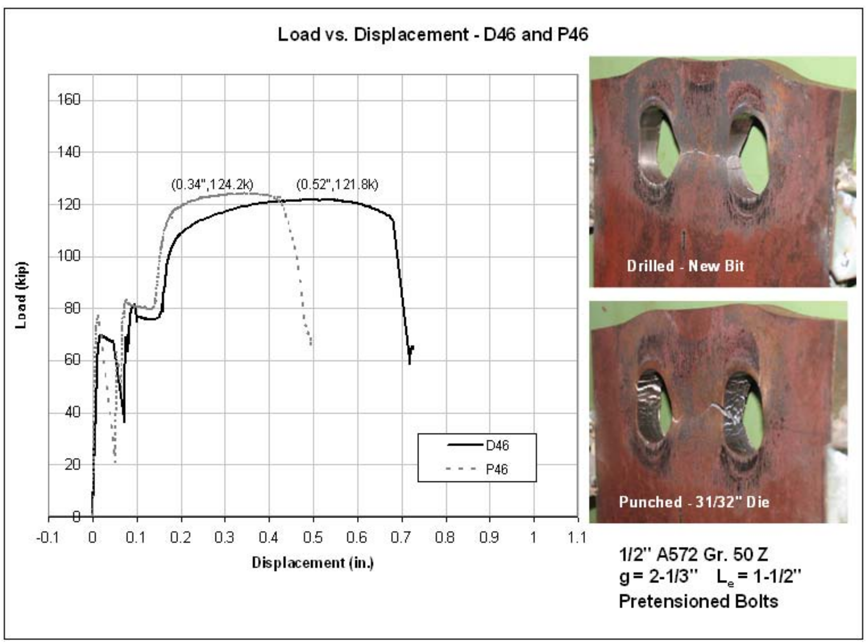

Figure 4.20: Typical Load vs. Displacement Curve—Specimen with 2 Pretensioned Bolts

Examples of determining the experimental failure modes are presented in Figure 4.21 and Figure 4.22. The connections were tested past the maximum load until a fracture occurred to further indicate the failure mode.

Figure 4.21: Experimental Block Shear Type Failures

Figure 4.22: Experimental Bearing Type Failures

The results of the connection tension tests are compared with the predicted design loads in Table 4.35 through Table 4.39. The predicted design loads listed in these tables are based off the controlling AISC 2005 design loads, listed in the previous tables. Each table shows the specimen name, predicted design load (either controlled by bearing or block shear), the predicted failure mechanism (bearing or block shear), the experimental ultimate (maximum) load, the observed failure mechanism (bearing, block shear, and if gross section yielding occurred), and the displacement at the maximum load. The load ratio is the experimental maximum load divided by the predicted design load. This presented a method to normalize the specimen strength for comparison, especially since the as-fabricated dimensions of each specimen varied slightly. The displacement at maximum load was adjusted to account for any initial slip in the system. A ratio is also given for the punched hole specimen displacement divided by the equivalent drilled hole specimen displacement.

Table 4.34: ½ in. A572 Grade 50 Connection Specimen Experimental Results—Snug Bolts, AISC 2005 Equations

B=Bearing
BS=Block Shear
GY=Gross Yield

Specimen	AISC 2005 Design Load (k)	Exp. Load (k)	Load Ratio	Predicted Failure Type	Exp. Failure Type	Adj. Δ at Ult. (in)	Punched Δ / Drilled Δ
P1	94.9	116.0	1.22	B	BS	0.30	0.59
D1	93.6	119.1	1.27	B	BS	0.52	
P2	93.3	115.2	1.23	B	B	0.32	0.64
D2	92.3	120.0	1.30	B	BS	0.50	
P3	92.9	115.6	1.24	B	BS	0.35	0.74
D3	91.0	117.8	1.29	B	BS	0.47	
P4	92.9	116.9	1.26	B	B	0.33	0.74
D4	89.5	117.4	1.31	B	B	0.44	
P5	94.9	120.4	1.27	B	B	0.34	0.77
D5	91.7	120.5	1.31	B	B	0.44	
P6	93.2	114.8	1.23	B	B	0.35	0.72
D6	92.3	119.1	1.29	B	B	0.48	
P7	121.5	133.1	1.10	BS	BS	0.31	0.71
D7	118.8	133.6	1.12	BS	BS	0.43	
P8	118.0	134.1	1.14	BS	BS	0.35	0.82
D8	117.8	138.3	1.17	BS	BS	0.42	
P9	119.4	132.1	1.11	BS	BS	0.35	0.86
D9	119.0	134.7	1.13	BS	BS	0.41	
P10	136.7	150.0	1.10	B	B	0.43	0.53
D10	137.6	157.2	1.14	B	B	0.82	
P11	138.3	157.0	1.13	B	B	0.53	0.89
D11	135.6	158.4	1.17	B	B	0.59	
P12	125.2	150.3	1.20	B	B	0.44	0.66
D12	124.7	160.7	1.29	B	B	0.66	
P13	124.0	153.2	1.24	B	B	0.45	0.66
D13	122.3	161.2	1.32	B	B	0.68	
P14	46.9	60.1	1.28	B	B	0.28	0.60
D14	46.2	62.5	1.35	B	B	0.47	
P15	46.5	61.5	1.32	B	B	0.29	0.64
D15	45.4	63.1	1.39	B	B	0.46	
P16	46.1	61.5	1.33	B	B	0.37	0.84
D16	45.0	62.0	1.38	B	B	0.44	
P17	67.7	79.2	1.17	B	B	0.41	0.52
D17	68.5	81.8	1.19	B	B	0.79	
P18	68.8	81.9	1.19	B	B	0.60	0.96
D18	67.6	81.7	1.21	B	B	0.63	

Table 4.35: ½ in. A36 Connection Specimen Experimental Results—Snug Bolts, AISC 2005 Equations

B=Bearing
BS=Block Shear
GY=Gross Yield

	AISC 2005						
Specimen	Design Load (k)	Exp. Load (k)	Load Ratio	Predicted Failure Type	Exp. Failure Type	Adj. Δ at Ult. (in)	Punched Δ / Drilled Δ
P19	85.4	98.2	1.15	B	B	0.30	0.49
D19	84.7	106.7	1.26	B	BS	0.60	
P20	86.1	99.5	1.16	B	B	0.35	0.61
D20	85.2	107.7	1.26	B	BS	0.58	
P21	86.4	98.5	1.14	B	B	0.31	0.60
D21	85.4	106.9	1.25	B	BS	0.53	
P22	86.6	101.8	1.18	B	B	0.26	0.49
D22	83.2	106.0	1.27	B	B	0.53	
P23	87.0	102.4	1.18	B	B	0.32	0.60
D23	86.1	110.9	1.29	B	B	0.52	
P24	85.2	99.6	1.17	B	B	0.28	0.54
D24	86.6	110.8	1.28	B	B	0.52	
P25	104.8	111.4	1.06	BS	BS	0.27	0.50
D25	105.9	125.1	1.18	BS	BS	0.54	
P26	104.8	118.2	1.13	BS	BS	0.34	0.71
D26	105.7	125.9	1.19	BS	BS	0.48	
P27	104.0	115.6	1.11	BS	BS	0.35	0.68
D27	106.0	124.5	1.17	BS	BS	0.51	
P28	125.9	128.3	1.02	B	B	0.40	0.58
D28	125.2	142.2	1.14	B	GY, B	0.68	
P29	126.3	127.8	1.01	B	B	0.36	0.58
D29	127.2	143.6	1.13	B	GY, B	0.62	
P30	115.5	130.0	1.12	B	B	0.45	0.58
D30	115.1	143.5	1.25	B	GY, B	0.76	
P31	116.4	128.2	1.10	B	B	0.44	0.64
D31	116.8	143.8	1.23	B	GY, B	0.69	
P32	43.2	51.6	1.19	B	B	0.26	0.48
D32	41.9	56.1	1.34	B	B	0.54	
P33	43.2	52.3	1.21	B	B	0.28	0.59
D33	43.8	58.3	1.33	B	B	0.48	
P34	43.4	53.2	1.23	B	B	0.32	0.73
D34	42.4	56.1	1.32	B	B	0.43	
P35	63.1	68.6	1.09	B	B	0.45	0.69
D35	63.0	71.2	1.13	B	B	0.65	
P36	64.7	70.8	1.09	B	B	0.51	0.78
D36	64.4	72.6	1.13	B	B	0.66	

Table 4.36: ¾ in. A572 Grade 50 Connection Specimen Experimental Results—Snug Bolts, AISC 2005 Equations

B=Bearing
BS=Block Shear
GY=Gross Yield

Specimen	AISC 2005 Design Load (k)	Exp. Load (k)	Load Ratio	Predicted Failure Type	Exp. Failure Type	Adj. Δ at Ult. (in)	Punched Δ / Drilled Δ
P37	142.9	183.7	1.29	B	B	0.47	0.92
D37	140.0	183.6	1.31	B	B	0.50	
P38	140.7	183.3	1.30	B	B	0.43	0.88
D38	143.1	186.9	1.31	B	B	0.49	
P39	75.5	92.3	1.22	B	B	0.36	0.78
D39	75.3	94.4	1.25	B	B	0.46	

Table 4.37: ¾ in. A36 Connection Specimen Experimental Results—Snug Bolts, AISC 2005 Equations

B=Bearing
BS=Block Shear
GY=Gross Yield

Specimen	AISC 2005 Design Load (k)	Exp. Load (k)	Load Ratio	Predicted Failure Type	Exp. Failure Type	Adj. Δ at Ult. (in)	Punched Δ / Drilled Δ
P40	125.6	142.2	1.13	B	B	0.29	0.48
D40	121.8	153.9	1.26	B	GY, B	0.60	
P41	126.2	147.1	1.17	B	B	0.27	0.49
D41	122.6	155.8	1.27	B	B	0.56	
P42	143.1	160.6	1.12	BS	BS	0.29	0.50
D42	143.9	180.0	1.25	BS	BS	0.59	
P43	178.9	192.5	1.08	BS	GY, B	0.48	0.67
D43	175.9	203.9	1.16	BS	GY, B	0.71	
P44	60.9	74.2	1.22	B	B	0.27	0.50
D44	59.7	80.3	1.35	B	B	0.53	
P45	89.6	98.0	1.09	B	B	0.43	0.58
D45	89.6	103.2	1.15	B	B	0.75	

Table 4.38: ½ in. A572 Grade 50 Connection Specimen Experimental Results—Pretensioned Bolts, AISC 2005 Equations

	AISC 2005	B=Bearing BS=Block Shear GY=Gross Yield					
Specimen	Design Load (k)	Exp. Load (k)	Load Ratio	Predicted Failure Type	Exp. Failure Type	Adj. Δ at Ult. (in)	Punched Δ / Drilled Δ
P46	93.3	124.2	1.33	B	BS	0.34	0.65
D46	90.3	121.8	1.35	B	BS	0.52	
P47	91.7	134.7	1.47	B	B	0.31	0.58
D47	90.7	132.9	1.47	B	B	0.52	
P48	118.1	139.0	1.18	BS	BS	0.34	0.68
D48	118.9	142.1	1.20	BS	BS	0.50	
P49	133.8	158.4	1.18	B	B	0.44	0.55
D49	136.0	165.5	1.22	B	B	0.80	
P50	46.2	69.4	1.50	B	B	0.31	0.64
D50	45.8	70.3	1.53	B	B	0.49	
P51	68.9	86.6	1.26	B	B	0.50	0.80
D51	66.7	86.1	1.29	B	B	0.62	

The results of the connection tension tests were compared to AASHTO 2004 predicted design loads. The predicted design load and predicted failure type changed for several specimens due to the different AASHTO 2004 block shear strength equations, discussed in Section 4.6. Because of this, the load ratio for these specimens was different than those listed for the AISC 2005 equations. The displacement values are the same, but listed again for reference.

As shown in Table 4.33 through 4.37, the majority of the specimens failed in the mode that was predicted, either a block shear type failure or a bearing type failure. However, one of the configurations, g = 2-1/3 in. and L_e = 1-1/2 in., had multiple instances of the experimental failure mode being different than anticipated. This configuration, combined with the plate tensile properties, resulted in the predicted block shear load being close to the controlling predicted bearing load. Therefore the experimental failure was close to both types of failure. Also noted in the tables was the fact that several of the A36 drilled hole specimens yielded in the gross section before reaching the desired failure mode. The design bearing equations under-predicted the actual failure load by a large enough amount to exceed the gross section yield strength prior to the bearing type failure load. The displacements reported were not affected by this yielding, as the test setup monitored hole elongation only.

The ½ in. thick specimens with snug bolts had replicate specimens tested with multiple hole fabrication methods, as shown in Table 4.30 and Table 4.31. The specimens with holes drilled with a worn bit and holes punched with an excessive die clearance (3/32 in. instead of 1/32 in.) had a hole quality that would likely be described as poorer than the holes drilled with a new bit and holes punched with the recommended die clearance. The appearance of the hole was initially thought to be related to the performance of the specimen. The holes drilled with a worn drill bit reduced the fatigue life of the plate specimens. Comparing the results presented in Table 4.35 and Table 4.36, there appeared to be no clear trend in the performance of a connection specimen between the drilled hole fabrication methods and between the punched hole fabrication methods. The load ratio for each of the drilled hole types was approximately equal. The ultimate displacement values were also similar, with the holes drilled with a worn bit having slightly lower displacements. Any differences can be attributed to the small amount of test result scatter. The same held true for specimens punched with different die clearances. There was no clear trend between the two punched hole types, and any difference was likely attributed to a small amount of test result scatter.

One noticeable trend observed in the test data was that the load ratio of the connection specimens decreased as end distance increased. This is shown in Table 4.40, along with average results for each configuration. Here, the load ratios are calculated from the maximum load determined from the AISC 2005 predicted design loads. The load ratio values determined from the design loads using AASHTO 2004 equations are shown in Table 4.41. The staggered hole configuration was not included in these tables. The results of the ¾ in. snug bolt connection specimens showed similar trends compared to the ½ in. connections. The ¾ in. A572 Grade 50 steel was not tested for the end distance of 2 in. since bearing capacity exceeded the bolt shear capacity. The hole diameter for design calculations was based off the top of hole diameter only for punched holes.

Table 4.39: Snug Bolt Connection Specimen Configuration Average Results (AISC 2005 Equations)

B=Bearing
BS=Block Shear

Specimen	Nom. g (in)	Nom. L_e (in)	Predicted Failure Type	Exp. Failure Type	Average Load Ratio: Punched Holes	Average Load Ratio: Drilled Holes	Punched LR / Drilled LR
1/2 in. A572 Grade 50	--	1-1/2	B	B	1.31	1.37	0.96
		2	B	B	1.18	1.20	0.98
	2-1/3	1-1/2	B	BS	1.23	1.29	0.96
		2	BS	BS	1.11	1.14	0.97
	3	1-1/2	B	B	1.25	1.31	0.96
		2	B	B	1.12	1.16	0.97
1/2 in. A36	--	1-1/2	B	B	1.21	1.33	0.91
		2	B	B	1.09	1.13	0.97
	2-1/3	1-1/2	B	B/BS	1.15	1.26	0.91
		2	BS	BS	1.10	1.18	0.93
	3	1-1/2	B	B	1.17	1.28	0.92
		2	B	B	1.02	1.13	0.90
3/4 in. A572 Grade 50	--	1-1/2	B	B	1.22	1.25	0.97
		2	--	--	--	--	--
	2-1/3	1-1/2	B	B	1.29	1.31	0.98
		2	--	--	--	--	--
	3	1-1/2	B	B	1.30	1.31	1.00
		2	--	--	--	--	--
3/4 in. A36	--	1-1/2	B	B	1.22	1.35	0.91
		2	B	B	1.09	1.15	0.95
	2-1/3	1-1/2	B	B	1.13	1.26	0.90
		2	BS	BS	1.12	1.25	0.90
	3	1-1/2	B	B	1.17	1.27	0.92
		2	BS	B	1.08	1.16	0.93

Table 4.40: Snug Bolt Connection Specimen Configuration Average Results (AASHTO 2004 Equations)

B=Bearing
BS=Block Shear

Specimen	Nom. g (in)	Nom. L_e (in)	Predicted Failure Type	Exp. Failure Type	Average Load Ratio: Punched Holes	Average Load Ratio: Drilled Holes	Punched LR / Drilled LR
1/2 in. A572 Grade 50	--	1-1/2	B	B	1.31	1.37	0.96
		2	B	B	1.18	1.20	0.98
	2-1/3	1-1/2	B	BS	1.23	1.29	0.96
		2	BS	BS	1.01	1.04	0.97
	3	1-1/2	B	B	1.25	1.31	0.96
		2	B	B	1.12	1.16	0.97
1/2 in. A36	--	1-1/2	B	B	1.21	1.33	0.91
		2	B	B	1.09	1.13	0.97
	2-1/3	1-1/2	B	B/BS	1.15	1.26	0.91
		2	BS	BS	0.99	1.07	0.93
	3	1-1/2	B	B	1.17	1.28	0.92
		2	BS	B	1.03	1.14	0.90
3/4 in. A572 Grade 50	--	1-1/2	B	B	1.22	1.25	0.97
		2	--	--	--	--	--
	2-1/3	1-1/2	B	B	1.29	1.31	0.98
		2	--	--	--	--	--
	3	1-1/2	B	B	1.30	1.31	1.00
		2	--	--	--	--	--
3/4 in. A36	--	1-1/2	B	B	1.22	1.35	0.91
		2	B	B	1.09	1.15	0.95
	2-1/3	1-1/2	BS	B	1.14	1.27	0.90
		2	BS	BS	1.01	1.13	0.89
	3	1-1/2	B	B	1.17	1.27	0.92
		2	BS	B	1.09	1.18	0.93

In general, for both types of failure modes presented in both grades of steel, the average load ratio decreased as end distance increased. This trend is also shown in Figure 4.23. Both grades of steel are combined. The load ratio for each specimen failure type, controlled by bearing strength or block shear strength, was compared at the two end distances used, 1-1/2 in. and 2 in.

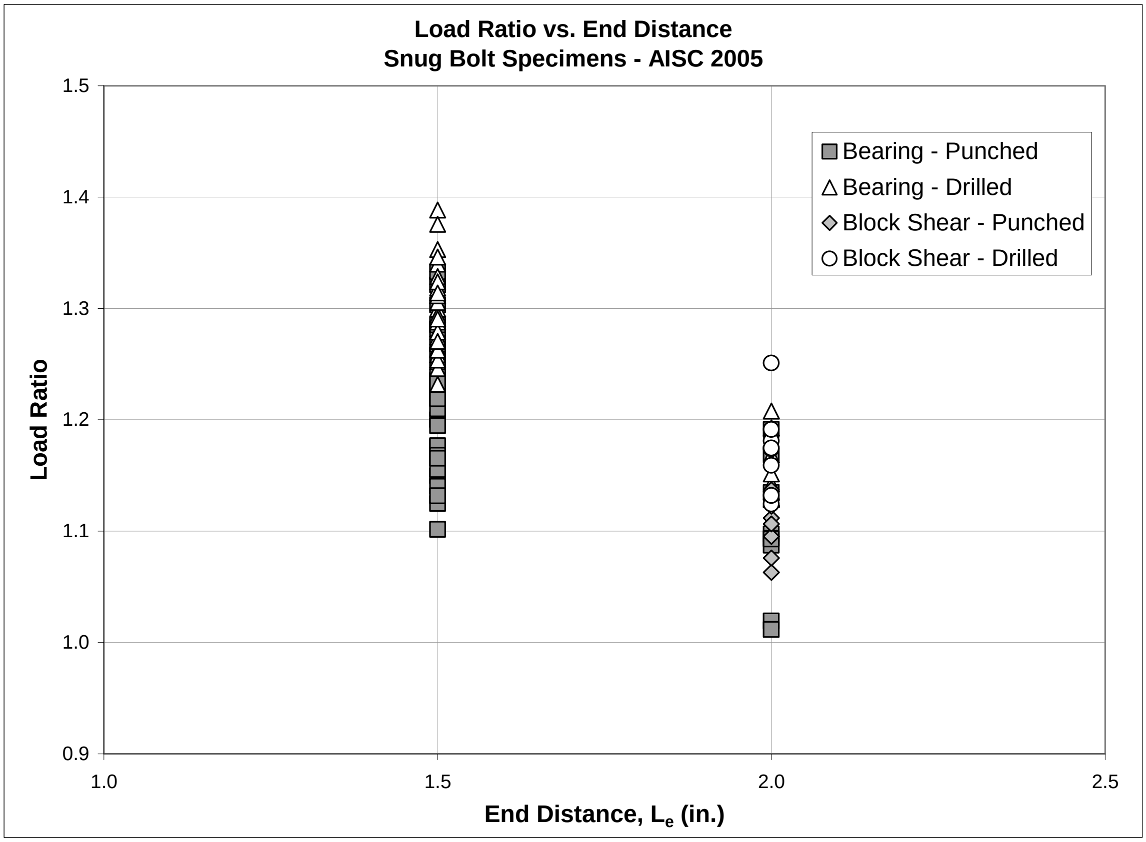

Figure 4.23: Effect of End Distance on Load Ratio

Table 4.40 and Table 4.41 also showed the general trend of punched holes having a lower load ratio compared to drilled holes, with the difference being larger in A36 steel. This is indicated by comparing the punched hole specimen load ratio to the replicate drilled hole specimen load ratio, the 'Punched LR / Drilled LR' column. This will be further discussed in Section 4.6.

The overall average results of the A36 and A572 Grade 50 ½ in. snug bolt connection specimens are shown in Table 4.42 and Table 4.43. Table 4.42 corresponds to the predicted design loads determined from AISC 2005, and Table 4.43 corresponds to predicted design loads determined from AASHTO 2004. The ratio of punched specimen displacement to drilled specimen displacement allowed for a better comparison of the performance between the two hole fabrication methods. The minimum load ratio corresponded to a load ratio for a punched hole specimen, as the punched hole specimens always had lower load ratios than the comparable drilled hole specimens.

Table 4.41: ½ in. Thick Snug Bolt Connection Specimen Average Results (AISC 2005 Equations)

	Average Load Ratio				
Specimen	Punched Holes	Drilled Holes	Punched LR / Drilled LR	Minimum Load Ratio	Punched Δ / Drilled Δ
1/2 in. A572 Grade 50	1.21	1.26	0.96	1.10	0.72
1/2 in. A36	1.13	1.23	0.92	1.01	0.60

Table 4.42: ½ in. Thick Snug Bolt Connection Specimen Average Results (AASHTO 2004 Equations)

	Average Load Ratio				
Specimen	Punched Holes	Drilled Holes	Punched LR / Drilled LR	Minimum Load Ratio	Punched Δ / Drilled Δ
1/2 in. A572 Grade 50	1.19	1.24	0.96	1.00	0.72
1/2 in. A36	1.11	1.21	0.92	0.96	0.60

For the ¾ in. specimens, the overall averages do not provide a good comparison, as there were more ¾ in. A36 connections tested. However, the ¾ in. A572 Grade 50 specimens generally had a punched hole load ratio closer to the drilled hole load ratio, and the punched hole displacement values were closer to the drilled hole displacement values. However, the punched hole specimens still underperformed the drilled hole specimens. The ¾ in. A36 specimens showed similar differences between punched and drilled holes as the ½ in. A36 specimens, both in terms of load ratio and displacement values. As with the ½ in. A36 drilled specimens, several of the ¾ in. A36 drilled hole specimens again yielded in the gross section before the bearing type failure occurred.

The results of the ½ in. A572 Grade 50 connection specimens with pretensioned bolts are summarized in Table 4.44, with predicted design loads calculated using AISC 2005 equations. The average values for the ½ in. A572 Grade 50 snug bolt connection tests are also presented for comparison.

Table 4.43: ½ in. Thick Pretensioned Bolt Connection Specimen Configuration Results (AISC 2005 Equations)

				Load Ratio - Pretensioned Bolts		Average Load Ratio - Snug Bolts	
Specimen	Predicted Failure Type	Nom. g (in)	Nom. L_e (in)	Punched Holes	Drilled Holes	Punched Holes	Drilled Holes
1/2 in. A572 Grade 50	Bearing	--	1-1/2	1.50	1.53	1.31	1.37
	Bearing		2	1.26	1.29	1.18	1.20
	Bearing	2-1/3	1-1/2	1.33	1.35	1.23	1.29
	Block Shear		2	1.18	1.20	1.11	1.14
	Bearing	3	1-1/2	1.47	1.47	1.25	1.31
	Bearing		2	1.18	1.22	1.12	1.16

A comparison of average results for the ½ in. A572 Grade 50 specimens with snug and pretensioned bolts is shown in Table 4.45.

Table 4.44: Comparison of ½ in. A572 Grade 50 Specimens with Snug and Pretensioned Bolts, Average Results (AISC 2005 Equations)

	Average Load Ratio				
Specimen	Punched Holes	Drilled Holes	Punched LR / Drilled LR	Minimum Load Ratio	Punched Δ / Drilled Δ
Snug Bolts	1.21	1.26	0.96	1.10	0.72
Pretensioned Bolts	1.32	1.34	0.98	1.18	0.65

The results of the pretensioned connection tests showed load ratio values significantly higher than the results of the snug bolt connection tests. The difference between punched hole specimens and drilled hole specimens also remarkably decreased. The difference between the displacement values for snug bolt specimens and pretensioned bolt specimens was not a significant amount, however.

While the use of pretensioned bolts appeared to improve the performance of both drilled and punched hole specimens, accounting for the additional load capacity from the friction of the connection should not be considered. The additional amount of load capacity will not be consistent. Other factors may have influenced the behavior of the connection, such as the clamping force of the pretensioned bolt confining the deformation of the hole as it started to deform due to bearing stress from the bolt.

4.6 CONNECTION TENSION TEST SUMMARY AND ANALYSIS

In total, 102 connection specimens were tested in tension. Half of the specimens were fabricated with drilled holes and half with punched holes. The test data from each grade and thickness of steel reported in Section 4.5 will be compiled and presented in this section.

From the results of the connection tension tests, the average load ratio for punched hole specimens was lower than the replicate drilled hole specimens. The difference was larger in A36 steel than in A572 Grade 50 steel. The minimum load ratio for a specimen was lower in A36 as well. The average ratio of punched displacement to drilled displacement was also lower in A36. This indicated that the drilled hole displacement values were larger than the punched hole displacement values by a larger amount than in A572 Grade 50. This trend was also noted in the plate tension tests described in Section 4.1. For the plate tension tests, the difference between strength ratios of the punched and drilled specimens was larger in A36 plate material than in A572 Grade 50 plate material.

As mentioned previously, AISC and AASHTO have different equations for determining the design bearing strength. AISC 2005 presents an equation for cases "When deformation at the bolt hole at service load is not a design consideration" in the form of $R_n = 1.5L_ctF_u \leq 3.0dtF_u$. The previously used bearing strength equation, when deformation is a consideration, was $R_n = 1.2L_ctF_u \leq 2.4dtF_u$. The clear end distance L_c was less than 2d for all of the specimens, thus the upper limit (2.4dtFu or $3.0dtF_u$) did not control any of the bearing strength values. The difference between the two equations would therefore be the 1.5 multiplier versus the 1.2 multiplier.

A series of histograms were used to determine the multiplier that each specimen controlled by bearing strength produced, determined by dividing the experimental maximum load by L_ctF_u. If the ratio was less than 1.5, the larger bearing strength equation would have over-predicted the ultimate load of the connection. The results are presented in Figure 4.24 through Figure 4.26. The data in these figures corresponded to only the connection specimens with predicted bearing failures with snug bolts. Figure 4.24 presents A36 specimens (19 punched and 19 drilled), while Figure 4.25 presents A572 Grade 50 specimens (18 punched and 18 drilled). Figure 4.26 presents combined results of both grades of steel, separated by punched and drilled holes.

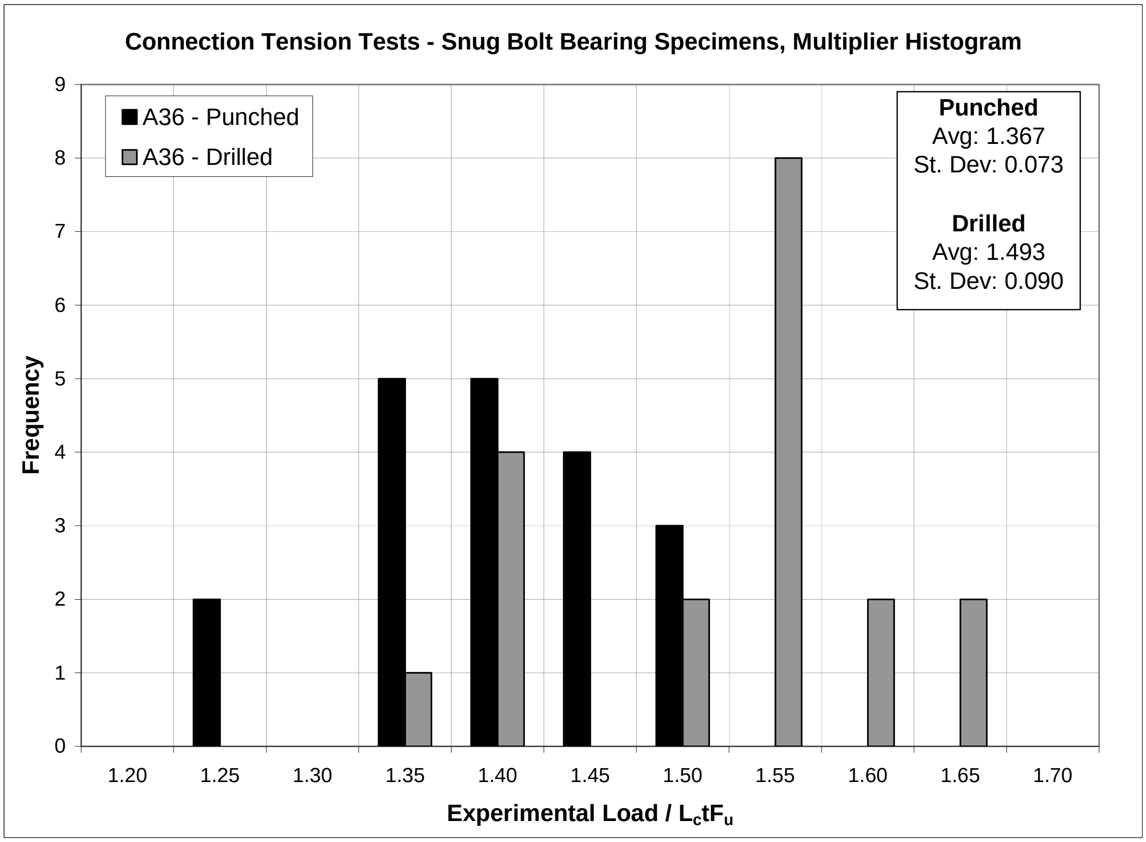

Figure 4.24: A36 Connection Bearing Test Data Comparison

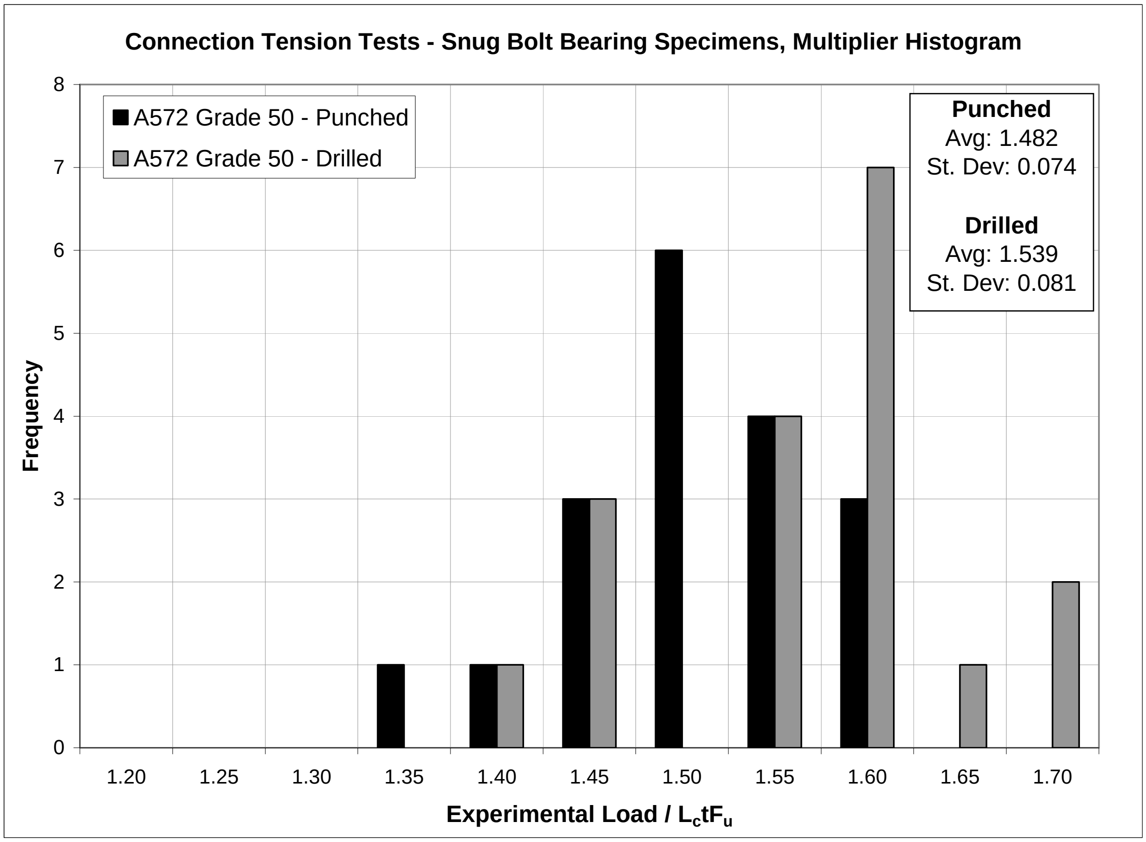

Figure 4.25: A572 Grade 50 Connection Bearing Test Data Comparison

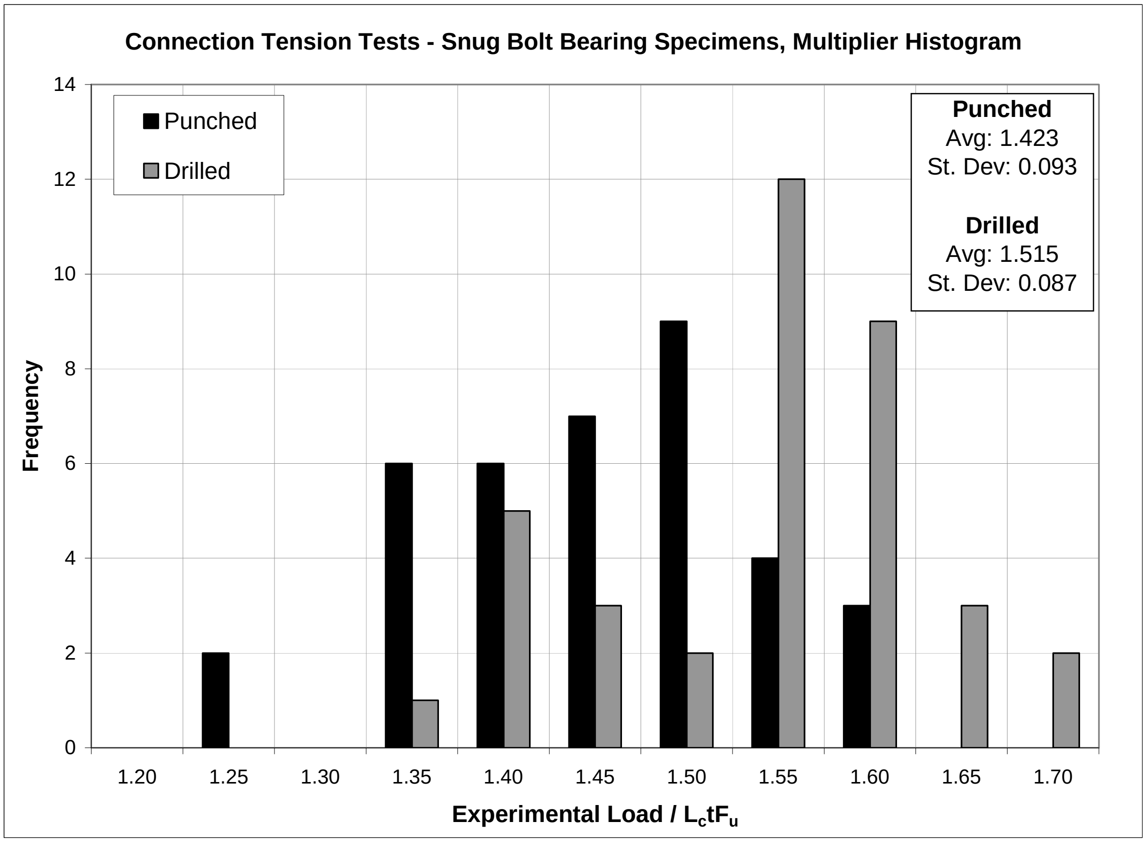

Figure 4.26: Connection Bearing Tests Data Comparison for Both Steels

Figures 4.24 through Figure 4.26 indicated that all connections controlled by bearing strength, determined using the lower bearing strength equation ($R_n = 1.2L_ctF_u$), had maximum capacities that exceeded the predicted design capacity. However, many of the specimens, especially the punched hole specimens, did not reach the multiplier of the larger bearing strength equation ($R_n = 1.5L_ctF_u$). The average values for drilled hole specimens were larger than punched hole specimens in each grade, with both averages higher in A572 Grade 50 steel than A36 steel.

AISC and AASHTO also have different equations for predicting the block shear rupture strength. The equations are presented as follows, with definitions of each abbreviation used in the equations listed in Chapter 1:

- **AASHTO Design 2004, 6.13.4: Block Shear Rupture Resistance**

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

$$R_r = \phi_{bs}(0.58F_yA_{vg} + F_uA_{tn}) \quad (6.13.4\text{-}1)$$

Otherwise:

$$R_r = \phi_{bs}(0.58F_uA_{vn} + F_yA_{tg}) \quad (6.13.4\text{-}2)$$

- **AISC 2005, J4.3: Block Shear Strength**

$$R_n = 0.6F_uA_{nv} + U_{bs}F_uA_{nt} \leq 0.6F_yA_{gv} + U_{bs}F_uA_{nt} \qquad (J4\text{-}5)$$

The configuration designed to produce a block shear type failure, in both grades of steel and both thicknesses, had g = 2-1/3 in. and L_e = 2 in. Example calculations are presented below for a ¾ in. thick A36 specimen (P42). This specimen had the largest difference in predicted design loads determined from AISC and AASHTO block shear equations. The predicted block shear failure loads calculated using AASHTO 2004 equations had $A_{tn} < 0.58A_{vn}$, thus $R_r = \phi_{bs}(0.58F_uA_{vn} + F_yA_{tg})$, and the AISC equations were controlled by $0.6F_yA_{gv} + U_{bs}F_uA_{nt}$. This held true for all of the predicted block shear type failures. Therefore, for the block shear controlled specimens, AISC predicted a shear yield-tension fracture mode, while AASHTO predicted a shear fracture-tension yield mode. The observed mode of failure for the configuration that produced a block shear failure was a fracture along the tension area, and yielding along the shear areas. This can be observed in Figure 4.21.

- **AASHTO Design 2004, 6.13.4: Block Shear Rupture Resistance**

  If $A_{tn} \geq 0.58A_{vn}$

  $1.038\text{in.}^2 < 0.58*2.257\text{in.}^2$ => Shear yield - tension fracture

  $R_r = \phi_{bs}(0.58F_uA_{vn} + F_yA_{tg})$

  $= 1.0(0.58*65.7\text{ksi}*2.257\text{in.}^2 + 42.2\text{ksi}*1.739\text{in.}^2)$ => $\underline{R_r = 159.4\text{ kip}}$

- **AISC 2005, J4.3: Block Shear Strength**

  $R_n = 0.6F_uA_{nv} + U_{bs}F_uA_{nt} \leq 0.6F_yA_{gv} + U_{bs}F_uA_{nt}$

  $=0.6*65.7\text{ksi}*2.257\text{in.}^2 + 1.0*65.7\text{ksi}*1.038\text{in.}^2 \leq 0.6*42.2\text{ksi}*2.958\text{in.}^2 + 1.0*65.7\text{ksi}*1.038\text{in.}^2$

  $= 157.1\text{ kip} > 143.1\text{ kip}$ => $\underline{R_n = 143.1\text{ kip}}$

Experimental Ultimate Load = 160.6 kip

From the test results, the average load ratios for both punched and drilled hole specimens determined with predicted design loads calculated from AASHTO 2004 equations were lower than design loads calculated from AISC 2005. A comparison between the two Specifications using only the specimens that had a predicted block shear type failure is shown in Figure 4.27. In this figure, the 45-degree line represents the case when experimental and predicted design loads are equal. Specimens above this line had a load ratio greater than 1.0. This figure showed that the AASHTO 2004 block shear strength equations over-predicted several of the ultimate loads, while the AISC 2005 block shear strength equations more conservatively predict the ultimate loads. The points with load ratios below 1.0 corresponded to punched hole specimens.

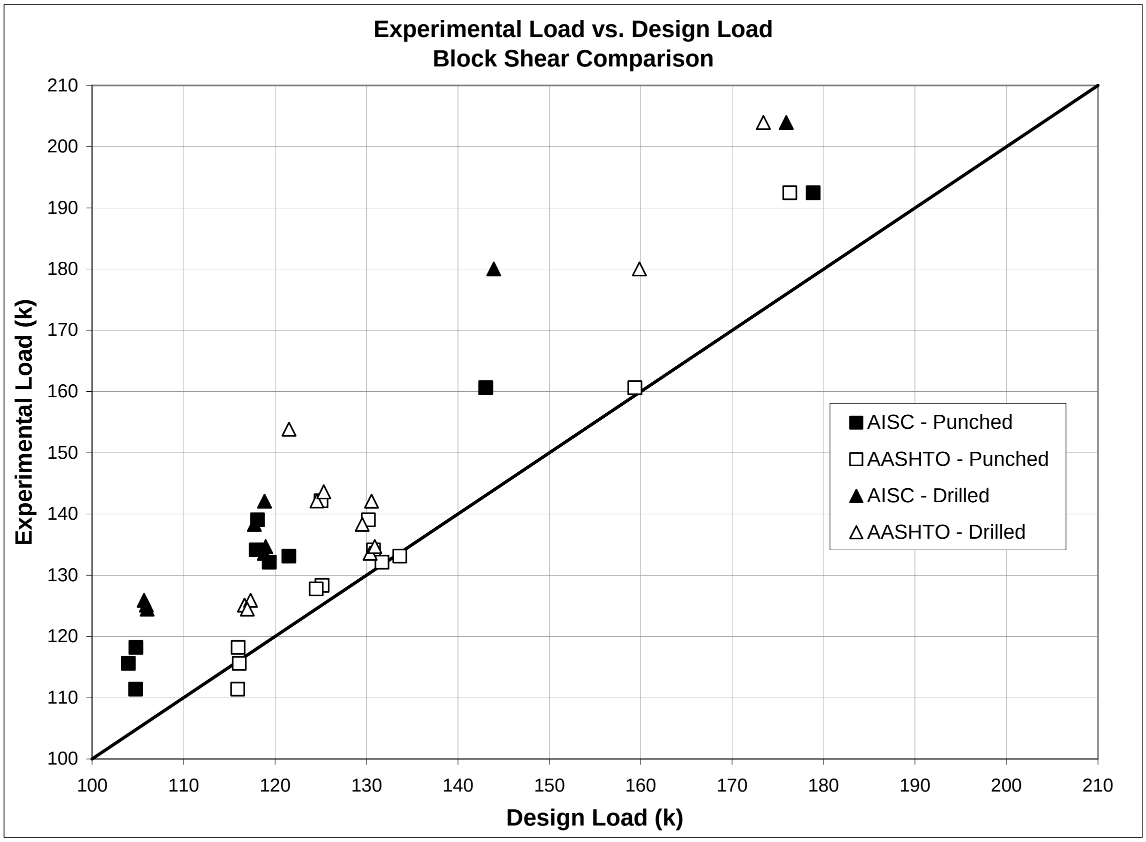

Figure 4.27: Comparison of Predicted Block Shear Type Failures

Using the block shear rupture strength and lower bearing strength equation from AISC 2005, with resistance factors taken as 1.0 and the as-fabricated dimensions, the design loads were determined and compared to the experimental maximum loads, as shown in Figure 4.28 and Figure 4.29. Figure 4.28 presents the snug bolt A36 connections, while Figure 4.29 presents the snug bolt A572 Grade 50 specimens. In these figures, the 45-degree line represented an experimental load that equaled the design load. Specimens with a strength ratio greater than 1.0 are above the 45-degree line. All of the specimens from the connection tension tests were above the line. As shown in the tables of results and in the figures, punched hole specimens had lower load ratios than the drilled hole specimens. The A36 specimens overall had load ratios lower than the A572 Grade 50 specimens, and the difference between punched and drilled specimens was larger in the A36 specimens.

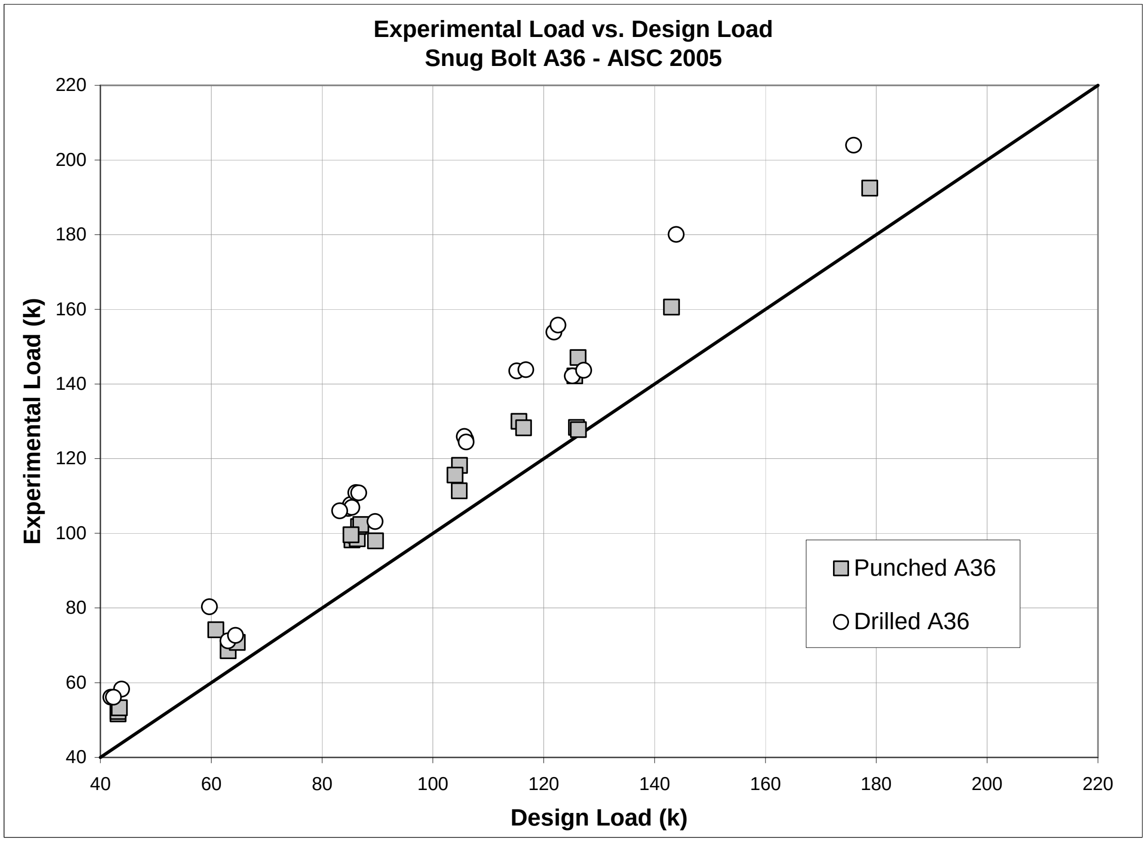

Figure 4.28: Connection Tension Test Data Comparison—A36 (AISC 2005 Equations)

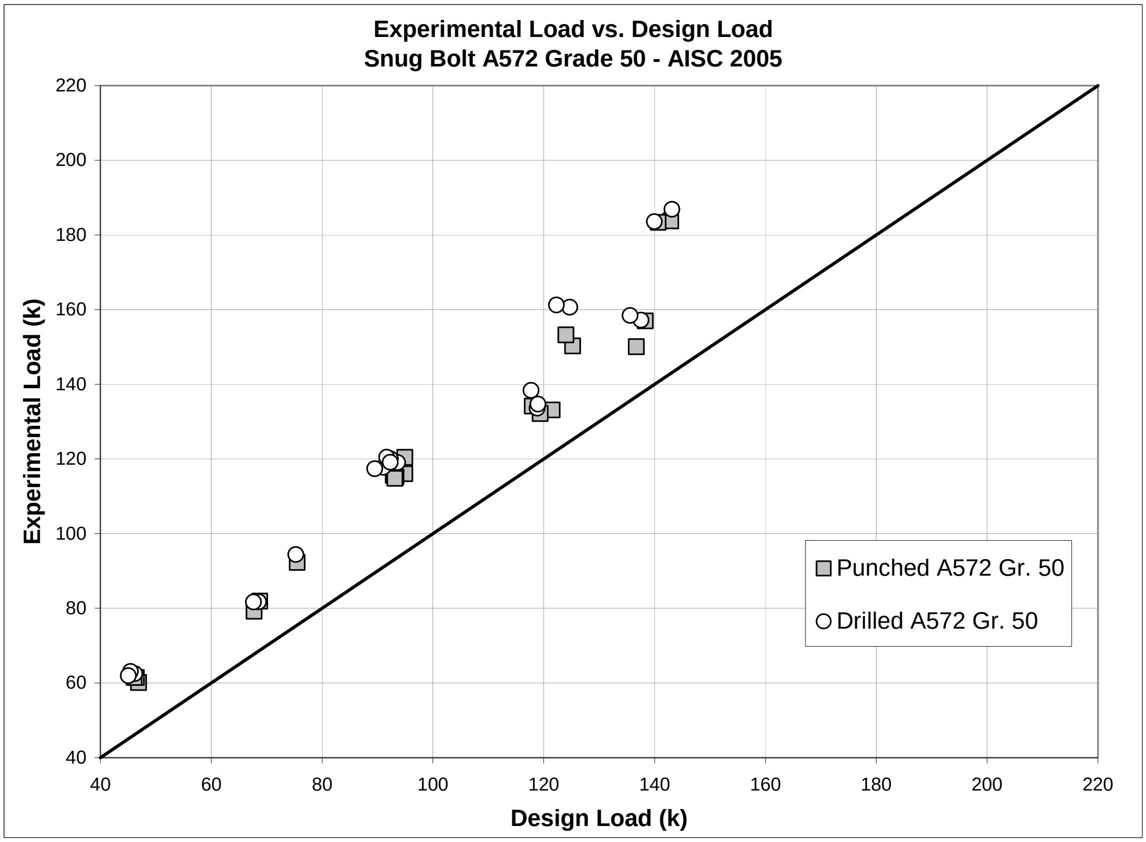

Figure 4.29: Connection Tension Test Data Comparison—A572 Grade 50 (AISC 2005 Equations)

A similar comparison for all of the connection tension tests is presented in Figure 4.30. Both the snug bolt specimens and the pretensioned bolt specimens are included. Design capacities were determined using the AISC 2005 block shear strength equation and the lower bearing strength equation using the 1.2 multiplier. Figure 4.31 presents a similar comparison if the larger bearing strength equation, 1.5 multiplier, were used in place of the lower bearing strength equation. Figure 4.31 again indicated how the larger bearing strength equation over-predicted the capacity of several of the specimens controlled by bearing strength.

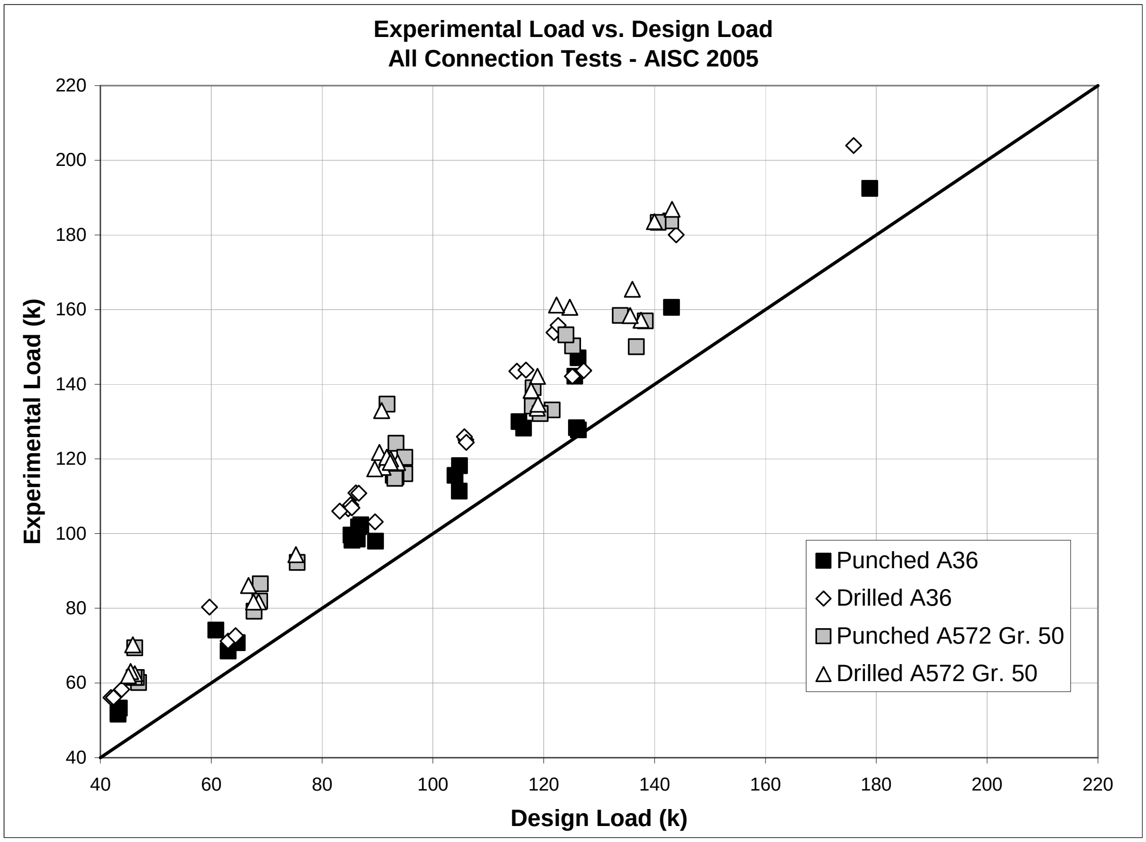

Figure 4.30: Connection Tension Test Data Comparison—All Specimens (AISC 2005 Equations, Lower Bearing Strength Equation)

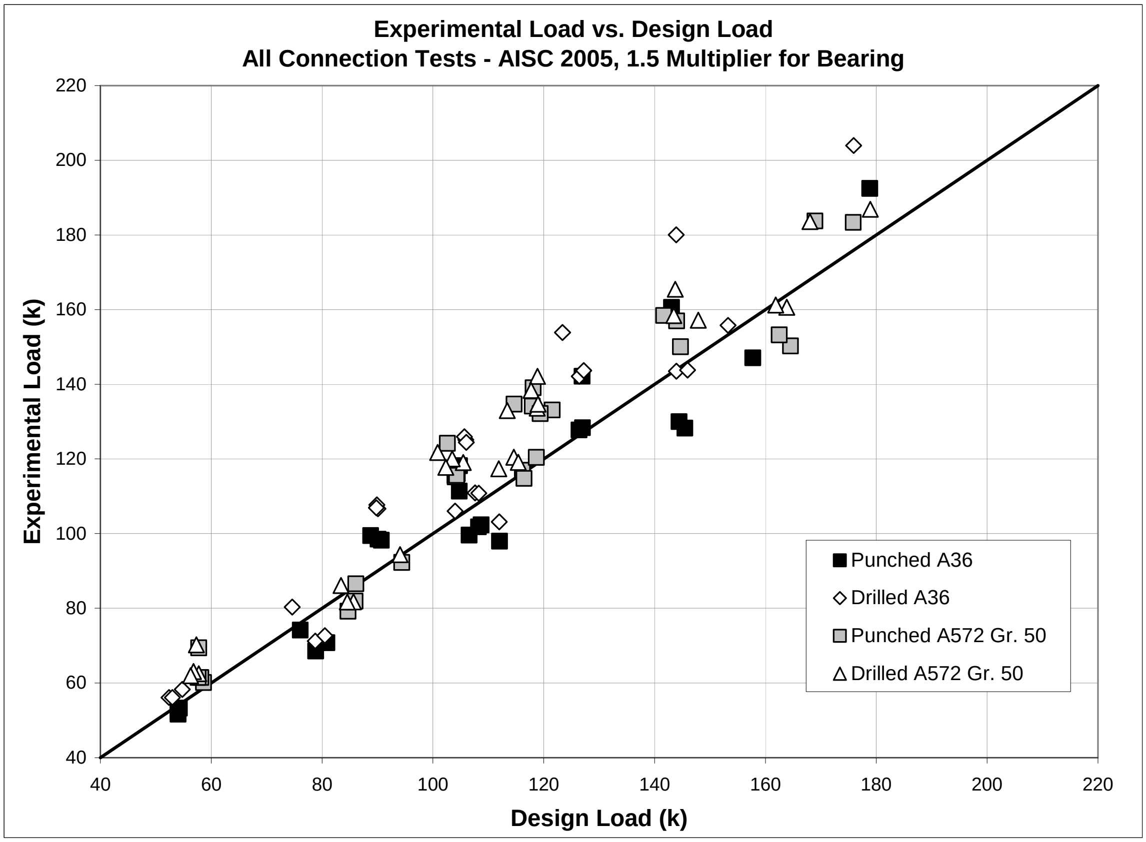

Figure 4.31: Connection Tension Test Data Comparison—All Specimens (AISC 2005 Equations, Larger Bearing Strength Equation)

The displacement at maximum load in the connection tension specimens showed similar results compared to the plate tension specimens. The punched hole specimens consistently had lower displacement values than the drilled hole specimens, as indicated by the histogram in Figure 4.32.

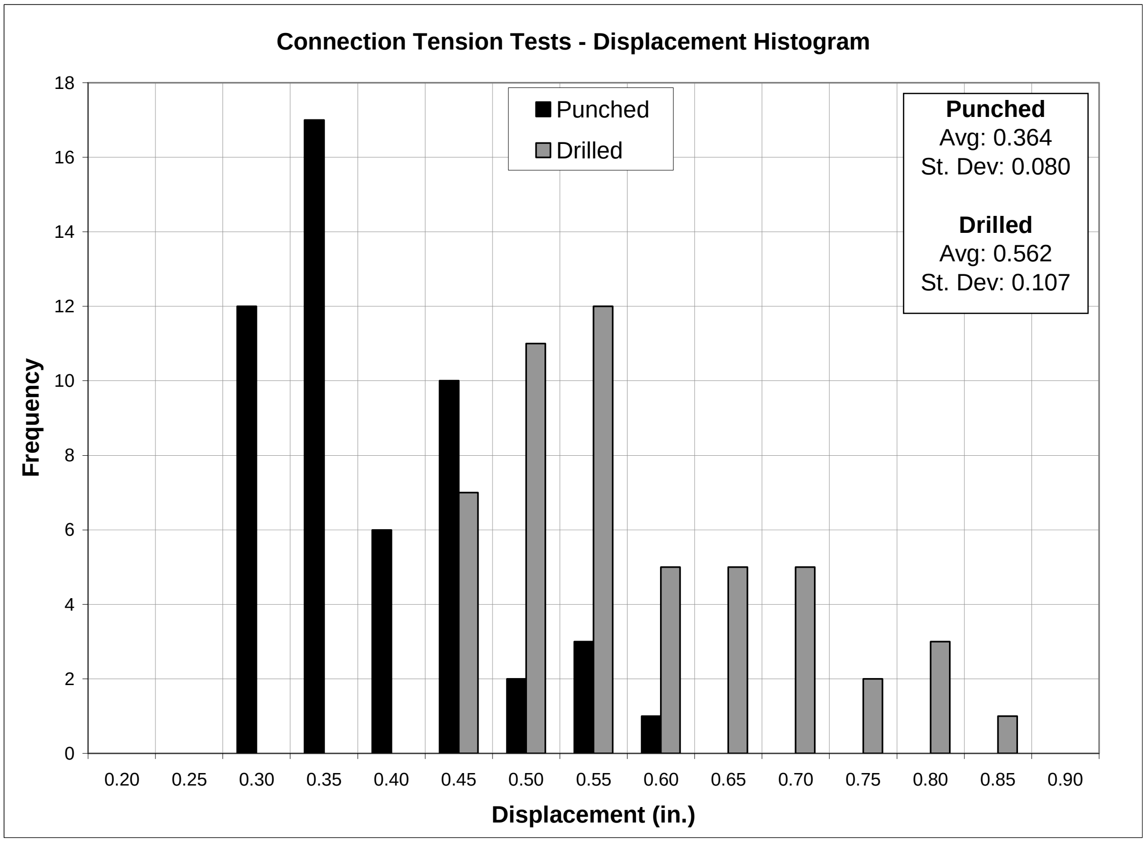

Figure 4.32: Connection Tension Specimen Displacement Histogram

Since all of the connection specimen configurations were replicated with punched holes and drilled holes, a direct comparison between the two hole types was made. Similar to the methods used in Section 4.2, a histogram is presented in Figure 4.33 showing the comparison of punched hole specimen displacement at ultimate load to the replicate drilled hole specimen displacement. The ratios were smaller for A36 steel, indicating that the punched hole displacement was lower than drilled hole displacement by a larger amount compared to A572 Grade 50 steel.

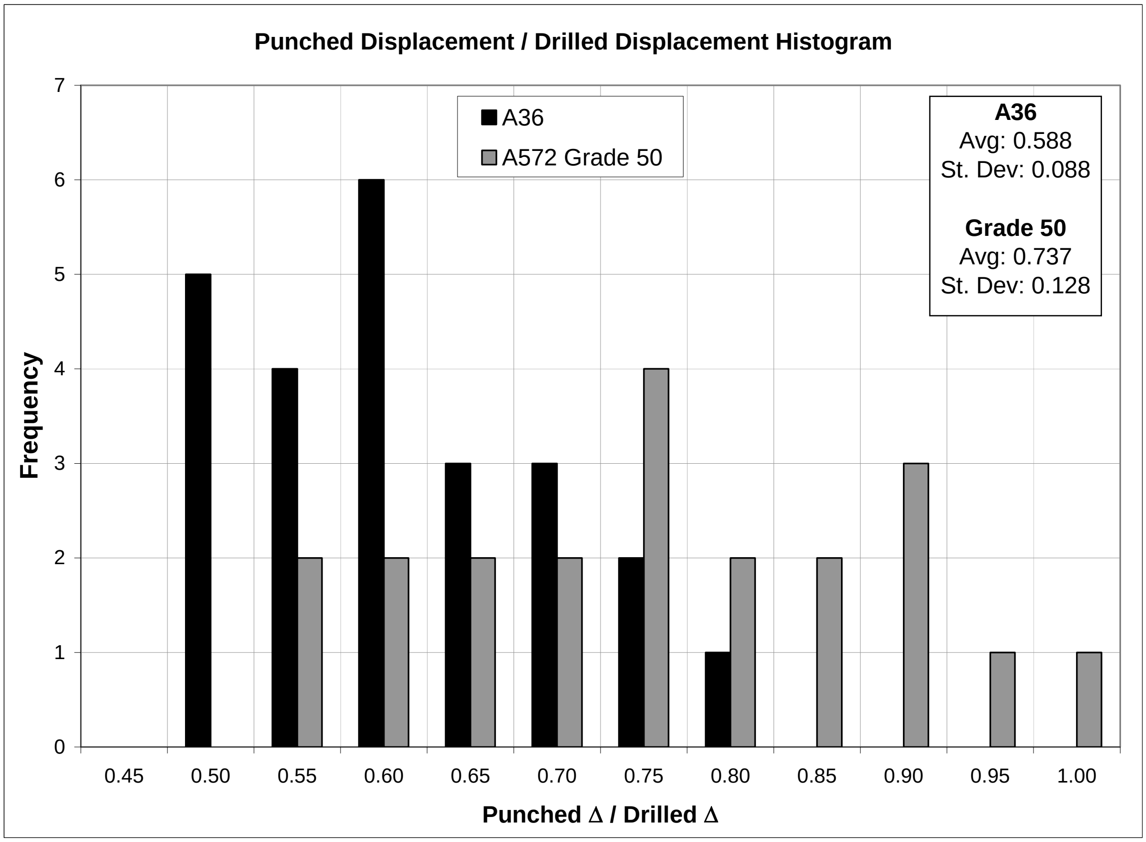

Figure 4.33: Punched Displacement / Drilled Displacement Histogram

A similar comparison was also made for the punched hole specimen load ratio divided by the replicate drilled hole specimen load ratio, presented in Figure 4.34. From this data, punched hole specimens consistently had a load ratio lower than the replicate drilled hole specimen. The punched hole load ratios were lower by a larger amount in A36 steel than the difference in A572 Grade 50 steel.

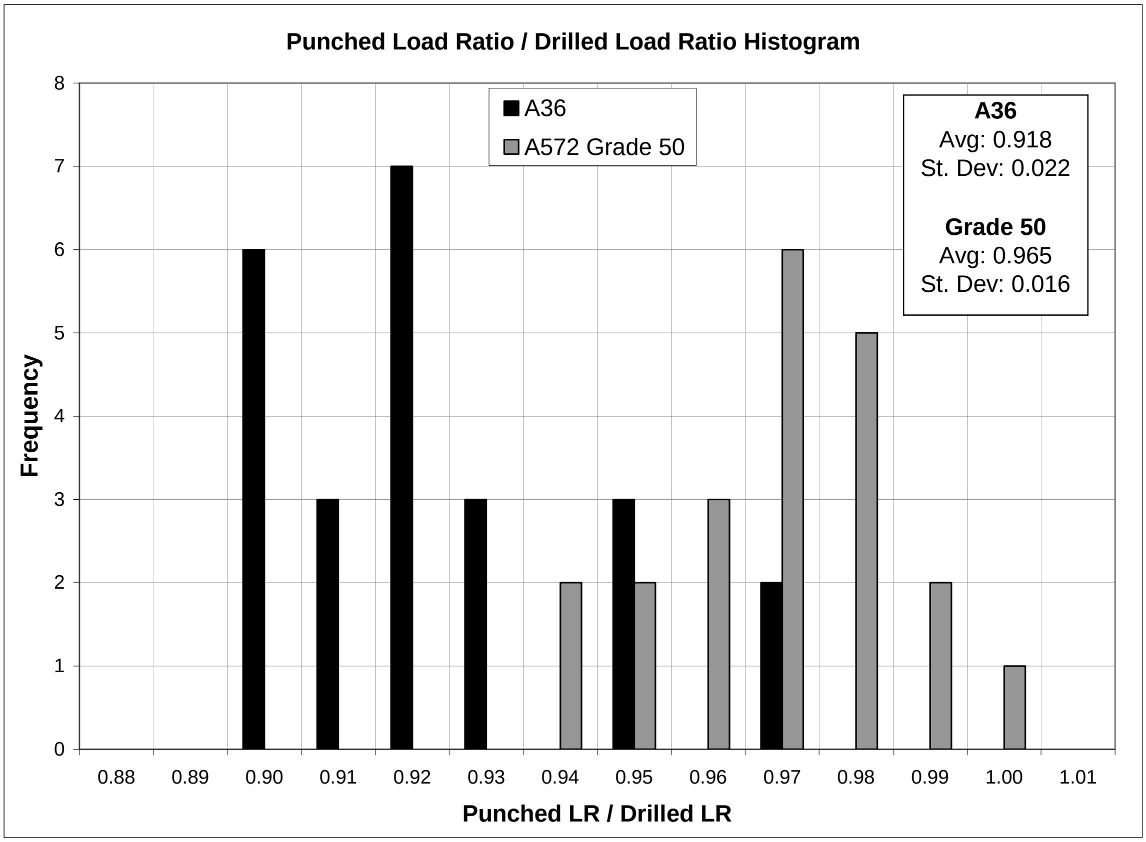

Figure 4.34: Punched Load Ratio / Drilled Load Ratio Histogram

The load ratios presented previously did not use the 1/16 in. addition to nominal hole diameter, as required by both AASHTO and AISC. As was done for the plate tension tests, the 1/16 in. addition to hole diameter and a 10% addition to hole diameter were used to see what effect hole size addition had on the load ratio values of the connection tension specimens. The hole size additions were again only used for the punched hole specimens, as the load ratios for the drilled hole specimens were well above 1.0. The effect on load ratio of the 1/16 in. and 10% hole size addition on the punched hole connection specimens with snug bolts is shown in Table 4.46. The load ratios were determined from the predicted design loads calculated from the AISC 2005 equations. Using AASHTO 2004 equations showed a similar result.

Table 4.45: Effect of Increasing Punched Hole Size on Average Load Ratio of Connections (AISC 2005 Equations)

Specimen	Nom. g (in)	Nom. Le (in)	No Hole Addition Punched Holes	1/16 in. Addition Punched Holes	10% Addition Punched Holes	Drilled Holes
1/2 in. A572 Grade 50	--	1-1/2	1.31	1.35	1.37	1.37
		2	1.18	1.20	1.22	1.20
	2-1/3	1-1/2	1.23	1.27	1.29	1.29
		2	1.11	1.14	1.16	1.14
	3	1-1/2	1.25	1.29	1.31	1.31
		2	1.12	1.14	1.15	1.16
1/2 in. A36	--	1-1/2	1.21	1.25	1.27	1.33
		2	1.09	1.11	1.12	1.13
	2-1/3	1-1/2	1.15	1.18	1.20	1.26
		2	1.10	1.12	1.14	1.18
	3	1-1/2	1.17	1.21	1.23	1.28
		2	1.02	1.04	1.05	1.13
3/4 in. A572 Grade 50	--	1-1/2	1.22	1.26	1.28	1.25
		2	--	--	--	--
	2-1/3	1-1/2	1.29	1.33	1.35	1.31
		2	--	--	--	--
	3	1-1/2	1.30	1.34	1.37	1.31
		2	--	--	--	--
3/4 in. A36	--	1-1/2	1.22	1.26	1.28	1.35
		2	1.09	1.12	1.13	1.15
	2-1/3	1-1/2	1.13	1.17	1.19	1.26
		2	1.12	1.15	1.16	1.25
	3	1-1/2	1.17	1.20	1.22	1.27
		2	1.08	1.09	1.10	1.16

The use of either the 1/16 in. or 10% addition to the hole diameter for the punched holes brought the punched hole specimen load ratio closer to the drilled hole specimen load ratio. The 10% addition further increased the punched hole load ratio. For the 15/16 in. diameter holes used, the 1/16 in. addition was equivalent to a 6.67% addition. For both the ½ in. and ¾ in. A572 Grade 50 specimens, the 10% addition brought the punched hole load ratio equal to or above the drilled hole load ratio. However, the A36 punched specimens with the hole size additions still remained beneath the drilled hole specimens.

From these results, the use of a 10% addition to hole diameter for punched hole specimens only could be recommended. The hole size addition appeared unnecessary for drilled hole specimens, as all load ratios were well above 1.0. Also, the 10% addition was not large enough to cause the A36 punched hole specimens to have load ratios similar to the punched hole specimens. As mentioned in Section 4.2, the use of a hole size addition larger than 10% was required to get all of the punched hole plate specimen strength ratios above 1.0, 48% for the punched hole plate specimens.

The connection tension test results will be used for comparison with the other research data in Section 4.9.

4.7 Connection Fatigue Test Results

Of the original 14 connection fatigue tests proposed, 12 were tested. However, the specimens that were tested in fatigue provided a clear representation of the performance of punched and drilled holes in connections with both snug and pretensioned bolts. Each specimen was made of 6 in. wide, ½ in. thick A572 Grade 50 steel with 15/16 in. diameter holes. The holes were either punched with a normal sized die or drilled with a new drill bit. The stress ranges listed were based off the gross section, with a minimum stress of 3ksi. The stress ranges were calculated from the measured dimensions of each specimen. The cycle counts for the fatigue specimens presented are the cycle count at failure or the cycle count when the test was stopped if no failure occurred above either 2 million cycles or 4 million cycles. The specimens that did not fail were considered runout specimens.

4.7.1 Pretensioned Bolt Fatigue Specimens

The results of the fatigue tests on connection specimens with pretensioned bolts are shown in Table 4.47. The pretensioned bolt specimens had a 4-bolt pattern, as described in Chapter 3. The specimens were tested at the stress ranges off the gross section indicated. The second 4-bolt punched specimen was stopped after 1 million cycles due to time constraints.

Table 4.46: Pretensioned Bolt Fatigue Test Results

Steel Grade	Number of Bolts	Gross Stress Range (ksi)	Hole Type: Punched Normal Die	Hole Type: New Drill Bit
1/2 in. A572 Gr. 50 Heat Z	4	20	3,611,171**	3,183,082**
			2,030,677**	4,032,602**
	4	30	1,927,929	N/T
			1,014,913**	N/T

Note: N/T = Specimen Not Tested, ** Runout Specimen

From the results of this investigation, the use of pretensioned bolts in a slip-critical type joint resulted in cycle counts well beyond the Category B design curve. In the joints with pretensioned bolts, the hole type used did not affect results. The load in a slip-critical type connection is transferred through friction between the faying surfaces, thus the hole type does not factor into the resistance.

Two million cycles was chosen to stop the tests to save time. Specimens which did not fail are indicated as runout tests. At the 20 ksi gross stress ranged used, 2 million cycles was well beyond a Category B design curve. At a stress range of 20 ksi, the limit for a Category B is 1.5 million cycles. The limit at a stress range of 30 ksi is approximately 450,000 cycles.

Typical examples of a pretensioned bolt connection fatigue specimen are shown in Figure 4.35 and Figure 4.36. Figure 4.35 shows the minimal damage that occurred to a connection that did not slip, had no cracking, and was labeled a runout specimen. Figure 4.36 shows a pretensioned bolt specimen that failed, though well beyond a Category B design curve.

Figure 4.35: Typical Pretensioned Bolt Connection Fatigue Runout Specimen Surfaces, N=3,611,171+

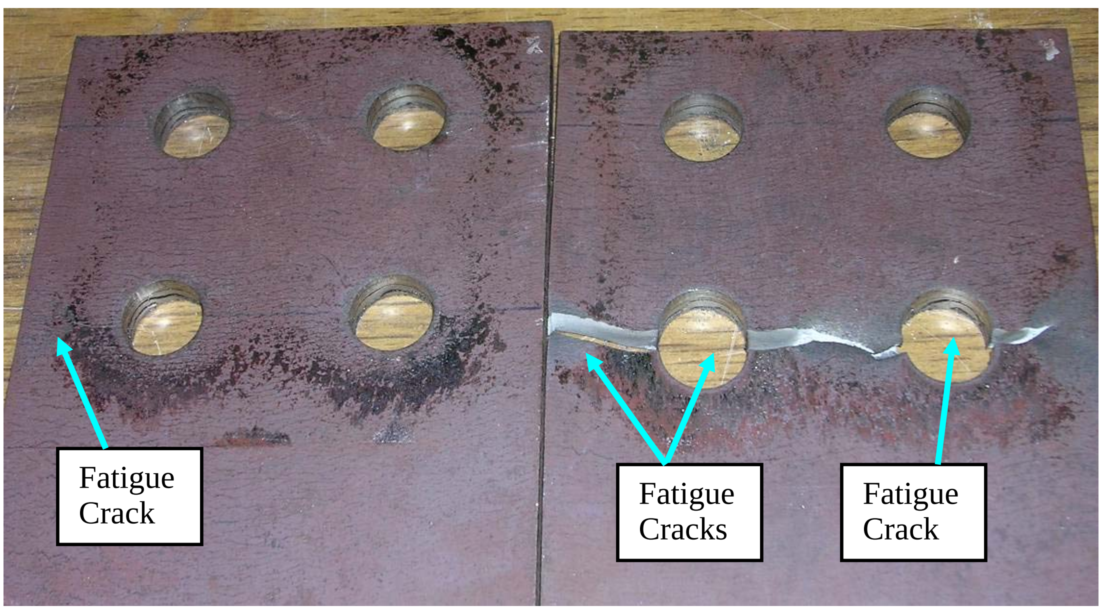

Figure 4.36: Pretensioned Bolt Connection Fatigue Specimen Failure, N=1,927,929

4.7.2 Snug Bolt Fatigue Specimens

The results of the fatigue tests on connection specimens with snug bolts are shown in Table 4.48. The specimens tested at a stress range of 20 ksi had a 4-bolt pattern, while the specimens tested at a stress range of 15 ksi had a 2-bolt pattern. The gross stress range of 20 ksi was equivalent to a net stress range of 29.1 ksi, while the gross stress range of 15 ksi was equivalent to a net stress range of 21.8 ksi.

Table 4.47: Snug Bolt Fatigue Test Results

			Hole Type	
Steel Grade	Number of Bolts	Gross Stress Range (Net) (ksi)	Punched Normal Die	New Drill Bit
1/2 in. A572 Gr. 50 Heat Z	4	20 (29.1)	233,477	205,816
			196,011	234,980
	2	15 (21.8)	525,840	379,423

From the results of the snug bolt connection fatigue tests, the use of a bearing type connection subjected to fatigue loadings resulted in a connection well below the limit of the Category B design curve. These cycle counts at failure were very low compared to the slip-critical type connections for both specimens with punched and drilled holes. From the results in Table 4.48, there appeared to be no difference between hole type in the fatigue life. With either hole making method, the connections failed at a low cycle count.

As noted in Chapter 3, several of the specimens failed at the bolt line closest to the end of the plate rather than at the second line of bolts. The bolt line closest to the end of the plate theoretically had a stress that was half of the second line of bolts, as shown in Figure 3.11. This problem was due to slight hole misalignment that caused the bolts in the far line to come into bearing before the other line of bolts could contribute. To compensate for some of the hole misalignment, the 4-bolt pattern was changed to a 2-bolt pattern, and the specimens were run at a lower stress range. From the results in Table 4.48, this improved the fatigue life of the snug bolt specimens, but not by a significant amount considering the lower stress range used.

Several examples of the failure of the snug bolt connection fatigue specimens are shown in Figure 4.37 through Figure 4.39. Figure 4.37 shows a snug bolt specimen that failed at the bolt line closest to the end of the plate, where the specimen should have failed at the second line of bolts. Figure 4.38 shows a snug bolt specimen failure at the bolt line that experienced the larger stress as expected. Figure 4.39 shows a snug bolt specimen that used a 2-bolt pattern rather than the 4-bolt pattern to eliminate hole misalignment.

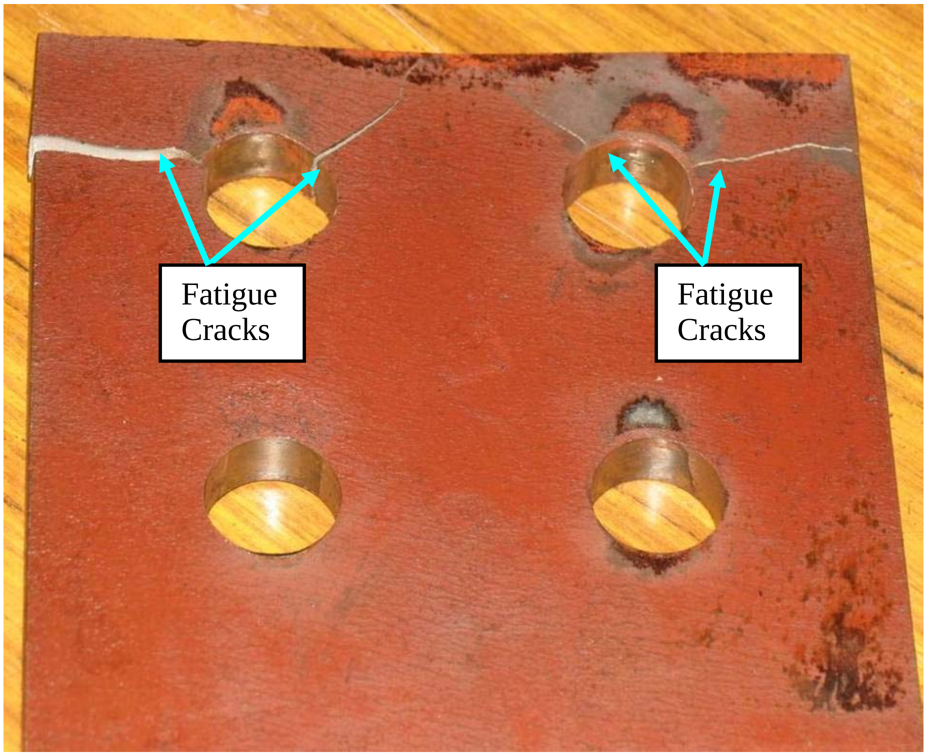

Figure 4.37: Snug Bolt Connection Fatigue Specimen at Failure, 4-Bolt Pattern, 20 ksi Stress Range, Drilled Holes, N=205,816

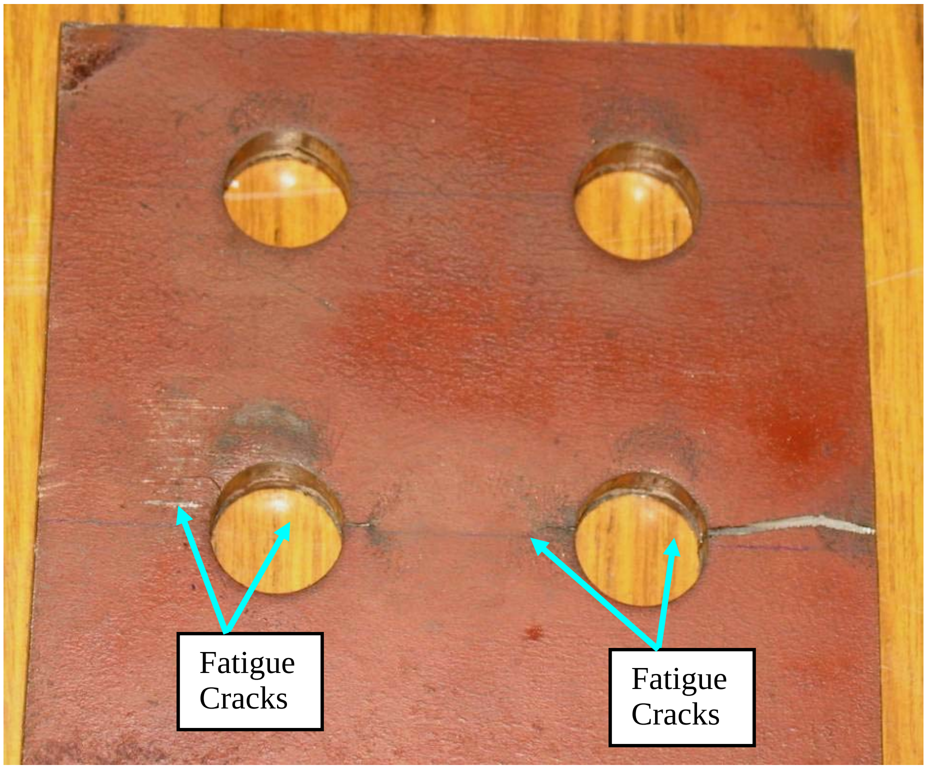

Figure 4.38: Snug Bolt Connection Fatigue Specimen at Failure, 4-Bolt Pattern, 20 ksi Stress Range, Punched Holes, N=233,477

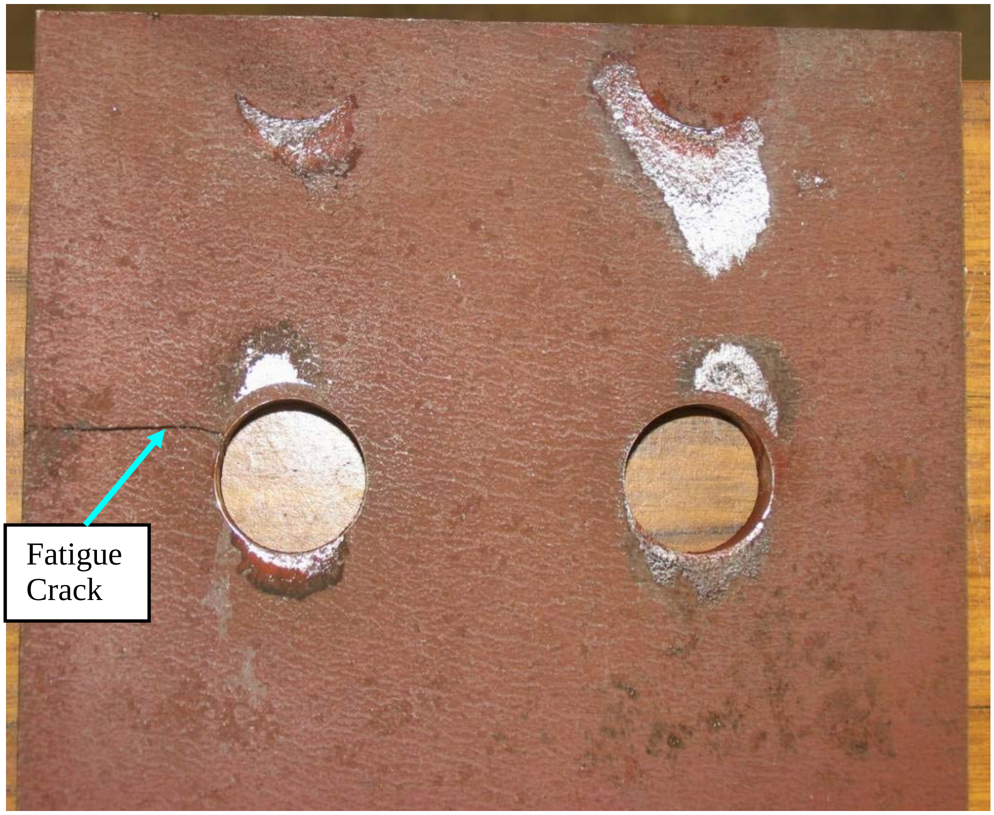

Figure 4.39: Snug Bolt Connection Fatigue Specimen at Failure, 2-Bolt Pattern, 15 ksi Stress Range, Drilled Holes, N=379,423

4.8 CONNECTION FATIGUE TEST SUMMARY

The summarized results of the connection fatigue test specimens are shown in Figure 4.40. This figure, a stress range versus number of cycles to failure curve (S.N), compared the punched hole specimens with the drilled hole specimens, both with pretensioned bolts and with snug bolts. The specimens with pretensioned bolts, a slip-critical type joint, are presented using the gross section stress range. The specimens with snug bolts, a bearing type joint, are presented using the net section stress range.

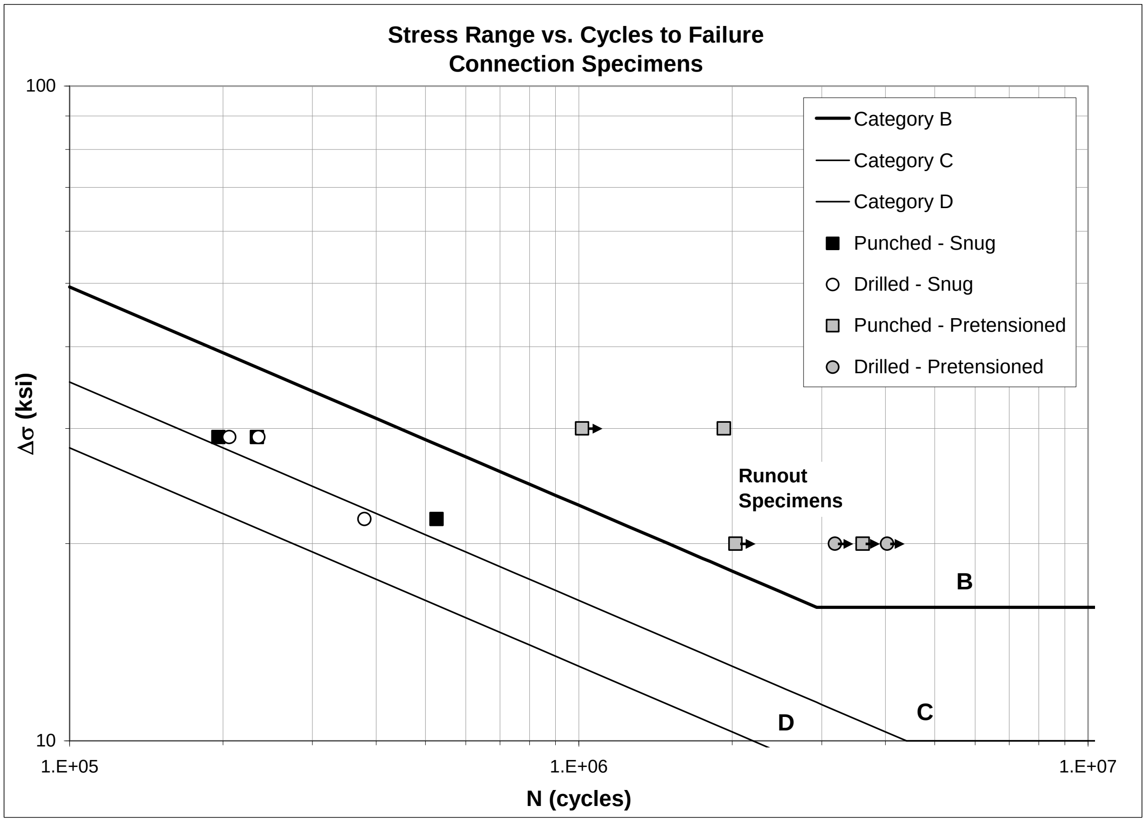

Figure 4.40: Connection Fatigue Test Results

From the results of the connection fatigue specimens summarized in Figure 4.40, it appeared that connections designed as slip-critical fall above the Category B design curve, with most of the specimens considered runout specimens. This was independent of how the holes were formed. The connection specimens designed as a bearing type connection appeared to fall into a Category C or a Category D.

The connection fatigue test results will be used for comparison with the plate fatigue test results in Section 4.9. Other research data will also be presented.

4.9 COMPARISON WITH PAST RESEARCH

As discussed in Section 4.6, the results of the connection tension tests were used to evaluate the different bearing strength equations presented in AISC 2005. The two bearing strength equations have different multipliers, $R_n = 1.2L_ctF_u \leq 2.4dtF_u$ or $R_n = 1.5L_ctF_u \leq 3.0dtF_u$. The larger bearing strength equation is used in situations “When deformation at the bolt hole at service load is not a design consideration.” As shown by comparing Figure 4.30 and Figure 4.31, several of the specimens had experimental ultimate loads that did not reach the predicted design loads determined using the larger bearing strength equation. That is, load ratios for these specimens were less than 1.0, and the points were located below the 45-degree line in the figures.

To further evaluate the significance of using the larger bearing strength equation, other research data was used in conjunction with the results of this project, as presented in Figure 4.41 using the smaller bearing strength equation and Figure 4.42 using the larger bearing strength equation. The figures include 102 data points from this project and 95 data points from past research for a total of 197 test results. The data presented did not include resistance factors or the 1/16 in. addition to hole diameter currently required by AISC. The past data used were not comparisons of punched hole performance versus drilled hole performance, but general bearing strength behavior results were still applicable.

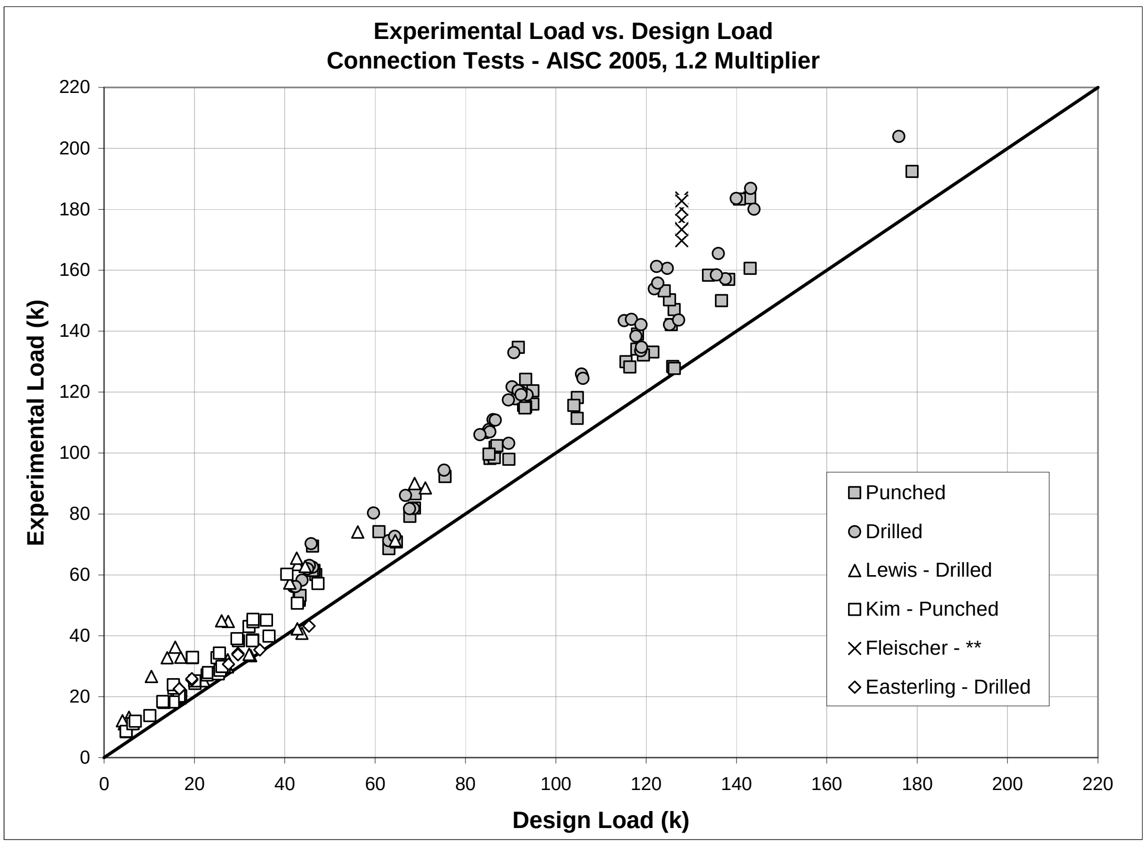

Figure 4.41: Comparison of FSEL Connection Tension Data with Other Research, using Smaller Bearing Strength Equation (AISC 2005 Equations)

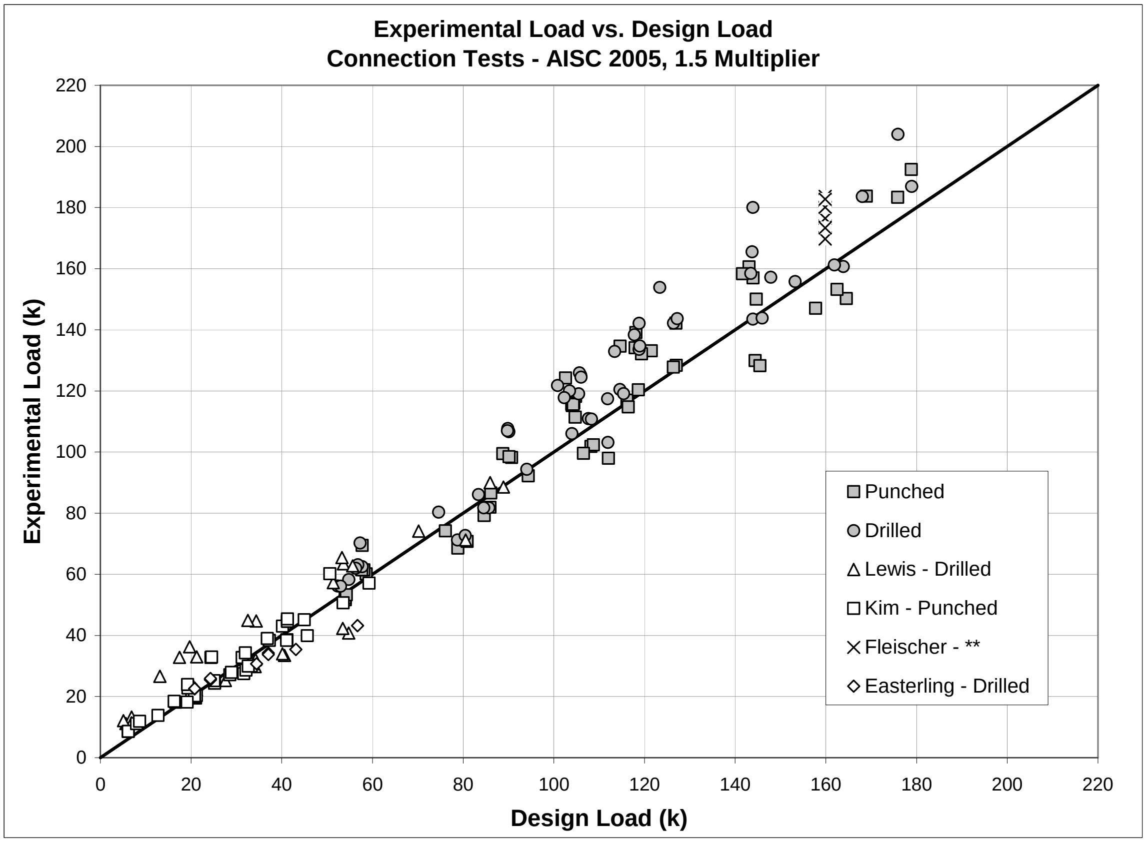

Figure 4.42: Comparison of FSEL Connection Tension Data with Other Research, using Larger Bearing Strength Equation (AISC 2005 Equations)

Lewis (1994) conducted an investigation into end distance effects with a double shear lap splice connection using a single or double bolt specimen, with bolts in a single line. Clear end distances (L_c) for the single bolt specimens ranged from 0.125 in. to 2.75 in. A gap was left between the test fixture and the test specimen to exclude friction and confinement from the results. All holes were drilled full-size. Several different heats of A36 steel were used, with ultimate strengths ranging from 62 ksi to 72 ksi. Single bolt specimens that were tested to their ultimate load were used in the figures. Other test results were presented by Lewis, but the final loads listed were the loads corresponding to a displacement of ¼ in.

Kim (1996) also investigated the effect of end distance on the bearing strength of a single shear lap splice connection. The specimens consisted of a single or double bolt in a single line. The clear end distances (L_c) for the single bolt specimens ranged from 0.3 in. to 1.5 in. The holes were punched full-size. Two heats of steel were used, with ultimate strengths of 62.3 ksi and 79.1 ksi. The setup was designed to eliminate friction from the test plate. All of the test results reported were used in the figures.

Fleischer and Puthli (2001) investigated end distance effects of high strength steel members. The steel had an ultimate strength of 93.5 ksi. A 2-bolt double shear lap splice connection was used, with a gap between the test setup and test specimen to eliminate friction and confinement. The hole type used was not presented. End distances (L_e) were 1.2 times the bolt hole diameter, for a clear end distance (L_c) of 0.8 in. Specimens that had edge distances less than AISC minimum values were not included in the figures.

Easterling and Rex (2003) performed a series of tests on single bolt double shear lap splice specimens with snug bolts. The effect of end distance, edge preparation method, plate thickness, and bolt diameter were investigated. The clear end distances used ranged from 0.5 in. to 2.5 in. Both high strength steel and mild steel were used, with many different heats included. Ultimate strengths ranged from 95 ksi to 100 ksi for high strength steel, and 64 ksi to 75 ksi for the mild steel used. The holes were drilled full size. Of the results presented, only the specimens that failed by bearing, tearout, or splitting were included in the figures. Other results were presented, but the specimens were not tested to failure, or failed by curling rather than bearing.

From the data presented in Figure 4.41 and Figure 4.42, the results from the connection tension tests conducted during this project appeared to match well with past research data. This was true for both punched hole specimens and drilled hole specimens, though the punched hole specimens consistently underperformed the drilled hole specimens. Most of the tests from this project and the past research used for comparisons consisted of connections using snug bolts or had a gap between the test pull plates and the test specimen. This eliminated friction and confinement from all results.

Comparing the two figures indicated the effect of using the larger bearing strength equation from AISC 2005, $R_n = 1.5L_ctF_u \leq 3.0dtF_u$. Many of the specimens went from being located above the 45-degree line, with a load ratio greater than 1.0, to below the line, corresponding to a load ratio less than 1.0. The lower bearing strength equation, $R_n = 1.2L_ctF_u \leq 2.4dtF_u$, provided a lower bound to all of the test data with the exception of a small percentage of points (1.5%). Conversely, the upper bearing strength equation, $R_n = 1.5L_ctF_u \leq 3.0dtF_u$, over-predicted a significant percentage of the data points (31%). More than half (62%) of these over-predicted data points were punched hole specimens from this project and Kim (1996). The larger multiplier on the bearing strength equation is not included in AASHTO 2004.

Past research data on the fatigue behavior of punched and drilled holes in plate specimens and the results of the plate fatigue tests from this project are presented for comparison in Figure

4.43. The past research, labeled 'Other-Punched' and 'Other-Drilled' includes work by Alegre, Aragon, and Gutierrez-Solana (2004), Gutierrez-Solana, Pesquera, and Sanchez (2004), and current research by Swanson at the University of Cincinnati, discussed further in Chapter 2. All of the stress ranges are based of net section properties.

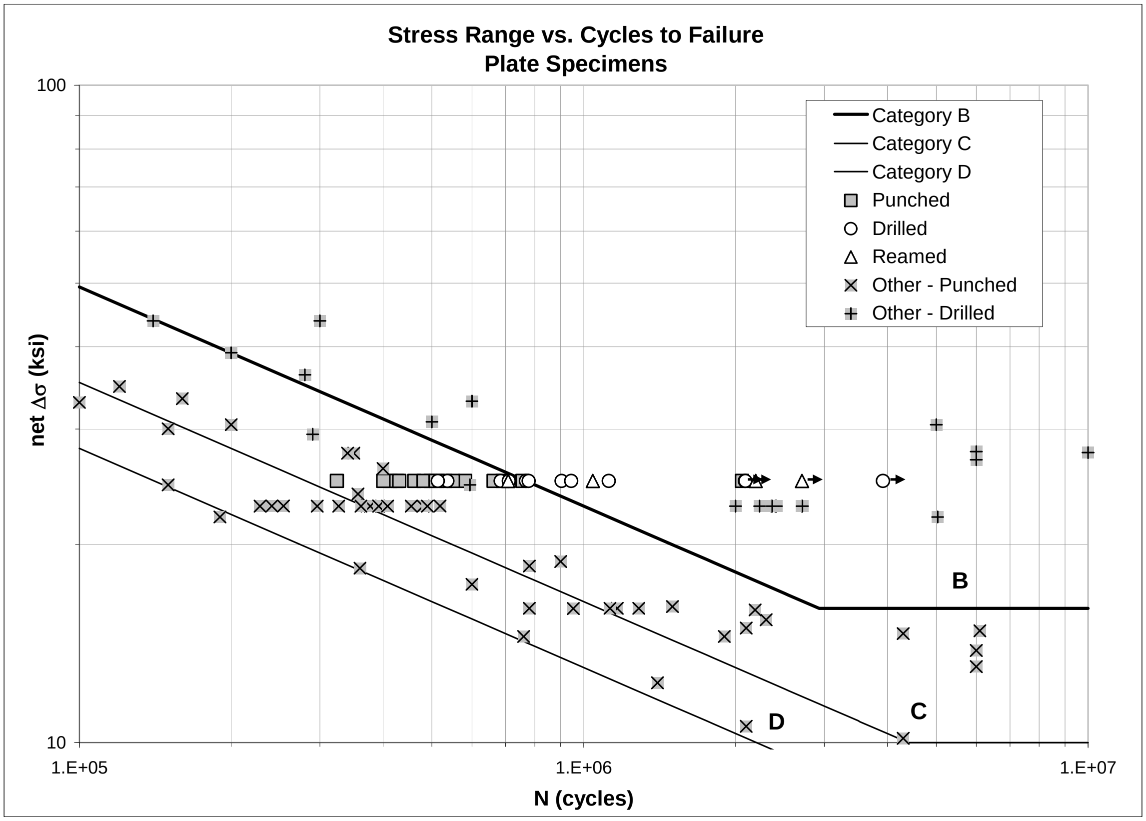

Figure 4.43: Comparison of FSEL Plate Fatigue Results with Other Research

From the data presented in Figure 4.43, the plate fatigue results from this project match reasonably well with past research data. The runout sub-punched and reamed specimens and specimens with holes drilled with a new drill bit match the performance of many of the other drilled hole specimens. However, as shown by both this project's data and a few of the 'Other-Drilled' points in the figure, several drilled hole specimens did fall into a fatigue detail Category C rather than an expected Category B. The specimens with punched holes from this project fell into a Category C, as did many of the 'Other-Punched' specimens. Several of the 'Other-Punched' specimens also fell into a Category D. Also, as the figure shows, there was a large amount of scatter in the fatigue test results. To specify a lower bound to the test data, a specimen with drilled holes would be Category C, while specimens with punched holes would be a Category D.

The results of the connection fatigue tests from this project are compared to data from other research in Figure 4.44. The stress ranges are based off the gross section for slip-critical type connections with pretensioned bolts and the net section for bearing type connections with snug bolts.

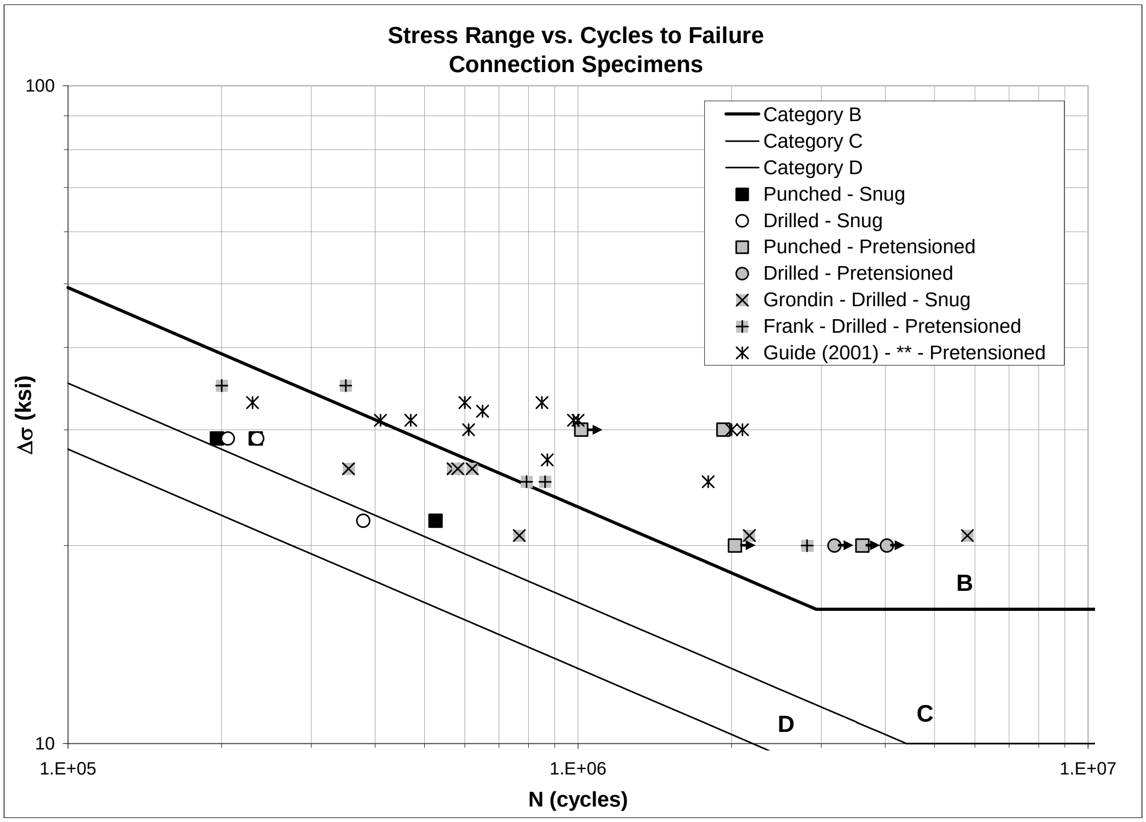

Figure 4.44: Comparison of FSEL Connection Fatigue Results with Other Research

Frank and Yura (1981) performed fatigue tests in a double shear lap configuration in slip-critical type joints. While fatigue tests were conducted on specimens with various coatings, only the blasted surface specimens were used for the comparison. Holes were drilled full size. The bolts were pretensioned, and the results presented in Figure 4.44 were plotted based off the gross section stress range.

Grondin, Josi, and Kulak (2004) also tested a double shear lap splice configuration in fatigue. The effect of staggered holes in joints was investigated in bearing type joints. However, only the specimens with non-staggered holes are used for comparison in Figure 4.44. Holes were match drilled full size. The bolts were first placed into bearing and then tightened to a snug-tight tension. The stress range used for the comparison was based off the net section.

In “Guide to Design Criteria for Bolted and Riveted Joints,” Fisher, Kulak, and Struik (2001) compiled additional data based off past fatigue research into slip-critical type joints. The configurations were similar to those used in this project. The hole types were not indicated. Since the data was presented in the form of an S-N curve, the points used in Figure 4.44 are approximate. The authors also noted the following: “Tests have indicated that the fatigue life determined from a plate with a hole provides a lower bound estimate of the fatigue strength of bolted joints that have slipped into bearing.” This claim was matched by the results of the plate and connection fatigue tests from this project. Comparing the results of the plate fatigue tests with the connection fatigue tests showed that specimens with snug bolts, a bearing type connection, had fatigue lives similar to the plate specimens, regardless of hole type in the bearing type connections.

From the data presented in Figure 4.44, both the pretensioned bolt specimens and snug bolt specimens from this project showed similar results compared to the past research data. In general, a bearing type connection had a lower bound of a fatigue detail Category C, regardless of the hole type. A slip-critical type connection would fall into Category B, regardless of hole type. Both of these lower bounds did have a few exception points.

Comparing Figure 4.43 and Figure 4.44, it appeared that the presence of a snug bolt in the bearing type connections improved fatigue life from a Category D to a Category C. However, since little fatigue data on bearing type connections without the presence of a pretensioned bolt if available, no clear conclusions can be made.

4.10 SLOTTED HOLE TESTS

4.10.1 Ultimate strength test results

The results of all tension tests are presented in this section. Each specimen consisted of 6 in. wide plate with 2 holes, which were conventional (round) or slotted holes/ The ultimate strength was calculated using the actual as-fabricated minimal net area. The strength ratio was determined by dividing the net section stress by the ultimate strength determined from the coupon tests. A strength ratio value less than 1.0 signifies a specimen that did not reach the measured ultimate strength on the net section. A strength ratio value greater than 1.0 signifies an ultimate strength greater than the measured ultimate strength. The elongation was taken as the displacement at the maximum load.

4.10.2 Oxy-act cut holes

The influence of using the oxy-act torch for creating slotted holes was investigated in this section. Results from the tests of punched holes at both ends and joint with oxy-act cut between them, drilled both ends and joint with oxy-act cut and holes cut full size with oxy-act torch are presented. Punched and drilled will be compared as reference. Tables 4.49, 4.50, and 4.51 show the results from the tests of A36 steel, 3/8” Grade 50 and ¾” Grade 50 steel.

Table 4.48: Oxy-act A36 steel ¾”

Specimen	Max Load (kips)	Elongation (in)	Max load/max load drilled	Elongation/ Elongation drilled	Strength ratio
Drilled Round 1	220.2	1.81	0.995	0.986	1.047
Drilled Round 2	222.7	1.86	1.005	1.014	1.002
Average Drilled round	**221.5**	**1.835**	**1**	**1**	**1.025**
Drilled – oxy 1	216.9	1.87	0.977	1.019	1.004
Drilled – oxy 2	212.9	1.91	0.961	1.041	0.981
Average Drilled - oxy	**214.9**	**1.89**	**0.969**	**1.03**	**0.9925**
Oxy full size 1	216	1.7	0.975	0.926	1.007
Oxy full size 2	219.3	1.92	0.99	1.046	1.016
Average Oxy full size	**217.7**	**1.81**	**0.982**	**0.986**	**1.012**
Punched - oxy 1	203.9	1.33	0.921	0.725	0.919
Punched - oxy 2	209.2	1.53	0.941	0.834	0.943
Average Punched - oxy	**206.6**	**1.43**	**0.931**	**0.779**	**0.931**
Punched round 1	208.1	1.34	0.94	0.73	0.948
Punched round 2	198.4	1.16	0.896	0.632	0.908
Average punched round	**203.3**	**1.25**	**0.917**	**0.681**	**0.928**

Table 4.49: Oxy-act Grade 50 3/8”

Specimen	Max Load (kips)	Elongation (in)	Max load/max load drilled	Elongation/Elongation drilled	Strength ratio
Drilled round 1	144.2	0.61	0.999	1	1.047
Drilled round 2	144.4	0.61	1.001	1	1.073
Average Drilled round	**144.3**	**0.61**	**1**	**1**	**1.06**
Drilled – oxy 1	137.2	0.694	0.951	1.138	0.95
Drilled – oxy 2	133	0.65	0.922	1.066	0.888
Average Drilled - oxy	**135.1**	**0.67**	**0.936**	**1.1**	**0.919**
Oxy full size 1	137	0.6	0.952	0.9836	0.944
Oxy full size 2	137	0.66	0.952	1.082	0.944
Average Oxy full size	**137**	**0.63**	**0.952**	**1.03**	**0.944**
Punched - oxy 1	134.7	0.64	0.933	1.049	0.939
Punched - oxy 2	136.9	0.57	0.949	0.934	0.923
Average Punched - oxy	**135.8**	**0.61**	**0.941**	**1**	**0.931**
Punched round 1	135.8	0.54	0.941	0.885	0.996
Punched round 2	140.4	0.53	0.973	0.869	1.022
Average punched round	**138.1**	**0.535**	**0.957**	**0.877**	**1.009**

Table 4.50: Oxy-act -Grade 50 ¾"

Specimen	Max Load (kips)	Elongation (in)	Max load/max load drilled	Elongation/Elongation drilled	Strength ratio
Drilled round 1	299.3	1.26	1.014	1.059	1.065
Drilled round 2	290.9	1.12	0.986	0.941	0.972
Average Drilled round	**295.1**	**1.19**	**1**	**1**	**1.019**
Drilled – oxy 1	265.1	0.6	0.898	0.504	0.93
Drilled – oxy 2	287.5	1.04	0.974	0.874	1.024
Average Drilled - oxy	**276.3**	**0.82**	**0.936**	**0.689**	**0.977**
Oxy full size 1	273.7	0.62	0.927	0.521	1.019
Oxy full size 2	277.2	0.71	0.939	0.597	1.045
Average Oxy full size	**275.5**	**0.665**	**0.934**	**0.559**	**1.032**
Punched - oxy 1	252.8	0.47	0.857	0.395	0.879
Punched -oxy 2					
Average Punched - oxy	**252.8**	**0.47**	**0.857**	**0.395**	**0.879**
Punched round 1	257.5	0.45	0.873	0.378	0.892
Punched round 2	247.8	0.44	0.84	0.37	0.839
Average punched round	**252.7**	**0.445**	**0.856**	**0.374**	**0.866**

The elongation for A36 steel is much higher than the elongation for Grade 50 steel. This is due to the yielding of the gross section of the A36 steel plates before the fracture at the holes occurred.

The maximum loads for slotted holes are higher than the values for punched round holes and lower than values for drilled holes. There are two exceptions for Grade 50 3/8" thick plate, where, drilled oxy and punched oxy are lower than punched round holes.

The elongation of the slotted holes was always higher than the elongation of the punched holes and was lower than the drilled holes, again with two exceptions. Drilled oxy and oxy full size specimens for Grade 50 3/8" thick plates had to 10 % larger elongation than the drilled holes.

The average strength ratio of drilled hole specimens was always more than 1 and only one specimen, Grade 50 ¾" specimen 2, failed before the net stress reached the ultimate strength of the steel. This is in agreement with the results reported by Brown (2006). The average strength ratio of punched holes specimens was more than 1 once - for Grade 50 3/8”. For the other two tests the ratio was less than 1.

The average strength ratio for drilled oxy and punched oxy was always less than 1, and for oxy full size twice was higher than 1 and once less than 1.

4.10.3 Plasma cut

The influence of using the plasma torch for creating slotted holes was investigated in this section. Results from the tests of punched holes at both ends and joint with plasma cuts between them, drilled both ends and joint with plasma cuts and holes cut full size with plasma torch are presented. Punched and drilled holes are compared as a reference. Tables 4.52, 4.53, and 4.54 show the results from the tests of A36 steel, 3/8” Grade 50 and ¾” Grade 50 steel.

Table 4.51: Plasma—A36 steel ¾”

Specimen	Max Load (kips)	Elongation (in)	Max load/max load drilled	Elongation/Elongation drilled	Strength ratio
Drilled round 1	220.2	1.81	0.995	0.986	1.047
Drilled round 2	222.7	1.86	1.005	1.014	1.002
Average Drilled round	**221.8**	**1.835**	**1**	**1**	**1.025**
Drilled – plasma 1	201.2	1.381	0.907	0.753	0.972
Drilled – plasma 2	201.3	1.207	0.908	0.658	0.947
Average Drilled - plasma	**201.25**	**1.29**	**0.907**	**0.703**	**0.96**
Plasma full size 1	207.5	1.353	0.934	0.737	1.018
Plasma full size 2	218.5	1.668	0.985	0.909	1.015
Average plasma full size	**213**	**1.51**	**0.96**	**0.823**	**1.0165**
Punched - plasma 1	202.1	1.19	0.911	0.649	0.966
Punched - plasma 2	199.6	1.041	0.9	0.567	0.934
Average Punched - plasma	**200.9**	1.12	**0.906**	**0.61**	**0.95**
Punched round 1	208.1	1.34	0.94	0.73	0.948
Punched round 2	198.4	1.16	0.896	0.632	0.908
Average punched round	**203.3**	**1.25**	**0.917**	**0.681**	**0.928**

Table 4.52: Plasma—Grade 50 3/8"

Specimen	Max Load (kips)	Elongation (in)	Max load/max load drilled	Elongation/Elongation drilled	Strength ratio
Drilled round 1	144.2	0.61	0.999	1	1.047
Drilled round 2	144.4	0.61	1.001	1	1.073
Average Drilled round	**144.3**	**0.61**	**1**	**1**	**1.06**
Drilled – plasma 1	139	0.6366	0.963	1.044	1.018
Drilled – plasma 2	136.1	0.6425	0.943	1.053	1.015
Average Drilled - plasma	**137.6**	**0.64**	**0.954**	**1.05**	**1.0165**
Plasma full size 1	133.9	0.4929	0.928	0.808	0.986
Plasma full size 2	134	0.5676	0.929	0.931	1.014
Average plasma full size	**133.95**	**0.53**	**0.928**	**0.869**	**1**
Punched - plasma 1	138.3	0.6075	0.958	0.996	1.039
Punched - plasma 2	138.2	0.6316	0.958	1.04	1.032
Average Punched - plasma	**138.25**	**0.62**	**0.958**	**1.02**	**1.0355**
Punched round 1	135.8	0.54	0.941	0.885	0.996
Punched round 2	140.4	0.53	0.973	0.869	1.022
Average punched round	**138.1**	**0.535**	**0.957**	**0.877**	**1.009**

Table 4.53: Plasma—Grade 50 ¾"

Specimen	Max Load (kips)	Elongation (in)	Max load/max load drilled	Elongation/Elongation drilled	Strength ratio
Drilled round 1	299.3	1.26	1.014	1.059	1.065
Drilled round 2	290.9	1.12	0.986	0.941	0.972
Average Drilled round	**295.1**	**1.19**	**1**	**1**	**1.019**
Drilled – plasma 1	265.6	0.5679	0.9	0.477	1.01
Drilled – plasma 2	282.1	0.6674	0.956	0.561	1.03
Drilled– plasma 3	271.1	0.5756	0.919	0.484	0.985
Drilled – plasma 4	269.5	0.6119	0.913	0.767	1.044
Average Drilled - plasma	**272.1**	**0.606**	**0.922**	**0.509**	**1.02**
Plasma full size 1	283	0.6826	0.959	0.574	1.038
Plasma full size 2	257.1	0.3918	0.871	0.329	0.936
Average plasma full size	**270.1**	**0.5372**	**0.915**	**0.451**	**0.987**
Punched - plasma 1	243.4	0.4373	0.825	0.367	0.88
Punched - plasma 2	248.9	0.4677	0.843	0.393	0.894
Punched – plasma3	242.6	0.4891	0.822	0.411	0.891
Punched – plasma4	250.1	0.5129	0.848	0.431	0.898
Average Punched - plasma	**246.25**	**0.477**	**0.834**	**0.401**	**0.891**
Punched round 1	257.5	0.45	0.873	0.378	0.892
Punched round 2	247.8	0.44	0.84	0.37	0.839
Average punched round	**252.7**	**0.445**	**0.856**	**0.374**	**0.866**

The maximum loads for most of the slotted holes are lower than the values for punched round holes. The elongation of the slotted holes varies from 0.401 to 1.05 of the drilled holes. There are three occasions where it is higher than the drilled holes, but there are also two occasions when it is lower than punched holes. The average strength ratio for the plasma-cut specimens is split almost in the middle. Five of the average values are above 1 and four are under 1. For Grade 50 steel 3/8" plates all the specimens are above 1.

4.10.4 Laser cut

Results presented in this section focus on the influence of using the plasma torch for creating slotted holes. The results from the tests of the laser cut full size and punched and drilled as reference are investigated. Tables 4.55, 4.56, and 4.57 show the results from the tests of A36 steel, 3/8" Grade 50 and ¾" Grade 50 steel.

Table 4.54: Laser cut A36 steel ¾"

Specimen	Max Load (kips)	Elongation (in)	Max load/max load drilled	Elongation/ Elongation drilled	Strength ratio
Drilled round 1	220.2	1.81	0.995	0.986	1.047
Drilled round 2	222.7	1.86	1.005	1.014	1.002
Average Drilled round	**221.8**	**1.835**	**1**	**1**	**1.025**
Laser 1	211	1.512	0.951	0.824	1.003
Laser 2	208.4	1.415	0.94	0.771	0.907
Average Laser	**209.7**	**1.464**	**0.945**	**0.798**	**0.955**
Punched round 1	208.1	1.34	0.94	0.73	0.948
Punched round 2	198.4	1.16	0.896	0.632	0.908
Average punched round	**203.3**	**1.25**	**0.917**	**0.681**	**0.928**

Table 4.55: Laser cut Grade 50 3/8"

Specimen	Max Load (kips)	Elongation (in)	Max load/max load drilled	Elongation/ Elongation drilled	Strength ratio
Drilled round 1	144.2	0.61	0.999	1	1.047
Drilled round 2	144.4	0.61	1.001	1	1.073
Average Drilled round	**144.3**	**0.61**	**1**	**1**	**1.06**
Laser 1	139	0.744	0.963	1.22	0.913
Laser 2	134.6	0.763	0.933	1.251	0.924
Average Laser	**136.8**	**0.754**	**0.948**	**1.236**	**0.919**
Punched round 1	135.8	0.54	0.941	0.885	0.996
Punched round 2	140.4	0.53	0.973	0.869	1.022
Average punched round	**138.1**	**0.535**	**0.957**	**0.877**	**1.009**

Table 4.56: Grade 50 ¾”

Specimen	Max Load (kips)	Elongation (in)	Max load/max load drilled	Elongation/ Elongation drilled	Strength ratio
Drilled round 1	299.3	1.26	1.014	1.059	1.065
Drilled round 2	290.9	1.12	0.986	0.941	0.972
Average Drilled round	**295.1**	**1.19**	**1**	**1**	**1.019**
Laser 1	279.8	0.7	0.948	0.588	0.964
Laser 2	278.1	0.713	0.942	0.599	0.967
Average Laser	**279**	**0.707**	**0.945**	**0.594**	**0.9655**
Punched round 1	257.5	0.45	0.873	0.378	0.892
Punched round 2	247.8	0.44	0.84	0.37	0.839
Average punched round	**252.7**	**0.445**	**0.856**	**0.374**	**0.866**

The maximum loads for most of the slotted holes specimens were less than the values for drilled holes and higher than the values for punched holes with the exception for Grade 50 3/8” thick specimens which are lower than the punched holes. For the same pair of specimens the average elongation is higher than the drilled holes and for the other two pairs the values are in the middle between the drilled and punched hole specimens. The average strength ratio for all the laser-cut holes is less than 1.

4.10.5 Punched holes

Results presented in this section are focusing on the influence of punching full size short and long slotted holes. Tables 4.58, 4.59, and 4.60 show the results from the tests of A36 steel, 3/8” Grade 50, and ¾” Grade 50 steel.

Table 4.57: Punched A36 steel ¾"

Specimen	Max Load (kips)	Elongation (in)	Max load/max load drilled	Elongation/Elongation drilled	Strength ratio
Drilled round 1	220.2	1.81	0.995	0.986	1.047
Drilled round 2	222.7	1.86	1.005	1.014	1.002
Average Drilled round	**221.8**	**1.835**	**1**	**1**	**1.025**
Fabricator's punched long slotted	205.8	1.205	**0.928**	**0.657**	**0.956**
Fabricator's punched short slotted	212.8	1.245	**0.959**	**0.678**	**0.972**
Ferguson punched short slotted 1	206.1	1.252	0.929	0.682	0.877
Ferguson punched short slotted 2	205.5	1.184	0.927	0.645	0.967
Average	**205.8**	**1.218**	**0.928**	**0.664**	**0.922**
Punched round 1	208.1	1.34	0.94	0.73	0.948
Punched round 2	198.4	1.16	0.896	0.632	0.908
Average punched round	**203.3**	**1.25**	**0.917**	**0.681**	**0.928**

Table 4.58: Grade 50 3/8"

Specimen	Max Load (kips)	Elongation (in)	Max load/max load drilled	Elongation/Elongation drilled	Strength ratio
Drilled round 1	144.2	0.61	0.999	1	1.047
Drilled round 2	144.4	0.61	1.001	1	1.073
Average Drilled round	**144.3**	**0.61**	**1**	**1**	**1.06**
Fabricator's punched long slotted	135.3	0.5	**0.938**	**0.82**	**1.006**
Fabricator's punched short slotted	140.1	0.47	**0.971**	**0.77**	**1.041**
Ferguson punched short slotted 1	140.5	0.446	0.974	0.731	1.034
Ferguson punched short slotted 2	141.8	0.467	0.983	0.766	1.039
Average	**141.2**	**0.457**	**0.979**	**0.749**	**1.037**
Punched round 1	135.8	0.54	0.941	0.885	0.996
Punched round 2	140.4	0.53	0.973	0.869	1.022
Average punched round	**138.1**	**0.535**	**0.957**	**0.877**	**1.009**

Table 4.59: Grade 50 ¾"

Specimen	Max Load (kips)	Elongation (in)	Max load/max load drilled	Elongation/ Elongation drilled	Strength ratio
Drilled round 1	299.3	1.26	1.014	1.059	1.065
Drilled round 2	290.9	1.12	0.986	0.941	0.972
Average Drilled round	**295.1**	**1.19**	**1**	**1**	**1.019**
Fabricator's punched long slotted	257.8	0.405	**0.874**	**0.34**	**0.905**
Fabricators punched short slotted	264	0.367	**0.895**	**0.308**	**0.931**
Ferguson punched short slotted 1	256.4	0.367	0.869	0.308	0.915
Ferguson punched short slotted 2	266.8	0.402	0.904	0.338	0.946
Average	**261.6**	**0.3845**	**0.886**	**0.323**	**0.931**
Punched round 1	257.5	0.45	0.873	0.378	0.892
Punched round 2	247.8	0.44	0.84	0.37	0.839
Average punched	**252.7**	**0.445**	**0.856**	**0.374**	**0.866**

The average maximum loads for the short slotted holes are higher than the values for punched round holes but lower than the values for drilled holes. For long slotted holes this is true only for two of the specimens. For grade 50 3/8" specimen the average maximum load is less than the average of the punched holes specimen. The elongations of all slotted hole specimens, short and long, were lower than the elongation of the punched specimens. The strength ratios of the A36 slotted hole specimens were less then one. It is interesting that the values for Grade 50 3/8" specimen all were higher than one, but for Grade 50 ¾" less than 1.

4.11 SUMMARY AND ANALYSIS

As was described in Chapter 3, the slotted holes that are made by oxy-act or plasma cut are rough, and the width of the holes varied along the hole. The strength ratios of the specimens were calculated by dividing the maximum load by the minimum net area. All these factors benefit the bad geometry holes because their net area was smaller than the specimens with good geometry holes. This resulted in a calculated higher strength ratio than a ratio calculated using their nominal hole size. From a designer's perspective, the minimum net area is calculated using the nominal hole diameter.

After the recalculation of the strength ratios with the nominal area, three drilled plasma specimens, one fabricator's long slotted specimen, one laser-cut specimen, three oxy full size specimens, and two plasma full size specimens, went from over 1 strength ratio to less than 1. As expected, the majority of the specimens that reduced to less than 1 when using nominal hole size were those made by oxy-act or plasma cutting.

The stress concentration at the edge of the hole is three times higher than the gross area stress. The stress concentration declines relatively quickly and the stress at the outside edge of the plate is equal to the net area stress as depicted in Figure 4.45.

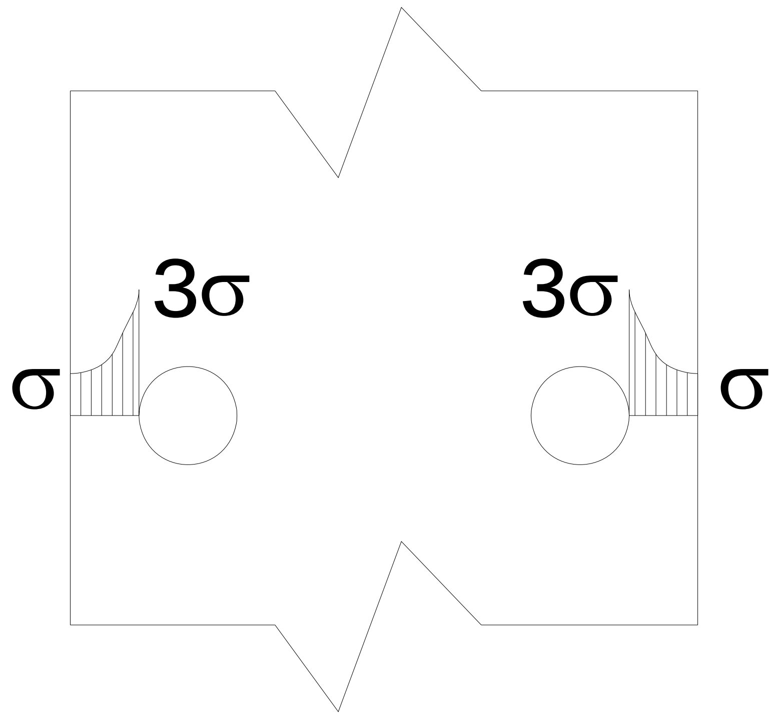

Figure 4.45: Distribution of stresses around round holes

Because of the sharp decline of the stress concentration only a small area region around the hole initially yields and then distributes the stresses to the material that is further from the hole. As a result, all the stresses even out above a certain stress level. For that reason, theoretically the nominal strength ratio would be equal to 1. In other words, when the stress of the net area gets to the ultimate strength, the specimen must fracture. But there are strength ratios, reported by Lubitz (2005) and Brown (2006), that are higher than 1. The reason for these higher ratios is that the cross section that is next to the most critical cross section stays elastic and constrains the inelastic deformation of the critical net section. The ultimate strength value is measured in a uniform cross section coupon test which is not subject this elastic constraint. The ultimate strength is controlled by the weakest cross section, the one with the most defects, along the length of the reduced section of the coupon specimen. All this leads to the ultimate strength values for drilled round holes to more than 1. However, the damage done when punching a hole overcomes these factors that reduce the ratio to less than 1.

The punched short slotted holes behave in a similar manner as the punched round holes. Figure 4.46 compares the strength ratios of the punched round and slotted holes for the three steels. The performance of the specimens with punched slotted holes was comparable to the punched round holes. The ¾" Grade 50 plates gave the lowest and 3/8" Grade 50 plates the highest strength ratios.

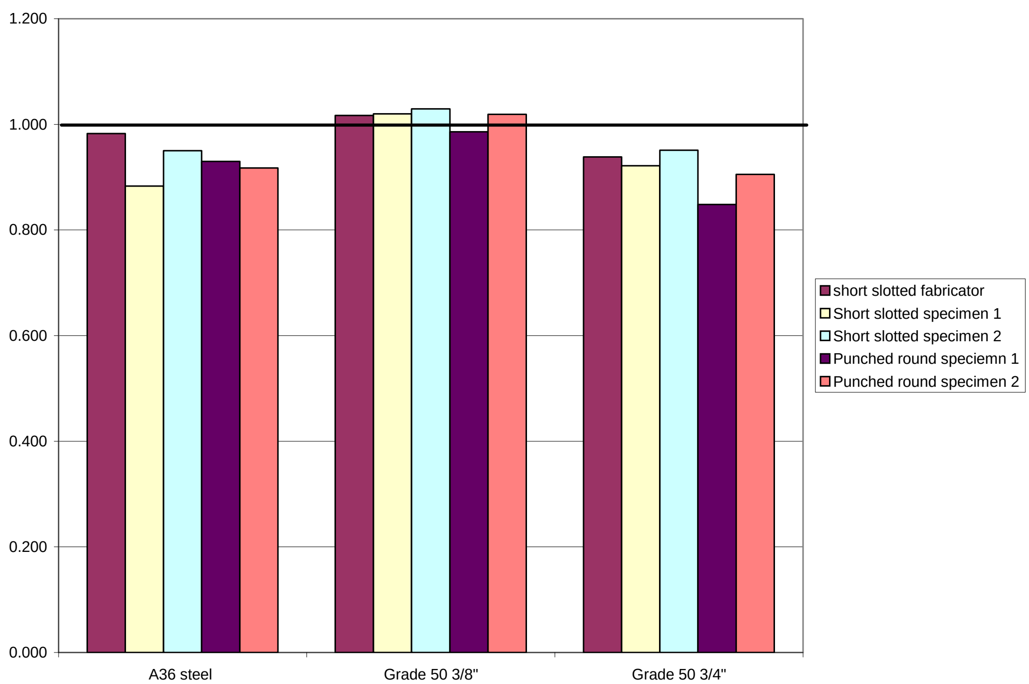

Figure 4.46: Strength ratio of short slotted and punched round holes

Figure 4.47 presents the long slotted punched full size compared with the punched round holes. The results of the long slotted holes specimens are comparable to the round holes specimens. The behavior is similar to the short slotted holes.

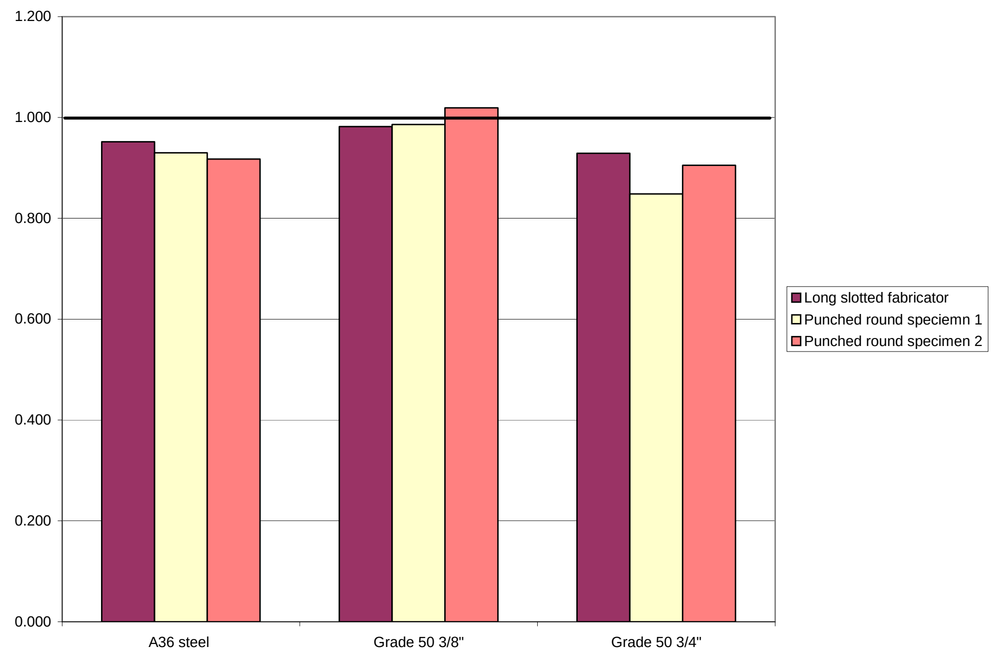

Figure 4.47: Long slotted punched holes vs. Punched round holes

There is significant difference in the behavior of round holes and slotted holes. First, round holes has only one section with minimal net area on both sides of which are sections that remain elastic when the critical section starts yielding. Slotted holes do not have this benefit since all the cross section along the line of the slotted holes have the same minimum net area. As a result, all of the cross sections along the slot are subjected to the same nominal net section stresses. The restraint provided by the large gross section adjacent to a round hole is not present along the sides of the slotted hole. Also when the hole is slotted the size effect is similar to a coupon test—there is higher chance to find a weaker cross section than when there is only one critical cross section in the specimens round holes. From this reasoning, slotted holes perpendicular to the direction of stress will behave more like round holes since the cracks will form at the rounded end of the slot. The results of this study provide a lower bound to the behavior of hole slotted in the direction of stress.

However, there are other factors that benefit the slotted holes such as smaller stress concentration factors when the hole is slotted. According to Peterson (Stress concentration factors, 1953) the stress concentration factor for round holes in infinitely wide plate is 3 while the factor increases to 3.5 for plates with a finite width. For two round holes next to each other, which provides an estimate for the slotted holes, they are 2.8 for the infinite plate and 3.25 for the specimen geometry. If the slotted hole is treated as elliptical hole the values are in the same range as the adjacent holes. Also, the stresses are not constant along the length of the slot. They peak at the first critical section (the first section with minimum net area), and then reduce in value. This is evident by the way all the slotted-holes specimens failed. The failure starts at the first and last minimum area cross section of the slotted holes where the slot is tangent to the round hole. Figure 4.48 shows a typical tensile failure of a specimen with two slotted holes.

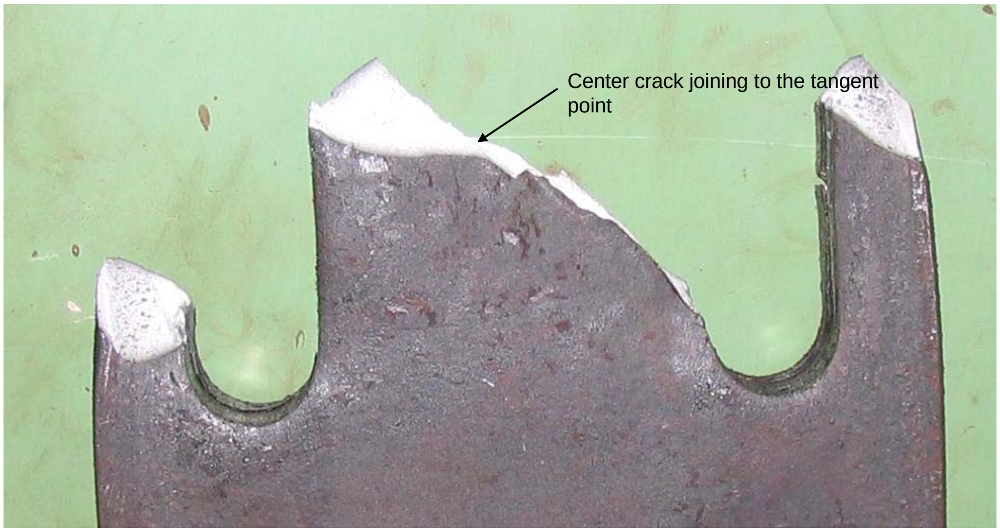

Figure 4.48: Typical failure mode of long slotted punched holes

The maximum load occured just before the development of the two side cracks. The crack between the holes formed after the side ligaments had fractured.

In most of the A36 steel and all grade 50 steel and 3/8” thick plate specimens, with the exception of one of the slotted cut full size with the plasma torch, the failure mode were similar to the failure shown above—with a diagonal crack, sign of yielding, between the two holes. A typical failure of Grade 50 3/8” thick plate specimen can be seen in Figure 4.49.

Figure 4.49: Typical failure for Grade 50 steel 3/8” plate

One Grade 50 3/8” plate failed in a brittle manner. It had 57% percent of the elongation and 90% of the maximum force of its replicate specimen. Figure 4.50 shows the fractures of the two replicate specimens.

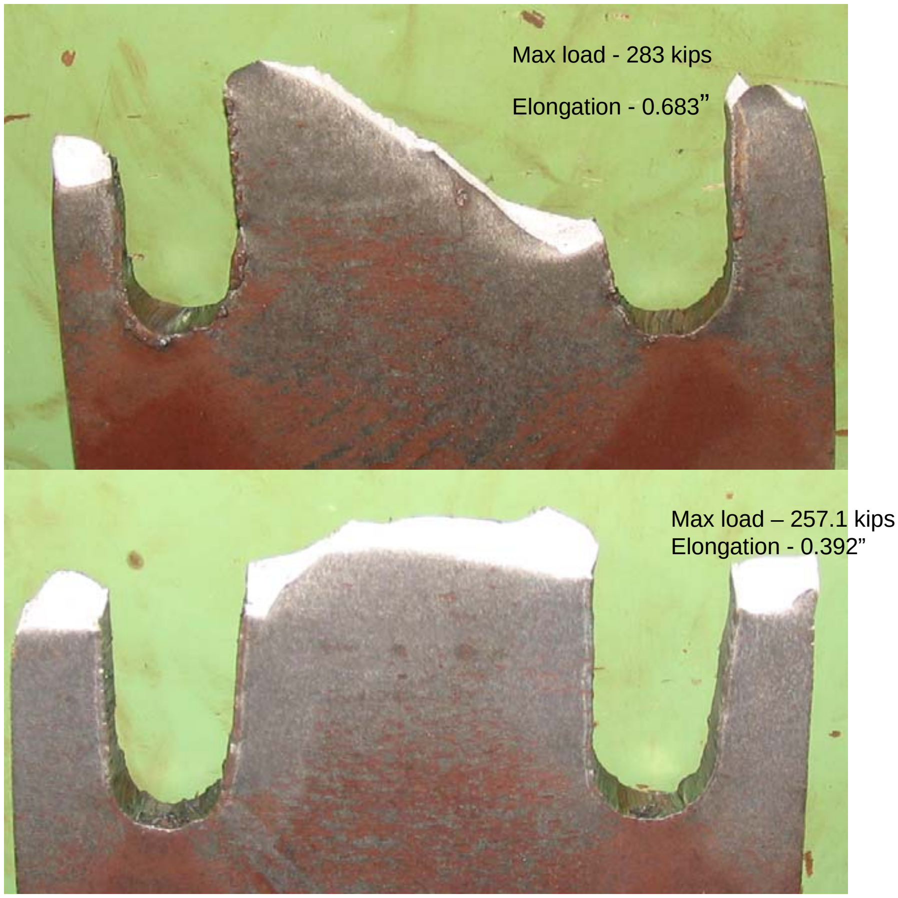

Figure 4.50: Grade 50 3/8” Specimens 1 and 2

The A36 specimens, such as the punched plasma and drilled plasma, plasma full size and oxy full size, failed in a ductile manner with a fracture in a single plane as shown in Figure 4.51.

Figure 4.51: Single plane failure of A36 steel specimen

Most of the Grade 50 ¾” specimens, with the exception of some of the replicate specimens, i.e. the drilled plasma specimens 1 and 2 (there are 4 specimens of this kind), the punch plasma specimen 4, and the plasma full size specimen 1, failed in a brittle manner. A typical Grade 50 ¾” plate specimen failure is shown in Figure 4.52. The cracks started where the punched wall of the hole met the plasma cut side of the hole. Consequently the two cracks which joined between the cracks do not allow the material between the holes to yield. However, even without the yielding of the holes the elongation of Grade 50 ¾” plates with slotted holes was larger than with the drilled holes.

One would expect that since the holes are longer, because of the yielding of the critical sections the elongation will be more than the elongation of the round holes which have only one critical section—one section that can yield. Interestingly enough, that is not true for the ¾” plates, in which most of the slotted holes have less elongation than the drilled holes. Most of the values of the elongation of slotted holes are between the values for the punched holes and the drilled holes as can be seen in Figure 4.53 and in Figure 4.54. In Figure 4.55, however, it can be seen that most of the specimens have higher elongation than the drilled holes. There is no explanation why there was a difference in the behavior between different heats of steel.

Figure 4.52: Brittle fracture of punched plasma Grade 50 ¾” plate

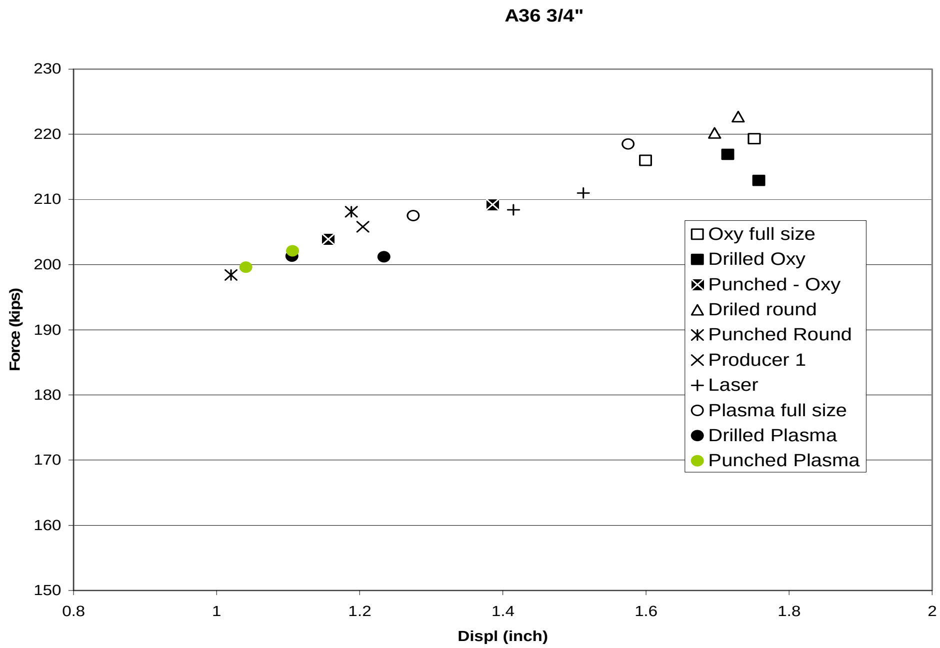

Figure 4.53: A36 Steel ¾" thick plate

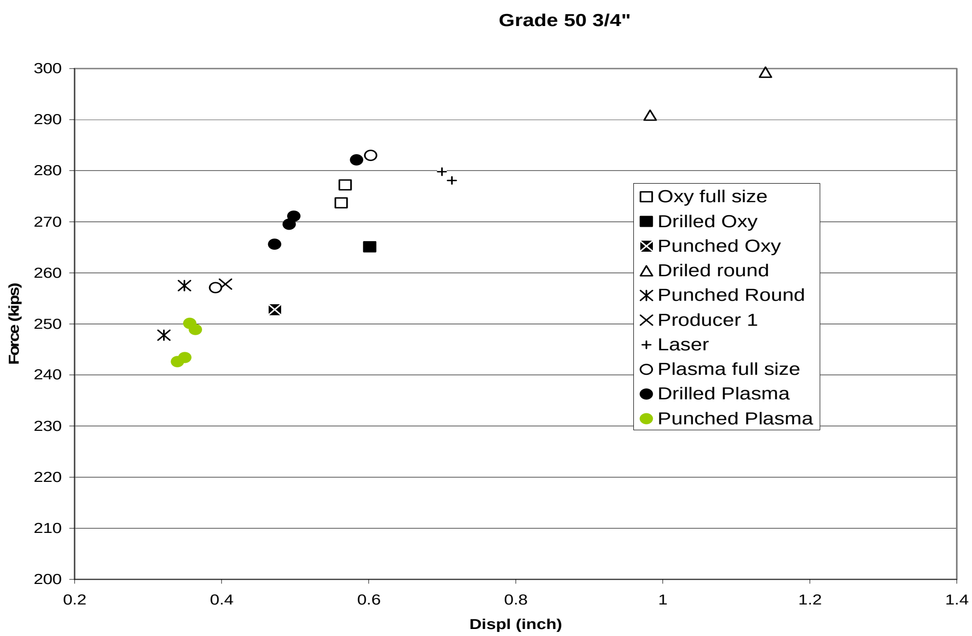

Figure 4.54: Grade 50 Steel ¾" thick plate

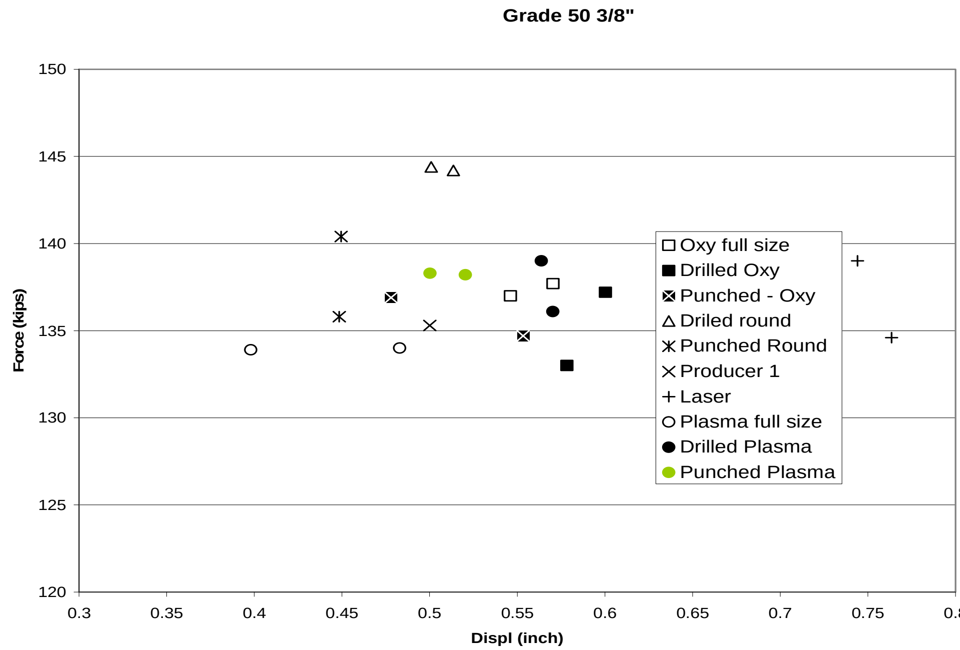

Figure 4.55: Grade 50 Steel 3/8" thick plate

The graphs above, show that the strengths of the slotted holes are bounded by the drilled and punched holes for the thick steel plates. For Grade 50 3/8" plates the strength in some case is lower than the punched holes.

From all the tests that were done and analyzed several conclusions can be made:

- The strength and elongation of the slotted holes are in between values for the punched and drilled
- long slotted punched full size holes from Producer 1 have strengths equal to and as much 10 percent more ductility than punched round holes
- short slotted holes have the same strength and 5 % more elongation when compared with the punched round holes
- oxy-act cut holes have better behavior than plasma cut holes, especially for the thick ¾" plates
- holes made only by oxy-act and plasma cut are better than the combination of punched or drilled ends with oxy- or plasma-cut slots between them
- laser cut holes, although having better surface appearance than the other slotted holes, have the same average strength

4.12 FATIGUE BEHAVIOR OF NON-LOADED BOLTED CONNECTIONS

The test matrix and corresponding fatigue test results for each specimen listed in Table 4.61. Note that for plate thicknesses up to 1.0 inch, both punched and drilled holes were tested. However, only one specimen with or without a gusset plate in each thickness up to 1 inches was tested with a drilled hole. For plate thicknesses 1.25 inches or greater, only specimens with drilled holes were tested due to the limitations to punch holes in thicker plates.

The in both sets of specimens the fatigue failure occurred at either of the outer holes. For the specimens with gusset plates, the crack initiated on one side of the hole, perpendicular to the longitudinal axis of the specimen (3 and 9 o’clock position) and maximum concentrated stress field around the hole. Figure 4.56 provides a view of the fracture surface typical for the specimens without a gusset plate. For specimens with gusset plates, the crack initiation location was influenced by the plate thickness. For the thinner plates, the crack initiated off the perpendicular plane, more toward the end of the gusset plate. This crack orientation is shown in Figure 4.57 for Specimen B-4. With increased plate thickness, crack initiation shifted back to the 3 and 9 o’clock position as shown in Figure 4.58.

Figures 4.59 through 4.64 show the test data on typical stress range versus number of cycles to failure (S-N) plots with AASHTO Fatigue Categories B, C, and D. As expected, the use of a bolted gusset plate improved the fatigue strength for each of the base plate thicknesses tested. For the punched hole specimens, the percent change in fatigue life improvement is skewed, however, by the fact that the fatigue strength increases with increasing plate thickness for the specimens without gusset plates. This increase in life with plate thickness can be seen by comparing the date in Figures 4.59 and 4.62. Therefore, fatigue life improvement was greatest with the 0.5-inch thick specimens. Additionally, it was the 0.5-inch thick bolted specimens that provided fatigue lives greater than 3 million cycles.

Table 4.61. Test Matrix and Results for Fatigue Behavior of Non-Loaded Bolted Connections.

Specimen Number	Hole Type	Gusset Plate	Cycles to Failure	Comment
0.5-inch Plate Thickness				
A-1	Punched	No	356,108	
A-2	Punched	No	346,620	
A-3	Punched	Yes	>4,747,100	Runout – No Failure
A-4	Punched	Yes	3,079,188	
A-5	Punched	Yes	>3,121724	Runout – No Failure
A-6	Drilled	No	297,421	
A-7	Drilled	Yes	1,784,822	
0.75-inch Plate Thickness				
B-1	Punched	No	543,476	
B-2	Punched	No	459,865	
B-3	Punched	Yes	1,790,467	
B-4	Punched	Yes	2,341,235	
B-5	Punched	Yes	2,905,333	
B-6	Drilled	No	422,324	
B-7	Drilled	Yes		Grip/Edge Failure
1.0-inch Plate Thickness				
C-1	Punched	No	992,083	
C-2	Punched	No	881,277	
C-3	Punched	Yes	1,098,730	
C-4	Punched	Yes	1,869,055	
C-5	Punched	Yes	1,613,510	
C-6	Drilled	No	220,773	
C-7	Drilled	Yes		
1.25-inch Plate Thickness				
D-1	Drilled	No	386,019	
D-2	Drilled	No	591,320	
D-3	Drilled	Yes	2,357,537	
D-4	Drilled	Yes	963,243	
D-5	Drilled	Yes	1,217,707	
1.5-inch Plate Thickness				
E-1	Drilled	No	447,947	

E-2	Drilled	Yes	834,448
E-3	Drilled	Yes	641,320
2.0-inch Plate Thickness			
F-1	Drilled	No	499,605
F-2	Drilled	Yes	616,880
F-3	Drilled	Yes	771,105

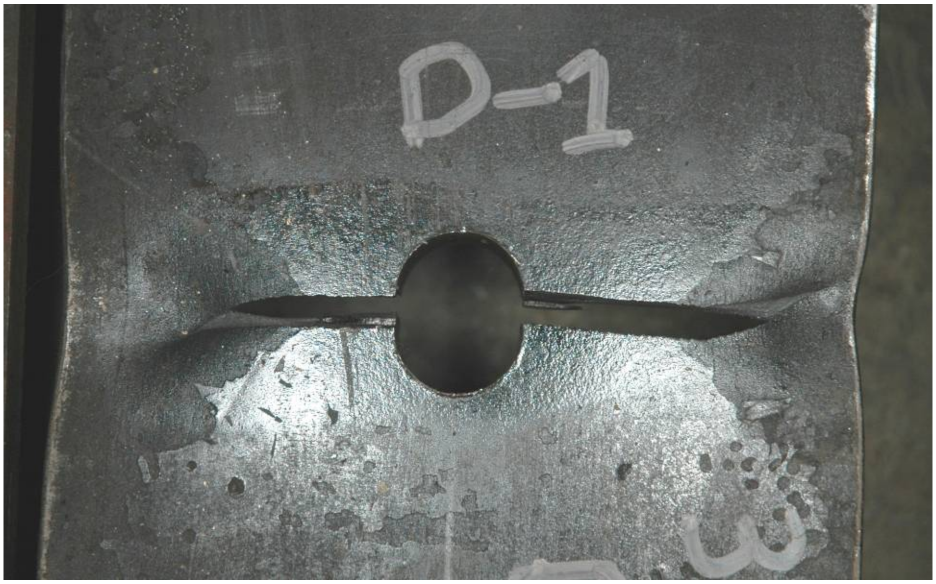

Figure 4.56 Typical Crack Orientation for Specimens with Bolted Gusset Plate (Specimen D-1)

Figure 4.57 Typical Crack Orientation for Thin Plates (<1.0 Inches) with a Gusset Plate (Specimen B-4)

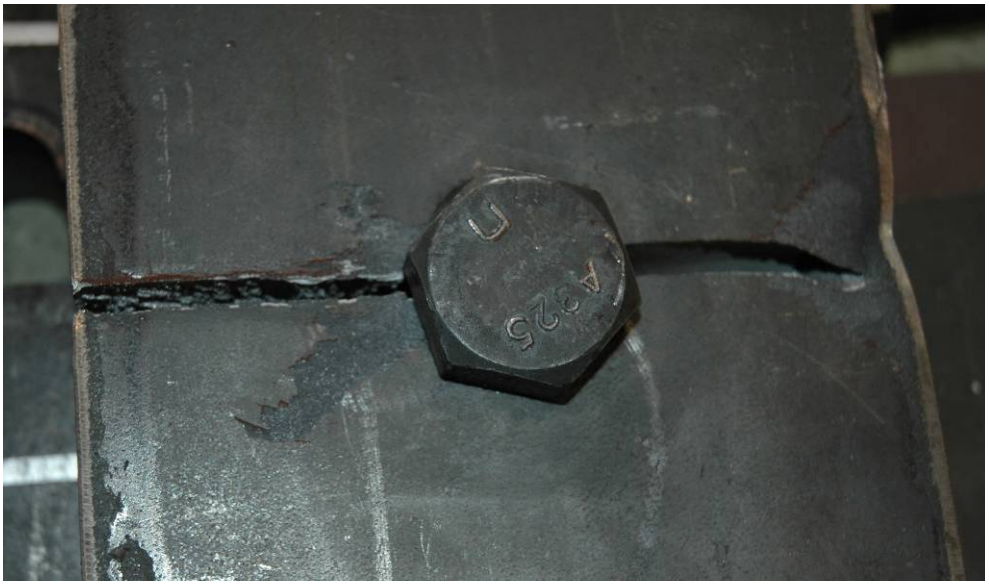

Figure 4.58 Typical Crack Orientation for Thick Plates (≥1.0 Inches) with a Gusset Plate (Specimen E-3)

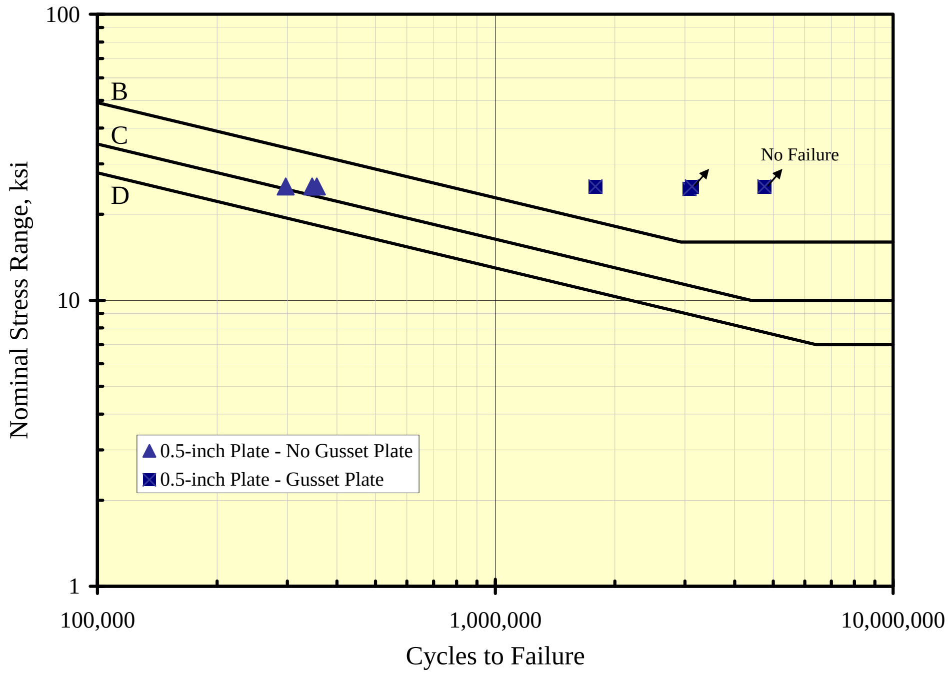

Figure 4.59 Stress Range vs. Number of Cycles to Failure for 0.5-Inch Thick Specimens

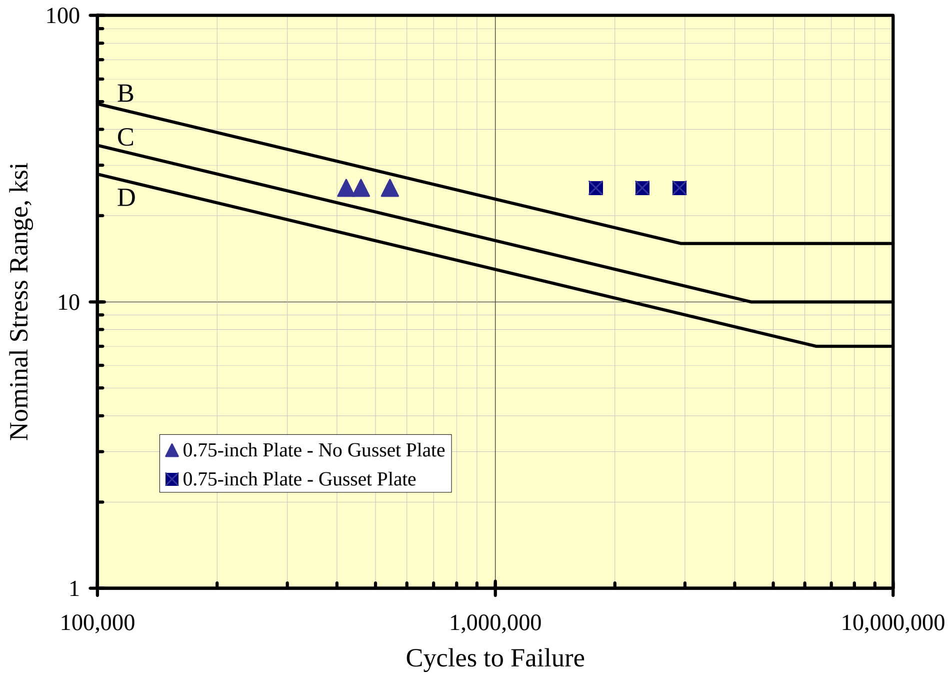

Figure 4.60 Stress Range vs. Number of Cycles to Failure for 0.75-Inch Thick Specimens

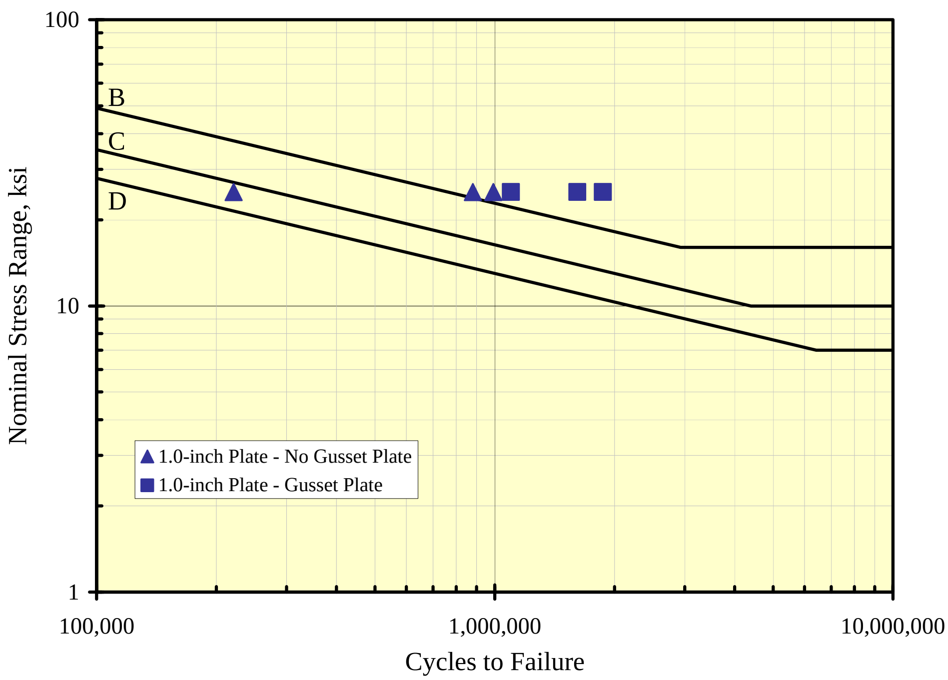

Figure 4.61 Stress Range vs. Number of Cycles to Failure for 1.0-Inch Thick Specimens

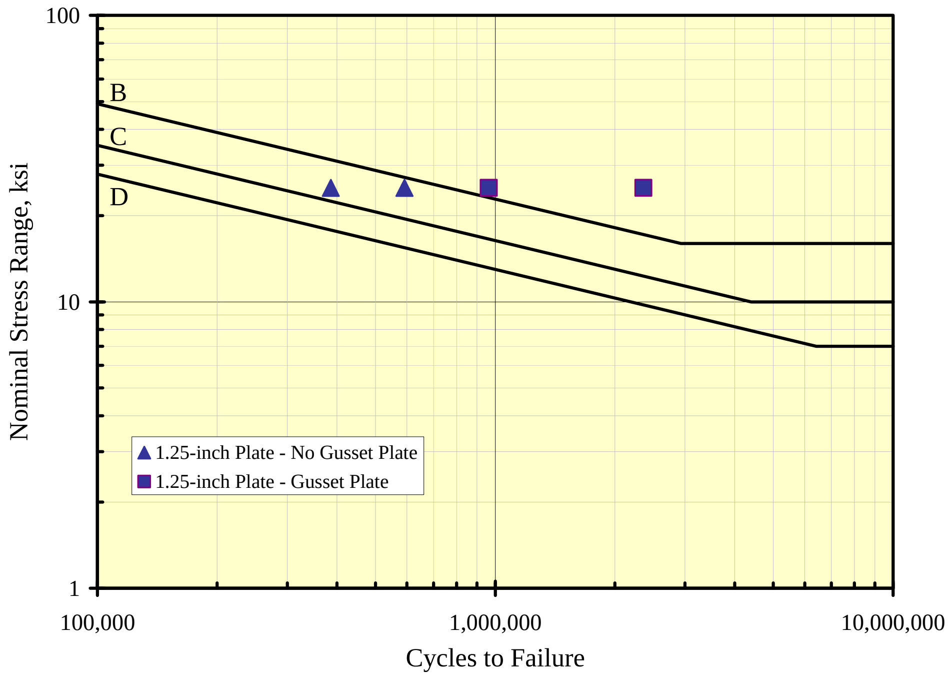

Figure 4.62 Stress Range vs. Number of Cycles to Failure for 1.25-Inch Thick Specimens

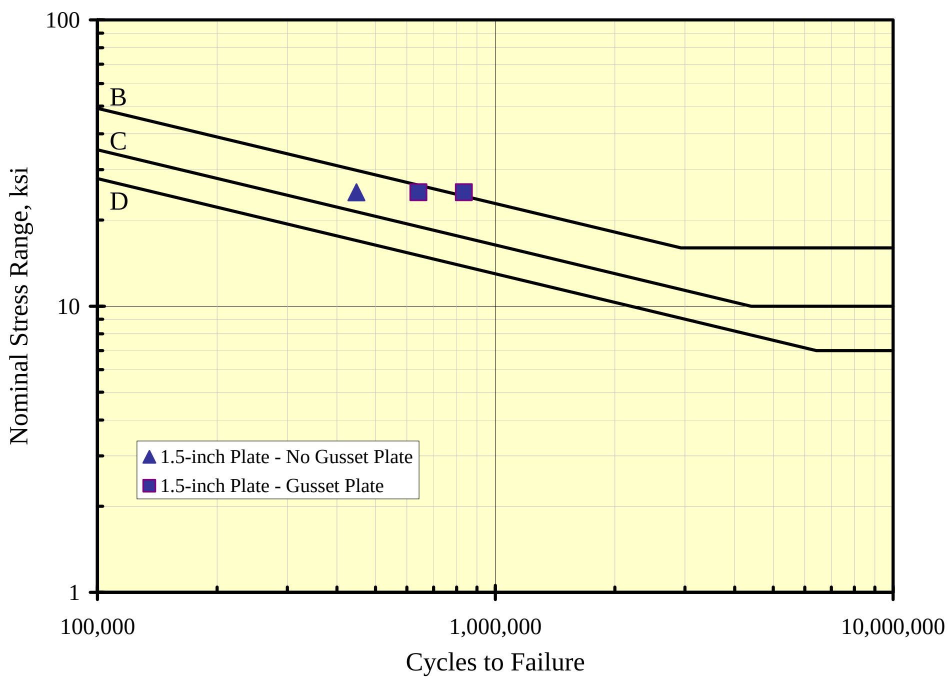

Figure 4.63 Stress Range vs. Number of Cycles to Failure for 1.5-Inch Thick Specimens

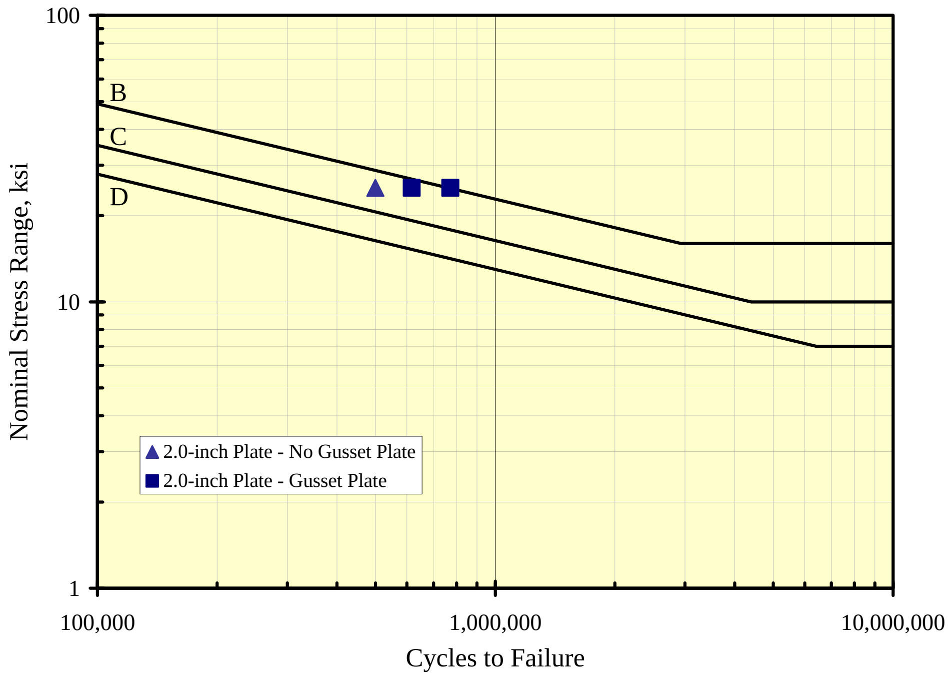

Figure 4.64 Stress Range vs. Number of Cycles to Failure for 2.0-Inch Thick Specimens

On average, there was no significant difference in fatigue life for the drilled hole specimens without gusset plates (Figures 4.62 through 4.64). All specimens resulted in fatigue lives that ranged between Categories B and C. The specimens with bolted gusset plates resulted in an increase in the fatigue life but not enough to achieve a fatigue strength defined by Category B. This reduction in fatigue life illustrates the influence plate thickness has on the fatigue behavior of non-loaded bolted connection details.

Chapter 5. Conclusions

5.1 Project Summary

Punched holes are commonly used in steel fabrication as a quicker, cleaner, and more cost-effective method of forming holes when compared to other fabrication methods. However, the use of punched holes is limited by practical considerations and banned by Specifications in certain instances.

To investigate the tensile and fatigue effects of punched holes in structural steel plates and connections, this project included the testing of 169 plate tension specimens, 38 plate fatigue specimens, 102 connection tension specimens, and 12 connection fatigue specimens. Of the 169 plate tension specimens, 50 drilled hole specimens were replicated with 50 punched hole specimens (100 total), allowing for a direct comparison. A similar set of 50 replicate slotted hole specimens was tested to compare with the drilled and punched round hole specimens. The plate tension tests used several grades and thicknesses of steel. Of the 102 connection tension specimens, 51 drilled hole specimens were replicated with 51 punched hole specimens (102 total). Both bearing-type failures and block-shear-type failures were investigated. Most connection specimens used snug bolts, while several used pretensioned bolts, with several grades and thicknesses of steel tested. Examples of the hole quality of multiple punched hole sizes through multiple grades of steel with different die clearance values are presented in Lubitz (2005), Brown (2006), and Cekov (2006).

Plate Tension Test Results

- The method of hole making (punched or drilled) showed the most influence. Punched hole specimens had strengths 5% to 12% lower than replicate drilled hole specimens. Punched hole specimens also had displacement amounts 20% to 70% lower than replicate drilled hole specimens.
    - All drilled hole specimens had experimental strengths exceeding the predicted design strengths, while 38% of punched hole specimens did not reach the predicted design strength.
    - Sub-punching and reaming a hole produced behavior similar to a drilled hole. Punch and die clearance amounts showed no significant influence.

Differences between the methods of drilling holes (with new drill bit or with worn drill bit) were only significant in fatigue performance.

- The grade of steel used also showed significant influence. A36 specimens on average had strengths 7% lower than equivalent A572 Grade 50 specimens. Displacement amounts on average were 25% lower in A36 specimens compared to equivalent A572 Grade 50 specimens. Differences between punched and drilled hole performance were also larger in A36 specimens than A572 Grade 50 specimens.
- Variables found to cause no significant affect on plate tension performance included hole size, plate thickness, punched hole quality, drilled hole quality, edge distance, edge fabrication method, and galvanizing.
- The slotted hole tests revealed the following:
    - Slotted holes made with all the techniques had strength and ductility that was slightly better than plates with punched round holes but less than plates with drilled round holes.
    - Punched slotted holes behave similarly to punched round holes in terms of strength and elongation
    - Oxy-act-cut holes have better behavior than plasma cut holes, especially for the thick plates
    - Holes made only by oxy-act and plasma cutting are better than the combination of punched or drilled end holes joined by either oxy-act or plasma cut.
    - Laser-cut holes were no better than the holes made by other methods even though they had much smoother and more uniform surfaces.
    - Slotted holes made by punching holes at both ends and then using oxy-act between the holes have less fatigue life than the punched holes.

Plate Fatigue Test Results

- Punched hole specimens had much lower fatigue lives compared to drilled hole specimens, and it was possible to drill a hole with a poor enough quality to significantly affect fatigue life.

    - Specimens with sub-punched and reamed holes and holes drilled with a new drill bit had the longest fatigue lives, with many runout specimens well above a Category B design limit.
    - Specimens with holes drilled with a worn drill bit often had fatigue lives similar to punched hole specimens, below a Category B limit and above a Category C limit.
    - Other research data has shown a similar difference between hole types, with many punched hole specimens with fatigue lives below a Category B limit and above a Category D limit.
- Galvanized plates with punched holes had very poor fatigue performance. Their fatigue life of galvanized plates with punched holes was at the lower limit of fatigue Category D. The galvanized plates with drilled holes were comparable to the punched holes in ungalvanized steel.
- The fatigue life of slotted hole specimens was comparable to specimens with punched round holes.
- Other variables such as steel grade, punched hole quality, edge distance, and hole size showed little noticeable influence on fatigue life.

Connection Tension Test Results

- Punched hole specimens had a 5% to 10% reduction in strength compared to replicate drilled hole specimens. Punched hole specimens also had displacement amounts 20% to 50% lower than replicate drilled hole specimens.
    - However, all punched hole specimens had experimental strengths exceeding predicted design strengths.
    - The performance of a specimen with holes drilled with a worn drill bit was equal to that of a specimen with holes drilled with a new drill bit. The differences between holes punched with varying die clearance amounts was also determined to be negligible.
- The grade of steel again showed a significant influence. The differences between punched and drilled hole specimen strength were larger in A36 specimens, while overall strengths on average were 5% lower in A36 specimens compared to A572 Grade 50 specimens. Also, displacement amounts on average were 25% lower in A36 specimens compared to A572 Grade 50 specimens.

- The use of pretensioned bolts was shown to remarkably increase the experimental strength of both the punched and drilled specimens due to the extra capacity from friction. The difference between punched hole performance and drilled hole performance was also found to decrease due to the influence of the pretensioned bolt.

Connection Fatigue Test Results

- Slip-critical-type connections had significantly longer fatigue lives than bearing-type connections, regardless of hole type.
    - The slip-critical type connections were determined to have a fatigue detail Category B, consistent with past research data.
    - Bearing type connections were determined to have a fatigue detail Category C, regardless of hole type.
    - The fatigue performance of a plate with an open hole, especially a punched hole, was determined to be similar to a bearing type connection.

Non Load Carrying Gusset Results

In reviewing the experimental data for the non-loaded bolted connections, the following observations and conclusions can be summarized:

- The fatigue strength of bolt holes increased with installation of pre-tensioned high-strength bolts.
- The fatigue strength of bolt holes with pre-tensioned high-strength bolts decreased with increasing plate thickness.
- The fatigue strength of bolt holes with pre-tensioned high-strength bolts was equal to Category B for plates up to 1.25 inches thick. The thicker plate fatigue strength was showed a smaller increase with the addition of the tightened bolt. The fatigue strength of the thicker plates with pre-tensioned high-strength bolts was equal to Category C.

5.2 Design and Construction Specification Considerations

Recommended specification changes are presented in Appendix A of this report. The basis for these changes is given in this section.

Currently, AISC 2005 no longer has any limits on the use of punched holes, and AASHTO Design 2004 also makes no mention of punched hole use. Strength equations, resistance factors, and fatigue categories are independent of hole type. However, AASHTO Construction 2004 has thickness limit restrictions and location restrictions.

Punched holes should not be allowed in connections that require ductility, as punched hole displacements from both the plate and connections tests at times were more than 50% lower than replicate drilled hole specimens. AASHTO Construction 2004 states that full-size punched holes are allowed in field connections, but not in connections for primary members. Thus the current restrictions banning punched hole use in primary members seems justifiable. However, the wording of AASHTO Construction 2004 should be changed to specifically state that punched holes are not allowed in primary members.

Also, practical limits on punching holes through thick plate limits punched hole use to thinner members, as punching large holes through thick plate requires very large forces. The current AASHTO Construction 2004 limit on the thickness of material that can be punched is dictated by punch equipment capacities. This was the stance taken by AISC in changing provisions from the 1999 Specifications to the 2005 Specifications. The 2005 Specifications removed any limitations and acknowledged that previous thickness limitations were controlled by common practice and equipment capabilities. Thus, the limitation on punched hole use based on thickness limits for different grades of steel in AASHTO Construction 2004 can be removed.

AASHTO Construction 2004 also has a provision limiting punch and die clearance amounts to 1/16 in. maximum. From both the tension and fatigue test results on plates and connections, the die clearance amount showed no significant effect on performance. However, a small die clearance amount has a detrimental effect on tool life and increases the work required to punch the hole. The amount of die clearance also affects the appearance of the punched hole, as a larger clearance results in a hole that flares outward at the bottom. Violating the general rule of thumb that the smallest hole diameter that can be punched is equal to the thickness of the material did not significantly affect performance, but a large decrease in tool life is expected. Therefore, the die clearance values used in fabrication and the minimum punched hole diameter should follow manufacturer recommendations.

From the results of the comparisons between the two bearing strength equations presented in AISC 2005 ($R_n = 1.2L_ctF_u \leq 2.4dtF_u$ versus $R_n = 1.5L_ctF_u \leq 3.0dtF_u$), the use of the 1.5 multiplier for bearing strength when deformation is not a design consideration did not provide a lower bound to the test results. From the results of this project and comparisons with other research data, many of the bearing specimens had experimental loads that did not reach the load predicted by the larger bearing strength equation. This was especially true for punched hole specimens in A36 steel, which had an average multiplier of 1.37. The larger 1.5 multiplier is not included in AASHTO 2004. Therefore, it appears justifiable to remove the larger bearing strength equation from AISC 2005.

The block shear rupture resistance equations in AASHTO 2004, (If $A_{tn} \geq 0.58A_{vn}$, then $R_r = \phi_{bs}(0.58F_yA_{vg} + F_uA_{tn})$, otherwise $R_r = \phi_{bs}(0.58F_uA_{vn} + F_yA_{tg})$), overestimated the capacity of several of the connection tension specimens. The shear fracture-tension yield mode predicted by AASHTO did not match the experimental failure mode, shear yield-tension fracture. Data compiled by Grondin and Kulak (2002), and Driver et al. (2006) has shown other shortcomings to the AASHTO 2004 equations, which were very similar to the block shear strength equations that appeared in AISC 1999. The shortcomings of these equations were enough to warrant a change in the block shear strength equations for AISC 2005 ($R_n = 0.6F_uA_{nv} + U_{bs}F_uA_{nt} \leq 0.6F_yA_{gv} + U_{bs}F_uA_{nt}$). The results from the connection tension tests agreed with the AISC 2005 equations. Thus, a change to AASHTO 2004 is recommended.

Current AASHTO and AISC Specifications require a 1/16 in. addition to hole diameter in the calculation of the net section, regardless of hole type. AISC 2005 commentary for Section D3.2 states the following: "Because of possible damage around a hole during drilling or punching operations, 1/16 in. (1.5mm) is added to the nominal hole diameter when computing the critical net area." For the plate tension specimens, it was shown that using a hole size addition of 10% was more consistent than a 1/16 in. addition to all hole diameters. However, the hole size addition to drilled hole specimens was unnecessary, as all drilled hole specimens without applying the 1/16 in. addition had experimental strengths well above predicted design strengths. The 10% addition was not large enough to adjust the experimental strength of all punched hole specimens above the predicted design strengths, especially the A36 punched hole specimens. An increase in hole size of 48% was required to produce strengths that matched the design equation predictions in all punched hole specimens.

The use of a hole size addition to punched hole diameter was also evaluated for the connection tension tests. The 1/16 in. addition required by AASHTO and AISC was not evaluated on drilled hole specimens, as all drilled hole connection specimens had experimental capacities well above predicted design capacities. The 10% addition to hole diameter was large enough to bring the performance of the punched hole specimens equal to the performance of the drilled hole specimens. This was only true in the A572 Grade 50 specimens, as the difference between punched hole specimens and drilled hole specimens in A36 was larger.

Therefore, one option to account for the reduced strength of members with punched holes would be to require a 10% or greater addition to hole diameter. This addition would only be necessary for members with punched holes.

Another option would be to apply a reduction factor for instances when punched holes are used. Both the plate tests and connection tests showed punched holes had strengths 5% to 15% lower than replicate drilled hole specimens. Chesson and Munse (1963) suggested a 7/8 multiplier to tensile stress when punched holes are used. Even though this suggestion was on older and lower strength steel, this multiplier is still in an acceptable range. Lubitz (2005) suggested a multiplier of 0.85, which brought 90% of the punched hole plate specimens to conservative levels compared to replicate drilled hole specimens and resulted in 95% of the punched hole specimens having experimental strengths greater than predicted design strengths. From the results of the connection tension tests, a multiplier of 0.90 on the punched hole specimens brought punched hole performance equal to or exceeding the performance of replicate drilled hole specimens. The 0.90 multiplier was larger than necessary for A572 Grade 50 specimens, but was required to cover the larger differences between punched and drilled hole connection specimens in A36 steel compared to A572 Grade 50 steel.

A multiplier 0.90 on punched hole strength would be in addition to regular resistance factors, or phi (ϕ) factors, currently used for strength calculations. The equations used to predict strength are calibrated from experimental results of specimens with drilled holes. The detrimental effects of punched holes compared to drilled holes should not be ignored, a 5% to 15% reduction in strength and often a 50% or greater reduction in displacement. These adjustments would also require the method of hole making be known in the design process. The recommended specification change is to limit punched holes to secondary members and to an additional strength reduction factor of 0.90 to be used when calculating the fracture strength on the net section and the block shear rupture strength of these members. It is also recommended that increase in hole diameter of 1/16 in. be eliminated when calculating these fracture limit states.

The fatigue strength of members with punched or slotted holes was in most cases less than plates with drilled holes. Galvanizing further reduced the fatigue strength. It is recommended that all open holes be classified as fatigue Category D. The influence of hole making upon fatigue performance diminished when they are used in connections with fully pretensioned bolts. However, no connection tests of connections with galvanized plates were undertaken. Based upon work by others, it is recommended that the fatigue strength of bolted connections in galvanized structures be taken as Category D until further study is undertaken. The predominant use of galvanized steel with bolted connection is the highway industry is for mast arms, traffic bridges, and other ancillary structures. The control of bolt tightening in these secondary structures is not as reliable as it is in bridges. Consequently, it seems prudent to not rely on the benefit in fatigue performance that results when the bolts are correctly pretensioned and to place these connections in Category D.

The fatigue strength of open holes left in structure after the removal of temporary members or from fabrication errors can be increased to Category B for thinner plates and to Category C for plates thicker than 1.25 inches by the installation of pre-tensioned high-strength bolts. It is recommended that the slight difference due to thickness of the plates can be ignored and the holes should be classified as Category D if no bolt is used or Category B if a pre-tensioned high-strength bolt (A325) is used in the hole.

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Appendix A. Recommended Specification Changes

AASHTO LRFD Bridge Construction Specifications Second Edition,2004:

1. Article 11.4.8.1.1 General

Delete: Current article.
Insert:
All holes for bolts shall be either be punched or drilled, except as noted herein. The width of each standard hole shall be the nominal diameter of the bolt plus 0.0625 in. The nominal hole diameter for metric bolts M24 and smaller shall be the bolt diameter plus 2 mm. For metric bolts M27 and larger, the nominal hole diameter shall be the bolt diameter plus 3 mm.

Material forming parts of a member composed of not more than five thicknesses of metal may be punched or drilled full size. When more than five thicknesses of material are joined or as required by Article 11.4.8.5, the material shall be subdrilled or subpunched and reamed full-size or drilled full-size while in assembly. When required, all holes shall be either subpunched or sub drilled 3/16 in. (5mm) smaller and after assembly reamed or drilled to full size.

Holes in members of cross frames and lateral bracing between girder and transverse connection plates maybe punched full size. All other punched holes must be subpunched and reamed full size, including the holes for the connection of the cross frames and lateral bracing to flange or web girders or other main members.

2. Article 11.4.8.1.2, Punched Holes

Delete: "The diameter of the die shall not exceed the diameter of the punch by more than 0.0625 in. (1.5mm)."

3. Article 11.4.8.5, Preparation of Field Connections

Delete: "Holes in all field connections and field splices of main member of trusses, arches, continuous-beam spans, bents, towers (each face), plate girders, and rigid frames shall be subpunched or subdrilled and subsequently reamed while assembled or drilled full-size through a steel template while assembled."

Insert: Holes in all field connections and field splices of main member of trusses, arches, continuous-beam spans, bents, towers (each face), plate girders, and rigid frames shall be subpunched or subdrilled and subsequently reamed while assembled or drilled full-size through a steel template while assembled. Holes in transverse connection plates maybe punched full size.

AASHTO LRFD Bridge Design Specifications 2004:

1. Article 6.5.4.2

Add definition for R_p after ϕ_u

Punched hole reduction R_p = 0.90 if the hole is permitted to be punched full size
=1.0 if hole is required to be drilled or reamed to full size.

2. Article 6.6.1.2.3- Table 6.6.1.2.3-1

Add the following bullets to Mechanically Fastened Connections:

• At gross section of connections with A307 bolts	D
• At gross section of a member with empty holes	D
• At net section of high strength bolted connection in galvanized members	D
• At gross section of a member with holes not part of a connection, with pretensioned high strength bolt installed	B

3. Article 6.8.3

Delete second sentence: “The width of each standard bolt hole shall be taken as the nominal diameter of the bolt plus 0.125 in. The width deducted for oversize and slotted holes, where permitted in Article 6.13.2.4.1, shall be taken as 0.0625 in. greater than the hole size specified in Article 6.13.2.4.2.”

Insert: The width of each standard bolt hole shall be taken as the nominal diameter of the hole. The width deducted for oversize and slotted holes, where permitted in Article 6.13.2.4.1, shall be taken as the hole size specified in Article 6.13.2.4.2.

4. Article 6.8.2.1

Equation 6.8.2.1-2 insert ϕ_p for reduction for punched holes

$P_r = P_{nu} = R_p \phi_u F_n A_n U$ (6.8.2.1-2)

Add definition for ϕ_p:

R_p = reduction for punched holes in bracing connections as specified in Article 6.5.4.2

5. Article 6.13.4

Delete equations 6.13.4-1 and 6.13.4-2 and replace with:

$$R_r = R_p \phi_{bs} (0.58 F_u A_{vn} + U_{bs} F_u A_{tn}) \leq R_p \phi_{bs} (0.58 F_y A_{vg} + U_{bs} F_u A_{tn}) \qquad (6.13.4\text{-}1)$$

Add the following definitions below the equations:

U_{bs} = 1 where the tension stress is uniform.
U_{bs} = 0.5where the tension stress is non-uniform.
R_p = reduction for punched holes in bracing connections as specified in Article 6.5.4.2